Review of grain harvest bag technology under Australian conditions

A comprehensive analysis and field evaluation of harvest bag technology: incorporating a review of hermetic and temporary storage, control of insects and fungi, and preservation of grain quality, under typical Australian storage and handling conditions

J.A. Darby and L.P. Caddick

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1. EXECUTIVE SUMMARY

Harvest bags are a polymer membrane based grain storage system that is being increasingly adopted by grain growers across Australia. The system is very cost competitive in comparison to other storage options but concerns over grain spoilage, contamination, insect control and out-turned processing quality are held by several industry stakeholders. In response, the GRDC and CSIRO undertook a project to evaluate the limitations and risks of this technology under Australian conditions, while also investigating its potential. This Technical Report describes the results of this analysis, providing harvest bag users with a detailed evaluation of the likely performance of the system under Australian conditions.

More specifically, this report explains the risks and limitations of harvest bag technology and makes a series of recommendations to achieve reliable outcomes. The report is written as a reference document to provide the basis for technical debate on this technology as its presence increases in Australia, while enabling the reader to address his/her interest without having to read the entire document. Insect control issues are analysed in depth with options presented to address the current lack of disinfestation capability; noting that the use of harvest bags as a hermetic system for dry grain is discredited. Grain spoilage and conditions for mould growth in grain, and end user quality outcomes for cereals, are defined. A summary of practical steps to achieve effective storage performance in scenarios realistic for use of harvest bags are included.

These limits and recommendations were developed from three components which form the basis of the report. Firstly, an extensive and critical review of the scientific literature was performed to define the underpinning science of harvest bags; hermetic storage, insect control, mould prevention, and grain processing quality. Secondly, the performance of harvest bags “on-farm” was evaluated with 1) field studies undertaken during 2005 to 2007 seasons, 2) harvest bag trials in Argentina and 3) the performance of bunkers in Australia. Finally, previously unpublished CSIRO data on mould growth rates and end user processing quality changes in cereals stored under dry conditions typical of Australia is presented to enable specific mould and quality recommendations to be made.

Overall, the harvest bag system offers farmers a low investment storage system that can be quite effective on farm in several scenarios. This is primarily a result of the integration of dedicated grain loading equipment with the low capital cost polymer bags. This factor provides a big advantage over other low cost or temporary storage options for growers (e.g. pit or farm bunker storage) which present many handling problems.

A major broadly applicable benefit is that harvest bags provide a “harvest buffer” storage option, which is cost effective and safe for growers to efficiently manage the harvesting and storage interface. This enables growers to optimise their harvest operations to avoid inflated costs and bottlenecks involved with delivery to commercial storage receival points, and deliver good quality grain within 3 to 4 months of harvest.

Limits occur in several ways. Harvest bags are prone to localized grain spoilage due to moisture ingress at leaks and accumulation of condensation. Preventing punctures and tears requires good loading skills, appropriate preparation of sites, protection from wildlife and regular inspection and maintenance of membrane. Localized condensation on the inside of the bag film is an inherent problem, especially in cool regions or times of the year and with marginally dry grain (e.g. 12% wheat). These issues could be addressed by implementing standardized inspection procedures and/or pressure tests to prove the integrity of bags. Such methods are cost effective and easily adopted to facilitate confidence in the use of bags commercially.

Effective hermetic conditions claimed for insect control, quality maintenance and high moisture harvesting are not being achieved with current practices, and are not likely with dry grain typically harvested in Australia. Appropriate levels of gas-tightness are not being instigated on-farm and there
are inherent difficulties in maintaining a sealed system for storage over several months. The predominance of dry grain harvested in Australia essentially impedes the development of hermetic conditions, even where a high standard of gas-tightness is achieved.

An insect disinfestation capacity is currently lacking with the current harvest bag system due to the ineffective hermetic capability. However, a phosphine method could be readily developed with variations of existing technologies. A small fan-forced system is envisaged to ensure that adequate fumigant concentrations are achieved throughout a harvest bag store for sufficient time and in a safe manner, noting that the length of the bags and the lack of head-space restrict successful passive distribution of the gas through the grain. This would include implementation of gas-tightness testing common with other store types. This avoids admixture of tablets within the grain to achieve distribution which is a breach of trade requirements.

Storing winter cereals for 6 to 12 months for marketing flexibility reasons is a risk to end-user processing quality in some scenarios. Harvest bags incur greater risks than other store types as a relatively high proportion of the grain is held in a surface layer (daily thermal peripheral layer) that undergoes large moisture and temperature changes. In harvest bags, in excess of 18% of the grain experiences such changes compared to 4-9% with large capacity commercial stores. Conservatively, sound wheat stored in a non-punctured bag that meets a receival moisture limit (12%) is expected to maintain all processing quality parameters for 9-12 months storage. Non-dormant sound malting barley stored under the same constraints is considered at risk of losing germination. Specific scenarios can be addressed using the recommendations on safe storage limits for barley and wheat stored in harvest bags described in this Technical Report.

The recommendations contained in this report will facilitate the safe and effective use of current harvest bag technology under Australian conditions, while providing approaches to improve current inadequacies of the system. The Australian grain industry needs a reliable storage system offering lower costs and increased flexibility that meets modern production rates and increased quality demands to keep abreast of international competition. This study indicates that harvest bag technology, with improvements to address Australian cropping issues, can contribute to this need.

2. INTRODUCTION

Harvest bags are a plastic membrane based grain storage system that is being increasingly adopted by grain growers across Australia. The system includes a specialized polymer “bag” and dedicated grain loading equipment. The term “harvest bags” is colloquial and other terms are often used, e.g. “silo-bags” and “grain sausages”. However, the term harvest bag used in this report refers to systems aimed at grain storage as distinct from silage or forage.

Harvest bags have become a major on-farm grain storage option in Latin American countries, especially in Argentina where in excess of 20 million tonnes was stored per year in the 2005/06 and 2006/07 seasons. Harvest bags are manufactured in several countries, but an Argentinian product has spear-headed recent acceptance of these systems by growers in Australia, with an estimated 500,000 tonnes of grains stored in grain harvest bags during the 2005/06 season (Neil McAlpine, Swan Hill Chemicals Ltd, personal communication).

The GRDC and CSIRO have undertaken a project to determine the limits and risks of existing harvest bag technology under Australian grain production conditions. This includes investigating the potential of this technology to be improved or used more effectively to overcome any issues identified. Harvest bags have substantially different features to storage options traditionally used in Australia, including other membrane-based systems, such as bunkers or pit type storage. Furthermore, they are promoted as providing non-chemical insect control and grain quality management due to their capacity to create hermetic conditions; a new technology for Australian growers.
There are a series of benefits attributed to harvest bags based around improved harvest management, increased marketing opportunities, and non-chemical insect control. The primary attraction of harvest bags to Australian growers identified in a GRDC-funded survey completed in May 2006 was their comparatively low investment cost. A recent cost analysis by Holmes Sackett and Associates (Francis, 2006) found that harvest bags provide the most cost-effective storage option where a total of 1,500 tonnes of grain is stored in seven seasons out of a ten-year period (given the assumptions the Holmes Sackett analysis).

A popular benefit is improved harvest management, which is based on using harvest bag storage as an on-farm “buffer” management option to make cost-savings in cartage, contract harvesting and delivery logistics to centralized stores. Harvest bags are also claimed to allow storage of higher moisture grain increasing the harvest window. Increased marketing opportunities relate to capturing higher prices with alternative buyers or avoiding accumulating charges of centralized storage. The capacity of the harvest bag system to control insects by generation of a hermetic atmosphere was initially a strong marketing point. However, less emphasis is now being placed on this aspect.

The benefits attributed to the harvest bag system include:

- A low capital cost storage system
- A rapidly implemented system for opportunistic or marginal cropping
- Improved harvest logistics and associated cost savings
- Easily expanded storage capacity to accommodate crop size variations
- A well-sealed storage for insect, mould and quality control
- Cost effective segregation
- Safe storage of early harvested high moisture grain
- A user-friendly on-farm grain handling system compared to bunkers, pits, weld mesh bins
- No residual insect populations in store structure as new bags are used each season
- Storage management is not complicated

Along with these benefits, several concerns have been raised by stakeholders. On-farm, the relatively light membrane is perceived as fragile with limited ability to prevent punctures and any associated grain spoilage due to moisture ingress. Harvest bags are also likely to be more prone to grain contamination as a result of attack from a variety of animals, compared to Argentina and other Latin American countries. There are numerous anecdotal reports of extensive film damage occurring on Australian farms due to stock and wildlife. The claim of insect, mould and quality control via hermetic conditions is doubtful due to lack of gas tight conditions and the typical dry state of Australian winter crops. Growers could incur increased risk of failing insect trade standards as harvest bags do not readily offer other forms of insect control. However, harvest bags are a technology in progress in Australia and growers have been responding to some of the practical problems, including the construction of suitable protective fences and the use of synthetic netting to prevent bird damage.

Centralized grain storage/marketing companies hold concerns that harvest bags will increase the amount of low quality, infested or contaminated grain that reduces the value of the large grain stacks in which it is admixed. A substantial risk is seen in the “surface” grain adjacent to the harvest bag membrane will incur substantial heating during Australian summers with potential associated loss of quality. These companies see harvest bags incurring the quality problems encountered with bunkers, but in an increased manner as membrane based stores require substantial operational care and harvest bags are being managed by non-specialist storers.

These concerns were a key motivation for this project which involved both laboratory studies and field trials. Firstly, an extensive and critical review of the scientific literature was performed to define the underpinning science of harvest bags; hermetic storage, insect control, mould prevention, and maintaining grain processing quality. Secondly, the performance of harvest bags “on-farm” was evaluated with 1) field studies undertaken during 2005 to 2007 seasons, 2) harvest bag trials in...
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Argentina and 3) the performance of bunkers in Australia. Finally, previously unpublished CSIRO data on mould growth rates and end user processing quality changes on cereals stored under dry conditions typical of Australia is presented to enable specific mould and quality recommendations to be made.

This technical report describes the results of this project. It is written as a reference document with each section being fairly “stand alone” to enable the reader to address their area of interest without having to read the complete (large) document. In each section, a technical risk or issue is analysed and the relevant available scientific evidence presented and reviewed. This approach provides the basis for technical debate and further research. The final part of each section is an explanation of how the risk is incurred in typical Australian storage conditions. The reliable and safe use of current harvest bag technology in Australia is provided in terms of grain moisture and storage duration limits for various grain types, along with a series of recommendations to support such use. Gaps in the technical knowledge needed to define the risks are also identified. Summaries of the extensive data for field trial results and grain quality issues are included in the Appendices.

3. THE HARVEST BAG GRAIN STORAGE SYSTEM

In this section, the harvest bags system is described with a brief overview of the present use of this technology in Argentina and Australia. Costs associated with the use of harvest bags on Australian farms is discussed, with reference to a cost benefit study produced by Holmes Sackett and Associates (Wagga Wagga, NSW) in 2006. A summary of the data from CSIRO field trials that evaluated the use of harvest bags on-farm and in commercial use is provided in Appendix 11.1.

3.1. Description of the harvest bag system

Harvest bags are a grain storage system that consists of a specialized polymer bag and dedicated grain loading and extraction equipment. There is a range of grain handling equipment versions and Australian distributors are working closely with local and international manufacturers to improve the design and practicability of machinery for use in Australia. The bag loading and extraction equipment is based on augering the grain. The polymer bag is described as a hermetic type of storage system. They are seamless and with careful closure and sealing of the ends during filling, the bag provides an enclosure that acts as a barrier to gaseous exchange. The film is also stretched during filling as grain is compacted into the bags to remove “headspace” air from the sealed system and to minimise any slackness in the film, especially along the top.

The major manufacturers of harvest bags are located in Argentina, with IPESA Industrias por Extrusion SA (Ipesasilo®), PLASTAR Grupo de Empresas (Silobolsa®) and Inplex Venados (Agrinplex®), being the dominant producers of these plastic membrane systems. Harvest bags manufactured by these companies presently being used in Australia. Forage or silage type bags are also being manufactured in Argentina to store both wet and dry grains. Forage bags have different film characteristics and appear to be less well suited for the long-term storage of dry grains.

Dow-Polisur linear low density polyethylene is primarily used in the manufacture of the films used in Silobolsa® and Ipesasilo® bags. Other types of polyethylene and ethyl vinyl acetate are added to improve the elasticity of the films and UV stabilisers are also added. The triple-layer film is co-extruded during manufacture and a seamless bag is formed by liquefying the polyethylene using a gas-fired system. The manufactured film bag is soft, flexible and tough, even at low temperatures. The film comprises two black and an outer white layer, and the film thickness ranges between 235 – 250 microns. The addition of titanium dioxide coating to the outer white film provides additional UV protection.
The manufacture of harvest bags is a highly specialised process that is completed to stringent quality ISO 9000 standards to minimise any flaws in the formation of 60, 75 and 90 metre seamless bags. Folding the manufactured bags is critical to the overall field performance.

Separate equipment is used for loading and outloading the grain from the harvest bags. Inloaders are essentially a feed chute located above a large single high capacity auger that can fill bags directly from the header or chaser bin at a rate up to 300 tonnes per hour, depending on grain type. Side-loaders that improve the loading rate from trucks into the hopper system are proving to be popular on Australian farms and several locally based engineering works are manufacturing these units.

Extractors are a sweep-auger system and the plastic film is reeled in by the machine as the bag is progressively split down the middle and emptied. Any grain not picked up by the sweep auger is fed-back into the feed path as the bag is rolled up by the hydraulic drum. Extractors have a capacity to empty bags at a rate up to 180 tonnes per hour. The effectiveness of the extraction system is heavily reliant on the bag remaining intact during outturn. There are anecdotal reports of bags splitting down the middle when attempts were made to use an extractor. Several farmers have used mobile pneumatic vacuum systems to empty harvest bags. The extraction rate is less, but the unit has the utility to be used for other conveying operations on the farm.

3.2. Harvest bag use in Argentina

The use of plastic membrane type bags for grain storage has evolved steadily in Argentina, burgeoning from initial experiences in 1995 to in excess of 20 million tonnes of grain in the 2005/06 and 2006/07 seasons being held on farms and commercial enterprises. Farm storage of grains in Argentina includes the use of harvest and forage type bags, and there are dedicated handling machinery designed specifically for the different bag types. Their success has resulted in a rapid expansion in the use of these bags to store soybean, wheat, maize, sorghum, sunflower and other grain types. High moisture maize (22 -30% mc), for example, is routinely stored in harvest bags and dried to meet market specifications. An estimated 3,500 commercial drying facilities spread throughout the Argentinean grain belt facilitate drying of wetter grains and local intensive livestock systems provide a ready market.

A consistent packing density is important to the success of the harvest bag system and a specially designed loader is used. The inloading procedure removes much of the excess air as grain is auger fed into the bags using adjustable tension on brakes of the loaders to regulate film stretch. The manufacturers of harvest bags recommend ten percent stretching of the film when bags are filled. Many harvest bags have graduated markings on the side to enable users to obtain a uniform degree of stretch along the bag length. Apart from the displacement of air from the filled bag, stretching also avoids slackness in the film that may cause excessive localised build-up of condensation and associated grain spoilage.

The National Institute of Agriculture (INTA), Argentina, has extensively evaluated the storage of grains in harvest bags and established recommended “safe” storage limits for different grain types, which are listed in Tables 1(a) and 1(b). These recommended levels are dependant on a range of factors, including ambient temperature, initial grain condition at harvest (or inloading) and level of impurities.

INTA’s general guide to grains storage is that moisture levels must not exceed the accepted industry limits. The maximum industry moisture receival limits established for different grains are typically higher than limits set in Australia, but generally below the minimum moisture requirement for fungal growth.
Table 1(a) Risks for grain moisture content

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>Low*</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean, wheat**, maize</td>
<td>≤14%</td>
<td>14 - 16%</td>
<td>&gt;16%</td>
</tr>
<tr>
<td>Sunflower</td>
<td>≤11%</td>
<td>11 – 14%</td>
<td>&gt;14%</td>
</tr>
</tbody>
</table>

* Moisture content for seed storage should be 1 -2% lower
** Not recommended to store wheat at >14% mc for long period of time

Table 1(b) Risks for period of time of storage

<table>
<thead>
<tr>
<th>Grain Type &amp; moisture content</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>14% cereals &amp; 11% oilseeds</td>
<td>6 months</td>
<td>12 months</td>
<td>24 months</td>
</tr>
<tr>
<td>14-16% cereals &amp; 11-14% oilseeds</td>
<td>2 months</td>
<td>4 months</td>
<td>6 months</td>
</tr>
<tr>
<td>&gt;16% cereals &amp; &gt;14% oilseeds</td>
<td>1 month</td>
<td>2 months</td>
<td>4 months</td>
</tr>
</tbody>
</table>

Source: The National Institute of Agriculture (INTA), Argentina, 2006

3.3. Harvest bag use in Australia

A survey on the use of harvest bags in Australia was completed by Strategic Economic Solutions, Canberra, in May 2006. This survey gauged the current performance and level of acceptance of the system. The survey was carried out from October 2005 to mid-March 2006 and a total of 145 responses were collated during the survey period, including grain growers, traders and storers. A follow-up telephone survey was completed during April 2006 and 29 respondents assessed level of user satisfaction.

Broad conclusions drawn from the surveys were:

- Harvest bags were already well known amongst respondents to the survey. Favourable coverage in the rural press combined with past publicity is likely to contribute to the adoption of harvest bags by growers.
- The bags were not seen by the majority as a magic bullet for storage. It was recognised that problems were possible and some of these had occurred in the user group.
- The use of harvest bags was more difficult than portrayed in manufacturers’ brochures, but this was not an impediment. Hands-on-learning from loading and unloading bags was invaluable experience, and users were keen to share their experiences.
- Capital cost considerations were a major driver in using harvest bags, but grain-marketing considerations were the main motivator. There was recognition that harvest bags had potential to change the landscape of grain handling and storage, returning management of the harvest and subsequent sale to growers, with potential increased farm-gate returns.

A 2006 CSIRO field survey (Appendix 11.1) of commercial harvest bags at six months post-harvest showed the majority of bags were not sealed according to a three-minute half-life pressure test, and their was a general lack of knowledge amongst users regarding testing methods for determining gas-tightness. The majority of bags showed evidence of film damage, and punctures and small tears had resulted from a variety of causes, including wandering stock, foxes, rodents and birds, and the placement of bags directly onto stubble and poorly prepared ground. There was also evidence of mechanical damage caused during grain loading and ineffective closure of the bags ends.

Australian distributors of the bag system recommend preparation of a suitable base for siting harvest bags by clearing sharp and protruding objects from the ground, and providing drainage by preparing a raised pad. It was also observed in the CSIRO farm survey that a prerequisite for long-term storage of grains in harvest bags on Australian farms is the erection of a suitable strung wire fence around the site where harvest bags are sited. A simple fence is necessary to prevent wandering stock that can readily cause substantial damage. Electrification and the use of hexagonal mesh wire (buried into the ground) are likely to be required to prevent access by feral animals. The feral animal problem is not as
prevalent in Argentina. The need to provide such protection is a further cost imposition on Australian farmers for the harvest bag system.

Reports of low insect infestation in the field during seasons 2005/06 and 2006/07 suggests that a combination of the characteristics of the harvest bag system (providing a reasonably well-sealed enclosure and barrier to insect infestation) and positioning of bags in paddocks and locations well away from existing permanent grain store (reducing infestation pressure), are reducing insect problems. The relative dryness of the grains stored in harvest bags during the past two seasons would also substantially reduce the rate of development of insects when present. Several reports of insects located only in proximity to the ends of harvest bags where moisture levels are likely to be higher would support this suggestion.

3.4. Costs associated with harvest bag storage and comparison to permanent on-farm systems

On Australian farms, storage cost considerations, better harvest management and substantial savings in transport time and costs have been major drivers in using harvest bags, with the opportunity to market grain from the farm the main motivator. Harvest bags have been seen as having the potential to change the landscape of grain handling and storage, returning management of the harvest and subsequent sale to growers, with potential increased farm-gate returns.

3.4.1. Costs (capital and operational) and farm-gate returns

The cost of grain storage includes capital (including annual interest on the capital equipment and depreciation) and other overhead costs, operational and variable costs, and opportunity costs. The actual costs associated with the use of harvest bag will vary substantially between farms. Farm-gate returns will be dependant on many factors, including seasonal fluctuations in climatic conditions and market prices and trends.

Cost will be influenced by factors such as:
- Farm locality and proximity to a central receival grain site
- Capacity of on-farm permanent storage
- Use of owner or contract harvesting
- Use of owner or contract transport
- Site preparation (including grading and fencing)
- Use of owner or contract loading and/or outturn machinery
- Risk of quality loss and down-grading
- Management of harvest bags, including insect control

Cost will be off-set by factors such as:
- Availability of a flexible storage option without high capital investment
- Timeliness of harvest
- Proximity of harvest bags to harvest operations
- Lower transport costs associated with post-harvest haulage
- Marketing opportunities to increase farm-gate return
- Premiums for better quality grains
- Premiums obtained through segregation of quality and grade
- Opportunity to use contract harvesting
- Reduced reliance on contact insecticides and fumigants
- Avoidance of OH & S issues associated with on-farm silos
- Less stress and anxiety suffered during harvest period
The costs associated with the use of harvest bags are variable depending on whether the user purchases dedicated inloading and extraction machinery, or uses contractors for one or both operations. Preparation of the pad and site generally needs to be costed. Cost of fencing required to protect bags from damage from stock and wildlife can vary depending on the level of sophistication required and may require electrification. Netting to protect film against bird attack is likely to become a necessary part of harvest bag management, with anecdotal reports of cockatoos and crows (ravens) causing extensive damage at several sites in New South Wales and Queensland. Other inputs may include measures to control rodents and weed management.

3.4.2. Cost analysis by Holmes Sackett and Associates

An approximate costing of selected inputs are listed below and a number of these costs were used in a recent cost analysis by Holmes Sackett and Associates (Francis, 2006) that compared the cost benefit of three grain storage systems including grain storage bags, sealed silos and warehousing, to capitalise on (potential) benefits associated with post-harvest grain price increases.

- Harvest bags - 60 m @ $1,000; 75 m @ $1,200; approximates $4 - 6/t, depending on manufacturer and bag type, type grain stored and packing density
- Loading/extraction (contractor) $8 - 10/m
- Loading machinery $17,000 to 23,000
- Extraction machinery $22,000 to 25,000
- On-farm freight $2 - 3/t
- Cost of sideways freight farm to central receival site $15 - 20/t
- Out of harvest freight discount up to 30%
- Total transport (e.g. to port) may exceed $40/t
- Premiums (season 2005/06) $30 - 40/t within 2 - 3 months; with anecdotal reports from users of harvest bags of price advantages of up to $80/t

The analysis by Francis (2006) concluded that grain storage bags provide the most cost effective system where 1,500 t of grain is to be stored in seven out of ten years (given the assumption used in the analysis). The analysis was taken over a period of 30 years (i.e. perceived useable life of a steel-clad sealed silo), including 21 years of storage. Bagging and extraction machinery was assumed to have a useable life of ten years and needed to be replaced every ten years.

Small capacity silos provided the lowest net present value (NPV, the return on investment after all costs and benefits have been discounted and summed for the period of the analysis) due to the substantial capital outlay required to establish a total capacity to store a 1,500 t harvest. Large 250 t capacity silos decreased the capital cost per tonne, and increased net present value (assuming they are filled to capacity). Although NPV for 250 t sealed silos remained lower compared to grain harvest bags in all scenarios given in the analysis, this option approximated the NPV for bags when the price advantage for 1,500 t grain reached $30 per tonne. The initial capital outlay for this total capacity of sealed silos however was substantial and a likely disincentive for small-farming enterprises.

A major advantage identified in the analysis was the capacity to use grain bagging machinery to continue storing grain to harvest completion. Permanent silo capacity is finite and this limits returns generated from permanent structures, especially in good harvest years. Forward planning is required to ensure sufficient quantities of harvest bags are available to store the entire harvest (given this is the objective), and unused bags can be stored for use during the following harvest.

There were numerous anecdotal reports in the rural press during the 2005/2006 season of substantial financial benefits being obtained where the bag system was used to manage the harvest; then grain was sold off-farm within three to four months premiums in excess of $30 per tonne. In these cases, farmers were able to cover the cost of the loading and extraction machinery within one season.
A cost comparison based on less than ten years is likely to favour harvest bags to a greater degree, and farmers that cost storage options on a short-term basis will be attracted to this disposable system. The harvest bag system is likely to show considerable economic advantage in marginal cropping regions, where “bumper” grain crops are expected only every four to five years. Recent climatic trends suggest that exceptionally good harvests may be even less frequent in such marginal regions and the bag system may play an important role in harvest management during the years where the crop exceeds existing on-farm permanent storage facilities.

4. HERMETIC STORAGE

In this section, hermetic storage is defined, with a technical analysis of the contribution that different forms of biological respiration make towards the modification of a contained atmosphere. The standard of gas-tightness required to achieve hermetic conditions is defined and an assessment is made on the capacity of the harvest bag system to achieve and maintain this standard.

4.1. Definition

Harvest bags are promoted as a hermetic storage system which provides non-chemical insect control and prevents grain quality losses. A useful working definition for hermetic storage is “where the storage structure is sufficiently gastight to allow the internal atmospheric composition to be modified by biological conversion from oxygen to carbon dioxide through respiration of biota contained within the system” (Annis, personal communication). For grain storage, the biota is composed of the grain, fungi and any insects present in the grain.

The success of hermetic systems to control biological activity requires a high level of gas-tightness and a significant respiration rate from the biota contained within the structure. The level of gas-tightness determines the rate that air, thus oxygen, can ingress into a hermetic system. The rate that biological respiration converts oxygen to carbon dioxide creates the hermetic atmosphere, which is dependent on the moisture content and temperature of the grain. Also, carbon dioxide is adsorbed by grains at rates depending on grain type, moisture and temperature. The levels of oxygen and corresponding carbon dioxide within the sealed system are a balance of these rates.

As moisture and temperature can vary substantially throughout a stored grain mass, and leaks will be at the store boundary, hermetic systems are complex with atmospheres that vary with time and position in the store. Gas measurements taken from harvest bags at farm and commercial locations show variable levels of oxygen and carbon dioxide can be established at different parts of the bags (Appendix 11.1). The variable moisture and temperature condition of grain at harvest, the influence of diurnal heating and cooling, the gradual decline and increase of temperatures across the grain profile, and the presence or absence of insect infestation, all contribute to variable gas composition that is difficult to predict.

In a system sealed to an acceptable standard of gas-tightness, the change in the composition of the contained atmosphere requires significant biological activity and/or long storage periods. This is often associated with higher moisture grain or very gas-tight structures. Where dry grains are stored, the conversion of oxygen to carbon dioxide can be a very slow process and the continual leakage of oxygen into the structure can preclude the system from achieving hermetic conditions during long-term storage.

4.2. Biological respiration

Biological respiration is required to create hermetic conditions. Biological respiration in air by grain and fungi consumes oxygen and produces carbon dioxide, water vapour and heat according to the
following equation. The production of moisture and heat illustrates how biological respiration can be a self-promoting process if the heat and moisture is not quickly dispersed.

\[ C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + 2835 \text{ kJ} \]

4.2.1. Apparent grain respiration

Many studies have been conducted investigating the capacity of grain to heat due to respiration. These studies indicate the capacity of grain to convert oxygen and carbon dioxide according to the respiration equation above. A lot of this effort focused on the relative contributions of seed and microfloral respiration causing self-heating of wet grain (0.75-0.95 Aw; 15 - 35°C) under conditions where moulding was not obvious.

Hyde & Oxley (1960) reported that the rate of respiration for wheat stored at 14% mc and 15°C was low and levels of only 2% CO2 were measured after 18 months storage. Milner et al (1947a) showed that carbon dioxide (CO2) was produced (at 30°C) by grain respiration and fungi growth increased when wheat was stored above 15% mc. However, moisture levels in excess of 18% moisture content were required to achieve rapid acceleration of the respiration rate and fungi were the more important contributors to total carbon dioxide production in the closed system. Milner et al (1947b) used a suitable mould inhibitor to isolate this contribution to respiration and at 20% mc and 35°C only 24 mg of carbon dioxide was produced per 100 g of wheat, a factor of ten lower than when the inhibitor was not used. Milner & Geddes (1954) showed that seed respiration is minor compared to microfloral heating with energy contributions of only 5 to 15%.

The respiration of dry grain has proved difficult to quantify and many early studies failed to distinguish the influence of fungi from seeds on the observed oxygen consumption rates. The cause of respiratory heat in stored drier grain has been well researched and the production of heat and carbon dioxide under favourable moisture conditions is predominantly produced by microflora. Where grain conditions are too dry for microflora to grow, the rate of carbon dioxide production is negligible. Fleurat-Lessard (2002) concluded that in most storage situations, when grain moisture is below 14% (wb), the release rate of carbon dioxide is very low and not practically measurable.

In practice, fungi is ever-present on grain and the “apparent grain” respiration rate which includes both fungal and grain respiration contributions, converts oxygen to carbon dioxide to create hermetic conditions if oxygen ingress is comparatively low. As fungal activity is the major conversion agent, defining the grain conditions that control fungal growth is a key factor with moist grain. These conditions are described in section 6. Where dry cereal grains are stored in a gas-tight system and the grain is not infested, the rate of atmosphere modification by grain respiration alone is expected to be negligible; however, cumulative changes will occur over several months. It was observed from ABB Grain Ltd. field trails sites at Bowmans and Roseworthy in South Australia during season 2006/2007 (Appendix 11.1) that freshly harvested dry grain can produce relatively high respiratory conversion.

The un-aerated storage of higher moisture grains is not common in Australia, except for summer cropping such as sorghum, rice and maize. High moistures and favourable temperatures accelerate the rate of modification of the atmosphere inside a harvest bag by aerobic respiration of endemic fungi and the stored commodity. Wheat stored at moistures above 18% can rapidly deplete oxygen from the internal atmosphere and oxygen ingress due to the presence of small leakage points is overcome without detriment to grain stored in the system. The likelihood of successfully creating a hermetic atmosphere increases with increasing moisture content. The storage of very wet grain is specifically aimed at feed for livestock, as the grain ferments to a degree due to anaerobic processes. Studies investigating the apparent respiration and creation of hermetic atmospheres of higher moisture grain are summarised in Appendix 11.3.
4.2.2. Insect respiration

Populations of stored grain insects will become the key driver for creating hermetic conditions in dry stored grain. A growing population will contain all development stages of an insect species (i.e. eggs, larvae, pupae and adults), resulting in significant respiration rates and oxygen conversion that increases over time in line with the population. Populations can grow in wheat when the relative humidity is as low as 45% (Beckett et al, 1994) for the major pest species, which is equivalent to 10.5% moisture content (wet basis) at 30°C. *Oryzaephilus surinamensis* (saw-toothed grain beetle) and *Rhyzopertha dominica* (lesser grain borer) are able to develop at an even lower relative humidity, with population increases observed at 35%; equivalent to 9.2% moisture content at 30°C (Beckett et al, 1994). In comparison, fungi cease development when relative humidity decreases below 68%, which at 30°C approximates moisture contents of 13.4 and 13.2% for wheat and barley respectively.

At higher moisture contents, populations of most insect species will develop at faster rates adding to the respiration products of fungi. Populations of all insect species will develop at grain temperatures between 15 and 35°C approximately (Driscoll et al 2000). When grain conditions are drier and/or cooler, insects will survive but development is slowed and the rate of oxygen conversion is reduced. Where insect numbers are low, the total oxygen conversion will be negligible.

Large numbers of insects are required to drive the rate of conversion of the contained atmosphere to one that is potentially toxic to insects. The uptake of oxygen by adult *Rhyzopertha dominica* in air at 30°C was measured at 3.38 and 3.96 μl/insect/h by Emekci et al (2004) and Birch (1947) respectively. A harvest bag holding 220 t of wheat contains approximately 110,000 l of air, thus 23,100 l oxygen within the intergranular air space. Assuming a conservative measure of 4.0 μl/insect/h and stoichiometric oxygen conversion of the equation in section 3.2, it would take approximately 1.3×10^6 individual insects to consume this amount of oxygen in 6 months. Alternatively, 1,000 adults will convert approximately 3 litres of oxygen to carbon dioxide per month. This illustrates how large numbers of insects are required to create hermetic conditions and low infestation levels have minimal influence in changing the contained atmosphere.

Stored grain insects will convert oxygen to carbon dioxide but the stoichiometry of the biological respiration equation given in section 4.2 is not always followed, with complex responses exhibited to decreasing oxygen environments, different species, development stages and temperature. Studies investigating biological conversion of oxygen to carbon dioxide often express this conversion as a respiratory quotient (RQ), which is the volume of carbon dioxide produced by an adult insect divided by the volume of oxygen consumed.

Low oxygen atmospheres have been shown to substantially reduce the uptake of oxygen and conversion to carbon dioxide by adult insects. Emekci et al. (2002) and White et al (1988) showed the Respiratory Quotient (RQ) substantially increases as oxygen is depleted and the increased production of CO₂ per unit volume of O₂ was considered an indicator of metabolic stress. In further studies, Emekci et al (2004) measured the respiratory response of *Rhyzopertha dominica* adults at reduced oxygen concentrations and showed the consumption of oxygen was 3.38, 2.85 and 0.69 μl/mg/h at oxygen concentrations of 21, 10 and 1% respectively. This was the equivalent to 3.05, 2.34 and 0.61 μl/insect/h at the same oxygen concentrations.

Different development stages and species exhibit different levels of conversion of oxygen to carbon dioxide. In grain studies conducted in air-tight storage, Bailey (1955) determined a RQ for mixed age *Sitophilus granarius* adults of 0.81 at 25°C & 70% RH. RQ for 0-21 day immature stages was 0.62-0.68, and RQ for 0-21 day immature stages, including adults, was 0.74-0.78. Earlier studies on *Sitophilus granarius* by Dendy & Elkington (1920) determined a RQ of 0.77 and 0.82. James and James (1940) obtained RQ of 0.64 for *Sitophilus granarius* cultured on dormant barley. Birch (1947) showed adults of *Rhyzopertha dominica* had a RQ of 0.94 to 1.10. Campbell and Sinha (1978) obtained a Respiratory Quotient for *Rhyzopertha dominica* from 0.8 to 1.0 under a range of conditions.
The influence of temperature on oxygen conversion by stored product insects was demonstrated by Birch (1947). This author showed adult *Rhyzopertha dominica* consumed oxygen at 2.02, 3.17, 3.96 and 5.05 μl/insect/h at temperatures of 22, 26, 30 & 34°C respectively with a RQ of 0.94 to 1.10 across the different temperatures. In more recent studies, Emekei et al. (2004) reflected Birch’s findings at the higher temperatures. Lower oxygen consumption was obtained at lower temperatures, with rates of 0.93, 2.37, 3.38 and 5.05 μl/insect/h at 20, 25, 30 and 35°C respectively.

The oxygen conversion ratio (RQ) and conversion rate of insects is clearly influenced by temperature and by changing gas levels within a closed system. The interaction between these factors is complex and each storage situation is likely to be unique in the response shown by insects to their immediate and changing environment. Research studies on the respiratory responses of insects are conducted under highly controlled and gas-tight conditions. These provide insight into the influence of different factors, but cannot predict the capacity of insects to create hermetic conditions in harvest bags very accurately where grain and gas conditions fluctuate widely.

### 4.3. Gas-tightness

The adequacy of the sealing of a grain store is often referred to as gas-tightness (Banks et al 1975). In order to create and maintain hermetic gas compositions for a sufficient period to disinfest grain, excessive dilution of the enclosed atmospheres with fresh air needs to be prevented. A major cause of dilution is inadequate gas-tightness or sealing. This is coupled with the nature of the driving forces for uncontrolled gas exchange across any leaks in the store. The key issue is the rate of gas exchange across the store boundary causing inadequate concentrations relative to the amount of time required to disinfest the grain by the hermetic gas composition. This is relevant for store in general, and at specific locations as large variations in gas composition can occur throughout a store. A gas-tight store also prevents insects re-infesting the stored grain (Oxley 1948; Banks et al 1980; Banks and Ripp 1984).

Tracer decay tests provide a direct measurement of the gas exchange incurred under the leakage and weather conditions encountered (Waters and Simons 1984). A known amount of tracer gas (e.g. carbon dioxide) is introduced into a store and the decrease in concentration over time is measured. Alagusundaram (1993) measured that 20-50% of the overall intergranular gas was lost per day through the walls of an unsealed bolted steel farm silo (approximately 40 t) common in Canada. While Wilson et al (1980) measured gas exchange rates of 2.4 to 4.3% per day for well-sealed 1,900 t stores (220 second pressure decay) filled with wheat under inland NSW (Rennie) conditions. These results illustrate how maintaining gas within a store is very dependent on sealing. Data directly measuring “levels” of sealing in relation to gas exchange rates, however, are sparse for all types of grain stores, with no results for modern harvest bags.

Banks and Annis (1984) identified four primary causes of air exchange that affect sheeted bulks and membrane type storages generally:

- Temperature variation of the gas inside a store
- Wind
- Atmospheric pressure variation
- Molecular diffusion

The significance of each cause is dependent on the gas-tightness standard and size of the store. The large surface to volume ratio characteristic of harvest bags, make this type of store particularly susceptible to gas leakage and ingress where a high standard of gas-tightness has not been achieved. Temperature variations within a harvest bag cause the internal gas to expand and contract. During heating, any internal gas expansion will vent via leaks followed by contraction during cooling where fresh air thus oxygen will enter the store in the same manner (Banks and Annis 1977; Newman 1990). If the bag is well-sealed, the bag will billow when internal gas expands. Wind has been reported to be the largest cause of gas loss from unsealed smaller stores (Banks 1991; Banks & Annis 1984), causing
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Air exchange due to the pressure difference induced across store boundaries. Air exchange due to barometric pressure variation, either synoptic or tidal, will result in fresh air entering and leaving a harvest bag via leaks. Flexible structures such as harvest bags can accommodate these temperature and pressure variations (Annis and Banks 1993), but if the bag is not gas-tight, air exchange via these modes will occur.

The other potential source of oxygen ingress is molecular diffusion across the bag membrane due to oxygen concentration difference. Gas loss and exchange by true molecular diffusion and by permeation are always small compared with those created by other forces (Banks and Annis 1984) and is dependent on the bag membrane which is promoted as a non-permeable polymer (230 – 250 µm triple-layered low density polyethylene used by Ipesasilo® and Silobolsa®). How the permeation properties of this polypropylene film are affected by the temperature changes and stretching that occurs in the field are not known. The capacity of a relatively well-sealed harvest bag to raise carbon dioxide levels to 9.4% for dry barley (av. 10.2% mc) in the ABB Grain Ltd. trial at Roseworthy in South Australia (Appendix 11.1) suggests that permeation is not a major source of oxygen ingress, compared to lack of gas-tightness.

In Australia, a pressure decay test has been adopted to test for gas-tightness in grain stores as it is easily carried out, relatively simple equipment is required, and tests are quick (Chantler 1984; Andrews et al 1994: Annis 2001; Banks 1997; Newman et al 2003). This test does not identify the location of an individual leak or its size, nor does it define the amount of air exchange likely to occur directly (Banks 1984; Banks and Annis 1984). This test was developed to indicate if a store would enable a successful fumigation under adverse weather and leak location conditions (Banks 1984). Pressure decay half-lives of 3 to 5 minutes are a high “guarantee of no failure” sealing standard which would be appropriate for harvest bags aimed at creating hermetic conditions. Despite the wide spread adoption of gas-tightness testing technology in Australia and the dependence of hermetic conditions on an appropriate level of gas-tightness, routine testing is not being undertaken on harvest bags in Australia at present.

4.4. Achieving hermetic conditions in harvest bags in Australia

Control of biological activity by hermetic conditions requires a high level of gas-tightness and a significant respiration rate from the biota contained within the structure. A harvest bag system provides the capability to achieve high gas-tightness standards if the system is constructed and maintained appropriately. Four 100t capacity harvest bags filled at Roseworthy in the ABB Grain Ltd. trials in South Australia (Appendix 11.1), exceeding a five-minute half-pressure decay standard (Table 8), with two of these bags exceeding 20-minutes. After 6 months storage, only one of the four bags exceeded a five-minute half-pressure decay standard and two bags exceeded four-minutes. Where the aim of harvest bag storage is to maintain grain insect-free for an extended storage time, the gas-tightness needs to be checked at regular intervals to ensure oxygen ingress is not occurring.

The capacity to seal and maintain levels of gas-tightness of harvest bags on farms has been relatively poor. The survey of bags on farms and at ABB Grain Ltd. sites (Appendix 11.1) suggests that only very minor damage to the film was required to render the system unsealed, with no capacity to hold a negative pressure. In the farm survey, only a few bags tested for gas-tightness held negative pressure and only one bag of a total thirteen tested in NSW and VIC approached a two-minute pressure decay standard (Table7).

The input required to protect bags on farms from film damage, and maintain the seal for extended periods is likely to be difficult. Repair of small punctures and tears has limited success with many adhesive tapes failing to achieve a good seal for prolonged periods. Damage to the film during bag loading is likely to be located on the base or close to the ground. These results indicate that a major improvement in gas-tightness awareness, site preparation, bag construction skill, gas-tightness testing equipment, and the availability of appropriate seal maintenance equipment is required on-farm to
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Protect bags from film damage, and maintain the seal for extended periods. Even in a well-managed storage environment, maintaining high levels of gas-tightness will be a challenge and maintaining bags in a farm situation is likely to require greater vigilance and management to ensure the integrity of the seal is maintained.

The failure of a harvest bag system however to achieve and maintain a high standard of gas-tightness (e.g. > five-minute half-life pressure decay time) will preclude its use as a hermetic storage. The lack of natural air circulation along the length of a 60 to 75 m harvest bag, however, can result in air ingress having a decreasing effect as distance from the leakage point increases. Considerable modification of the atmosphere may still occur in a proportion of the grain, which may lead to incorrect interpretation of the success of any given bag system. For example, dry canola (6.0-6.3% mc) was stored in a non-gastight harvest bag at Roseworthy in South Australia where pressure testing could not achieve a significant half-life, but was shown to have levels of carbon dioxide exceeding 8.8% and oxygen levels below 9.1% at six months after loading of the bag (Table 8).

With current practices, harvest bags are not sealed sufficiently to achieve a hermetic state and the creation of hermetic conditions in harvest bags under Australian winter cropping scenarios is expected to be inconsistent at best. Considerable improvement to practices is required to achieve this in Australia and, assuming a gas-tight bag is achieved, the predominance of dry grain means that high levels of insect activity (respiration) is required to achieve hermetic atmospheres that are complex and difficult to predict.

5. INSECT MANAGEMENT

In this section, the risks that insects pose to the storage of dry grains is discussed in view of the relevant available scientific evidence on control by hermetic atmospheres and the practical problems encountered with this form of control generally and specifically to the harvest bag system.

Stored product insects are endemic throughout the storage and handling systems of Australia’s grain industry. Trade of grain is based on satisfying a “nil tolerance” insect specification, either directly or implied, which requires very effective insect management. Nil tolerance requires that grain is “free from live insects” according to specific sampling procedures that vary depending whether trade is international (Grain, Plants and Plant Products Orders 1999, Schedule 5) or domestic trade (Anon, 2007). Nil tolerance is a pass/fail measurement that essentially expresses the chance that sampling will find an infestation, i.e. a detection limit. This standard is high by international standards and a key part of Australia’s marketing approach.

Insect surveys on the farm (Cotton et al., 1953; Greening 1969; Sinclair and White, 1980; Sinclair, 1982) and during bulk handling company (BHC) receivals (Johnston, 1981; Price et al., 1986) have demonstrated that the size of infestations is highly uneven. Insect occurrence is localised within a grain bulk and inconsistent between bulks. “Infestation pressure” causing failure of trade specifications comes from existing insects growing out to detectable levels, insects being added to the store with grain, and insects entering the store, or combinations of the above. In particular, infestations were observed to occur in harvesting equipment, residues of grain stored over seasons, and environments with poor hygiene. Harvest bags are expected to incur infestation pressure from several of these sources, depending on the storage scenario employed.

The major insect control option used on farm in Australia is phosphine fumigation. Sealable storage technology is employed to facilitate its effective use. Fumigations are usually applied near the point of trade and without awareness of whether insects were actually present in the grain. This reflects that applying phosphine is easier, can be carried out instantly and is often more cost effective than measuring insect presence.
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5.1. Insect control by hermetic atmospheres

Stored product insects can be controlled by a hermetic atmosphere, which involves creation of combined raised carbon dioxide (CO₂) and low oxygen (O₂) gas concentrations relative to natural air. This is often generated biologically, but can be created by chemical oxidation processes such as combustion. The study of the insecticidal effect of hermetic atmospheres on insect development and survival is reasonably well advanced (Banks & Annis, 1990; Calderon & Navarro, 1980; Calderon & Navarro, 1979).

There is a synergistic effect on insect mortality when low O₂ and raised CO₂ concentrations occur simultaneously, in comparison to low O₂ in N₂, or high CO₂ in air atmospheres (Banks & Annis, 1990; Calderon & Navarro, 1980; Calderon & Navarro, 1979). Banks & Annis (1990) suggest that above 3% O₂, CO₂ has the predominant influence on mortality. For atmospheres with O₂ below 3%, the synergy between O₂ and CO₂ has a substantial influence on insect mortality improving efficacy rates. Calderon & Navarro (1980) showed atmospheres containing a mixture of 2% O₂ and 15% CO₂ at 26°C were far more insecticidal than a mixture of 5% O₂ and 15% CO₂ against eggs and adults of Tribolium castaneum and Rhyzopertha dominica. Calderon & Navarro (1980) showed that Tribolium castaneum adults used available O₂ more rapidly in the presence of raised CO₂, requiring greater O₂ concentrations to maintain survival. Similar observations in low O₂, raised CO₂ atmospheres have been reported in detailed studies on insect respiration (Emekci, et al 2004; Emekci et al. 2002), where the respiration rate of insects slowed and the production of CO₂ per unit volume of O₂ is increased.

When a hermetic atmosphere is generated in dry grain by stored product insects, the insect mortality response is a complex interaction of changing gas concentrations and insect numbers. As the insect population growth rate and respiration rate are also dependent on the temperature, grain moisture content and gas concentrations, the mortality response is confounded further. The observed synergy on mortality of raised CO₂ amid O₂ below 3% is difficult to identify in practical hermetic stores where variable oxygen ingress rates occur and insect numbers are unknown.

5.2. Hermetic insect control in practice

The Department of Stored Products at the Volcani Centre, Israel, carried out a series of commercial scale trails on the insect control capability of hermetic storage systems. Navarro et al (1998) showed that very high insect numbers were required to effect control in a small capacity (700 l) hermetic village store where 540 kg of dry (10.1% mc) corn was stored for 40 days. The grain was contained in an inner PVC cylindrical bag with inloading and outturn sleeves that could be securely sealed. The PVC formulation used in the structure had an estimated diffusion rate of 25 ml O₂/day/m² at an average concentration of 15% O₂. In excess of 10,000 insects (approximately 18.5 insects per kilogram) were estimated to have effectively reduced numbers at outturn to low levels. In a village situation, this outcome was viewed as favourable.

The level of gas-tightness achieved under typical farm conditions will be the predetermining factor to successful insect control. CSIRO trials at Black Mountain (ACT) showed heavy insect infestations can rapidly (within 14 days) modify a contained atmosphere to the extent that all insects are killed (Appendix 11.1). The initial gas-tightness standard was two-minute pressure decay time and grain temperatures ranged from 25 to 30°C. Oxygen was rapidly depleted below 5.6% and the very heavy insect infestation (83 adults per kilogram) provided the inertia to compensate for any oxygen ingress into the contained atmosphere.

The CSIRO Black Mountain trials were an artificial situation where approximately 20 t of untreated old season’s wheat was loaded into a harvest bag. Insect infestations are not likely to increase to such high densities when initial numbers are low. The likely scenario is an increasing population that modifies the contained atmosphere to a composition that is toxic to a large proportion of individuals, but not all (refer section 4.2.2). Where oxygen ingress occurs, the insect population will continue to
increase to levels that are once more lethal to a proportion of the population. In a very well-sealed system, an insect population may increase to levels that modify the contained atmosphere to the extent that effective control is achieved. However, even in the absence of live insects detected at outturn, the presence of large numbers of dead insects and fragments may exceed permissible tolerances set for Australia’s trading and export standards.

There are anecdotal reports (T. Maitland, Agsave Merchandise, Kimba, SA, personal communication) where harvest bags used for storage of barley in South Australia during season 2004/05 and 2005/06 were outturned with obvious evidence of heavy insect infestation, but few live insects were detected. Other barley bags were outloaded with heavy infestations and many live insects were detected. The presence of live insects suggests these bags were not well-sealed, or the storage time was not sufficient for the resident insect population to increase to levels sufficient to modify the contained atmosphere to a “toxic” composition.

Further anecdotal reports received from farmers and commercial stockfeed companies (forward purchasing grain stored in harvest bags on-farm), and reports in the rural press suggest the incidence of insect infestation in harvest bags is low. The apparent success of the harvest bag system to deliver grain “insect-free” is more likely associated with benefits obtained using a clean storage system that is often located well away from other sources of insect infestation. The incidence of stored grain insect pests in the harvested crop is likely to be low. Bags do not have residual populations as new bags are used each season. The seamless film bag also provides an effective barrier to insect infestation. Any punctures or tears to the film will increase infestation pressure, especially where high residual insect populations exist. However, the time-lag between initial low insect numbers and an infestation that is detectable using manual probing and screening is expected to be considerable, and likely extend past the months of cool weather that prevails during winter and early-Spring in temperate climatic zones.

### 5.3. Insect control by fumigation

Insect control in harvest bags was initially promoted in Australia as being effective through the generation of insecticidal hermetic atmosphere, i.e. a chemical-free storage option. However, harvest bags are a membrane based gas-tight store which could be fumigated like other analogous storage systems used in Australia, such as bunkers. Fundamentally, disinfesting grain by fumigation requires contacting any insects present with the gaseous chemical sufficiently to completely kill the population. The mortality response of insects has been well defined by laboratory investigations, and any disinfestation in harvest bags in the field will be dominated by practical factors such as fumigant distribution and store sealing.

Farm based fumigation in Australia is based on phosphine generated from reactive solid preparations. At present, an appropriate dispensing arrangement for harvest bags is not available. Anecdotally, phosphine “pellets” have been inserted directly into the grain within a bag by penetrating through the membrane. This practice however creates pellet residues in the grain and does not ensure adequate distribution of the generated phosphine. Such practices are not permitted according to the phosphine label.

### 5.4. Controlling insects in harvest bags in Australia

The options for controlling insects in harvest bags in Australia are the generation of insecticidal hermetic atmospheres or the use of fumigants, predominantly phosphine. In either case, the capacity of a harvest bag system to modify the internal air to a hermetic atmosphere or maintain phosphine concentrations requires a high standard of gas-tightness be achieved and maintained. For hermetic insect control, gas-tightness must be maintained for the entire storage period, while for phosphine up to 21 days is needed. This would involve the use of pressure testing as practiced with other storage types and durable “patching” arrangements. Due to the relative ease with which the harvest bag membrane seal can be punctured by stock and wildlife, a schedule for regular pressure testing to prove
Assessing the limits of existing harvest bag technology under Australian conditions

gas-tightness would seem appropriate when hermetic storage is planned. A pressure test is also recommended prior to undertaking phosphine fumigation.

A five-minute pressure test standard (e.g. half-life pressure decay time is five minutes or greater) is recommended as the minimum requirement to potentially achieve hermetic conditions during long-term storage of dry grains. Navarro et al (1994) reported that an oxygen ingress rate of 0.24% per day corresponds to a well-sealed store and is achievable in practice where flexible film structures pass a five-minute pressure test standard. Based on observations from CSIRO’s farm survey, (Appendix 11.1), such a high standard of gas-tightness is not likely to be achieved over an entire storage period. Even in a well managed commercial situation, harvest bags sealed to a high standard of gas-tightness (e.g. > 20-minute half-life pressure decay time) were inevitably damaged.

Annis & Banks (1993) reviewed work on Australian bunker stores and suggested that air ingress could be restricted to about 2% air per day with considerable effort, although much higher rates were frequently recorded in the field. However, even at the lower ingress rate of about 0.5% oxygen per day, they concluded that hermetic storage was not suited to reliable maintenance of the quality of dry, lightly-infested grain which is typical of contemporary Australian conditions. Annis & Banks (1993) suggest that hermetic conditions would require up to ten insects per kilogram of grain to maintain hermetic atmospheres for moistures and temperatures typical of the Australian grain crop. The level of insect infestation required to achieve hermetic condition in a well-sealed harvest bag is likely to be below ten insects per kilogram of grain; but even five insects per kilogram would be commercially unacceptable and poses significant problems for the storage manager. Relying on insect numbers to grow to create hermetic conditions in order to disinfest these same insects to a Nil Tolerance standard, is deemed as a fragile insect control approach.

The nature of insect generated hermetic atmospheres over time, as influenced by different population densities, has been described in controlled studies. Oxley & Wickenden (1963) used a fixed oxygen ingress rate and monitored changes in oxygen concentration during storage at varying insect densities. Oxygen concentration was shown to oscillate over time, with a percentage of the population surviving low oxygen levels, followed by increasing numbers as ingress of oxygen back into the system replenished the depleted atmosphere. Similar observations have been reported in small-scale farm systems by Navarro, et al (1998) and Hyde et al (1973). These studies suggest that complete insect control is not achievable where air ingress occurs and for dry grains (e.g. ≤ 13% mc), where the generation of hermetic conditions is largely insect driven (section 4.2.2), unacceptably high insect densities will be required to modify the atmosphere to a composition that is toxic to insects. It is more likely however that oxygen ingress into a harvest bags system will enable the population to increase up to the time that an effective control strategy is implemented, e.g. phosphine fumigation or outturn and treatment with residual protectants.

6. MANAGMENT OF MOULD BASED QUALITY LOSS

In this section, the risk of mould based quality loss in stored grains is analysed through the review of relevant available scientific evidence. The conditions that influence the growth of storage type moulds generally are discussed, with particular reference to Australian storage conditions. The role that modified atmospheres have in controlling moulds is reviewed, with reference to the storage of grains in harvest bags at different moisture levels.

Mould (fungi, micro-flora) can degrade the quality of grain in storage depending on the moisture and temperature conditions experienced. The appearance and presentation of the grain is affected by mould causing colour changes often referred to as increased dullness or loss of brightness. These changes can result in specific black/blue/brown discolouration of the grain kernels or a grey-black sooty/dusty coating on kernels. Odours and taints are also associated with mould activity. Aggressive moulding can occur in localised parts of a grain stack due to condensation, leaks, etc which can be difficult to separate from the rest of the grain in the stack.
6.1. Storage moulds

Fungi are endemic to all stages of grain production and storage. The relatively dry conditions present in grain storage favour the growth of specialist fungi adapted to growing in these dry conditions. These fungi are often referred to as xerophilic or storage fungi. When moisture and temperatures are favourable for growth, the insulated nature of bulk grain storage provides an ideal environment for the rapid proliferation of mould. Specialist xerophilic micro-flora species can increase in number and diversity to take advantage of a substrate maintained at fairly constant conditions (Pitt & Hocking, 1997).

The availability of moisture to support the growth of fungi on different substrates is measured by water activity (aw). For grain, water activity is equivalent to the equilibrium relative humidity exerted by the grain, usually expressed as a decimal. Water activity of grain is dependent on moisture content and temperature. Different grain types will exert different water activities for the same moisture content and temperature. This reflects that water within different grain types is not equally available to fungi due to bonding that exists between the water molecules and the grain.

The interaction between water activity (aw) and temperature largely determines which species of fungi that can germinate and sporulate, and to what extent growth will occur and at what rate (Lacey & Magan, 1991). Storage fungi are able to grow under conditions of reduced water activity, however, their growth is slower as aw decreases below 0.85 (Pitt & Hocking, 1997).

The primary invaders of stored grains are *Eurotium* species, *Aspergillus* series *Restricti* species, particularly *A. penicillioides*, *A. restrictus* and *Wallemia sebi* (Hocking & Banks, 1991). *A. penicillioides* and other closely related pioneer species have the ability to grow under relatively dry conditions. In recent studies, Hocking (2003) showed that the most xerophilic species *A. penicillioides* can germinate and grow at aw values of 0.66-0.67 and other closely related pioneer species can develop at aw = 0.68 at favourable temperatures.

Fungi colonise in a self-promoting and inter-related fashion, with the establishment of “pioneer” species like *A. penicillioides* promoting moisture content increases up to aw = 0.7 whereupon common *Eurotium* and *Wallemia* spp. can begin to grow (Hocking, 2003). These species in turn act as the precursor for growth of less dryness tolerant fungal species.

Although the availability of water has the predominant influence on mould development, the influence of temperature is also significant, with growth slowed or even inhibited at low or higher temperatures. White et al (1982) showed visible moulding occurred on 17.8% mc wheat within 11 days at 30°C, but none was observed at 40°C by 21 days. Low temperatures slowed mould growth and damp grain (e.g. 17 – 20% mc) was stored without visible moulding below 10°C for extended periods. White et al (1982) showed no visible moulding was present on 18.4% mc wheat by 35 days at 10°C; but it was observed by 23 days at 20°C.

6.2. Grain conditions for mould growth

Moisture isotherms provide a good estimate of the grain moisture and temperature conditions that will prevent micro-floral activity over prolonged storage (Ayerst 1969; Lacey 1980). Based on contemporary moisture isotherm data, the limiting aw at different temperature conditions for pioneer fungi are expressed in terms of equilibrium moisture contents of various grains in Table 1. Isotherms for wheat (Table 2) show the critical moisture content for fungi growth (aw = 0.68) is 13.4 to 14.1% at 30 and 20°C respectively, and, 13.1 and 14.1% for barley at 30 and 20°C respectively (Cassells et al, 2003b). This minimum threshold water activity allows pioneer species to grow at favourable temperatures. The growth of *A. penicillioides* and other closely related pioneer species would be slow at margin moisture levels and evidence of moulding may not be apparent for six months or more. Mould growth is more likely to be observed on stored grains as available moisture exceeds water
activities of 0.70. These higher moisture levels enable other invasive species to grow (e.g. *Eurotium* and *Wallemia* spp.), which out-compete pioneer species to become the predominant cause of the dustiness and odour observed in moulded grains.

### Table 2. Moisture content threshold (aw = 0.68) for growth of *A. penicillioides*

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>20°C</th>
<th>27°C</th>
<th>30°C</th>
<th>35°C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>14.1</td>
<td>13.4</td>
<td></td>
<td></td>
<td>Cassells et al, 2003b</td>
</tr>
<tr>
<td>Barley</td>
<td>14.1</td>
<td>13.1</td>
<td></td>
<td></td>
<td>Cassells et al, 2003b</td>
</tr>
<tr>
<td>Canola</td>
<td>8.7a</td>
<td>8.1a</td>
<td></td>
<td></td>
<td>Cassells et al, 2003a</td>
</tr>
<tr>
<td>Chickpeas (Desi type)</td>
<td>14.3</td>
<td>12.8</td>
<td></td>
<td></td>
<td>Cassells &amp; Caddick, 2002</td>
</tr>
<tr>
<td>Field Peas (var. Bohatyr)</td>
<td>13.5</td>
<td>12.7</td>
<td></td>
<td></td>
<td>Cassells &amp; Wright, 1996</td>
</tr>
<tr>
<td>Field Peas (Dun type)</td>
<td>14.4</td>
<td>13.4</td>
<td></td>
<td></td>
<td>Cassells &amp; Caddick, 1999</td>
</tr>
<tr>
<td>Lupins (var. Merrit)</td>
<td>13.6</td>
<td>12.6</td>
<td></td>
<td></td>
<td>Cassells &amp; Wright, 1996</td>
</tr>
</tbody>
</table>

a – moisture threshold based on canola with oil content of 42% (dry basis); higher oil contents reduce moisture content, e.g. 45% oil content, moisture threshold is 8.4 and 7.7% mc at 20 and 30°C respectively.

The extent that mould deteriorates grain quality is dependent on the time period for mould growth in conjunction with the moisture and temperature conditions. The most useful data defining the relationship between mould-based grain quality and time, grain moisture and temperature involve indexes of visible mould, as this is used in trade. Various indexes of visible mould have been used and include various colour changes, sootiness, greying, clumpiness, mustiness and loss of germination (Karunakaran et al, 2001; Lacey et al, 1994; Wallace et al, 1983; White et al, 1982; Christensen & Kaufmann, 1965; Hummel et al, 1954; Christensen & Drescher, 1954). Data relating visible moulding to grain conditions and time is available for higher grain moisture content conditions of Europe, Canada and the United States. These studies illustrate the inter-relation between these factors; the higher the moisture, the faster mould will be visible. This trend is enhanced at warm temperatures of 20 to 35°C.

For grain moisture conditions considered marginal for storage of wheat in Australia (e.g. 12% < M < 15%), Caddick (1999) measured the rate of visible storage fungal infection on wheat stored at different moisture levels and temperatures. Visible fungal activity for several specialist xerophilic moulds was exhibited by dustiness and off-odours and the data are shown in Table 3. At the threshold moisture requirement for *A. penicillioides* and *E. repens*, growth is slow and visible moulding is not evident for months, even though the level of infection increased during this time. The lower moisture threshold required by *A. penicillioides* (aw = 0.68) is shown by prolific growth at 14% mc and 30 °C, while infection levels of *E. repens* remain low during 12 months storage. Moulds did not develop on wheat at 12%, 13% and 14% mc and stored at 20°C for a 12 month period, and the level of contamination was generally lower than the initial count determined following inoculation of the wheat.

### 6.3. Mould control by hermetic and modified atmospheres

Many food spoilage fungi, including xerophilic storage fungi, have an absolute requirement for oxygen and are unable to survive in an anaerobic state. However, they are often efficient scavengers of oxygen, so that the total amount of oxygen available, rather than the oxygen tension determines growth (Pitt & Hocking, 1997). *Aspergillus* and *Penicillium* spp. are particularly tolerant of low oxygen concentrations. Shejbal & Di Maggio (1976) reported that in nitrogen containing up to 0.2% oxygen, moulds develop slower than in air, but are not inhibited. The growth of *Eurotium*, *Penicillium* and *Aspergillus* spp. was shown by Petersen *et al*, (1956) to limit the storage of grain with greater than 14% m.c. (about aw = 0.75) in nitrogen atmospheres containing only 0.2% oxygen.
Mould growth was only inhibited when the nitrogen was totally free of oxygen. Banks & Annis (1990) also conclude that O₂ must be low, at least <1%, preferably <0.2% to effectively inhibit the growth of a range of mould species.

Table 3. Infection levels of *A. penicillioides* and *E. repens* on wheat at 12, 13, 14 and 15% mc and stored at 20 and 30°C. Figures shown in bold type highlight visible evidence of dustiness and off-odours.

<table>
<thead>
<tr>
<th>Fungi species</th>
<th>Moisture Content (% wb)</th>
<th>Storage Temp. (°C)</th>
<th>Storage time (weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td><em>A. penicillioides</em></td>
<td>13</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td><em>E. repens</em></td>
<td></td>
<td>61</td>
<td>54</td>
</tr>
<tr>
<td>Total infection</td>
<td></td>
<td>92</td>
<td>71</td>
</tr>
<tr>
<td><em>A. penicillioides</em></td>
<td>14</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td><em>E. repens</em></td>
<td></td>
<td>61</td>
<td>*</td>
</tr>
<tr>
<td>Total infection</td>
<td></td>
<td>92</td>
<td>70</td>
</tr>
<tr>
<td><em>A. penicillioides</em></td>
<td>15</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td><em>E. repens</em></td>
<td></td>
<td>61</td>
<td>58</td>
</tr>
<tr>
<td>Total infection</td>
<td></td>
<td>62</td>
<td>81</td>
</tr>
<tr>
<td><em>A. penicillioides</em></td>
<td>12</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td><em>E. repens</em></td>
<td></td>
<td>61</td>
<td>54</td>
</tr>
<tr>
<td>Total infection</td>
<td></td>
<td>92</td>
<td>86</td>
</tr>
<tr>
<td><em>A. penicillioides</em></td>
<td>13</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td><em>E. repens</em></td>
<td></td>
<td>61</td>
<td>*</td>
</tr>
<tr>
<td>Total infection</td>
<td></td>
<td>92</td>
<td>85</td>
</tr>
<tr>
<td><em>A. penicillioides</em></td>
<td>14</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td><em>E. repens</em></td>
<td></td>
<td>61</td>
<td>*</td>
</tr>
<tr>
<td>Total infection</td>
<td></td>
<td>92</td>
<td>100</td>
</tr>
<tr>
<td><em>A. penicillioides</em></td>
<td>15</td>
<td>*</td>
<td>2</td>
</tr>
<tr>
<td><em>E. repens</em></td>
<td></td>
<td>61</td>
<td>100</td>
</tr>
<tr>
<td>Total infection</td>
<td></td>
<td>92</td>
<td>100</td>
</tr>
</tbody>
</table>

*a* Values are the average result of duplicate assessments and given as % seed infected using direct plating techniques. (*) indicates where fungi were only detected by dilution plating techniques. *b* Individual sub-samples of wheat taken from 3 x 60 kg replicates and mixed to form composite. Bold type or (**) indicates a high colony forming unit (cfu) value (≥10⁵). Mycological testing by Food Science Australia. Ref: Table modified from Caddick (1999).

Several fungi are reported to grow under anaerobic conditions, including *Mucor* species, *Fusarium oxysporum* and *F. solani* (Curtis, 1969). However, most food spoilage problems due to filamentous fungi occur under aerobic conditions. In contrast, a number of fermentative yeasts are capable of growth in the complete absence of oxygen (Pitt & Hocking, 1997).

In hermetic storage of dry grains (0.68 ≤ aw ≤ 0.75), the depletion of O₂ appears to be the critical factor determining the rate of fungal growth as the levels of CO₂ are not likely to exceed 20% due to the stoichiometry of biological respiration. The rate of oxygen depletion is also critical to the safe storage of high moisture grain, and early studies by Hyde & Oxley (1960) showed that (at 15°C) minimum levels of O₂ for wheat at 24.4% mc was reached within 2 days, compared to 70 days for wheat at 17.9% mc. A brief review of the hermetic control of mould growing at high moisture grain is given in Appendix 3. At higher temperatures (≥25°C), Bottomley et al (1950) showed that growth was affected most by variations in water activity between 0.75 and 1.0, and least by variations in oxygen concentrations down to 0.1%.
The effect of low oxygen and high carbon dioxide on fungi development has been studied in some detail and reviewed by Lacey & Magan (1991), Banks (1981), and Busta et al (1980). In wetter grains ($a_w \geq 0.85$), the inhibition of fungal growth is most significant where oxygen has been depleted below 0.5%, or where carbon dioxide exceeds 50%. However, the level of fungal growth inhibition achieved in low O$_2$ atmospheres is often incomplete and terms such as “substantially reduced” or “retarded substantially” are used. The ability of moulds to tolerate low oxygen, raised carbon dioxide atmospheres (Pelhate, 1980; Landers et al, 1967; Petersen et al, 1956) suggests that sufficient xerophilic storage moulds will be able to proliferate in practical hermetic atmospheres where oxygen would be present at some level, even though mould growth could be slow.

In hermetic storage, carbon dioxide levels exceeding approximately 21% cannot be achieved by biological or chemical oxidation of the oxygen in natural air (21%v/v). The capacity of a biological system to produce an atmosphere with 50% carbon dioxide or greater requires anaerobic respiration of some type. The range of microflora on grains is diverse and several types and species have an ability to grow under anaerobic conditions (Pitt & Hocking, 1997), but there are no studies specifically describing anaerobic biological respiration in grain.

In controlled atmosphere storage of moist grains ($0.85 \leq a_w$), carbon dioxide retards the growth of fungi to a greater degree (Landers et al, 1967) compared to dry grains, and the action of CO$_2$ levels above 50% appear to be largely independent of oxygen (Banks & Annis, 1990). Nevertheless, anaerobic respiration in a hermetic store will require very low levels of oxygen thus an exceptionally gas-tight enclosure. Any synergistic toxicity to fungi from very high carbon dioxide atmospheres with low levels of oxygen cannot therefore be defined at this stage.

### 6.4. Controlling mould in harvest bags in Australia

A major risk of mould related quality loss of grain in harvest bags occurs at localised points of moisture aggregation due to condensation and seepage of water into the grain through punctures. The moisture content of relatively small parcels of grain can get very high and the likelihood of mould quality loss is high accordingly. Furthermore, as condensation and leaks are likely to occur at the boundaries of a bag, oxygen ingress is more immediate and mould control due to a hermetic atmosphere very unlikely.

Cereal grains are typically harvested in Australia between 10 to 12.5% mc (wet basis), and often the average moisture content for a given storage bin ranges between 11 to 11.5% mc. These moisture levels are well below the critical moisture threshold for fungal growth and development. Cassells et al (2003b) showed the critical moisture content for fungi growth for wheat at $a_w = 0.68$ is 13.4 to 14.1% at 30 and 20°C respectively, and for barley, 13.1 and 14.1% at 30 and 20°C respectively. At these conditions, general quality loss due to visible mould is not expected.

Where grain is stored at moisture contents corresponding to the water activity range $0.7 \leq a_w \leq 0.8$, (e.g. wheat between 13.5 and 15.5% mc at 30°C), the conditions are marginal for mould growth. Hermetic processes are not expected to be able to create very low oxygen (<0.5%) or high carbon dioxide atmospheres (>50%) that suppress mould growth, even if good gas-tight conditions were achieved. Mould growth would consequently be controlled by the moisture and temperature conditions of the grain, not the hermetic atmosphere. This is definitely the case if high levels of gas-tight conditions are not achieved. At these moistures, the growth rate of fungi is relatively slow and will suppress quality loss for some time depending on the temperature conditions (see Table 3). For example, wheat at 14% moisture or less will not exhibit visible mould for six months at typical storage temperatures.
Where grain moisture contents are high, corresponding to water activities $0.85 \leq a_w \leq 0.92$, (e.g. wheat between 16.5 and 19.0% mc at 30°C); hermetic atmospheres could be created in a very gas-tight harvest bag which could ultimately suppress visible mould. This scenario requires the fungal activity to be sufficient to deplete oxygen to very low levels that suppress mould growth before the presence of these moulds becomes visible. This is very difficult to predict with the changing environment for storage moulds resulting from the interaction between water activity, temperature, gas concentrations and localised oxygen ingress rates. This scenario is highly dependent on very high standard of gas-tightness being achieved and maintained. Hyde (1969) reported that wheat stored above 17% in sealed store (pressure test not used) tends to be tainted due to anaerobic fermentation processes. If oxygen ingress does occur, mould would be visible with 3-8 weeks, with the oxygen ingress rate determining the rate of deterioration.

In hermetic storage of very moist grain corresponding to water activities $a_w > 0.92$, (e.g. wheat; >19% at 30°C), it is more likely that biological activity can be suppressed in a reasonably gas-tight harvest bag. In this scenario, both aerobic and anaerobic micro-organism activity occurs at rates sufficient to deplete oxygen for mould control. The rate that carbon dioxide is produced in such anaerobic systems will influence the degree of spoilage that occurs before safe storage conditions are achieved. Hyde & Oxley (1960) reported that wheat stored at moisture levels above 23% was out-turned without visible moulding and was free-flowing. If oxygen ingress does occur, mould would be visible and odours strong within three weeks.

7. GRAIN QUALITY

In this section, grain quality issues are discussed in context of the risks associated with the peripheral layer of plastic membrane type stores and the influence that such localised deterioration can pose to loss of quality generally. To better understand this issue, an overview is provided of the storage factors that affect processing changes in barley and wheat, and examples are given of the field performance of Australian bunker stores and harvest bags in Argentina. The storage of barley and wheat in harvest bags under Australian conditions is discussed, including recommended safe storage times based on data from previous extensive CSIRO studies of these grains stored under controlled conditions.

Grain quality includes presentation and contamination factors typically measured during trade and specified by National Agricultural Commodities Marketing Association Incorporated (NACMA), or by grain marketers and end users that seek specific processing traits or performance characteristics. Presentation factors address cleanliness, brightness and discolouration, and odours; while contamination includes rodent and bird carcass and faecal contaminants, weed seeds and other admixtures. Processing traits refer to the specific quality attributes of grain that are critical to the end user being able to manufacture food or beverage products to specification in a cost-effective manner. Many of these factors are known to change during storage and are a key issue for assessing the performance of the harvest bag storage system.

7.1. The peripheral grain layer

A key grain quality concern of harvest bags is the relatively high proportion of grain that exists in the daily thermal peripheral layer of the store (refer section 7.6.1) compared to other store types. In all grain stores, the layer of grain at the outer edge of the grain bulk experiences more rapid changes in temperature compared to the rest of the grain. When this layer is in contact with the store boundary material that is exposed to the weather, this temperature change occurs in a layer from 100 to 150mm thick following a 24 hour daily cycle, referred to as the daily thermal peripheral layer.

Peripheral layers establish due to the good insulation properties of bulk grain, which prevent changes in temperature at the store boundary in contact with the grain penetrating into the bulk. The size of the temperature change and the specific thickness of the peripheral layer are dependent on the store
construction material such as metal, concrete and PVC and various heat transfer processes; exposure/orientation to direct sun or night sky; weather events such as wind, rain and frost. Harvest bags are made with a reflective white finish to the polymer bag membrane claimed to provide good radiant heat reflective properties, which would attenuate the grain temperature excursions compared to a non-reflective membrane. The extent of this heat reflective property is unquantified.

The peripheral layer that occurs in polymer membrane grain storage systems are subject to large fluctuations in temperature as a result of relatively large amount of surface exposed to radiant heat gain from the sun and loss to clear night skies; amid the other heat transfer phenomena. Figure 1 illustrates the temperature response of the peripheral layer in an Australian PVC bunker on the northern face (sunny side) over a 48 hour period. Temperature sensors were set on the surface and at grain depths of 4, 10 and 20 cm. At 20 cm, the influence of diurnal heat and cooling is negligible. During prolonged storage, extreme variations in grain temperatures (e.g. exceeding 50°C and falling below 0°C) can lead to grain moistures drying out by over 1% and moistening up to 3%.

These rapid temperature changes in the peripheral layer lead to condensation on the inside of the bag membrane and on the adjacent grain within the peripheral layer. The amount of condensation is dependent on the size of the temperature fluctuation and the moisture content of the grain in the store, with wetter grain providing more condensation potential. The transfer of moisture by natural convection currents within harvest bags is suspected to compound this problem, but specific experimental evidence is not available. The accumulation of moisture (≥1%) in the peripheral layer was observed in a number of harvest bags inspected on New South Wales and Victorian farms during May 2006 (Appendix 11.1). An increase of up to 1.1% was also observed in the surface peripheral layer of 11.4% wheat stored for 15 months in trials at Black Mountain CSIRO site, Canberra.
Harvest bags have a large proportion of the stored grain within the peripheral layer due to the high surface area relative to storage volume. For example, a 75 metre long harvest bag has in excess of 400 m² of film exposed to radiant heat and cooling with a depth of less than 2 m and a capacity of 250 t of wheat. A peripheral layer of 150 mm will exceed 18% of the total stored wheat. This is compared to less than 4% of the total tonnage stored in commercial-sized bunkers used in Australia. Details of these calculations are given in Appendix 11.4. Furthermore, the tight packing of the bags prevents membrane billowing typical of bunker stores which can disperse localised accumulation of condensation.

7.2. General grain spoilage

Grain spoilage refers to damage and contamination caused by insects, rodents, birds, moulding, and heating of grains to the extent that they appear burnt and are tainted. Industry receival and export standards established by NACMA (Anon, 2007) in consultation with grain handling and marketing organisations, address grain spoilage issues in trade. The nil tolerance standard for live insects (refer Section 5) also applies for rodent contamination, and the presence of moulded, souring or musty odours resulting from improper storage. The presence of moulds and taints is measured by visual and sensory assessment of representative samples of grain at key points in the supply chain. However, visual imaging technologies are increasingly being evaluated to quantify presence of contamination, grain colour change and dustiness of grains.

7.3. Processing quality

Processing quality refers to the properties of the grain that describe its performance in end user processing such as barley malting and brewing, wheat flour milling, bread making and noodle making, and the refining of oils from oilseeds. Processing quality differs from receival assessment of grain which is used to segregate grain for market grades at delivery and is the basis of payment to growers (often referred to as “rapid acceptance tests”). Receival standards address physical or visual measures of quality and include moisture content, grain density, sprouting index, mould index, seed size and colour, breakage percentage, screenings content and contamination by foreign material and weed seeds. A few rapid processing quality indexes are used at receival to determine the chemical composition (e.g. protein, water, oil) and enzyme activity (e.g. α-amylase via Falling Number) and free fatty acid content of oilseeds which provide a broad indication of processing quality. However, overall receival standards are quite limited in their capacity to determine specific specifications of end-users.

International and domestic marketing of grains has become increasingly more sophisticated and industry receival standards are becoming less relevant to the overall marketing process. The chemical composition, physiology and biochemistry that influence the nutritive value and end-product performance of grain has a key role in the marketing of many grain types, and “safe” storage needs to address these quality parameters to a greater degree than has historically been the case.

7.3.1. Storage factors that affect processing quality

The primary storage factors that affect the various end user quality parameters are grain moisture and temperature. Apart from the daily thermal peripheral layer, grain temperatures throughout a stored grain bulk will change gradually over many weeks throughout a year, as heat is gained and lost depending on weather and store details. These gradually changing grain temperatures lie mostly between 10 and 35°C throughout the year in Australian stores (Wilson 1949, Griffiths 1964, White 1988) with extremes being 5°C and 40°C. Grain temperatures towards 45°C have occurred on occasions with very hot windrowing conditions at harvest.
The moisture of grain during storage remains close to that inloaded for the bulk of the grain stack, apart from localised zones where condensation, moisture migration and water ingress cause changes. Moisture change processes are dependent on the various changes in grain temperature. As different store types exhibit different grain temperature change rates and extents due to their size, geometry and construction materials, different end user quality outcomes can occur between store types.

There are numerous studies into the influence of storage factors on various grain quality indexes. A primary index is based on seed germination (a viability index), which has demonstrated consistent and reproducible trends across 40 years of research results, despite many different workers and variations on the specific germination assay used. The main outcome from these studies is that for a given lot (or batch) of grain, the final level of a germination index is dependent on the initial quality of the lot, the duration of storage, and the storage temperature and moisture (see Appendix 11.5.3. for wheat and 11.6.3. for barley). Initial germination level is also influenced by grain type, variety and growing/harvesting conditions incurred. For example, dormant and hard-seeded varieties affect the rate of maturity and provide a degree of protection against weather damage to the ripe standing crop prior to harvest. The rate of germination loss is most dependent on initial quality, then moisture then temperature, but all these factors are significant.

Various correlations quantifying the rate of change from the initial germination level as functions of moisture and temperature have been developed (Bason et. al., 1993; Ellis and Roberts 1982a, 1982b; Roberts 1960). The extensive literature demonstrating the relationship between germination and grain moisture and temperature has focused on relatively constant temperature and moisture conditions held over months to years (Bason et. al., 1993; Ellis and Roberts 1980a, 1980b; Roberts 1960). The basic mathematical relationships of these studies were also effectively applied to modelling germination loss during heated air grain drying where high temperatures (40 to 90°C), moistures (barley 14 to 22%) and very short exposures of 10 to 200 minutes were involved (Nellist 1981, Nellist & Bruce 1987), demonstrating that the relationship of germination on temperature and moisture applies across a broad range of conditions.

The seed germination index does not directly correlate to wheat processing and end-product quality indexes as it is more sensitive to moisture and temperature conditions than most processing indexes (refer Appendix 11.5.2.). Caddick (1999) showed that a substantial loss of viability (10 -15%) had no adverse affect on bread-making or noodle quality, as measured by the pan-bread and white noodle system of evaluation. Pomeranz (1988) supports these findings, concluding in his comprehensive review of the biochemical and functional changes in wheat during storage that substantial decreases in germination capacity (10 - 20%) were not reflected in bread-making potential. Nellist & Bruce (1987) also demonstrated this dependency applies with several processing quality indexes. For barley, germination has proven useful as an “early indicator” of quality loss in malting potential (refer Appendix 11.6.3), resulting from the storage factors moisture and temperature. This has enabled the more cost effective germination index to be used as an indicator of malting quality changes.

The relationship between the sensitive germination index and diurnal oscillating temperatures typical of the daily thermal peripheral layer has not been studied. An experimentally validated approach/model to predict quality changes expected in the rapidly changing temperatures of the daily thermal peripheral layer of grain stores is therefore unavailable.

7.3.2. Wheat processing quality changes in storage

A variety of wheat processing quality indexes are used in industry which change at different rates as a function of grain moisture and temperature, and therefore may change during storage. These indexes fall into three groups based around technical functionality; flour extraction, rheology of the dough, and baking performance. To assess the total processing quality of wheat for bread-making, standardized tests of rheological, flour extraction and baking factors are often combined to provide an overall appraisal. For noodle making, firmness and elasticity of the dough are key indexes. Even though the final product is dependent on these indexes, the actual product depends on the bakery or noodle
production enterprise, as many additives and improvers are added to any given batch of flour to maximise performance and meet consumer expectations of the end-product (e.g. texture and taste).

The rheological indexes refer to the viscoelastic properties of flour dough made from the wheat and include flour dough water absorption capacity, strength, consistency and elasticity. Farinograph and Extensograph tests are extensively used to quantify rheological properties of flour dough for bread-making and analogous tests are used for noodle making. Pilot-scale baking with assessment of the resultant breads (e.g. loaf volume and crumb structure) describes baking performance.

Overall, rheological and baking properties change slowly during storage following a general trend. Initially, bread dough improves, showing increased strength and consistency while noodle dough exhibits a parallel increased firmness and elasticity. Baking performance for bread dough also exhibits improvement following these changes in rheological properties. Then an optimum quality is attained at some point during storage, followed by a gradual decline as storage continues. The higher the grain moisture and/or temperature, the faster this trend occurs, but changes will occur slowly over many months unless very moist and/or hot conditions are encountered.

The slow rates of change of the wheat processing quality indexes essentially means that good sound quality wheat held at conventional storage conditions of moistures less than 12% mc and temperatures less than 30°C will not exhibit deterioration during storage over a season, but will steadily improve according to rheological indexes. Grain conditions that are dryer and cooler may require storage for up to 12 months to achieve optimum bread-making or noodle-making quality. Germination changes may be exhibited under these scenarios, as it is a more sensitive indicator of change.

For wheat with marginal quality at the start of storage, processing quality deterioration is more likely within 12 months, possibly 6 months, during storage under conventional conditions (< 12% moisture and < 30°C). This is a result of the initial quality of wheat having a major influence on how fast quality changes occur (as described above). As initial quality is affected by growing and harvest conditions such as moisture stress (lack of rain), frost, rain at harvest, weathering and ageing of the standing crop, etc, these circumstances will influence the processing quality changes incurred during storage. CSIRO’s studies on wheat storage and the influence of conditions and time on processing and end-product quality are detailed in Appendix 11.5.

7.3.3. Barley processing quality changes in storage

Barley processing quality refers to malting and brewing performance and is measured by a relatively large number of indexes. Many of these indexes measure the activity of different enzyme systems inherent in barley in a manner specifically relevant to the malting or brewing process. It is these enzyme based indexes that are affected by storage. Broadly speaking, malting indexes indicate the availability of enzymes, for conversion of carbohydrate and protein components of the barley to complex sugars and soluble nitrogen during downstream brewing processes. Storage related brewing indexes also indicate the quality or suitability of the barley components for breakdown by enzymes during fermentation stages, noting that there are a series of other indexes indicating performance of various brewing process stages. These enzyme systems are very dependent on the moisture and temperature conditions experienced by the barley during storage.

For malting, barley with high and uniform vigour is required by commercial malt-houses which are measured by various germination indexes. Maltsters specify minimum germination energy of 98% for stored barley (Anon, 1998) and generally will not receive barley below 96%. The fact that malt processing quality is based on germination indexes means that the relationship between germination and storage moisture, temperature, initial barley quality and variety described in Appendix 11.6.3., applies directly to malt quality. In summary, for a given lot of initially sound barley, overall malting and brewing quality will improve during storage as the grain matures, reach a peak and then decline over subsequent months as germination and vigour is lost with continuing storage.
Overall, storage plays an important role in maturing barley post-harvest to reach optimum malting potential. Freshly-harvested barley requires a period of post-harvest maturation to develop enzyme-based systems. This is especially the case for dormant varieties where initial germination response is strongly related to the dormancy of the variety. Although moderate levels of dormancy have been largely bred out of many Australian varieties, the condition has been retained in varieties that are grown in regions prone to adverse weather during harvest as protection against sprout-damage. Reuss et al (2004) and Woonton et al (2002) showed the activity of malt enzymes (α-amylase and β-glucanase) increased significantly in dormant barleys maintained under moderate storage conditions, and overall malt quality improved. Dormant varieties are often known as late maturing varieties (e.g. Franklin) and up to nine months storage under moderate conditions are normally required for these barleys to reach full malting potential. The level of seed dormancy which is present at harvest is also strongly influenced by environmental factors such as temperature and rainfall (Mares, 1987).

The initial condition of barley has a strong influence on time to reach optimum malting performance and the rate that peak malting quality is lost during storage. Reuss et al (2004) indicated that maturity at harvest was important to the overall storage potential of barleys, as samples of low maturity (high water sensitivity and high dormancy) were less vulnerable to germination loss and subsequent loss in malting quality. Weathered or aged barley is susceptible to rapid deterioration of malting quality during storage and can be past optimum performance at the time of harvest. CSIRO’s studies on barley storage and the influence of conditions and time on malting quality are detailed in Appendix 11.6.

It is difficult to make generalized predictions of barley germination, thus malting performance expected during storage due to the complex interaction between varietal characteristics, seed condition and maturity when harvested, and storage conditions confounding the rate that malting/brewing quality is lost. Different barley varieties harvested in a similar condition and stored in the same environment will exhibit substantial differences in many malting and brewing indexes at outturn, as a result of their genetic make-up. Storage of barley at high moisture and/or temperature conditions will generally result in a faster change of enzyme activity, and this can result in malt grade loss within a few months if the initial germination level was low due to weathering, but can also be favourable if initial germination levels were low due to dormancy.

7.3.4. Effect of modified atmospheres on processing quality

The effect of low oxygen and high carbon dioxide atmospheres on quality parameters of cereals is minimal, especially for grain stored ≤13% mc. For dry grain, Banks (1981) suggests that controlled atmosphere storage is of little benefit compared with storage in air when commodities are stored at an equilibrium relative humidity of less than 60%, except for very long-term storage (e.g. 5 years). Gras et al (2000) evaluated the performance of flours derived from dry wheat stored under atmospheres containing 1.0 and 4.6% oxygen in nitrogen. Storage under modified atmosphere had no significant influence on the performance of flour stored at 4 and 35°C. For marginally dry grain, there was some correlation shown by Lombardi et al (1980) between mould growth and low oxygen atmospheres (under nitrogen), suggesting that controlled atmospheres may be able to extend storage life of grains at moistures normally considered marginal for safe storage (i.e. $a_w = 0.7$ to 0.8).

For higher moisture grains, low oxygen and high carbon dioxide atmospheres are of greater benefit to the preservation of germination of grains (Banks, 1981), implying that malting quality of barley which is based on germination could be influenced by modified atmospheres.

Moulds are a major cause of quality deterioration in cereals stored at higher moisture contents and controlled atmospheres have shown benefits in maintaining viability and end-product quality by inhibiting their growth. In controlled laboratory scale experiments, high moisture wheat stored in low oxygen atmospheres provided better retention of dough properties compared to storage in air (Shejbal, 1979). The overall benefit to end-product quality however remains poorly quantified.
7.4. Grain quality in Australian bunker stores

Bunkers are a large-scale membrane based storage system extensively used under Australian grain production conditions since the 1970s. Australian bunkers exhibit some characteristics that are similar to harvest bags with their lack of a headspace, large near horizontal surface area for heat transfer, reliance on the structural properties of a polymer membrane to protect the grain, and relatively low capital cost. Grain quality issues observed with bunkers under Australian conditions can therefore shed some light on the expected performance from harvest bags in Australia. However, as there are significant differences between harvest bags and bunkers, making predictions on some quality effects based on bunker performance needs to be done cautiously.

A key issue is the capacity of membrane based stores to protect the stored grain from water ingress through leaks (rain, dew, melting frost) and contamination from rodent and bird droppings. Bunkers have a long history of severe localised grain spoilage due to water seepage through tarpaulin joints/seams, sampling holes where patches have weathered, and inadequately finished loading points in the store. Penetrations due to rodents at ground level and birds across the whole membrane, especially various Australian cockatoos, can exacerbate this problem substantially. When a bunker site has not been prepared to shed water effectively, ground level water ingress and associated spoilage can be extensive. Generally, water ingress related spoilage is addressed by careful attention to detail in the construction and maintenance of the bunker membrane envelope. Pressure testing can indicate if all leaks have been conclusively addressed, although a thorough inspection can also be effective. Harvest bags will incur this quality risk due to water ingress in a similar fashion to bunkers and require the same attention to detail to minimise such losses.

Moisture accumulation in the grain at the surface of Australian bunkers, just under the tarpaulin, is often observed during the colder months, and grain spoilage can result. The exact mechanism by which this moisture increases is believed to be the accrual of condensation on the underside of the covering tarpaulin and adjacent peripheral layer; moisture migration across the whole grain bulk due to natural convection cycles exacerbates this phenomenon. However, the size of the role of these mechanisms has not been studied sufficiently to quantify their respective influences. Major condensation during cold mornings on the underside of the roof of non-bunker stores is a very common observation and an analogous process will occur in bunkers, but bunkers do not have headspaces that enable ready ventilation of accumulated moisture at the grain surface during the periods where condensation is not occurring. Bunkers illustrate this surface spoilage and crusting, especially at the ridge, with storage of wheat at higher average moistures of 11 to 12% for 9 months or greater. Bunkers of field peas and pulses are known to crust when held over the winter months in Australia, which involves storage for more than 6 months.

Processing quality loss in the daily peripheral layer grain at the surface of bunkers has been observed by industry enough times to reduce the acceptance of this low cost storage system for certain grain types and grades. This quality loss is often attributed to high temperatures incurred by the peripheral layer, but a specific scientific study is lacking. GrainCorp Operations Limited has records of barley germination dropping almost completely (<3%) in the peripheral layer, while the average of the whole bunker out-turned at 91 – 92%. The use of roof covers to reduce the degree of radiant heating has been evaluated by GrainCorp, and shading was shown to effectively reduce heating in the peripheral layer.

ABB Grain Limited (formerly the Australian Barley Board) encountered barley losses in bunkers during 1993/94 season at four sites in northern Victoria (Ken Saint, ABB Grain; pers. comm.). In one of these bunkers, barley with average moisture contents less than 11% was stored for up to 15 months and extensively sampled prior to outturn early in season 1994/95. At outturn, germination had significantly declined in the upper 120 cm (longitudinal transact along centre of bunker) and damage was most extensive in the eastern end of the bunker. At the eastern end, all barley was dead. Apart from the eastern end of the bunker, loss in germination was generally restricted to the upper 30 cm of grain in the peripheral layer.
These observations on bunkers illustrate the potential for quality loss in harvest bags due to comparable phenomena in bunkers. Water ingress through the polymer membrane, moisture accumulation in the surface grain layer, and processing quality loss in the peripheral layers are all likely to occur in harvest bags. The extent and rate of these problems is inadequately understood for Australian conditions at this stage.

### 7.5. Grain quality in Argentine harvest bags

The commercial evaluation of harvest bags in Argentina has largely been undertaken at INTA’s agricultural complex near Tandil in the south-west of Buenos Aires Province. This involved trials measuring grain quality and storage information for wheat, maize, soybean and sunflower (Bartosik et al 2002; Rodriguez et al 2004) over a six month storage period. The wheat trial commenced soon after harvest (January) and unusually cool summer weather leading into the Argentine autumn (March/April) rapidly cooled grain in the peripheral layer. Bags were filled with wheat at 12.5 and 16.4% mc and peripheral layer temperatures in the 30°Cs progressively cooled to below 20°C within two months. The middle of the bags remained warmer, and cooled to 30°C and below 25°C within 4 and 8 weeks respectively. In these trials, commercially significant germination loss was measured in the centre of these bags in 6 months and 1 month respectively, but not as significantly in the peripheral layers, reflecting the warmer internal temperatures incurred (at these high moistures). There was also no evidence of insect infestation in any of the bags used in these trials.

Overall, Rodriguez et al (2004) concluded that these trials indicated that harvest bags provide favourable results. However, these results cannot be directly applied to typical Australian winter cropping scenarios. It appears that under the cool conditions of the Argentinean trials, the large surface to volume ratio characteristic of the harvest bag system suppressed potential quality loss with the high moisture wheat over the cooler months. The grain temperatures incurred were also not favourable for insect growth, given the initial low grain temperatures for maize and soybean (<23°C), and the steady decline in grain temperature of stored wheat and sunflower seed (<15°C). Data from the field evaluation of barley in harvest bags has not been made available in a published report.

Australian grains are typically stored under prolonged periods of hot weather, and the risk of potential quality loss is largely associated with the exposed peripheral layer compared to the more insulated inner part of the bulk. The reverse was true for the Argentinean trials reported by Rodriguez et al (2004), with the greatest risk of overall quality loss being associated with the warmer inner part of the bulk. A detailed account of the harvest bag trials in Argentina is provided in Appendix 11.2.

### 7.6. Maintaining grain quality in harvest bags in Australia

Firstly, the key issue for harvest bags to effectively maintain grain quality under Australian conditions is ensuring the bag membrane is not punctured or torn such that water can enter the grain stack in some manner. As described in section 4.4, the harvest bag is susceptible to puncturing and damage from a variety of causes, and much more susceptible than other stores used on-farm in Australia. Separating grain spoiled from water ingress from unspoiled grain is an annoying and troublesome handling problem. However, such leaks are a risk with all on-farm store types, and leaks in conventional stores are not always easy to locate and fix. To protect grain from spoilage caused by water leaks in harvest bags, good site location and preparation, proficient skills in filling of the bag, protection of bags from stock and wildlife, regular and frequent inspection of the integrity of bag membrane and patching will all be required as part of a management plan. These tasks are not required for conventional stores.
7.6.1. Peripheral layer: a challenging environment

The end-user processing quality issues of harvest bags, and any store, are a complex mixture of several influences. Firstly, higher temperatures or moistures will cause faster change of most processing quality indexes, but this change can involve an initial improvement followed by gradual loss in quality. The rate that quality changes over time is also substantially influenced by the initial quality of grain inloaded into bags which varies due to grain variety, growing season, and harvesting influences. Small on-farm stores (<100 tonnes) usually hold the harvest from just one or two paddocks and so the range of initial quality levels in these stores is narrower compared to large stores, which can contain grain sourced from numerous growers with subsequent wider growing and harvesting variation.

Secondly, the temperature and moisture of the grain varies during storage and with location in a store. For the interior of a harvest bag and most grain stores, grain temperatures in Australia follow the seasons with temperatures of 25-35°C occurring during summer and gradually lowering to below 15°C during winter. Interior grain moisture will remain fairly constant to the conditions when grain was inloaded into the store. Grain in the daily thermal peripheral layer of a store (100-200mm) undergoes daily oscillations in the range of approximately 20 to 50°C in summer and 0 to 20°C in winter. The moisture of this layer can experience substantial increases of up to 2% over cooler months depending on store type, due to accumulation of condensation and convection processes. When stores are outloaded, the peripheral layer and the interior grain mix with the final quality being a composite of these parts.

In the light of all these inter-related factors, the processing quality of grain out-turned from a harvest bag store will vary substantially between seasons, grain types and varieties, and geographic location, in a similar manner to other store types. The essential issue becomes: when it is likely that the use of harvest bags will result in greater processing quality loss compared to existing store types if the same grain, weather and storage period was involved? As there are no studies of processing quality loss in harvest bags under Australian conditions, this issue can only be addressed by analysing how harvest bags incur different temperature and moisture changes compared to other store types. Any loss of processing quality is then inferred from its dependence on grain moisture and temperature. Quality loss observations from other stores are used to corroborate any inferences.

The high proportion (up to 18%; refer section 7.1) of grain in harvest bags within the daily peripheral layer and their relatively shallow grain depth increases the risk of overall quality loss. As the greatest temperature and moisture changes occur in the peripheral layer, processing quality changes in this layer are expected to be greater. This is supported by observations in Australian bunkers (see section 7.4) where the peripheral layer grain was observed to have substantially reduced quality compared to the interior grain over long storage periods. On this basis, predicting broad quality changes in the peripheral layer was used to indicate processing quality changes for wheat and barley stored in harvest bags (sections 7.6.2. and 7.6.3 respectively). As only a few specific temperature and moisture profiles in harvest bag peripheral layers have been measured under Australian conditions, only a few obvious and conservative temperature and moisture scenarios were analysed.

7.6.2. Wheat

Previous CSIRO controlled studies on the storage potential of wheat provide a basis for recommended safe storage time for sound wheat stored in harvest bags (based on peripheral layer losses) and these are summarised in Table 4. The wheat data of Reuss & Cassells (2005) and Caddick (1999) suggests that wheat received up to the industry’s current 12.5% mc (wet basis) limit should maintain quality in harvest bags at temperatures up to 35°C for up to six months storage. The harvest condition of wheat stored in harvest bags will however substantially influence storage potential over time. Premium quality wheat stored at average moisture levels ≤11.5% is likely to be outturned at 12 months with minimal risk of overall quality loss. This low moisture level provides a buffer to compensate for potential localised increase in grain moisture due to condensation and moisture aggregation.
Caddick (1999) showed baking and noodle quality of southern-hard wheat stored at 13% mc and 30°C for 12 months and 14% mc and 30°C for 6 months was similar and not significantly different to control wheat stored at 4°C. Storage time had improved overall noodle quality as the strength and elasticity of the flour dough had increased. Wheat stored at 14% mc and 20°C for 12 months produced the best quality noodle and maintained baking quality. Similar results were obtained for wheat stored at 15% mc and 20°C for 6 months.

Premium quality wheat is therefore expected to store well in harvest bags as conditions should not exceed these moistures and temperatures, and the data of Caddick (1999) provide a useful guide to “safe” storage conditions and time. There are no data available for the effects of medium- to long-term storage on flour and end-product quality at 35°C. However, an estimated “safe” storage time is listed. These storage times are only a guide and approximating an average temperature for the peripheral layer is difficult, even with extensive monitoring of grain conditions. A more detailed discussion of the data underlying these recommendations is provided in Appendix 11.5.

Table 4. Recommended safe storage time (months) for sounda wheat stored in harvest bags

<table>
<thead>
<tr>
<th>Storage Temperature (°C)</th>
<th>Moisture Content (%)</th>
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<td>40</td>
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</table>

a – wheat that has been substantially aged or weather damaged by rain will have significantly lower storage potential than the time (months) listed. Data from Reuss & Cassells (2005) and Caddick (1999) used as basis for recommendations.

7.6.3. Malting barley

Predictions of the affect of storage of malting barley in harvest bags is based on quality changes expected in the peripheral layer, following the logic explained in section 7.6.1. The safe storage limits of non-dormant varieties with a good condition following harvest in harvest bags can be indicated using the germination energy data of Reuss et al (2005) and Caddick (unpublished data). These limits are summarized in Table 5 and are conservative for non-dormant varieties of malting barley and very conservative for dormant varieties. In general, non-dormant malting barley is less robust than wheat to store and is not as well suited to long-term storage in un-aerated stores.

The storage of non-dormant but sound dry barley (≤ 11% mc) in non-punctured harvest bags are estimated to incur peripheral layer moistures of up to 13% over winter but remain dry over summer with temperatures above 30°C. This will provide 6 months of safe storage, basically as dry grain provides a substantial buffer against loss of germination energy and malting quality loss during summer. A similar storage scenario, however, the barley moisture approaches the industry’s 12% mc (grain just meeting maximum receival limit) will be reliably safe for only 2-3 months storage where a substantial risk is possible with peripheral layer barley exceeding 40°C during the summer months.

Although exposure to temperatures in the peripheral layer above 35°C may only occur for 2 to 3 hours maximum during hot days, the cumulative effect and exposure to widely fluctuating temperatures may be detrimental to overall malting quality, even during short-term (e.g. 3 months) storage. The influence of peripheral layer conditions on overall malting quality needs to be studied in commercial situations to quantify such changes. A more detailed discussion of the data underlying these recommendations is provided in Appendix 11.6.
Table 5. Recommended safe storage time (months) for sound non-dormanta barley stored in harvest bags

<table>
<thead>
<tr>
<th>Storage Temperature (°C)</th>
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</table>

a - barley that has been substantially aged or weather damaged by rain will have significantly lower storage potential than the time (months) listed. Barley with moderate to high levels of seed dormancy will have a considerable buffer against loss of malting quality. Data from Reuss et al (2005) and Caddick (unpublished data) used as basis for recommendations.

7.6.4. Harvest buffer storage

A key use of harvest bags on Australian farms is to provide a relatively short term “harvest buffer” storage option; approximately 4 months or less. This enables growers to optimise their harvest operations without the inflated costs and bottlenecks involved with delivery to BHC receival points. Assuming no water ingress, wheat harvested to meet receival moisture limits with acceptable initial quality and then stored in bags for less than 3 months, mostly over summer, would not expect any significant change in processing quality in the peripheral layer. For example, assuming grain temperatures in the peripheral layer averaged 40°C for these 3 months, all wheat processing quality indexes would pass acceptable standards (see Table 4). This conclusion does not hold for malt grade barley. When passable initial quality malting barley is stored for 3 months in harvest bags, the processing quality of the peripheral layer may fall below the 98% GE limits at 12% and 40°C (see Table 5). This reflects that wheat processing quality is more robust than malt barley. However, if the initial quality of malt barley was good or a dormant variety was involved, quality loss in the peripheral layer would not be significant over 3 months. The storage potential of wheat and barley in harvest bags is discussed further in sections 7.6.2 and 7.6.3 respectively.

7.6.5. Longer term storage for marketing flexibility

Using harvest bags to store winter cereals for 4 to 9 months for marketing flexibility reasons, will involve storage over summer then winter. The processing quality in the peripheral layer is a cumulative result of continual moisture and temperature changes, with accumulated condensation over the cooler months. To estimate risk here, the peripheral layer grain is assumed to increase in moisture by 2% for winter, but considerable cooling occurs for the peripheral layer and store in general, noting that predictions are considerably less accurate based on available information. Out-loading dry grain during the colder winter months when condensation issues are at highest likelihood presents a potential risk of encountering spoiled grain at the surface. Conservatively, sound wheat stored in a non-punctured bag that meets receival moisture limit (12%) is expected to maintain all processing quality parameters for 9 to 12 months storage. Non-dormant sound malting barley stored in non-punctured bags that meets the receival moisture limit (12%) is considered at risk of losing germination based quality stored over such periods. To provide a more precise (less conservative) estimate of processing quality storage limits for harvest bags requires a detailed study of peripheral layer issues.
8. IMPLEMENTATION OF HARVEST BAGS IN AUSTRALIA

This section describes limitations of the existing harvest bag system being traded in Australia, recommendations to address these limitations using available technologies, and then provides a description of options to develop the technology further to meet the needs of Australian growers.

8.1. Limitations of harvest bags with current technology

A major output of this project is to identify and report the limits of existing harvest bag technology for Australian conditions, including inadequacies in how the system is being used. These limits are grouped into several categories as follows.

8.1.1. Handling and management

Harvest bags require substantial operational involvement and associated skill to achieve the weather proof and gas tight system as designed. This is required during the site preparation, loading of the bags, and overall management of the bags during storage. In many cases, harvest bags are being managed by “novices” and it has been found that considerable experience is needed to achieve good results. Farmers are already preparing suitable raised pads, constructing more sophisticated fences around the bags and using synthetic nets to minimise bird damage. The limitations and related issues identified in this study, primarily via the surveys and field trial collaborations are summarized as follows:

• Experience and skill required with loading machinery
• Sealing ends is difficult and a common moisture ingress point
• Regular and careful management of bag membrane required to ensure weatherproof state
• Bag membrane easily punctured by poor base, wildlife, etc
• Less secure to vandalism, grain theft and interference during fumigation
• Problematic for removal of small batches of grain
• Requirement to dispose of spent plastic bags
• Deterioration of plastic film limits storage time (e.g. 18 months maximum)
• Disposable bags do not have any asset value when storage is completed
• Lack of flexibility post-filling, e.g. grain cannot be turned or blended

8.1.2. Lack of gas-tightness

The surveys and field trial collaborations have demonstrated that effective levels of gas-tightness as measured by pressure decay tests are not being achieved for farm sited harvest bags with current skills and practices. Also, there are inherent difficulties in maintaining a sealed system for an extended time (refer section 4.4). Operators with good experience and skill (bag suppliers) were able to achieve a high gas-tightness standard at loading, but even professional storers (ABB Grain Limited) found maintaining this high level is difficult and required substantial input, e.g. pressure test and inspect on regular basis and repair when necessary. The limitations and related issues identified in this study are summarized as follows:

• Constructing a bag without any punctures to an effective gas tightness standard requires good skill and experience and site preparation.
• Maintaining the integrity of membrane seal requires regular interaction during storage.
• A key risk to tears and perforations is livestock, foxes, rodents and birds which requires security fencing and possibly bird netting.
• The bag membrane has proved difficult to repair damage or reseal inspection points using common adhesive tapes or silicon-based gels.
8.1.3. Insect control

The current system lacks a reliable disinestation capacity as hermetic conditions are not achieved in non gas tight or dry grain scenarios. Even if an appropriate gas-tightness level was implemented, high insect densities are required to create insecticidal conditions, which is an unwanted situation for commercial trade. If insects are found during out-loading of a harvest bag, the “split” unloaded bag does not enable conventional tablet phosphine fumigation to be implemented readily. Fumigating with phosphine before outloading involves inserting the aluminium phosphide product (e.g. tablets or pellets) at regular intervals along the length of the bag, breaching approved label requirements. Other available disinestation options such as chemical grain protectants are not accepted by several markets. The limitations and related issues identified in this study are summarized as follows:

- A reliable insect disinestation capability with harvest bags is not available
- Insects detected at outturn pose considerable logistical problems
- Use of solid phosphine preparations breaches label requirements
- Use of residual chemicals to control insect infestation only possible where sufficient permanent storage capacity is available to turn and treat grain
- Bags are difficult to sample for insect infestation

8.1.4. Localised spoilage

Localised spoilage of grain stored in harvest bags can result where moisture has accumulated with internal condensation or water ingress through perforations and tears to the film. This will result in localised moulding of dry grains with the marginal or lower water activity of the surrounding dry grain preventing widespread downgrading. Condensation on the inside of the film is an inherent problem with plastic membrane type stores such as harvest bags, especially during cooler times of the year and cool locations. The removal of localised spoilage is a difficult process and not practicable where a bag extractor is used. During outturn, grain is not accessible to the operator unless the bag is manually split ahead of the machine taking up the plastic film onto the hydraulic drum. The limitation identified in this study is:

- Condensation and water aggregation under film can cause localised moulding and spoilage

8.1.5. Grain processing quality

Grain within the surface peripheral layer of harvest bags (surface 150mm) has the greatest risk of end user processing quality loss due to the higher temperatures and moistures incurred. Harvest bags have a higher proportion of their grain within this layer with in excess of 18% of the total grain stored in harvest bags is exposed to peripheral layer influences (refer section 7.1). The harvest bag system does not enable surface grain to be separated once loaded. This can result in non-dormant sound barley that meets a receival moisture limit (12%) losing malt grade if stored for over 6 months storage in a non-punctured bag. Conservatively, sound wheat stored under the same constraints is expected to maintain all processing quality parameters. Data for other grain types is lacking. Limitations and related issues identified in this study are summarized as follows:

- Risk of quality loss and down-grading
- Malting barley can be at risk when stored in harvest bags for over 6 months.
- Harvest bags incur a greater risk of processing quality losses compared to other store types due to the high proportion of surface peripheral layer in total mass stored.

8.1.6. Early-harvesting

Harvest bags are reported as being successful at storing high moisture grain in Latin America. Early harvesting grains at higher moisture contents can provide increased harvest flexibility, reduce weather damage risks, increase overall productivity and maximise specific quality traits. High moisture harvesting of winter crops in Australia is expected to result in moisture contents of 12 to 15% (wheat). Anecdotally, growers have successfully used harvest bags to hold higher moisture grain for 2 to 3 months but specific details are lacking. Early harvested grain typically has considerable variation in
moisture and large variations in self heating and moulding occur across such moistures (e.g. wheat spoilage rates vary markedly across ≈14%). Field trial experience is essential here. As a result of this lack of technical evidence, high moisture storage in harvest bags is regarded as a risk which is highly dependent on the actual grain moistures encountered. The limitation identified in this study is:

- Storing high moisture grain (wheat > %14) is at risk of mould spoilage when stored in harvest bags for over 8 weeks.

8.2. Recommendations for use of existing harvest bag technology

Overall, it is assumed that users will adopt procedures currently promoted by harvest bag suppliers for preparing sites to prevent punctures, enable good drainage, provide security, patch bag membrane leaks, etc, and correctly loading bags. It was apparent in the surveys that users were well aware of the need to prevent punctures by excluding wildlife, especially foxes and birds.

A series of more specific recommendations to improve aspects of the existing harvest bag technology based on the findings of this study are described below. It is assumed that effective hermetic conditions will not be achieved in the bags. Recommendations on safe storage periods are conservative and are only made where both controlled laboratory results and confirming field trial results were available. This should reliably cater for decisions involving investment in harvest bags.

Recognize harvest bags provide a safe option for storage of dry grain for less than 4 months. Harvest bags can provide a cost-effective and safe storage option for grain that meets receival standards when used for less than 4 months following winter crop harvest. This assumes moisture ingress is prevented and insect control is available. This is particularly attractive for “harvest buffer” storage. This enables growers to optimise their harvest operations to avoid inflated costs and bottlenecks involved with delivery to commercial storage receival points. Storage of 6 months and longer can be more problematic and storers should refer to sections 6 and 7 of this report to ascertain their needs.

Develop and implement a gas tightness testing method for harvest bags. The presence of punctures and inadequate sealing of the ends of the bag will be readily detected by a pressure test that is currently used for other grain stores in Australia. The same principles apply and a suitable air extraction arrangement is conventional equipment. This method would also be used for proving capability of the bag for hermetic atmosphere generation or fumigation.

Develop a reliable and durable patching system for the bag membrane. Repairing punctures or sampling penetrations requires an effective repair/patching arrangement. It appears that an appropriate kit is not currently available or has not been promoted sufficiently by suppliers. It is expected that this practical detail would be readily addressed by bag suppliers.

Promote reliable procedures to maintain the integrity of harvest bag membranes. As harvest bags are prone to grain spoilage from leaks through punctures and tears; a convenient and credible system to test and repair membrane integrity would assist users to prevent such losses and create confidence in the use of bags to grain buyers. As leaks can occur during bag construction or storage, the procedure would require a schedule of regular testing. A very reliable approach would be the use of a gas tightness pressure test, but thorough visual inspection can identify most punctures and related contamination issues.

Develop appropriate insect disinfestation options, especially for farm use. A reliable disinfestation system is needed for harvest bags. For on-farm, a phosphine system based on tablets/pellets with an accompanying distribution system that will not mix pellets directly with the grain is recommended, as dry aluminium phosphide preparations will remain the mainstay for on-farm fumigation. A small fan-forced system is envisaged to ensure that adequate fumigant concentrations are achieved throughout a harvest bag store for sufficient time and in a safe manner, noting that the length of the bags and the lack of head space restricts effective distribution of the gas through the grain. Theoretically, this is not
Assessing the limits of existing harvest bag technology under Australian conditions

Technically difficult but requires development. The more expensive blanket or cylindered phosphine with such a fan-forced system may suit larger scale storers. An alternative approach can be the use of introduced carbon dioxide or suitable oxygen absorbers to deplete oxygen. Achieving and maintaining sufficient gas-tightness is imperative for successful insect control by either method.

Promote recommendations on safe storage limits for barley and wheat stored in harvest bags, based on moisture content, temperature and time periods (with no hermetic conditions) contained in this report. For example, sound quality wheat harvested at moistures below 12.0 will not incur visible moulding or processing quality loss for over 12 months (refer sections 6.2 & 7.3) when moisture ingress is prevented and insect control is available. In practice, sampling of the surface peripheral layer for mould inspection and quality assays can be used to monitor the “weak point” of harvest bags, especially for storage throughout the winter periods.

Develop a credible trade arrangement to prove the processing quality of grain in harvest bags. Where a grain type and/or grade requires specific processing quality standards to be met and storage for longer than 4 months is anticipated, a practical and credible agreement between the storer and the buyer that proves the quality of the grain stored, would facilitate the creation of confidence in the use of harvest bags for grain buyers. This would be based on a sampling protocol from the “weak point” of harvest bags, the surface peripheral layer, and associated quality assays (e.g. falling number, germination, free fatty acid) to manage this risk. Samples from the peripheral layer will conservatively define the performance of the harvest bag system during medium to long-term storage as in excess of 18% of the total grain capacity of harvest bags is exposed to peripheral layer influences.

Recommendations on the appropriate time limits for storage of early harvested higher moisture grain (e.g. wheat at 13-15% moisture) in harvest bags are not provided, as specific field trial evidence under Australian conditions is not available. Early harvested grain typically has considerable variation in moisture and large variations in self heating and moulding occur across such moistures (e.g. wheat spoilage rates vary markedly as moisture increases above approximately 14%). Field trial experience is essential here. However, a guide for times for safe storage of mildly wet cereals at consistent moisture is provided in Table 3 of section 6.2.

9. ACKNOWLEDGEMENTS

The financial support of the Grains Research and Development Corporation (GRDC) is greatly appreciated. We thank Peter Annis (CSIRO Entomology) for his significant contribution to the science of controlled atmosphere and hermetic storage, and his valued assistance with the preparation and review of this report. Peter Kerr (CSIRO Entomology) also provided valued input into the review of this report. Jane Green provided technical assistance with the CSIRO field and farm surveys, and compiled project data.
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Assessing the limits of existing harvest bag technology under Australian conditions


11. APPENDICES

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CSIRO evaluation of harvest bags on-farm and in commercial use
L.P. Caddick & J. Green (September 2007)

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CSIRO field evaluation of harvest bags on-farm and in commercial use

L.P. Caddick and J. Green

September 2007
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11.1.1. INTRODUCTION

The CSIRO Stored Grain Research Laboratory completed a field evaluation of harvest bags on-farm and in commercial use during February 2006 to June 2007.

The field evaluation was part of GRDC Project CSE00035 “Assessing the limits of existing harvest bag technology under Australian conditions”, and incorporated three separate studies:

2. Survey of the harvest bag system on farms in New South Wales and Victoria, May to October 2006
3. Commercial evaluation of grain harvest bags at ABB Grain Limited sites at Bowmans and Roseworthy, South Australia, December 2006 to June 2007

The CSIRO Black Mountain trial was a pilot-scale study of harvest bags containing wheat conditioned to 11.4 and 14.1% moisture contents. The gas-tightness of the two bags was assessed, gas composition was measured at regular intervals, and grain and weather conditions monitored on a continual basis during the trial period from February 2006 to May 2007. This introduction to harvest bag technology was designed to refine experimental protocol and develop equipment for subsequent assessment of harvest bags on farms and at commercial grain storage sites.

The farm survey aimed to assess the level of gas-tightness achieved and the durability of the film and system to maintain a level of gas-tightness for a prolonged storage period. Selected harvest bags located on farms in New South Wales and Victoria were pressure tested under vacuum in May and October 2006. The bags had been standing in a paddock environment for up to 11 months post-harvest. Where an acceptable standard of gas-tightness was not achieved, the reasons for lack of seal and the overall condition of harvest bags and grain stored were reported. The farm study complemented results from a harvest bag user survey completed by Strategic Economic Solutions (Canberra) in May 2006 and reported to GRDC in June 2006.

The collaborative field evaluation of harvest bags at ABB Grain Limited sites at Bowmans and Roseworthy in South Australia comprised four bags of canola and two of malting barley, each approximately 100 t capacity. Canola and barley were loaded into harvest bags in early December 2006 and included the use of bags from the two major manufacturers of bags in Argentina. The harvest bags will be out-loaded in September 2007 (i.e. 9 months storage) and CSIRO’s collaboration in this commercial field evaluation is reported to June 2007.

Described as a hermetic type of storage system, harvest bags are manufactured seamless and careful closure and sealing of the ends at loading can provide an enclosure that acts as a partial barrier to gaseous exchange. A key feature of the initial promotion of harvest bag technology in Australia has been the claim that the system provides air-tight hermetic storage and requires no chemicals to control insects.

This report assesses the current performance of harvest bags on farms and identifies a number of advantages and disadvantages associated with their use. Particular emphasis was placed on determining the gas-tightness of the system and the maintenance of a sealed system during storage.
11.1.2. PROCEDURES AND EQUIPMENT

11.1.2.1 Experimental design

11.1.2.1.1 CSIRO Black Mountain

Approximately 20 t of wheat was conditioned to 11.4 and 14.1% mc and placed into a commercial-sized silo bag and stored for 15 months from February 2006 to May 2007. HOBO data loggers were inserted into the grain to monitor grain temperature and relative humidity. The gas-tightness and integrity of the bag was determined using a standard pressure test. Mould levels were determined at 10 and 15 months storage. A composite of the inner core and peripheral layer from each bag were taken at completion of the trial and subsequently assessed by Agrifood Technology P/L for processing and end-product quality.

11.1.2.1.2. Farm survey

In May 2006, harvest bags on 7 farms in New South Wales and Victoria were surveyed. Farm visits were organised in consultation with Mr Neil McAlpine, Swan Hill Chemicals, Swan Hill (VIC). Harvest bags ranged in capacity and included barley, wheat, field peas and lentils. In October 2006, a farm site near Hillston was re-visited to sample barley that had been stored for 11 months. Gas-tightness was determined, gas samples taken for subsequent analysis, and grain samples were collected for moisture determination and germination assessment.

11.1.2.1.3. ABB Grain Ltd. trials

Bowmans

Canola was loaded into SiloBolsa™ bags at Bowmans on 01/12/2006. Feed and Forage Bags P/L (Adelaide) provided the bags and loader and supervised the loading operation. Two bags of approximately 100 t capacity were set on a sandy soil base. Both bags were damaged during the loading operation. Canola loaded into the bags was dry and visually appeared to have been weathered. No fencing was erected around the bag site. Gas-tightness was checked one week after filling and HOBO U12 data loggers were inserted into bags at different points to monitor temperature and relative humidity during storage. Gas samples were taken from bags at 3 and 6 months for subsequent analysis using GC techniques. At 6 months, gas-tightness was checked, grain samples collected, and HOBO loggers were replaced.

Roseworthy

Barley and canola was loaded into IPESAsilo™ bags at Roseworthy on 08/12/2006. Silo Bags P/L (Springsure, VIC) provided the bags and loader and supervised the loading operation. Existing bunker pads were carefully swept and prepared, and four bags of approximately 100 t capacity were set on a firm gravel base. Two barley bags were set on one pad and two canola bags set on a separate pad. The loading operation was completed without any film damage. No fencing was erected around the bag site. Barley and canola loaded into the bags was dry and appeared weathered. Gas-tightness was checked 1 week post-filling, grain samples collected and a total 24 HOBO U12 data loggers inserted into the bags at different points to monitor temperature and relative humidity during storage. Gas samples were taken at 0, 3 and 6 months for subsequent analysis using GC techniques. At 6 months, gas-tightness was checked, grain samples collected, and HOBO loggers were replaced.
11.1.2.2. Grain conditions

11.1.2.2.1. CSIRO Black Mountain

Initial germination energy (GE) was 95.2 and 98.7% for 11.4 and 14.1% mc wheat respectively (Table 9). Both batches of wheat used in the trial were weather damaged. 2004/05 seasons wheat contained excessive proportion of small grains and screening; the “pinched” grains evidence of a dry finish to the harvest. 2005/06 seasons wheat was stained by black-point, evidence of weather damage; however, no sprouted kernels were observed under magnification.

11.1.2.2.2. Farm survey

The condition of the different grain types stored in harvest bags (Table 10) was variable. In general, grains were stored at low moisture contents (e.g. 9.2 to 11.6% wet basis). Barley at 12.2 to 13.2% mc was stored in one bag at Sea Lake. Field peas and lentils had been weathered prior to storage, and wheat and barley in several bags appeared to also be late-harvested.

11.1.2.2.3. ABB Grain Ltd. trials

Roseworthy

Initial germination energy (GE) of barley ranged between 95.8 to 100%; indicating a proportion of the barley used to fill bags had been weathered (Table 13). The moisture content of canola loaded into bags 1 and 2 ranged between 4.5 to 5.2%. Initial germination energy ranged between 92.3 to 98%; indicating a proportion of the canola used to fill bags had been weathered (Table 14).

Bowmans, canola

The moisture content of canola loaded into bags 1 and 2 ranged between 4.9 to 6.3%, with bag 2 storing the higher moisture seed. Initial germination energy ranged between 91.0 to 97%; indicating a proportion of the canola used to fill bags had been weathered (Table 15).

11.1.2.3. Gas-tightness

Gas-tightness was measured using a Halstrup-Walcher digital pressure gauge, Model EMA 84 (Halstrup-Walcher GmbH, Kirchzarten, Germany). A negative pressure was formed under vacuum and the pressure decay time recorded for the loss of negative pressure from 1200 to 600 Pascals. The pressure was initially increased to 1400 Pascals, the vacuum source removed and film perforation sealed. An inclined manometer (Mk 4 Airflow Testing Set, Airflow Developments Limited, UK) was also used to measure gas-tightness and verify the accuracy of the digital pressure gauge. A negative pressure was formed under vacuum and the pressure decay time recorded for the loss of negative pressure from 1200 to 600 Pascals. The pressure was initially increased to 1300 Pascals, the vacuum source removed and film perforation sealed.

11.1.2.4. Gas composition

A low-flow pulse pump (Midan Company, California) was used to draw approximately 1.5 l of modified air through a sampling line inserted into the centre of the grain into a Tedlar bag (3.0 l capacity; SKC Incorporated, PA, United States). Gas samples were analysed within 72 hours of collection using GC techniques. Analysis of oxygen and carbon dioxide was carried out using a Fisher Model 1200 Gas Partitioner (Fisher Scientific Company, PA, United States) with 80-100 mesh Columnpak™ PQ (6.5” x 1/8”) and 60-80 mesh Molecular Sieve 13X (11” x 3/16”) columns in series. The conditions used were: carrier gas, helium at a flow rate of 22 mL per minute; oven temperature, 50°C. Concentrations were calculated on the basis of peak areas. The Gas Partitioner was checked for
accuracy using a standard gas mixture of known oxygen, nitrogen and carbon dioxide. A low carbon dioxide method developed at SGRL was used for the analysis.

11.1.2.4.1. CSIRO Black Mountain

Gas was drawn from various points along the length of each bag and included west- and east-facing aspects as shown diagrammatically in Figure 2 and 3. Gas was drawn from total of 8 and 10 different points from the 11.4% mc and 14.1% mc harvest bags respectively.

11.1.2.4.2. ABB Grain Ltd. trials

Gas was drawn from two separate points along the length of each bag and included west- and east-facing aspects as shown diagrammatically in Figure 4.

11.1.2.5. Grain temperature and relative humidity

Grain temperature and relative humidity was monitored using HOBO U12 data loggers (ONSET Computer Corporation, MA, United States). The data loggers have capacity to record and store up to 43,000 measurements and are well-suited to monitor grain conditions in harvest bags over a 6 month period.

11.1.2.5.1. CSIRO Black Mountain

The positioning of HOBO data loggers in the harvest bags was designed to provide a profile down the centre axis. One logger was located to measure grain conditions close to the film at the wall. The location of loggers at each insertion point was: surface within 10 cm of the wall film; surface within 10 cm of the top film; below surface 30 to 40 cm below the top film; and deep between centre & base. Insertion points included both west- and east-facing aspects. Measurements were recorded every 20 minutes. A diagrammatic representation of the plan and cross-sectional location of HOBO data loggers is given in Figures 5 and 6.

11.1.2.5.2 ABB Grain Ltd. trials

The positioning of HOBO data loggers in the harvest bags was designed to provide a profile down the centre axis. One logger was located to measure grain conditions close to the film at the wall. The location of loggers at each insertion point was: surface within 10 cm of the wall film; surface within 10 cm of the top film; below surface 30 to 40 cm below the top film; and deep between centre & base. Insertion points included both west- and east-facing aspects of the bags. Bag one was selected to measure the west-facing aspect; bag two the east-facing aspect. Measurements were recorded every 20 minutes. A diagrammatic representation of the plan and cross-sectional location of HOBO data loggers is given in Figures 7 and 8.

11.1.2.6. Grain sampling

Grain samples were taken from selected points for grain moisture determination and germination assessment. A cyclone type dust collector, which operates external to a vacuum cleaner, was used to draw wheat samples. A metal probe with a 16 mm ID plastic pipe was attached to the cyclone collector and under vacuum sample was drawn into the collection chamber. For the CSIRO Black Mountain trial, multiple 1 kg samples were drawn at 15 months to make up the composite required by AWB Limited for subsequent flour and end-product quality assessment.
11.1.2.7 Moisture content

Grain moisture content was determined using a standard oven-dried method (Anon, 1985), and results are expressed on a wet weight basis (wb). Sub-samples for the CSIRO Black Mountain trial were taken at 8 and 15 months storage times and placed into sealed glass vials for subsequent moisture determination. Sampling points are shown in Figure 9.

11.1.2.8. Germination Energy

Germination Energy (GE) was evaluated under standard conditions as defined by the ISTA International Rules for Seed Testing (Anon, 1993). Germination Energy was determined on 4 replicates of 100 kernels, placed between paper towelling (Eqwip™, Grade R6), standardised with 50 ml distilled water, placed into sealable plastic sleeves and maintained under artificial illumination in an incubator at 20°C for 7 days. Results for viability are also listed in tables; however, seeds that show poor vigour or abnormal development are discounted in the ISTA assessment of GE.

11.1.2.9. Mould Assessment: CSIRO Black Mountain

Mould infection levels on 14.1% mc wheat were assessed at 8 and 15 months storage. Sub-samples were taken from selected points (Figure 9), placed into sealed plastic bags and forwarded to Food Science Australia (Sydney) for testing.

FSA completed direct and dilution plating assays. Direct plating involved a 100 seed assay each on Dichloran Rose Bengal Chloramphenicol (DRBC) agar and Dichloran 18% Glycerol (DG18) agar. Dichloran Rose Bengal Chloramphenicol (DRBC) agar, a general purpose fungal isolation and enumeration medium and Dichloran 18% Glycerol (DG18) agar, is a reduced water activity medium used to detect xerophilic fungi such as Eurotium species. DRBC plates were incubated at 25°C for 7 days, while the DG18 plates were incubated at 25°C for 10 days. The plates were then examined microscopically to determine the genera present.

Dilution plating involved a 10 g sub-sample being homogenised with 90 mL of 0.1% peptone solution and the resulting homogenate was spread plated onto duplicate plates of yeast and mould isolation media comprising Dichloran Rose Bengal Chloramphenicol (DRBC) and Dichloran 18% Glycerol (DG18) agar. The plates were incubated as detailed above. The plates were then examined microscopically to determine the genera present and counts made of each organism detected.

11.1.2.10. Wheat processing and end-product evaluation: CSIRO Black Mountain

Agrifood Technology P/L (Werribee, VIC) completed processing, flour rheology and end-product assessment of wheat composites prepared from the 11.4 and 14.1% mc wheat harvest bags. The 15 month postharvest composite wheat samples comprised wheat from sampling points shown in Figure 9. The peripheral (surface) layer composite comprised sub-samples from points A1, A2, A3, A4, A5, B1, B2, B3, B4, B5, C1, C2, C3, C4 and C5. The inner core composite comprised sub-samples from points A6, A7, A8, A9, B6, B7, B8, B9, C6, C7, C8 and C9. This sampling regime was used for preparing composites from both 11.4 and 14.1% mc harvest bags. Control samples were collected during filling of the bags and were subsequently stored frozen (-15°C) up to the despatch time.

The processing, flour rheology and end-product assessment included standard procedures used by AWB Limited to prepare a client-based Shipping Quality Report. Selected quality parameters were used in this report (Table 19); however, the assessment was more extensive and included physical tests for whole grain and extensive colour analysis for flour, bread and raw and cooked noodles.
11.1.3. RESULTS

11.1.3.1 Sealing standard

11.1.3.1.1. CSIRO Black Mountain

The sealing standard for 11.4% and 14.1% mc wheat harvest bags at two months post-filling was 117 and 66 seconds respectively (Table 6). A sealing standard of two-minutes is reasonable for small capacity bags (i.e. < 20 t); however, a one-minute standard is unsatisfactory. For both bags, the closed ends were potential leakage points. The ends were closed with a plastic strip designed to seal the two layers of film; potentially, this seal was incomplete. The bags were also fitted with numerous measurement cables and gas sampling lines and effective sealing of the film at these entry point proved more difficult than anticipated. A small leak though the end(s) or a cable entry point would substantially reduce the seal of a small capacity bag.

11.1.3.1.2. Farm survey

Harvest bags surveyed were generally poorly sealed (Table 7) with only 2 of the 13 bags tested holding a negative pressure to any degree. The “sealed” bag at Sea Lake was repaired with adhesive tape to achieve the 1.53 second standard. Prior to sealing, no negative pressure was formed under vacuum for this Sea Lake bag.

11.1.3.1.3. ABB Grain Ltd. trials

Barley and canola harvest bags at Roseworthy were sealed to a high level of gas-tightness (Table 8). At the initial test, two bags exceeded 20-minute half-pressure decay standard, and the remaining bags exceeded 7 and 10 minutes.

The canola harvest bags at Bowmans were not well sealed and failed to meet a two-minute half-pressure decay standard. The film was damaged during filling and several large tears in the film had been repaired with adhesive tapes.

Gas-tightness of the harvest bags was re-assessed at 6-months post-filling (Table 8). Three bags at Roseworthy exceeded a four-minute half-pressure decay standard, and the remaining bag was 1.34 minutes. HOBO data loggers had been inserted into these bags and potentially these points were a source of air leakage into the sealed system. Several punctures due to fox damage were observed in the film of the canola bags and the leaking bag (i.e. 1.34 minutes) was extensively damaged at one end by pin-sized punctures and several small tears caused by foxes. Fox activity was also observed around the barley bags, but damage was not obvious. Several small tears had been repaired on the barley bags. Barley at the point of one tear was heavily infested by insects. A data logging access point on the west-facing wall of a barley bag was similarly heavily infested. Both these points had been re-sealed prior to the gas-tightness test.

The harvest bags at Bowmans failed to register a substantial negative pressure at the six-month assessment. Both bags had been extensively damaged by foxes, including tears and numerous pin-like punctures to the ends, top and walls. Protective fences had been erected after the damage had occurred. The extent of the damage however was too substantial to repair and this was reflected in the lack of gas-tightness.
11.1.3.2. Gas composition

11.1.3.2.1. CSIRO Black Mountain

11.4% mc wheat
Gas composition was measured at regular intervals (Table 6). 11.4% mc wheat was very heavily infested with insects prior to filling and gas composition changed significantly within 14 days when oxygen (O2) and carbon dioxide (CO2) levels were 5.6 and 10.8% respectively. It is likely that O2 levels had declined below 5.6% prior to the initial gas sample time, and air ingress subsequently increased O2 in the system. Infestation data (Table 16) suggests complete insect death had occurred within the initial 14 day storage period. After this time, O2 levels progressively increased and CO2 decreased.

14.1% mc wheat
Modification of the gas composition within the 14.1% mc wheat harvest bag was a gradual process up to early May 2006. The cold winter months resulted in a decline in CO2 levels as air ingress into the system increased O2 levels up to 19.5% in early November. The rapid decline in O2 (10.8%) and raised CO2 (11.9%) levels from early January to early May 2007 suggests mould activity and grain respiration (to a lesser degree) had increased during the hot summer months, with moisture levels recorded up to 14.8% in the peripheral layer in early May 2007.

11.1.3.2.2. Farm survey

Level of gas modification in the harvest bags (Table 7) was low. At six months, levels of 2.3 and 2.0% CO2 were recorded for lentils and barley stored at Swan Hill and Sea Lake respectively.

11.1.3.2.3. ABB Grain Ltd. trials

Roseworthy
Oxygen and carbon dioxide levels at Roseworthy were measured at 0, 3 and 6 months post-filling (Table 8). Change in gas composition in barley bag 1 at Roseworthy was significant with O2 and CO2 measured at 15.0 and 6.1% respectively at 3 months and 9.8 and 9.4% respectively at 6 months storage. Carbon dioxide in barley bag 2 at Roseworthy was 4.4% at 6 months. The conversion rate of O2 to CO2 was substantially slower in the canola bags at Roseworthy, measured at 3.1 and 4.4% at 6 months storage. Insects were detected in barley bag 1 at 6 months and the data suggests that barley was infested at filling.

Bowmans
Oxygen and carbon dioxide levels at Bowmans were measured at 3 and 6 months post-filling (Table 8). Conversion of O2 to CO2 had occurred at a slow rate in both harvest bags containing canola, with CO2 levels in bags 1 and 2 measuring 1.8 and 5.9% respectively at 6 months storage. Canola stored at Bowmans was at higher moisture levels than canola stored at Roseworthy. The higher average 5.9% level of CO2 in bag 2 suggests changes in gas composition occurred at a moderate rate and, had a higher level of gas-tightness been achieved for this bag, the modification of the atmosphere is likely to have been greater. The ingress of air into bags at puncture points influenced gas composition, especially in the immediate vicinity of the leak. For canola bag 2, gas drawn from two points showed CO2 levels varied between 3.0 and 8.8% along the length of the 40 m bag.
11.1.3. 3. Moisture content and condensation

11.1.3.3.1. CSIRO Black Mountain

11.4% mc wheat sampled at 7 and 15 months
Samples were taken for moisture content determination at 7 and 15 months post-filling (Table 11). Moisture contents increased in the peripheral layer at the top and upper wall (both west- and east-facing). An increase of 1.1% was the maximum recorded in the peripheral layer at the northern end of the bag.

14.1% mc wheat sampled at 7 and 15 months
Moisture levels increased in the peripheral layer at the top and upper wall for both west- and east-facing aspects (Table 12). The peripheral layer was 14.8% mc at the three top measurement points. Moisture levels within the peripheral layer of the west-facing wall ranged from 14.3 to 14.5%.

The moisture profiles for both 11.4 and 14.1% mc wheat bags suggest moisture content of grain at or close to the base decreased slightly during storage and water was redistributed to the upper third of grain stored in the bag.

11.1.3.3.2. Farm survey

Grains tested were relatively dry (i.e. \(\leq 11.0\%\) mc) with some evidence of moisture aggregation in the peripheral layer at the top of the bags (Table 10). Barley stored in bags at Quambatook (VIC) showed increases of up to 1.1% mc in the peripheral layer at 6 months storage. Moisture aggregation at the top in one bag increased moisture levels from 12.2 to 13.2%.

11.1.3.3.3. ABB Grain Ltd. trials

Roseworthy, barley
The moisture content of barley loaded into bags 1 and 2 ranged between 9.0 to 10.3% (Table 13). At 6 months, moisture levels in the peripheral layer at the top and walls of the barley bags had increased up to 0.7%. Condensation inside the film at the walls appeared to have caused localised water damage at the sampling points. However, it was not clearly apparent whether water ingress through the sampling points had contributed to the damage observed.

Roseworthy, canola
At 6 months, moisture levels in the peripheral layer at the top and walls of the canola bags had increased up to 0.8% (Table 14). Condensation inside the film at the walls caused localised water damage at several points sampled. However, it was not clearly apparent whether water ingress through the sampling points had contributed to the damage observed. Moisture levels remained low and 5.5% was the highest level recorded at 6 months storage.

Bowmans, canola
At 6 months, moisture levels in the peripheral layer at the top and walls of the canola bags had increased up to 0.7% (Table 15). Condensation inside the film at the walls caused localised water damage at several points sampled. However, it was not clearly apparent whether water ingress through the sampling points had contributed to the damage observed. Moisture levels remained low and 6.8% was the highest level recorded at 6 months storage.
11.1.3.4. Germination energy

11.1.3.4.1. CSIRO Black Mountain

11.5% mc wheat sampled at 7 and 15 months
Samples were taken for germination energy (GE) assessment at 7 and 15 months post-filling. There was no loss in GE during storage (Table 11).

14.1% mc wheat sampled at 7 and 15 months
Germination energy was maintained up to 7 months storage. After 15 months, significant loss of GE occurred for wheat sampled from the peripheral layer and the upper parts of the harvest bags (Table 12). Germination energy at the base of the bag was maintained at initial levels. The loss in GE was particularly severe for wheat in the top and upper west-facing part of the peripheral layer. The difference in GE between wheat in the upper west-facing compared to upper east-facing was significant, with up to 40% greater loss in GE in the warmer west-facing part of the bag.

11.1.3.4.2. Farm survey

The relative dryness of all the grains stored minimised loss in GE during six months storage (Table 10). There was minimal difference in the GE between samples taken from the surface (within 10 cm from the top of the bag) to samples taken from the centre of the stored bulk. The only exception was for the higher moisture content, slightly weathered barley stored at Quambatook. At six months post-harvest, water had accumulated in the surface of the bulk (13.2% mc) and germination energy at this point had decreased to 90.3% from an initial harvest level above 97.3%. GE in the centre of bulk was maintained at harvest levels.

11.1.3.4.3. ABB Grain Ltd. trials

Roseworthy, barley
At 6 months, a substantial loss in GE occurred at one point in the peripheral layer at the top of the bag (i.e. 99.5 to 93.0%) and in a deep sample (i.e. 100 to 95.5%). Barley in the peripheral layer generally maintained GE (Table 13). Quality assessment by ABB Grain Limited of composite samples taken from the peripheral layer and the inner core of the bulk at 6 months showed no significant difference in viability and vigour (S. Buick, ABB Grain, Personnel Comm.).

11.1.3.5. Temperature and relative humidity

11.1.3.5.1. CSIRO Black Mountain

11.4% mc wheat
Wider fluctuations in grain temperature and humidity occurred in the west-facing aspect and grain remained warmer for a longer period following the onset of cooler weather conditions during March 2007. Temperature in the peripheral layer frequently exceeded 30°C during mid-November to mid-February, reaching maximum 40°C on several days. The magnitude of diurnal temperature changes often exceeded 20°C following high daytime temperatures. Wheat 30-40 cm below the film reached maximum temperatures (26-27°C) during January and the centre of the bulk heated up to 24°C during February; then cooled to 20°C in early-April. Wheat in the peripheral layer rapidly cooled in response to cooler ambient conditions during March and April, and wheat within 40 cm of the film cooled and was maintained at temperatures below 25°C by mid-March.

14.1% mc wheat
Changes in the temperature profile over time mirrored the 11.4% mc wheat. However, the magnitude of temperature fluctuations in the peripheral layer was reduced and overall grain temperatures within
30 cm of the film were lower. Temperatures within 30-40 cm of the film and in the centre of the bulk were similar to the 11.4% mc wheat.

11.1.3.5.2. ABB Grain Ltd. trials

Roseworthy, barley
Temperatures within 5 cm of the film peaked at 40°C only a few days during December to February, 35°C frequently and 30°C most days. During hot weather, temperature fluctuated widely in response to ambient conditions, with differences up to 15°C occurring with diurnal heating and cooling. At 15 cm from the film, temperatures peaked between 25 to 30°C and heating and cooling response to diurnal ambient conditions varied within a 5°C range. Within 30 to 40 cm of the film, changes in temperature were gradual and trended in response to changing ambient conditions over weeks, compared to the daily response measured for the peripheral layer. Relative humidity conditions in the peripheral layer fluctuated widely within 5 cm of the film; however, even peak levels reached were below 52%. The profile of relative humidity in the peripheral layer at the wall showed apparent condensation occurring in response to ambient temperatures during the summer months.

Roseworthy, canola
Temperature and relative humidity profiles for the west-facing aspect of bag 2 are shown in Figures 10(a)-(d), and for bags 1 and 2 at the wall in Figure 10(e)-(f). Temperature profiles within the peripheral layer during December to February were similar to the barley bags. Peak temperatures at 40°C were infrequent and generally temperatures peaked at between 30 to 35°C during summer. The profiles of relative humidity in the peripheral layer at the walls of the canola harvest bags shows apparent condensation occurring in response to ambient temperatures during the summer months. These HOBO loggers were located within 5 cm of the film and water damage was observed at these points during sampling.

Bowmans, canola
Grain temperatures in the peripheral layer were generally lower than recorded for the canola bags at Roseworthy. The profile of relative humidity in the peripheral layer at the wall of the canola harvest bag showed apparent condensation occurring in response to ambient temperatures. The HOBO logger was located within 5 cm of the film and water damage was observed at this point during sampling.

11.1.3.6. Insects

11.1.3.6.1. CSIRO Black Mountain

High insect numbers were present in the 2004/05 seasons wheat used for the 11.4% mc harvest bags (Table 16). The rapid depletion of oxygen from the contained atmosphere resulted in the complete kill of all insects. There were no live insects detected in wheat sampled from the 11.4% mc at 7 and 15 months. No live insects were detected in the 14.1% mc wheat at loading. Similarly, no insects were detected at 7 months storage. At the completion of the trial, live R. dominica adults were detected at five sampling points on the west-facing wall of the harvest bag, including 23 adults at one point.

11.1.3.6.2. ABB Grain Ltd. trials

Insects were detected in barley bag 1 at 6 months. These infestations may have been localised at the points where the film had been damaged or cut for sampling purposes. Insect numbers at these points were heavy.

11.1.3.7. Mould activity: CSIRO Black Mountain

Alternaria and Cladosporium species were the predominant fungi present on the 14.1% wheat after 10 months storage (Table 17). Wheat was shown to have high levels of fungal staining at the time of
processing. Up to 11.3% of kernels exhibited a black stain, typical of black point stain caused by weathering of the ripe crop prior to harvest. *Aspergillus* and *Eurotium* spp. were detected at low infection levels in several 10 month samples, suggesting growth had been slow during the previous summer and autumn periods.

At 15 months, *Eurotium* and *Aspergillus* species were predominant, with low detection levels of *Alternaria* and *Wallemia* species also present (Table 18). *Eurotium* species were detected in all samples by direct plating and, in most cases, *Eurotium* species were the dominant mould on the grains. The organisms identified as *Eurotium* represent a range of species, differentiated by colony morphology, with as many as 5 or 6 different species being present.

### 11.1.3.8. Wheat processing and end-product evaluation: CSIRO Black Mountain

The processing and end-product evaluation by Agrifood Technology P/L showed no significant differences between the control samples for 11.4 and 14.1% mc wheat and the 15 month composite samples taken from the inner core of the bulk and the peripheral layer (Table 19). The protein content of 14.1% wheat was only 8.4%, which was less than ideal for the dough rheology and pan-bread evaluation. However, the results are presented on a comparative basis to the control samples. The 14.1% wheat composite for the peripheral layer was taken from 15 different sampling points (refer Figure 10) and included wheat with germination energy level as low as 41.0 up to 97.5%.

### 11.1.4. DISCUSSION

These field trials provided insight to problems likely to be encountered with the use of harvest bags on-farm and in a large commercial situation. Insects and moisture accumulation and ingress are identified as the major risks for harvest bag storage of dry grains. The general lack of gas-tightness achieved on-farm and the predominance of dry grain in storage indicates that hermetic conditions will not be achieved and insect control will be a key issue. Localised spoilage resulting from water ingress and condensation on the inside of the film will be problematic in some situations.

### 11.1.4.1. Sealing standard and gas composition

A harvest bag system can potentially achieve a standard of high gas-tightness when the system is handled, filled and maintained appropriately. The harvest bags at Roseworthy (SA) achieved an initial high level of gas-tightness, with four bags of 100 t capacity exceeding a five-minute half-pressure decay standard. At Bowmans (SA), problems were encountered during filling and several tears in the film near the base of the bags demonstrated that the filling operation is often not straight-forward and requires considerable skill to achieve a high standard of gas-tightness.

The farms survey showed that only a few bags testing during the 2005/2006 season held negative pressure during testing under vacuum. Only one harvest bag of a total thirteen tested in New South Wales and Victoria approached a two-minute pressure decay standard. Testing was not undertaken when the film of bags was clearly damaged. Close inspection of a number of harvest bags that failed the pressure test failed to shown any evidence of punctures or small tears, suggesting that either the base of the bags had been punctured during loading or the ends were poorly sealed.

At CSIRO’s Black Mountain, the failure to achieve a high standard of gas-tightness for either the 11.4 or 14.1% mc harvest bags indicated that closure of the ends appears to be a major weakness in the sealing process even when undertaken by experienced operators. There was no indication that the film was damaged during loading and the pads had been carefully prepared to remove all sharp objects that may have punctured the base film. Both harvest bags were initially fitted with gas sampling and grain monitoring cables and sealing the insertion points proved difficult as silicone sealants and other adhesive gels failed to bond securely to the polyethylene film. Adhesive tapes also varied in
performance. All sampling points were resealed at least three times during storage and all gas lines and measurement cables were subsequently removed from the bags in early-January 2007. However re-sealing did not improve the gas-tightness of the harvest bags.

### 11.1.4.2. Maintaining gas-tightness during storage

The survey of bags on farms and at ABB Grain sites suggests that only very minor damage to the film was required to render the system unsealed, with no capacity to hold a negative pressure. After six months storage, only one harvest bag at the Roseworthy site exceeded a five-minute half-pressure decay standard and two bags exceeded four-minutes; illustrating that maintaining high levels of gas-tightness requires vigilance. Even at a well-managed site, the thin polymer bag membrane was susceptible to small punctures and tears caused (largely) by fox activity. The harvest bags at Bowmans were extensively damaged through fox activity within weeks of filling. The erection of suitable protective fencing is a prerequisite to prevent such damage in areas of high fox activity.

The input required to protect bags on farms from film damage and maintain the seal for extended periods is likely to be difficult. Repair of small punctures and tears has limited success with many adhesive tapes failing to achieve a good seal for prolonged periods. The farm survey and the damage to bags at Bowmans show damage to the film during bag loading is likely to be located on the base or close to the ground, which is difficult to repair and monitor. Large tears low to the ground resulting from loading bags are extremely difficult to repair due to the slackness and folds in the film. The extent of damage at loading is likely to decrease as users gain greater expertise with the preparation of a suitable raised pad and with loading procedures.

The placement of monitoring devices into the grain or sampling using manual/vacuum probes requires cutting and repairing the film. Where a cable or sampling line is fitted, sealing using adhesive tapes and silicone gel is required to seal the entry point. The ABB Grain trials showed that films are under considerable pressure, with the combined effects of stretching in response to diurnal heating and cooling influences and the pressure from the weight of grain against the film can increase the size of the initial cut, making repair and maintenance more difficult over time. The lack of capability to regularly sample grain for quality and insects without compromising the integrity of the gas-tight seal is a significant disadvantage for grain storers, especially for commercial enterprises.

At Black Mountain the 11.4 and 14.1% mc wheat harvest bags consistently failed to achieve a two-minute pressure decay half-life standard and were inadequate for the purpose of monitoring changes in gas composition of the contained atmosphere during storage. Despite repeated attempts to improve the gas-tightness of these bags, the leakage points were either too numerous or inaccessible, or the ends were poorly sealed.

The failure of a harvest bag system to achieve an initial high standard of gas-tightness (e.g. > 5-minute half life pressure decay times) and maintain this seal during prolonged storage will preclude its use as a hermetic storage. However, considerable modification of the atmosphere may still occur in a proportion of the grain. At 6 months, carbon dioxide levels exceeding 8.8% and oxygen levels below 9.1% were measured in dry canola (6.0-6.3% mc) stored at Roseworthy (SA), in a bag that was not considered gas-tight.

Major improvements in gas-tightness awareness, site preparation, bag construction skill, gas-tightness testing equipment and the availability of appropriate seal maintenance equipment, will be required on-farm and in commercial storage enterprises to protect bags from film damage and maintain the seal for extended periods. The failure to achieve an adequate sealing standard will limit the utility of harvest bags on farms.
11.1.4.3. Film damage

There are numerous anecdotal reports of damage to the film of harvest bags by wandering stock, feral animals and wildlife. Damage was observed in the farm survey and at Black Mountain where film damage by foxes was a precursor for bird damage as the food source is revealed. There are increasing anecdotal reports of damage by birds, with crows and ravens causing extensive damage to harvest bags on farms.

Farmers are adapting to protecting the bags through the use of fences, and the majority of bags are being placed in open areas well away from bushlands and grass verges that provide harbourage to rodents and other wildlife. The threat of birds (especially cockatoos, corellas and galahs) to the gas-tightness of the harvest bags system remains of major concern. A number of farmers are utilising the synthetic netting used in horticultural production systems to protect against hail damage as an effective method to minimise bird damage. These mesh nets have a three to four years useable life.

The risk of insect infestation and potential water ingress is substantially increased where damage to harvest bags is extensive and not repaired. Bags are generally located well away from permanent grain storage facilities and this will decrease the chance of insects accessing grain through punctures and tears. The trials at Black Mountain and Roseworthy, however, show infestation is likely to occur even at low infestation pressures.

Water ingress is less of a problem when the damage is located on the sides of the bags, compared to the top or base. Bags generally maintain a tight profile during storage (i.e. initial 10% stretching of the film recommended during filling) and water is shed off the sides. Depressions in the top of a filled bag due to poor filling procedures or over-stretching due to excessive heating of the film can cause pooling of water on top of the film and ingress though any punctures. Over-stretching of the bag film during hot weather is a problem for inexperienced operators and the braking (clutch) systems needs continual adjustment as daytime temperatures increase.

11.1.4.4. Insects

In a well-sealed system, modification to the contained atmosphere within a harvest bag at low moisture levels (i.e. <13% mc) will largely dependant on hidden insect infestation. In dry grains, the rate of grain respiration is very slow and mould growth is inhibited. In the Black Mountain study, the initial heavy insect infestation in the 11.4% mc wheat compensated for any leakage of oxygen into the system, and the depletion of oxygen to levels below 5.6% (initial gas measurement) consequently led to the complete kill of all insects. Following control of this heavy infestation, the level of oxygen gradually increased over time and reached 18.6% at the completion of the trial.

Data from the Black Mountain study showed grain conditions in the upper part of the west-facing wall of the 14.1% mc harvest bag favoured insect development to a greater extent as temperatures were consistently higher in this part of the bag during storage and moisture aggregation also occurred. Despite the lack of gas-tightness, the system provided a barrier against infestation at a site where residual insect populations exists in close proximity.

There are anecdotal reports (T. Maitland, Agsave Merchandise, Kimba, SA, personal comm.) where harvest bags used for storage of barley in South Australia during season 2004/05 and 2005/06 were out-turned with evidence of heavy insect infestation, but few live insects were detected. Other barley bags were out-loaded with heavy infestations and many live insects were detected. The presence of live insects suggests these bags were not well-sealed, or the storage time was not sufficient for the resident insect population to increase to levels sufficient to modify the contained atmosphere to a “toxic” composition.
Further anecdotal reports received from farmers, commercial stockfeed companies and reports in the rural press suggest the incidence of insect infestation in harvest bags is low. There will be a time-lag between initial low insect numbers and an infestation detectable using manual probing and screening. Short storage times (e.g. <6 months), using a clean storage system, and location remote from other sources of insect infestation, are all factors likely to contribute to the apparent success of the harvest bag system to deliver grain “insect-free”. The seamless film bag also provides an effective barrier to insect infestation. However, any punctures or tears to the film will increase infestation pressure, especially where high residual insect populations exist.

The options for controlling insects in harvest bags in Australia are the generation of insecticidal hermetic atmospheres or the use of fumigants, predominantly phosphine. In either case, the capacity of a harvest bag system to modify the internal air to a hermetic atmosphere or maintain phosphine concentrations requires a high standard of gas-tightness be achieved and maintained.

A heavy reliance is likely to be placed on phosphine to control insects in harvest bags as the system is increasingly adopted and medium- to long-term storage becomes commonplace. Anecdotal evidence of present on-farm use suggests dry aluminium phosphide preparations are being admixed with grain in harvest bags. The alternative, treating with residual chemical protectants, requires the transfer of infested grain from bags to permanent storage; a costly process and limited to the capacity available. A major advantage potentially offered by the harvest bag system is minimal handling, fast loading and outloading capacity using tailor-designed machinery, and outturn of insect-free grain. Where insects persist as a problem, repeated handling of the grain to apply residual chemical treatment or transfer to sealed storage for fumigation will devalue the system’s worth.

In-situ phosphine fumigation of insect infested grain in harvest bags will be the most practicable and cost-effective option for farmers. However, safe use is paramount and phosphine use in harvest bags needs evaluation and safe procedures established. There is also the legal ramification of direct admixing tablet/pellets with grain, which is no longer permitted on the Australian label for dry aluminium phosphide preparations.

11.1.4.5. Moisture and temperature

Water had aggregated to varying degrees in the peripheral layer of both 11.4 and 14.1% mc wheat harvest bags at Black Mountain. The highest peripheral layer moisture levels were recorded at the top and upper part of the west-facing wall, where changes in moisture content between 0.7 to 1.1% were recorded. The condensation of water inside the film would have largely contributed to aggregation of water in the peripheral layer. However, the data suggests there had been moisture movement to the upper parts of the bag, with slight drying of wheat close to the base and middle of the bags. The magnitude of grain temperature differentials within the respective bags was generally less than 5°C. This differential was greatest (>10°C) during late-December and January when the centre of the bulk gradually heated up from low winter grain temperatures and the peripheral layer was subject to above 30°C temperatures.

The placement of harvest bags in a north to south orientation will be particularly important to distribute the effects of radiant heating between the east- and west-facing walls. Grain in the peripheral layer of the west-facing wall and top of the bags will generally be exposed to a substantially greater heat load than grain in the east-facing wall and consequently pose the greatest risk of localised damage. At Black Mountain, the aggregation of water at these localised points in 14.1% mc wheat were sufficient to increase the rate that fungi, especially Eurotium spp., were able to grow. Localised insect infestation was also detected at these “vulnerable” points.

Data from the Black Mountain and ABB Grain trials suggest grain temperatures immediately under the film will closely mirror ambient temperatures, with rapid heating and cooling occurring in response to diurnal temperature patterns. The difference between grain temperature in the peripheral
Assessing the limits of existing harvest bag technology under Australian conditions

layer (i.e. within 5 - 10 cm of film) and ambient temperatures was not excessive and levels above 40°C was recorded on only a few occasions during the course of the Black Mountain and ABB Grain field trials. Harvest bags are made with a reflective white finish to the polymer bag membrane claimed to provide good radiant heat reflective properties, which would attenuate the grain temperature excursions compared to a non-reflective membrane. The extent of this heat reflective property is unquantified. Moisture content also influences the magnitude of changes in temperature within the peripheral layer, with increasing moisture contents having a moderating effect.

Condensation on the inner surface of the film is a recognised problem with plastic membrane storages. Data from the ABB Grain Ltd. trials suggest this may be a significant problem for harvest bag storage in temperate climatic regions where diurnal temperatures can fluctuate widely. Condensation on the inside of the film causes rewetting of the surface grain. The amount of condensation is dependent on the size of the temperature fluctuation and the moisture content of the grain in the store, with wetter grain providing more condensation potential. Water damage of canola stored in bags at Bowmans and Roseworthy was evident at six months; however, the damage was localised to within 5 cm of the film. The transfer of moisture by natural convection currents within harvest bags may compound the condensation problem; however, this remains unquantified. Data from the Black Mountain trials suggest there had been slight drying of wheat close to the base and middle of the bags, with increased moisture levels within the peripheral layer at the upper walls and top. The accumulation of moisture at greater than 1% in the peripheral layer was observed in a number of harvest bags inspected on New South Wales and Victorian farms in May 2006.

Removal of damaged grain will prove difficult where extractors are used to outload bags as the operator has limited access to the grain. A pneumatic grain handler has the capacity to separate water damaged grain during outturn; however, outloading capacity is limited and separation would be a slow process. The advantage of a pneumatic system is its greater utility on the farm and several growers have already invested in this type of machine for general grain handling. Anecdotal reports suggest water damaged grain largely adheres to the film during outloading and is taken up onto the hydraulic drum.

11.1.4.6. Germination energy

In the Black Mountain study, significant damage had occurred to wheat located on the west-facing wall and the top of the harvest bag after 15 months storage. Samples were taken within 15 cm of the film at these points and wheat germination energy had declined to 41% in the upper part of the west-facing wall. The west-facing side of harvest bags was subject to the greatest amount of radiant heating and remained at a higher temperature during the cooler autumn and winter months. The rate of quality loss for wheat located on the east-facing wall was significantly less and retained germination to over 90% at 15 months postharvest.

Lower moisture content wheat and barley is likely to store well in harvest bags up to six months and longer in cool temperature regions where winter and early-Spring conditions extend safe storage time. Lower moisture 11.4% mc wheat at Black Mountain was outturned after 15 months storage without any significant change in germination energy for wheat from the peripheral layer. The germination energy of dry barley sampled from the peripheral layer after 11 months storage on-farm near Hillston (NSW) and after 6 months storage in bags as part of the ABB Grain Ltd. trial at Roseworthy (SA) was retained at initial harvest levels. At six months, the barley at Roseworthy showed an increase in germination energy (S. Buick, ABB Grain, personal comm.) as expected for barley that is maturing and losing dormancy during storage. Storage is an important part of the overall maturation process for barleys, and maltsters in South Australia will generally not draw on new seasons malting barley for up to six months post-harvest.
11.1.4.7. Mycology

Cereal grains are typically harvested in Australia between 10 to 12.5% mc (wet basis), and frequently the average moisture content for a given storage ranges between 11 to 11.5% mc. These moisture levels are well below the critical moisture threshold for fungal growth and development. Cassells et al (2003) showed the critical moisture content for fungi growth for wheat at \( \text{aw} = 0.68 \) is 13.4 to 14.1% at 30 and 20°C respectively, and for barley, 13.1 and 14.1% at 30 and 20°C respectively. In harvest bags, localised spoilage can result from water ingress and accumulation due (largely) to condensation on the inside of the film.

The Black Mountain trial showed that mould growth is slow even when sufficient moisture is available. The field type fungi *Alternaria* and *Cladosporium* species were the predominant fungi present on the 14.1% wheat after ten months storage. Wheat stored at 14% moisture content is well below the water activity required for the growth of these field fungi. However, these species are known to be relatively stable on stored wheat under favourable conditions and even on dry wheat the decrease in infection levels can be slow. At 15 months, *Eurotium* and *Aspergillus* species were the predominant species recorded on 14.1% mc wheat. The transition from predominantly field type fungi (e.g. *Alternaria* and *Cladosporium* spp.) to predominantly storage (xerophilic) fungi (e.g. *Eurotium* and *Aspergillus* spp.) occurred between 10 months to 15 months storage. *Aspergillus* and *Eurotium* spp. out-competed the less moisture tolerant field type fungi for available nutrients as grain temperatures increased leading into the summer months. The *Aspergillus* species detected were primarily slow growing extreme xerophiles such as *Aspergillus restrictus* and *A. penicillioides*. These organisms are common in stored commodities such as wheat and other grains. Some other *Aspergillus* species were detected but at very minor levels.

The low winter temperatures, including frequent sub-zero temperatures, curbed mould growth in the peripheral layer and the 14.1% mc wheat bulk generally. Extreme winter conditions within the peripheral layer on the eastern aspect of the bag substantially decreased infection levels. Fungal activity gradually increased during the 2006/07 summer period and continued into autumn. Substantial modification of the atmosphere in the 14.1% mc wheat harvest bag only occurred in response to increased fungal growth during January-March 2007. Oxygen declined to 10.8% and carbon dioxide was raised to 11.9% at the completion of the trial in May 2007; a significant change in gas composition given this bag was not well sealed. Changes in gas composition corresponded to high infection levels of *Eurotium* species detected on all wheat samples assayed, with the highest infection levels recorded on the higher moisture content wheat taken from localised points within the peripheral layer where moisture had increased up to 0.7%.

11.1.4.8. Wheat processing and end-product quality

The germination energy (GE) of wheat samples taken from the peripheral layer of the 14.1% mc harvest bag ranged from 41.0 to 97.5%, and the blended composite performed slightly better than the control sample in the testing undertaken. The admixture of low GE with high GE wheat diluted the affect that localised damage in the upper parts of the peripheral layer had on end-product performance. However, the composite was representative of the peripheral layer. Changes in technological processing potential in wheat are less affected, compared to barley, by the loss in germination capacity due to storage influences. Caddick (1999) showed that a substantial loss of viability (10 -15%) had no adverse affect on bread-making or noodle quality, as measured by the pan-bread and white noodle system of evaluation. In a comprehensive review of the biochemical and functional changes in wheat during storage, Pomeranz (1988) concluded that substantial decreases in germination capacity (10 - 20%) were not reflected in bread-making potential.

The lack of any significant difference in processing and end-product quality suggests that wheat is particularly robust commodity to store in harvest bags, within limits of moisture content. During
Assessing the limits of existing harvest bag technology under Australian conditions

outloading using commercial extractors, wheat will be blended and the peripheral influences on quality diluted. Extractors use a V-shaped sweep auger to move grain into a secondary auger that feeds into transport or transfer vehicles.

11.1.4.9. Overview

Farmers face a considerable challenge to improve their knowledge of grain storage generally, especially in view of the lack of extension services and information in this area. The use of harvest bags is a case in point, where first-hand experience will be invaluable in better managing the bags. Farmers are already preparing suitable raised pads, constructing more sophisticated fences around the bags and using synthetic nest to minimise bird damage. Anecdotal reports of successful grain storage in harvest bags will remain a major driver behind the adoption of the harvest bag system on farms. In the same way, anecdotal reports of failures will slow down the likely adoption rate.

Harvest bags use has already become established on Australian farms and the benefits voiced by users generally outweigh the disadvantages. However, farming enterprises in inland temperate regions are likely to be better placed to take advantage of the harvest bag system to a greater extent than growers in sub-tropical or coastal regions where the options of early harvesting at “safe” moisture levels is often limited. The Mallee and Wimmera regions of Victoria and the Riverina region of New South Wales are particularly well suited to harvest bag use, as is the Mallee region in South Australia. The prevailing climatic conditions in these inland areas during harvest are often conducive to continuous harvesting. The harvest bag system is well suited to maximise available harvesting machinery and transport capacity, as storage capacity is only limited by the number of bags available, and larger capacity bags (e.g. 90 and 120 m) are likely to streamline harvest operations to a greater degree.

The CSIRO farm survey and anecdotal reports from farmers, grower meetings and the rural press, suggest that the bag system will be increasingly used as a harvest buffer and cater for the overflow from on-farm permanent storage. The advantage of this approach is that late-harvested drier grain will generally be placed into bags. The disadvantage is that there is a higher risk of weather damage to this grain.

There is a need for further commercial evaluation of different grain types stored in harvest bags for up to 12 months. The ABB Grain Ltd. field trials evaluated the performance of harvest bags to store barley and canola under commercial conditions. However, the low moisture content increased the storage potential of these grains. Moisture aggregation in the peripheral layer and the upper walls of the bulk was evident and insects were a problem. However, the dryness of the grain is likely to have reduced the magnitude of these problems, and there was minimal risk of overall grain quality being lost during storage. Importantly, the industry needs to evaluate the storage of cereals and oilseeds in harvest bags at or close to the established moisture content receiveal limits.

11.1.5. Acknowledgements

The financial support of GRDC is greatly appreciated. We thank Peter Annis for his significant contribution to the science of controlled atmosphere & hermetic storage and valued assistance with preparation of this report. Expert assistance was provided by Swan Hill Chemicals P/L (VIC) & Feed & Forage Bags (SA) for the trial at CSIRO’s Black Mountain site; especially we acknowledge the support given by Neil McAlpine of SHC. Stephen Buick and Jeanette Marszal, ABB Grain Ltd. organised and supervised the trials at Bowmans and Roseworthy as part of their company’s field evaluation of the harvest bag system.
11.1.6. References


Table 6. Sealing standard and gas composition of harvest bags at CSIRO’s Black Mountain site, Canberra, over a 15 month storage period

<table>
<thead>
<tr>
<th>Wheat Description &amp; Sampling Date</th>
<th>Sealing Standard&lt;sup&gt;a&lt;/sup&gt; (seconds)</th>
<th>O&lt;sub&gt;2&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt; %</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt; %</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4% mc wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09/03/06</td>
<td>5.6</td>
<td>10.8</td>
<td></td>
<td>Gas lines inserted (8)</td>
</tr>
<tr>
<td>15/03/06</td>
<td>6.5</td>
<td>10.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23/03/06</td>
<td>8.9</td>
<td>9.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30/03/06</td>
<td>6.1</td>
<td>8.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06/04/06</td>
<td>7.0</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/04/06</td>
<td>8.5</td>
<td>8.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04/05/06</td>
<td>117</td>
<td>9.7</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>08/06/06</td>
<td>11.9</td>
<td>6.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/07/06</td>
<td>13.6</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04/10/06</td>
<td>94</td>
<td>13.7</td>
<td>5.7</td>
<td>Grain samples taken</td>
</tr>
<tr>
<td>09/11/06</td>
<td>91</td>
<td>13.6</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>04/01/07</td>
<td>14.3</td>
<td>6.1</td>
<td></td>
<td>Hobo loggers inserted, gas lines and humitters removed.</td>
</tr>
<tr>
<td>20/02/07</td>
<td></td>
<td></td>
<td>Fox damage to film. Fence erected and film repaired</td>
<td></td>
</tr>
<tr>
<td>08/05/07</td>
<td>67</td>
<td>18.9</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>14.1% mc wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09/03/06</td>
<td>21.2</td>
<td>2.1</td>
<td></td>
<td>Gas lines inserted (10)</td>
</tr>
<tr>
<td>15/03/06</td>
<td>20.1</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23/03/06</td>
<td>19.6</td>
<td>2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30/03/06</td>
<td>18.0</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06/04/06</td>
<td>16.9</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/04/06</td>
<td>15.8</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04/05/06</td>
<td>66</td>
<td>14.9</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>08/06/06</td>
<td>15.8</td>
<td>4.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/07/06</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04/10/06</td>
<td>56</td>
<td>18.2</td>
<td>2.7</td>
<td>Grain samples taken</td>
</tr>
<tr>
<td>09/11/06</td>
<td>57</td>
<td>19.5</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>04/01/07</td>
<td>19.4</td>
<td>2.4</td>
<td></td>
<td>Hobo loggers inserted, gas lines and humitters removed.</td>
</tr>
<tr>
<td>20/02/07</td>
<td></td>
<td></td>
<td>Fox damage to film. Fence erected and film repaired</td>
<td></td>
</tr>
<tr>
<td>08/05/07</td>
<td>65</td>
<td>10.8</td>
<td>11.9</td>
<td></td>
</tr>
<tr>
<td>18/06/07</td>
<td>13.9</td>
<td>8.9</td>
<td></td>
<td>Bird damage to top of bag, numerous small punctures caused by fox activity</td>
</tr>
</tbody>
</table>

<sup>a</sup>- capacity of a harvest bag to maintain a negative pressure over time, and standard is given in minutes to reach half the original pressure measured in kilopascals (kPa)

<sup>b</sup>- average eight measurements for 11.4% wheat and ten measurements for 14.1% wheat
Table 7. Sealing standard and gas composition of harvest bags sampled at different farm localities in north-western Victoria and south-western New South Wales during season 2005/06

<table>
<thead>
<tr>
<th>Farm Locality</th>
<th>Bag Type</th>
<th>Grain Type</th>
<th>Survey Date</th>
<th>Sealing Standard(^a) (seconds)</th>
<th>O(_2)(^b) %</th>
<th>CO(_2)(^b) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swan Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Field Peas</td>
<td>15/05/06</td>
<td>NA</td>
<td>22.5</td>
<td>0</td>
</tr>
<tr>
<td>Swan Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Lentils</td>
<td>16/05/06</td>
<td>NA</td>
<td>20.1</td>
<td>1.8 (1.4-2.3)(^c)</td>
</tr>
<tr>
<td>Swan Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Wheat</td>
<td>16/05/06</td>
<td>NA</td>
<td>22.2</td>
<td>0.6 (0-0.7)(^c)</td>
</tr>
<tr>
<td>Swin Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Wheat</td>
<td>16/05/06</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quambatook, VIC</td>
<td>Hyplast™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quambatook, VIC</td>
<td>Hyplast™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea Lake, VIC</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>1.53</td>
<td>20.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Sea Lake, VIC</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>NA</td>
<td>20.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Sea Lake, VIC</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>15/06/06</td>
<td>1.34</td>
<td>21.3</td>
<td>0.9 (0.6-1.5)(^c)</td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>15/06/06</td>
<td>NA</td>
<td>21.4</td>
<td>0.7 (0.5-1.1)(^c)</td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>18/10/06</td>
<td>NA</td>
<td>20.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>18/10/06</td>
<td>NA</td>
<td>21.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\(^a\) Capacity of a harvest bag to maintain a negative pressure over time, and standard is given in minutes to reach half the original pressure measured in kilopascals (kPa)

\(^b\) Average eight measurements for 11.4% wheat and ten measurements for 14.1% wheat

\(^c\) Range of gas levels within harvest bag shown in parentheses ( )

NA – the required level (i.e. 1300 Pascals) of negative pressure was not obtained under vacuum during a 5-minute period and pressure decreased within seconds when vacuum was removed and the film sealed.
Table 8. Sealing standard and percentage of oxygen and carbon dioxide in harvest bags at Bowmans and Roseworthy, South Australia

<table>
<thead>
<tr>
<th>Storage site</th>
<th>Grain Type</th>
<th>Sampling Date</th>
<th>Bag Number</th>
<th>Sealing Standarda (min.sec)</th>
<th>O2 %</th>
<th>CO2b %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roseworthy</td>
<td>Barley</td>
<td>Dec 2006</td>
<td>1</td>
<td>22.0</td>
<td>21.83</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>7.48</td>
<td>21.94</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mar 2007</td>
<td>1</td>
<td>14.99</td>
<td></td>
<td>6.05 (4.19-7.92)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>19.81</td>
<td></td>
<td>1.64 (1.53-1.76)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jun 2007</td>
<td>1</td>
<td>4.01</td>
<td>9.80</td>
<td>9.38 (9.16-9.72)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>5.31</td>
<td>17.02</td>
<td>4.18 (3.06-5.30)</td>
</tr>
<tr>
<td>Roseworthy</td>
<td>Canola</td>
<td>Dec 2006</td>
<td>1</td>
<td>10.0</td>
<td>20.38</td>
<td>0.62 (0.57-0.68)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>22.0</td>
<td>20.71</td>
<td>0.73 (0.69-0.76)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mar 2007</td>
<td>1</td>
<td>10.85</td>
<td>3.61 (2.70-4.17)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>10.93</td>
<td>3.99 (2.73-5.25)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jun 2007</td>
<td>1</td>
<td>4.30</td>
<td>12.80</td>
<td>3.13 (2.92-3.34)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>1.34</td>
<td>11.67</td>
<td>4.35 (4.34-4.37)</td>
</tr>
<tr>
<td>Bowmans</td>
<td>Canola</td>
<td>Dec 2006</td>
<td>1</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>1.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mar 2007</td>
<td>1</td>
<td>21.03</td>
<td>1.14 (1.00-1.36)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>16.95</td>
<td>1.84 (ND-2.76)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jun 2007</td>
<td>1</td>
<td>0.0c</td>
<td>20.02</td>
<td>1.92 (1.47-2.38)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>0.0c</td>
<td>12.99</td>
<td>5.86 (2.95-8.81)</td>
</tr>
</tbody>
</table>

a- capacity of a harvest bag to maintain a negative pressure over time, and standard is given in minutes to reach half the original pressure measured in kilopascals (kPa)
b- values in parentheses shown range of CO₂ levels at given sampling time
c- negative pressure obtained was too low for standard assessment, indicating too many leakage points in plastic film or at end seals
Table 9. Moisture content and germination energy of wheat delivered and 11% and 14 % mc wheat post-conditioning at CSIRO’s Black Mountain site, Canberra

<table>
<thead>
<tr>
<th>Sample description</th>
<th>Sample Date</th>
<th>Moisture Content&lt;sup&gt;a&lt;/sup&gt; (% wb)</th>
<th>Germination Energy&lt;sup&gt;b&lt;/sup&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005/06 Wedgetail ASW wheat</td>
<td>23/12/05</td>
<td>10.1</td>
<td>98.1 (98.5)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Post-conditioning to 14.1% mc</td>
<td>26/04/06</td>
<td></td>
<td>99.0 (99.0)</td>
</tr>
<tr>
<td>Inloaded composite 14.1% mc</td>
<td>27/04/06</td>
<td>14.1</td>
<td>98.7 (99.3)</td>
</tr>
<tr>
<td>2004/05 season’s ASW wheat</td>
<td>23/12/05</td>
<td>9.8</td>
<td>96.0 (97.3)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Post-conditioning to 11.4% mc</td>
<td>27/04/06</td>
<td></td>
<td>97.0 (97.8)</td>
</tr>
<tr>
<td>Inloaded composite 11.4% mc</td>
<td>27/04/06</td>
<td>11.4</td>
<td>95.2 (97.3)</td>
</tr>
</tbody>
</table>

<sup>a</sup> - Grain moisture content average of two determinations and given as % wet basis  
<sup>b</sup> - Germination energy assessed on 800 seeds  
<sup>c</sup> - Viability shown in parentheses ( )
Table 10. Moisture content and germination energy of harvest bags sampled at different farm localities in north-western Victoria and south-western New South Wales during season 2005/06

<table>
<thead>
<tr>
<th>Farm Locality</th>
<th>Bag Type</th>
<th>Grain Type</th>
<th>Survey Date</th>
<th>Sample Point</th>
<th>Moisture Content(^{a}) (% wb)</th>
<th>Germination Energy(^{b}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swan Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Field Peas</td>
<td>15/05/06</td>
<td>Deep</td>
<td>9.7</td>
<td>82.3 (95.4(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>10.0</td>
<td>92.3 (97.8(^{d}))</td>
</tr>
<tr>
<td>Swan Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Lentils</td>
<td>16/05/06</td>
<td>Deep</td>
<td>9.4</td>
<td>91.8 (98.4(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>9.8</td>
<td>92.5 (98.6)</td>
</tr>
<tr>
<td>Swan Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Wheat</td>
<td>16/05/06</td>
<td>Deep</td>
<td>9.6</td>
<td>94.3 (95.3(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>10.0</td>
<td>94.3 (95.5)</td>
</tr>
<tr>
<td>Swan Hill, VIC</td>
<td>IPESAsilo™</td>
<td>Wheat</td>
<td>16/05/06</td>
<td>Deep</td>
<td>11.2</td>
<td>96.5 (96.8(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>11.4</td>
<td>96.8 (97.3)</td>
</tr>
<tr>
<td>Quambatook, VIC</td>
<td>Hyplast™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>Deep</td>
<td>10.5</td>
<td>98.8 (99.0(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>11.6</td>
<td>99.3 (99.8)</td>
</tr>
<tr>
<td>Quambatook, VIC</td>
<td>Hyplast™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>Deep</td>
<td>12.2</td>
<td>97.3 (99.1(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>13.2</td>
<td>90.3 (96.4)</td>
</tr>
<tr>
<td>Sea Lake, VIC</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>Deep</td>
<td>10.1</td>
<td>99.8 (100(^{e}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>10.2</td>
<td>99.5 (99.8)</td>
</tr>
<tr>
<td>Sea Lake, VIC</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>Deep</td>
<td>11.4</td>
<td>99.3 (99.8(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>11.1</td>
<td>99.8 (99.8)</td>
</tr>
<tr>
<td>Sea Lake, VIC</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>16/05/06</td>
<td>Deep</td>
<td>9.0</td>
<td>99.8 (100(^{e}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>9.9</td>
<td>99.8 (99.8)</td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>15/06/06</td>
<td>Deep</td>
<td>10.4</td>
<td>99.8 (100(^{e}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>11.0</td>
<td>99.8 (99.8)</td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>15/06/06</td>
<td>Deep</td>
<td>10.0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>10.3</td>
<td>99.5 (99.8)</td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>18/10/06</td>
<td>Deep</td>
<td>9.4</td>
<td>98.9 (99.3(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>10.3</td>
<td>99.0 (99.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wall</td>
<td>9.4</td>
<td>99.1 (99.5(^{c}))</td>
</tr>
<tr>
<td>Hillston, NSW</td>
<td>IPESAsilo™</td>
<td>Barley</td>
<td>18/10/06</td>
<td>Deep</td>
<td>9.6</td>
<td>99.3 (99.6(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface</td>
<td>9.4</td>
<td>99.3 (99.6(^{c}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wall</td>
<td>9.2</td>
<td>99.4 (99.6)</td>
</tr>
</tbody>
</table>

\(^{a}\) Grain moisture content average of two determinations and given as % wet basis
\(^{b}\) Germination energy assessed on 400 seeds
\(^{c}\) Viability shown in parentheses ( )
\(^{d}\) Hard seeded peas were assessed as non-viable
Table 11. Moisture content and germination energy of 11.4% mc wheat sampled after 7 and 15 months storage in harvest bag (No. 1) at CSIRO’s Black Mountain site, Canberra

<table>
<thead>
<tr>
<th>Sampling point</th>
<th>Sample Point</th>
<th>Moisture Content&lt;sup&gt;a&lt;/sup&gt; (% wb)</th>
<th>Germination Energy&lt;sup&gt;b&lt;/sup&gt; (%)</th>
<th>Moisture Content&lt;sup&gt;a&lt;/sup&gt; (% wb)</th>
<th>Germination Energy&lt;sup&gt;b&lt;/sup&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Date</td>
<td></td>
<td>Sept 2006</td>
<td></td>
<td>May 2007</td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), west facing, southern end</td>
<td>A1</td>
<td>11.7</td>
<td>95.5 (97.8)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, southern end</td>
<td>A2</td>
<td></td>
<td>12.0</td>
<td>96.8 (99.3)&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), southern end</td>
<td>A3</td>
<td>11.3</td>
<td>96.5 (98.8)</td>
<td>12.2</td>
<td>99.0 (99.3)</td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, southern end</td>
<td>A4</td>
<td></td>
<td>11.6</td>
<td>96.0 (97.3)</td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), east facing, southern end</td>
<td>A5</td>
<td></td>
<td>11.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (base), southern end</td>
<td>A6</td>
<td></td>
<td>11.4</td>
<td>96.8 (97.5)</td>
<td></td>
</tr>
<tr>
<td>Deep (centre), southern end</td>
<td>A7</td>
<td>11.4</td>
<td>97.8 (98.5)</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), west facing, southern end</td>
<td>A8</td>
<td></td>
<td>11.7</td>
<td>96.5 (97.8)</td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), east facing, southern end</td>
<td>A9</td>
<td></td>
<td>11.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), west facing, middle</td>
<td>B1</td>
<td></td>
<td>11.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, middle</td>
<td>B2</td>
<td></td>
<td>11.3</td>
<td>95.3 (98.1)</td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), middle</td>
<td>B3</td>
<td></td>
<td>12.1</td>
<td>95.3 (98.3)</td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, middle</td>
<td>B4</td>
<td></td>
<td>11.7</td>
<td>96.8 (98.6)</td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), east facing, middle</td>
<td>B5</td>
<td></td>
<td>11.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (base), middle</td>
<td>B6</td>
<td></td>
<td>11.5</td>
<td>95.5 (97.8)</td>
<td></td>
</tr>
<tr>
<td>Deep (centre), middle</td>
<td>B7</td>
<td>11.7</td>
<td>95.5 (96.5)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), west facing, middle</td>
<td>B8</td>
<td></td>
<td>11.6</td>
<td>95.8 (99.1)</td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), east facing, middle</td>
<td>B9</td>
<td></td>
<td>11.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), west facing, northern end</td>
<td>C1</td>
<td></td>
<td>11.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, northern end</td>
<td>C2</td>
<td></td>
<td>11.5</td>
<td>94.5 (97.3)</td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), northern end</td>
<td>C3</td>
<td>12.1</td>
<td>95.3 (96.8)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12.5</td>
<td>95.0 (97.8)</td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, northern end</td>
<td>C4</td>
<td></td>
<td>12.2</td>
<td>95.5 (98.3)</td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), east facing, northern end</td>
<td>C5</td>
<td></td>
<td>11.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (base), northern end</td>
<td>C6</td>
<td></td>
<td>11.4</td>
<td>96.8 (97.8)</td>
<td></td>
</tr>
<tr>
<td>Deep (centre), northern end</td>
<td>C7</td>
<td></td>
<td>11.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), west facing, northern end</td>
<td>C8</td>
<td></td>
<td>12.2</td>
<td>95.8 (97.8)</td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), east facing, northern end</td>
<td>C9</td>
<td></td>
<td>11.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> - Grain moisture content average of two determinations and given as % wet basis
<sup>b</sup> - Germination energy assessed on 400 seeds, <sup>c</sup> - Viability shown in parentheses ( )
### Table 12. Moisture content and germination energy of 14.1% mc wheat sampled at 7 and 15 months postharvest from harvest bag (No. 2) at CSIRO’s Black Mountain site, Canberra

<table>
<thead>
<tr>
<th>Sampling point</th>
<th>Sample Point</th>
<th>Moisture Content(^a) (% wb)</th>
<th>Germination Energy(^b) (%)</th>
<th>Moisture Content(^a) (% wb)</th>
<th>Germination Energy(^b) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peripheral (wall, low), west facing, southern end</td>
<td>A1</td>
<td>14.4</td>
<td>98.8 (99.0)(^c)</td>
<td>14.0</td>
<td>89.5 (94.8)(^c)</td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, southern end</td>
<td>A2</td>
<td>14.5</td>
<td>64.3 (78.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), southern end</td>
<td>A3</td>
<td>13.3</td>
<td>99.5 (99.5)</td>
<td>14.8</td>
<td>83.0 (90.3)</td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, southern end</td>
<td>A4</td>
<td>14.4</td>
<td>91.0 (93.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), east facing, southern end</td>
<td>A5</td>
<td>14.1</td>
<td>97.5 (98.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (base), southern end</td>
<td>A6</td>
<td>13.9</td>
<td>98.0 (99.5)</td>
<td>14.2</td>
<td>98.0 (98.3)</td>
</tr>
<tr>
<td>Deep (centre), southern end</td>
<td>A7</td>
<td>13.6</td>
<td>98.8 (99.5)</td>
<td>14.3</td>
<td>94.8 (96.3)</td>
</tr>
<tr>
<td>Deep (off-centre), west facing, southern end</td>
<td>A8</td>
<td>14.5</td>
<td>94.0 (96.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), east facing, southern end</td>
<td>A9</td>
<td>14.2</td>
<td>96.5 (97.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), west facing, middle</td>
<td>B1</td>
<td>14.0</td>
<td>90.5 (95.8)(^c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, middle</td>
<td>B2</td>
<td>14.3</td>
<td>51.8 (55.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), middle</td>
<td>B3</td>
<td>14.8</td>
<td>58.8 (71.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, middle</td>
<td>B4</td>
<td>14.3</td>
<td>90.5 (94.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), east facing, middle</td>
<td>B5</td>
<td>14.4</td>
<td>96.8 (98.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (base), middle</td>
<td>B6</td>
<td>14.1</td>
<td>96.8 (98.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (centre), middle</td>
<td>B7</td>
<td>14.3</td>
<td>96.8 (98.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), west facing, middle</td>
<td>B8</td>
<td>14.6</td>
<td>92.8 (96.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), east facing, middle</td>
<td>B9</td>
<td>14.1</td>
<td>96.5 (99.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), west facing, northern end</td>
<td>C1</td>
<td>14.5</td>
<td>82.0 (89.5)(^c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, northern end</td>
<td>C2</td>
<td>14.5</td>
<td>41.0 (51.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), northern end</td>
<td>C3</td>
<td>15.3</td>
<td>99.0 (99.0)(^c)</td>
<td>14.8</td>
<td>50.5 (64.3)</td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, northern end</td>
<td>C4</td>
<td>14.4</td>
<td>81.5 (90.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall, low), east facing, northern end</td>
<td>C5</td>
<td>14.3</td>
<td>96.8 (99.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (base), northern end</td>
<td>C6</td>
<td>14.2</td>
<td>100</td>
<td>14.2</td>
<td>97.3 (98.5)</td>
</tr>
<tr>
<td>Deep (centre), northern end</td>
<td>C7</td>
<td>14.2</td>
<td>94.3 (98.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), west facing, northern end</td>
<td>C8</td>
<td>14.8</td>
<td>90.3 (93.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep (off-centre), east facing, northern end</td>
<td>C9</td>
<td>14.1</td>
<td>97.5 (98.0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Grain moisture content average of two determinations and given as % wet basis

\(^b\) Germination energy assessed on 400 seeds

\(^c\) Viability shown in parentheses ( )
Table 13. Moisture content and germination energy of barley sampled from harvest bags at Roseworthy, South Australia

<table>
<thead>
<tr>
<th>Storage site and sampling point</th>
<th>Moisture Contenta (% wb)</th>
<th>Germination Energyb (%)</th>
<th>Moisture Contenta (% wb)</th>
<th>Germination Energyb (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Date</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec 2006</td>
<td></td>
<td></td>
<td>June 2007</td>
<td></td>
</tr>
<tr>
<td>Bag 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), south facing, eastern end</td>
<td>9.1</td>
<td>99.5 (99.8)c</td>
<td>9.3</td>
<td>93.0 (99.8)c</td>
</tr>
<tr>
<td>Peripheral (wall), south facing, eastern end</td>
<td>11.1</td>
<td>98.5 (99.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep, south facing, eastern end</td>
<td>9.0</td>
<td>99.0 (100)</td>
<td>9.0</td>
<td>98.8 (100)</td>
</tr>
<tr>
<td>Peripheral (top), south facing, western end</td>
<td>9.9</td>
<td>95.8 (98.8)</td>
<td>10.4</td>
<td>98.3 (99.5)</td>
</tr>
<tr>
<td>Peripheral (wall), south facing, western end</td>
<td></td>
<td>11.0</td>
<td>95.3 (97.5)</td>
<td></td>
</tr>
<tr>
<td>Deep, south facing, western end</td>
<td>10.3</td>
<td>98.8 (99.5)</td>
<td>10.1</td>
<td>98.0 (98.8)</td>
</tr>
<tr>
<td>Bag 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), north facing, eastern end</td>
<td>9.5</td>
<td>98.8 (99.5)c</td>
<td>9.8</td>
<td>99.0 (99.5)c</td>
</tr>
<tr>
<td>Peripheral (wall), north facing, eastern end</td>
<td></td>
<td>9.7</td>
<td>99.0 (99.8)</td>
<td></td>
</tr>
<tr>
<td>Deep, north facing, eastern end</td>
<td>9.3</td>
<td>99.0 (99.5)</td>
<td>9.4</td>
<td>99.0 (99.8)</td>
</tr>
<tr>
<td>Peripheral (top), north facing, western end</td>
<td>9.2</td>
<td>98.0 (99.5)</td>
<td>9.8</td>
<td>97.5 (99.5)</td>
</tr>
<tr>
<td>Peripheral (wall), north facing, western end</td>
<td></td>
<td>9.3</td>
<td>99.5 (99.5)</td>
<td></td>
</tr>
<tr>
<td>Deep, north facing, western end</td>
<td>9.2</td>
<td>100</td>
<td>9.3</td>
<td>95.5 (99.0)</td>
</tr>
</tbody>
</table>

a - Grain moisture content average of two determinations and given as % wet basis  
b - Germination energy assessed on 400 seeds  
c - Viability shown in parentheses ( )
Table 14. Moisture content and germination energy of canola sampled from harvest bags at Roseworthy, South Australia

<table>
<thead>
<tr>
<th>Storage site and sampling point</th>
<th>Moisture Content a (% wb)</th>
<th>Germination Energy b (%)</th>
<th>Moisture Content a (% wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Date</td>
<td>Dec 2006</td>
<td>Dec 2006</td>
<td>June 2007</td>
</tr>
<tr>
<td>Bag 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), south facing, eastern end</td>
<td>5.1</td>
<td>94.5</td>
<td>5.4</td>
</tr>
<tr>
<td>Peripheral (wall), south facing, eastern end</td>
<td>5.5</td>
<td>94.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Deep, south facing, eastern end</td>
<td>5.2</td>
<td>94.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Peripheral (top), south facing, western end</td>
<td>4.5</td>
<td>97.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Peripheral (wall), south facing, western end</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep, south facing, western end</td>
<td>4.7</td>
<td>92.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Bag 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), north facing, eastern end</td>
<td>4.7</td>
<td>95.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Peripheral (wall), north facing, eastern end</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep, north facing, eastern end</td>
<td>4.6</td>
<td>96.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Peripheral (top), north facing, western end</td>
<td>4.9</td>
<td>98.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Peripheral (wall), north facing, western end</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep, north facing, western end</td>
<td>5.1</td>
<td>98.0</td>
<td>5.1</td>
</tr>
</tbody>
</table>

a - Grain moisture content average of two determinations and given as % wet basis
b - Germination energy assessed on 400 seeds
Table 15. Moisture content and germination energy of canola sampled from harvest bags at Bowmans, South Australia

<table>
<thead>
<tr>
<th>Storage site and sampling point</th>
<th>Moisture Content&lt;sup&gt;a&lt;/sup&gt; (% wb)</th>
<th>Germination Energy&lt;sup&gt;b&lt;/sup&gt; (%)</th>
<th>Moisture Content&lt;sup&gt;a&lt;/sup&gt; (% wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Date</td>
<td>Dec 2006</td>
<td>Dec 2006</td>
<td>June 2007</td>
</tr>
<tr>
<td>Bag 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), south facing, eastern end</td>
<td>6.1</td>
<td>96.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Peripheral (wall), south facing, eastern end</td>
<td>6.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep, south facing, eastern end</td>
<td>5.8</td>
<td>97.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Peripheral (top), south facing, western end</td>
<td>4.9</td>
<td>91.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Peripheral (wall), south facing, western end</td>
<td></td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td>Deep, south facing, western end</td>
<td>5.0</td>
<td>92.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Bag 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral (top), north facing, eastern end</td>
<td>6.0</td>
<td>97.0</td>
<td>6.4</td>
</tr>
<tr>
<td>Peripheral (wall), north facing, eastern end</td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep, north facing, eastern end</td>
<td>6.3</td>
<td>96.5</td>
<td>6.4</td>
</tr>
<tr>
<td>Peripheral (top), north facing, western end</td>
<td></td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Peripheral (wall), north facing, western end</td>
<td></td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Deep, north facing, western end</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> - Grain moisture content average of two determinations and given as % wet basis  
<sup>b</sup> - Germination energy assessed on 400 seeds
Table 16. Insects detected in 11.4% and 14.1% mc wheat post-conditioning and during storage at CSIRO’s Black Mountain site, Canberra, February 2006 – May 2007

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Sampling Date</th>
<th>Insect Species</th>
<th>No. Live Adults (adults/kg)</th>
<th>No. Dead Adults (adults/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5% mc conditioned wheat</td>
<td>22/02/06</td>
<td>Rd</td>
<td>65</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tc</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>14.1% mc conditioned wheat</td>
<td>22/02/06</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11.5% mc wheat</td>
<td>28/09/06</td>
<td>Rd</td>
<td>-</td>
<td>71</td>
</tr>
<tr>
<td>(7 months)</td>
<td></td>
<td>Tc</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14.1% mc wheat</td>
<td>28/09/06</td>
<td>Rd</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>(7 months)</td>
<td></td>
<td>Tc</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>11.5% mc wheat</td>
<td>16/05/07</td>
<td>Rd</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>(15 months)</td>
<td></td>
<td>Tc</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14.1% mc wheat</td>
<td>16/05/07</td>
<td>Rd</td>
<td>0.3*</td>
<td>0.5</td>
</tr>
<tr>
<td>(15 months)</td>
<td></td>
<td>Tc</td>
<td>-</td>
<td>0.2</td>
</tr>
</tbody>
</table>

a – Live Rd adults detected at five different points in wheat after 15 months storage, including 23 live adults detected at a low sampling point on the west-facing wall.
Table 17. Mould infection levels measured during storage of 14.1% mc wheat at CSIRO’s Black Mountain site, Canberra, October 2006 (7 months storage)

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Sampling Date</th>
<th>Moisture Content (%)</th>
<th>Total Infection (%)</th>
<th>Total Count (cfu/g)²</th>
<th>Major Mould Species Detectedb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peripheral, north end</td>
<td>10/10/06</td>
<td>15.3</td>
<td>1.0 x 10⁴</td>
<td>99</td>
<td><em>Alternaria, Cladosporium</em></td>
</tr>
<tr>
<td>Peripheral, south end</td>
<td></td>
<td>13.3</td>
<td>3.0 x 10⁴</td>
<td>100</td>
<td><em>Alternaria, Cladosporium</em></td>
</tr>
<tr>
<td>Peripheral, side wall, west-facing</td>
<td></td>
<td>14.4</td>
<td>1.4 x 10⁴</td>
<td>100</td>
<td><em>Alternaria, Cladosporium</em></td>
</tr>
<tr>
<td>Centre, south end</td>
<td></td>
<td>13.6</td>
<td>3.1 x 10³</td>
<td>100</td>
<td><em>Alternaria, Penicillium, Cladosporium</em></td>
</tr>
<tr>
<td>Centre, north end</td>
<td></td>
<td>14.2</td>
<td>5.2 x 10³</td>
<td>100</td>
<td><em>Alternaria, Penicillium, Fusarium</em></td>
</tr>
<tr>
<td>Base, south end</td>
<td></td>
<td>13.9</td>
<td>1.9 x 10³</td>
<td>98</td>
<td><em>Alternaria, Penicillium, Fusarium, Aspergillus</em></td>
</tr>
</tbody>
</table>

a – cfu is a approximation of the number of colony forming units per gram, where 10 g of wheat was homogenised with 90 ml of 0.1% peptone solution.

b – The major mould species detected by both direct and dilution plating techniques are listed. Generally only one or two species predominated. Yeasts were present in relatively high levels in several of the 7 month samples; but have not been recorded in the tabulated data.

c – Not detected.
Table 18. Mould infection levels measured during storage of 14.1% mc wheat at CSIRO’s Black Mountain site, Canberra, May 2007 (15 months storage)

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Sampling Date</th>
<th>Moisture Content (%)</th>
<th>Total Infection (%)</th>
<th>Total Count (cfu/g)(^a)</th>
<th>Major Mould Species Detected(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peripheral (wall, middle), west facing, south end A2</td>
<td>15/05/07</td>
<td>14.5</td>
<td>3.0 (\times) 10(^2)</td>
<td>31</td>
<td>Eurotium, Aspergillus</td>
</tr>
<tr>
<td>Peripheral (top), south end A3</td>
<td></td>
<td>14.8</td>
<td>4.5 (\times) 10(^3)</td>
<td>58</td>
<td>Aspergillus, Eurotium, Alternaria</td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, south end A4</td>
<td></td>
<td>14.4</td>
<td>ND(^c)</td>
<td>24</td>
<td>Eurotium</td>
</tr>
<tr>
<td>Deep (base), south end A6</td>
<td></td>
<td>14.2</td>
<td>1.0 (\times) 10(^2)</td>
<td>19</td>
<td>Eurotium</td>
</tr>
<tr>
<td>Peripheral (wall, low), west facing, middle B1</td>
<td></td>
<td>14.0</td>
<td>1.0 (\times) 10(^2)</td>
<td>5</td>
<td>Eurotium</td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, middle B2</td>
<td></td>
<td>14.3</td>
<td>2.8 (\times) 10(^4)</td>
<td>78</td>
<td>Eurotium, Alternaria</td>
</tr>
<tr>
<td>Peripheral (top), middle B3</td>
<td></td>
<td>14.8</td>
<td>3.6 (\times) 10(^4)</td>
<td>94</td>
<td>Eurotium, Alternaria</td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, middle B4</td>
<td></td>
<td>14.3</td>
<td>ND</td>
<td>18</td>
<td>Alternaria, Eurotium, Aspergillus</td>
</tr>
<tr>
<td>Peripheral (wall, low), east facing, middle B5</td>
<td></td>
<td>14.4</td>
<td>ND</td>
<td>23</td>
<td>Alternaria, Eurotium</td>
</tr>
<tr>
<td>Deep (base), middle B6</td>
<td></td>
<td>14.1</td>
<td>2.9 (\times) 10(^3)</td>
<td>89</td>
<td>Eurotium, Alternaria</td>
</tr>
<tr>
<td>Deep (centre), middle B7</td>
<td></td>
<td>14.3</td>
<td>4.5 (\times) 10(^2)</td>
<td>59</td>
<td>Eurotium</td>
</tr>
<tr>
<td>Deep (off-centre), west facing, middle B8</td>
<td></td>
<td>14.6</td>
<td>8.8 (\times) 10(^4)</td>
<td>36</td>
<td>Aspergillus, Eurotium, Wallemia</td>
</tr>
<tr>
<td>Deep (off-centre), east facing, middle B9</td>
<td></td>
<td>14.1</td>
<td>1.5 (\times) 10(^2)</td>
<td>21</td>
<td>Eurotium, Alternaria</td>
</tr>
<tr>
<td>Peripheral (wall, middle), west facing, north end C2</td>
<td></td>
<td>14.5</td>
<td>1.3 (\times) 10(^4)</td>
<td>30</td>
<td>Aspergillus, Eurotium, Penicillium</td>
</tr>
<tr>
<td>Peripheral (top), north end C3</td>
<td></td>
<td>14.8</td>
<td>4.6 (\times) 10(^4)</td>
<td>84</td>
<td>Eurotium, Aspergillus, Alternaria</td>
</tr>
<tr>
<td>Peripheral (wall, middle), east facing, north end C4</td>
<td></td>
<td>14.4</td>
<td>1.5 (\times) 10(^3)</td>
<td>36</td>
<td>Aspergillus, Eurotium, Wallemia, Alternaria</td>
</tr>
<tr>
<td>Deep (base), north end C6</td>
<td></td>
<td>14.2</td>
<td>2.1 (\times) 10(^3)</td>
<td>69</td>
<td>Eurotium, Alternaria</td>
</tr>
</tbody>
</table>

\(^a\) cfu is an approximation of the number of colony forming units per gram, where 10 g of wheat was homogenised with 90 ml of 0.1% peptone solution.

\(^b\) The major mould species detected by both direct and dilution plating techniques are listed. Generally only one or two species predominated. Yeasts were present in relatively high levels in several of the 7 month samples; but have not been recorded in the tabulated data.

\(^c\) Not detected.

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Protein 11% mb (%)</th>
<th>Extensograph Extensibility (cm)</th>
<th>Extensograph Max Height (BU)</th>
<th>YAN Firmness Score (N)</th>
<th>YAN Brightness Score (L<em>a</em>b*)</th>
<th>Loaf Volume (c.c.)</th>
<th>Total Loaf Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4% mc control composite</td>
<td>11.1</td>
<td>17.2</td>
<td>440</td>
<td>1.56</td>
<td>70.7</td>
<td>780</td>
<td>65.8</td>
</tr>
<tr>
<td>11.4% mc Inner core 15 months composite</td>
<td>11.2</td>
<td>18.4</td>
<td>335</td>
<td>1.52</td>
<td>70.6</td>
<td>790</td>
<td>66.6</td>
</tr>
<tr>
<td>11.4% mc peripheral 15 months composite</td>
<td>11.3</td>
<td>15.4</td>
<td>475</td>
<td>1.73</td>
<td>69.4</td>
<td>740</td>
<td>62.6</td>
</tr>
<tr>
<td>14.1% mc control composite</td>
<td>8.4</td>
<td>16.8</td>
<td>425</td>
<td>1.26</td>
<td>69.8</td>
<td>600</td>
<td>50.3</td>
</tr>
<tr>
<td>14.1% mc Inner core 15 months composite</td>
<td>8.4</td>
<td>13.6</td>
<td>475</td>
<td>1.44</td>
<td>69.6</td>
<td>600</td>
<td>46.3</td>
</tr>
<tr>
<td>14.1% mc peripheral 15 months composite</td>
<td>8.5</td>
<td>13.9</td>
<td>480</td>
<td>1.35</td>
<td>70.1</td>
<td>625</td>
<td>47.7</td>
</tr>
</tbody>
</table>
Assessing the limits of existing harvest bag technology under Australian conditions

Figure 2. Gas sampling points in 11.5% mc wheat harvest bag

Figure 3. Gas sampling points in 14.1% mc harvest bag

Figure 4. Gas sampling points in harvest bags at ABB Grain trial sites
Assessing the limits of existing harvest bag technology under Australian conditions

Figure 5. Diagrammatic plan view of HOBO data logger location in harvest bags at CSIRO’s Black Mountain site, Canberra, ACT

Figure 6. Diagrammatic cross-sectional view of HOBO data logger location in harvest bags, CSIRO

Figure 7. Plan view of HOBO U12 data loggers in harvest bags at Bowmans and Roseworthy, SA
Assessing the limits of existing harvest bag technology under Australian conditions

Figure 8. Cross-sectional view of HOBO U12 data loggers in harvest bags at Bowmans and Roseworthy, South Australia

Figure 9. Diagrammatic cross-sectional view of sampling plan in harvest bags at CSIRO’s Black Mountain site, Canberra, ACT
Figures 10 (a). Temperature and Relative Humidity recorded by HOBO data loggers placed within 5-10 cm of film of canola harvest bag No 2 at Roseworthy (SA); 08/12/06 to 07/06/07; north-facing, eastern end. (b) Enlargement of grain conditions measured between 01/02/07 to 01/03/07.
Figures 10 (c) – (d). Temperature and Relative Humidity recorded by HOBO data loggers placed at different points in the cross-sectional area of canola harvest bag No 2 at Roseworthy (SA); 08/12/06 to 07/06/07; north-facing, eastern end (b) within 30-40 cm of film, and (c) centre, deep.
Figures 10 (e) – (f). Temperature and Relative Humidity recorded by HOBO data loggers placed at the wall, within 10-15 cm of film of canola harvest bags No 1 & 2 at Roseworthy (SA); 08/12/06 to 07/06/07; (d) Bag1, south-facing, western end (e) Bag 2, north-facing, eastern end.
Appended 11.2

Argentina’s National Institute of Agriculture (INTA) evaluation of harvest bags: wheat, barley and other grain types

11.2.1. Wheat

The storage of wheat stored in harvest bags for 160 days was reported by Rodriguez et al (2004). Wheat was harvested in January 2001 and loaded into bags at 12.5 & 16.4% mc (wb). Grain conditions were monitored and samples collected for subsequent quality assessment at 45, 80 and 150 days. Wheat was collected at upper, middle and lower sampling points, and repeated at three different points along the bag length.

The authors concluded that wheat at 12.5% mc and stored for 150 days, showed no significant loss in germination energy (GE) or baking quality. In comparison, germination energy of wheat stored at 16.5% mc rapidly declined in the middle and lower parts of the bag, but was maintained to a greater degree in the upper part where lower temperatures prevailed during storage. Moisture levels remained in equilibrium in both bags, with a 1% increase in moisture content at the top measurement point in the drier bag and 1% decrease in moisture content at the top point for the wetter wheat bag.

Germination energy used in the INTA study was not clearly defined. Seedling vigour is incorporated into the measure to a degree and is therefore likely to be comparable to an ISTA (Anon, 1993) assessment. The initial low germination rate for wheat (i.e. 89% and 90% for 12.5% mc and 16.4% mc wheat respectively) suggests that the weathering and loss of quality had occurred. After 150 days storage, the average GE for 12.5% mc wheat had declined by 7% and 16.4% mc wheat declined by 69%.

The position of wheat in the 16.4% mc bag had a significant influence on the rate that germination energy was lost. GE declined to zero within 45 days in the middle and lower parts of the bag. Wheat in these parts remained relatively insulated from low autumn ambient temperatures and the temperatures gradually declined during late-autumn to below 15°C leading into winter. In the upper part of the bag, GE decreased to 87.3% after 80 days, and to 64.7% after 150 days storage. The position of wheat in the drier 12.5% mc wheat bag had less influence on the rate that germination was lost. After 150 days storage, wheat in the upper part of the bag was 4% higher (84.2%) compared to the middle (81%) and lower (80%) parts of the bag.

Baking quality was also affected at the higher moisture level, with significant decrease in loaf volume within 45 days. The loaf volume derived from wheat taken from the upper part of the bag however showed no decrease. Loaf volume is a relative measure and often included as one component to rate the baking performance of flour derived from the grain sample. Flours that produce a higher loaf volume and loaf score are likely to make bread of good quality and texture when used under commercial bread making conditions. Decline in loaf volume reflects poor storage conditions resulting in a decline in enzymatic activity and changes in other biochemical processes.

11.2.2. Barley

The barley study was completed in May 2005. However, results of the malting & brewing component of the study have not been published. Barley used in the field evaluation was loaded into two bags in May 2004 at an average grain temperature of 25°C, with a relatively homogeneous moisture profile. Average ambient temperatures approximate 10°C (5 - 17°C) in this region during May and conditions remain at or below this level until September.

The experimental protocol was similar to the field trials by Rodriguez et al (2004). The average moisture content for barley was 11.5%. Information obtained from Silo Bags P/L (Victoria) suggests
that few problems were experienced with the storage of malting barley up to 6 months, when the first bag was outturned. No information is available for the 12 months barley bag.

Germination power (GP) and germination energy (GE) were used to assess barley quality during storage. GP is a measure of viability and GE includes an arbitrary assessment of seedling vigour. Initial GP was high (> 99.5%) for barley in both bags. After 2 months, the temperature of stored barley had decreased from 25°C to below 10°C in the upper part of the bags. At 6 months, GP at the surface was 99.3%, and in the middle and bottom of the bag, GP values were 100 and 99.5% respectively. GE was maintained above 97.8% (middle), with surface and bottom GE values were 98.0 and 98.2% respectively. The results available from the barley study support CSIRO field data. Premium quality barley harvested relatively dry (up to 11.5% mc) and stored at moderate temperatures should maintain germination and malting quality.

Under the conditions of this barley study, the deterioration of grain quality in the middle and lower parts of a harvest bag posed greater risk post-harvest. Grain quality in the peripheral layer was maintained to a greater degree, and the large surface to volume ratio characteristic of the harvest bag system was a substantial advantage in this evaluation.

11.2.3. Climatic influences and relevance to Australian situation

The Buenos Aires Province is the major grain production region in Argentina. The harvest season generally commences in November in the northern areas for late-winter and early-spring sown crops, and continues into February in the southern areas. The reported harvest bag evaluation of wheat and barley was undertaken near Tandil in the south-west of Buenos Aires Province. The mean maximum and minimum temperatures in the Tandil area during the months of January, February and March are 30.0, 28.9 and 26.1°C and 12.8, 12.8 and 11.1°C respectively, followed by cooler autumn conditions. The grain quality and storage information for wheat reported by Rodriguez et al (2004) has limited application to an Australian situation. The Tandil area would be similar to growing cereals in proximity to the Victorian towns of Benalla and Seymour, which are at the same latitude and similar elevation to the city of Tandil. These areas in Victoria are marginal temperate cropping areas. The long-term mean maximum and minimum temperatures for Benalla during the months of January, February and March are 31.0, 30.8 and 27.4°C and 14.9, 14.8 and 12.2°C respectively; and Seymour 29.5, 29.3 and 26.1°C and 12.7, 12.9 and 10.8°C respectively.

Cooling of barley and wheat post-harvest in the upper part of the bag provides a substantial advantage to maintaining quality during storage. The data on changes in germination and other quality parameters are useful as a case study where harvest bags are used in cool temperate climatic zones, and the storage of wheat at 12.5% mc is particularly useful in this regard. Australian grains however are typically stored post-harvest under prolonged periods of hot weather. Temperature has a profound influence on the storage potential of grains and an increase of 3 to 5°C in the average temperature over 3 to 4 months storage can significantly increase the rate of quality loss.

The study also fails to account for the seasonal variability of harvested wheat. The rate of quality loss is substantially influenced by initial grain condition, and a single study cannot account for such seasonal variation. The barley storage results have limited relevance to an Australian post-harvest situation. Barley was loaded into the trial bags at the Tandil experimental site during May, amidst cool autumnal weather leading into winter. The germination results are likely to reflect similar grain bulks that are cooled during winter.

An initial average 25°C grain temperature is considered moderate storage conditions for Australian barleys that are received into aerated storage by ABB Grains up to 13.5% mc (wet basis). At harvest an initial target temperature of 25°C is set to reach safe conditions for malting barley, with gradual lowering of the grain temperature to between 20 to 23°C during the course of storage.
11.2.4. Storage of other grain types in harvest bags

Rodriguez et al (2004) reported the storage of maize, soybean and sunflower in harvest bags near Tandil in the south-west of Buenos Aires Province. The experimental protocol was similar to that used to gather storage data for the barley and wheat trials.

July is a particularly cold month in the Tandil Province, with frequent sub-zero minimum temperatures. Maximum temperatures begin to exceed 20°C during late-November, and 30°C maximum temperatures are common during December-January. The commencement of field trials during the winter months exposed stored maize and soybean to very moderate storage conditions, and sunflower was loaded into bags in early-autumn when ambient temperatures were steadily decreasing. Grain conditions are summarised in Table 20.

Table 20. Grain conditions of maize, soybean and sunflower stored in harvest bags near Tandil in the south-west of Buenos Aires Province during season 2001/02

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>Moisture Content (%)</th>
<th>Inloading Date</th>
<th>Av. Temp. at Loading (°C)</th>
<th>Outturn Date</th>
<th>Av. Temp. at Loading (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>14.8</td>
<td>23/08/2001</td>
<td>14.6</td>
<td>23/01/2002</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>19.5</td>
<td>06/07/2001</td>
<td>11.2</td>
<td>05/12/2001</td>
<td>18.0</td>
</tr>
<tr>
<td>Soybean</td>
<td>12.5</td>
<td>05/06/2001</td>
<td>7.4</td>
<td>12/11/2001</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>15.6</td>
<td>05/06/2001</td>
<td>5.5</td>
<td>12/11/2001</td>
<td>13.5</td>
</tr>
<tr>
<td>Sunflower</td>
<td>8.4</td>
<td>08/03/2001</td>
<td>27.8</td>
<td>15/08/2001</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>16.4</td>
<td>08/03/2001</td>
<td>34.5</td>
<td>15/08/2001</td>
<td>14.5</td>
</tr>
</tbody>
</table>

The conclusions made for these storage trials were generally favourable towards the use of the harvest bags system to safely store these grain types. There was also no evidence of insect infestation in any of the bags used in these trials. However, these trials were undertaken within safe storage limits, given the initial low grain temperatures for maize and soybean, and the steady decline in grain temperature of stored sunflower seed. This type of evaluation may be useful for grains destined for livestock feeding and may reflect common usage of the harvest bags in Argentina. Stored sunflower seed was the only instance where initial storage conditions could be considered above moderate (e.g. ≥25°C).

The quality of grains used in these trials was poor; for example, the initial germination of sunflower seed was too low to include this part of the quality assessment in the trial results. There was a significant (4%) increase in the FFA level of the higher moisture content sunflower seed at the completion of the trial. In comparison, the FFA level of lower moisture content sunflower seed increased by 1.2%. Table 21 summarises germination results and changes in gas composition from initial levels in air (i.e. O₂ – 20.95%; CO₂ – 0.03%). The loss in germination for maize and soybean at both moisture contents (Table 21) are indicative of poor quality, weathered grains. At low temperatures, the expected loss in germination would be negligible for both these grain types, especially at the lower moisture content (e.g. 14.8% and 12.5% mc for maize and soybean respectively).

The INTA studies provide useful data on the modification of the atmosphere within the sealed bags, and profiled changes in temperature and re-distribution of moisture. Modification of the atmosphere showed that conversion of oxygen to carbon dioxide continued during the cooler months and the levels of conversion achieved within 160 days were significant. Rodriguez et al (2004) concluded that the modified atmosphere was insecticidal. However, initial low insect numbers used in the assays and the cooling of grain during the trial period, may have also influenced the control insects.
Table 21. Germination and gas composition of maize, soybean and sunflower stored in harvest bags near Tandil in the south-west of Buenos Aires Province during season 2001/02

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>Moisture Content (%)</th>
<th>Storage Time (Days)</th>
<th>Initial Germination (%)</th>
<th>Final Germination (%)</th>
<th>Final O₂ Level (%)</th>
<th>Final CO₂ Level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>14.8</td>
<td>153</td>
<td>68.0-70.5</td>
<td>54.5-60.0</td>
<td>2.1</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>19.5</td>
<td>153</td>
<td>88.0-89.5</td>
<td>79.0-89.5</td>
<td>2.6</td>
<td>18.5</td>
</tr>
<tr>
<td>Soybean</td>
<td>12.5</td>
<td>160</td>
<td>74.3-75.0</td>
<td>57.3-66.0</td>
<td>10.0</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>15.6</td>
<td>160</td>
<td>72.7-77.0</td>
<td>52.0-55.7</td>
<td>2.5</td>
<td>16.2</td>
</tr>
<tr>
<td>Sunflower</td>
<td>8.4</td>
<td>160</td>
<td>-</td>
<td>-</td>
<td>4.5</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>16.4</td>
<td>160</td>
<td>-</td>
<td>-</td>
<td>4.6</td>
<td>70.0</td>
</tr>
</tbody>
</table>

The gas-tightness standard was not determined for any of the harvest bags use in the trials, including barley and wheat trials. The modification of the contained atmosphere in the trial bags suggests a reasonable standard of gas-tightness was achieved. The high level of carbon dioxide (70%) achieved in the damp stored sunflower bag was not explained by the authors. Such high CO₂ levels suggest that biological anaerobic processes occurred. However, the presence of oxygen (4.6%) suggests either air ingress was occurring, or the generation of carbon dioxide was through biochemical or other processes that are unclear at this stage.
Appendix 11.3

An overview of the hermetic storage of grains at high moisture content

During the 1950s and 1960s, the Pest Infestation Laboratory at Slough (England) extensively evaluated the effect of air-tight storage on wheat or barley of between 17 to 24% moisture content. Sheeted steel 10 tonne bins fitted with a special gas-tight opening for filling and emptying were incorporated in the evaluation. The field studies showed conclusively that the hermetically stored grain remained bright in colour, free-flowing and free from moulds for periods up to five years.

During storage the grain fermented to varying degrees and a sour-sweet smell and bitter taste developed. Venting and drying the stored grain removed the odour to some degree. The rapid depletion of oxygen (through microflora and grain respiration) from the sealed system prevented the growth and development of moulds and yeasts. The anaerobic conditions formed favoured the development of other micro-organisms that produced carbon dioxide and alcohol, resulting in taint.

Germination was generally reduced to low levels, and changes to the chemical composition of the grain rendered it unsuitable for the production of leavened breads. A taint emanated from flour derived from the high moisture stored wheat and the odour was also distinctive on bread. Admixture with a high proportion of normally stored wheat however effectively avoided problems during milling.

Similar work in the United States showed that air-tight storage of damp grain (ranging between 27 to 30% mc) provided safe storage conditions for grains destined for livestock use. Grains stored at such high moisture levels darkened, softened and fermented to varying degrees. However, the grain maintained free of moulds and remained palatable for livestock. The smell is generally less sweet and similar to that of green silage. Hyde (1974) suggests that this very damp grain may have a large proportion of immature kernels with high sugar content and the darkening may be due to a non-enzymic reaction of the Maillard type, as described by Linko (1960), or it may be microbiological in origin (Desikachar et al, 1959).

In well-sealed hermetic storage, the rapid depletion of oxygen from the atmosphere retards self-heating of the bulk. Hyde (1974) showed that fermentation results in considerably less production of energy; i.e. only 92 kilojoules per gram-molecule of hexose sugar is produced during fermentation, compared to 2,833 kilojoules when oxygen is present.

The storage of grains in plastic membrane type systems at high moisture levels (up to 30% mc) for livestock purposes is now common in commercial practice in Europe and South America. This has been an extension of the use of the systems to store freshly-cut forage for livestock purposes. The Gilgandra Cooperative in northern NSW has adopted this technology to store grains up to 30% mc for use in intensive feedlots that are in close proximity to bag stored grain (C. Kirby, personal communication). Barley harvested between 28 – 32 % mc was loaded into 100t capacity, 2.28 m wide heavy duty bags using a machine that crimped (rolled) the grain before being augured into the bags. At outturn, damp grain was immediately admixed with lucerne silage, barley straw and lime (approximately 1% by volume). Damp barley was allowed to ferment for 4 – 5 weeks within the bags before feeding out. The grain was also sprayed with a mould inhibitor at outturn.

The recommended moisture range for damp grain storage is between 25 – 30% mc (wet basis) as higher moisture levels substantially reduce harvesting efficiency. In Argentina, purpose-designed ensiling inloading machines are used that incorporate breaking hammers to cut maize or soybean during the bagging process. Ensiling machines have a capacity to load bags up to 20 t/hr, depending on the calibration selected to break and press grain during bagging. Feeding studies in Argentina show that no livestock acidosis or feeding problems occur from damp grains stored in harvest bag systems (C. Kirby, personal communication). Changes in the structure and composition of the damp grain...
during storage apparently makes it immediately available as feed. This compares to drier whole grains used for stockfeed, which are processed to varying degrees prior to feeding out. There is an active market for damp (30% mc) maize and soybean in Argentina and grain is directly transported from the bag site to the feedlot for immediate feeding out.

The potential leakage of oxygen into a plastic membrane system remains a high risk for the safe storage of damp grains. Ingress of oxygen into the system will lead to rapid moulding in the vicinity of the leakage point(s). The removal of grain from plastic membrane systems also poses a problem. Moulding occurs rapidly once removed from an oxygen depleted atmosphere and outturn and feeding to stock needs to be undertaken within days. Opening and resealing bag ends also poses a storage risk. However, careful sealing to ensure a gas-tight seal would soon curb mould growth and maintain the integrity of the system. The trials by the Gilgandra Cooperative show that approximately 1.5 – 2 tonne of grain (equivalent to 1 m length of the bag) of grain is lost due to moulding when bags are only partially outloaded and re-sealed (C. Kirby, personal communication).

The rate that germination is lost in damp grain stored under oxygen-free conditions is largely influenced by the temperature and moisture content. Even under moderate storage temperatures (e.g. 22 - 25°C) germination is expected to rapidly decline to zero within weeks for grains stored above 22% mc (Hyde, 1965).
Appendix 11.4

Proportion of harvest bag contained in daily thermal peripheral layer compared to other stores

11.4.1. Grain harvest bags

Ipesasilo® and Silobolsa® bags are commercially available in Australia. The bags are available in a range of length with the 60 and 75 m being commonly used on Australian farms. 90 and 120 metre bags are also available and are likely to gain acceptance as the harvest bag system is increasingly adopted.

Figure 11. Diagrammatic representation of harvest bag profile when filled with cereals compared to pulses (where A is height of the bag profile and B the base width)

The maximum recommended stretch of the film during filling is 19 cm. The film characteristically stretches between 2.5 – 3% on the top and approximately 1% on the sides. The bag profile depends on seed type and filling procedure. Pulses (e.g. peas and lentils) tend to form a lower profile (Figure 11) and bags stand between 1 to 1.2 m from ground level. Barley forms a more rigid bag and can stand up to 2 m from ground level. Wheat bags typically have a lower profile than barley.

The surface to volume ratio is based on a typical barley bag, 75 m in length storing 220 t (reported capacity of 440 m³) with a base approximating 2.75 m and standing 2 m high. The filled bag approximates a half oval shape.

\[
\text{Circumference} = (2\pi \sqrt{\frac{A^2 + B^2}{2}})/2
\]
\[
= (2\pi \sqrt{\frac{2.0^2 + 2.75^2}{2}})/2
\]
\[
= 5.34 \text{ m}
\]

(The maximum circumference of 11.4 and 14.1% wheat bags at CSIRO Black Mountain was 5.3 and 5.5 m respectively).
The total surface area of a 75 m bag exposed to radiant heating approximates 400 m².

Assuming the peripheral layer is 15 cm in depth, approximately 40.2 t (60 m³ @ bulk density of 670 kg/ m³) of stored barley is subjected to peripheral layer influences. Where 220t is stored, this approximates 18.3% of the total barley in harvest bags.

Proportion of barley exposed to peripheral layer = (40.2/220) x 100 = 18.27% ≈ 18.3%

This figure is an approximation and compaction ratio and capacity will be influenced by grain size and condition and filling procedure.

11.4.2. Commercial bunker storage

These calculations are based on typical 10,000 t bunker construction by ABB Grain Limited in South Australia. The standard dimensions of a 10,000 t bunker are 100 m in length and 33 metres wide (Figure 12). Prefabricated concrete walls are 1.0 m and the height of the completed stack (for the purpose of this calculation) approximates 9.4 m. The angle of repose for wheat is 27 degrees and the slope of the bunker approximates this angle; however, the top of the grain stack is typically flattened (rounded). The peripheral layer influence through the thick concrete walls would be minimal and this is discounted from the calculation.

![Diagram](image)

Figure 12: Diagrammatic representation of the cross-sectional area of a typical PVC covered bunker store in South Australia.

Total surface area (m²) of tarpaulin approximates = 18.5 x 2 x 100 = 3700

Total capacity of peripheral layer (m³) = 3700 x 0.15 = 555

Total tonnes of barley exposed to peripheral layer influences @ 670 kg/m³ = 555 x 0.67 = 371.9

Total capacity of bunker = 10,000 t

Proportion of barley in peripheral layer = (371.9/10,000) x 100 = 3.719% ≈ 3.7%
11.4.3. On-farm storage

The dimensions of on-farm steel clad storage is variable and the example used below is given for a 114 m³ welded steel bin manufactured by Modern Engineering & Construction P/L in Walla Walla (NSW). In this example, the hopper bottom is included in the eve height calculation.

Capacity: 114 m³
Dimensions: Height (eve) 8.1 m; Height (centre) 9.4 m; Diameter 4.6 m; Cone angle 35°
Surface area of conical roof (m²) = \( \pi \times 2.3 \times 2.64 = 19.08 \)
Surface area of cylindrical body (m²) = \( 2\pi \times 2.3 \times 8.1 = 117.1 \)
Total surface area (m²) = 136.2

Capacity for barley @ 67.0 kg/hl = 77 t
Capacity for wheat @ 80.0 kg/hl = 92 t
Peripheral layer assumed at 20 cm depth

Proportion of barley and wheat influenced by peripheral layer:
Barley = (136.6 x 0.15 x 0.67)/77 = 17.83% ≈ 17.8%
Wheat = (136.6 x 0.15 x 0.80)/92 = 17.82% ≈ 17.8%

This figure is an approximation and for small capacity (80 - 100 t) farm silos and bins the proportion of grain subjected to peripheral layer influences will range between 17 to 18.5% depending on dimensions. The peripheral layer influence will substantially increase for smaller capacity farm bins (e.g. 50 t).
Appendix 11.5

Wheat processing and end-product quality: influence of storage conditions

Flour millers and bakers define quality using parameters that evaluate the performance of grain to deliver an accepted and consistent standard of processing and end-product quality. Flour extraction rate, and flour dough water absorption capacity, strength, consistency and elasticity, are important measures of quality to millers. Standard indexes are applied to evaluate the performance of flours to produce a wide range of end-products, for example, leaven (pan) breads, Asian style steamed breads, Arabic style flat breads, white-salted and yellow alkaline noodles, and cake and biscuit mixes.

The types of physical tests used to assess the performance of flour dough and bread-making quality are described in section 11.5.1. An overview of the influence of storage conditions on processing and end-product performance is given in section 11.5.2, and the use of a viability index to gauge the loss in performance during storage is appraised in section 11.5.3.

11.5.1. Dough rheology and bread-making indexes

Changes in the milling and baking parameters of wheat can be quantified using a range of physical rheological measurements that standardise the performance of flour dough. Wheat flour dough is viscoelastic as it exhibits both viscous flow and elastic recovery (Hoseney, 1994). Farinograph and Extensograph tests are extensively used to quantify the rheological properties of flour dough. Mechanical testing assesses the consistency, mixing tolerance and strength of a dough. It is inherently difficult to compare dough measures between different laboratories, and their value is often for comparative assessment within a laboratory; e.g. between different varieties and grades, and between samples stored under different conditions.

Farinograph data provides information on the water absorption of flours and determines the stability and other characteristics of doughs during mixing. Starch damage in the grain due to α-amylase activity reduces the re-hydration capacity of flour (Ekstrom, 1978). The dough development time is that point in the maximum consistency range that weakening of the dough is indicated. The stability and breakdown values of the dough are closely related to the development time and the peak point reached during the test. Doughs derived from sound wheat are more stable, produce higher peak values, and the breakdown time tends to be shorter.

Extensograph testing provides information on the breakdown or damage that has occurred to wheat gluten and other general characteristics of flour that affect baking quality. In an extended test, the dough is processed on three occasions to simulate the fermentation period in conventional bread making, interrupted by punching and moulding (Bloksma & Bushuk, 1988). In the shorter 45-minute test, the dough is stretched and shaped only once. Extensibility, maximum resistance (height) and area under the curve are used to describe the characteristics of an Extensogram, and the curve height and area under the curve indicate the flour's strength. Larger values indicate greater strength. Gluten protein, comprised of gliadin and glutenin fractions, gives dough its viscoelastic properties and the results of the Extensograph test may be expected to reflect protein content of the flour where significant damage has not occurred to the gluten component.

Loaf volume is a relative measure and often included as one component to rate the baking performance of flour derived from the grain sample. The baking test is conducted by a fermented dough procedure using a bromate-free formulation. The method is often developed to meet the objectives of the assessment. Agrifood Technology (AWB Limited) has a total loaf score of 100, which comprises loaf volume (max 36 pts), external appearance (max 20 pts), crumb texture (max 30 pts), and crumb colour (14 pts). Loaf volume is measured by rapeseed displacement.
Flours that produce a higher loaf volume and loaf score are likely to make bread of good quality and texture when used under commercial bread making conditions. The protein content of flour processed from sound wheat may be used as an indicator of the expected loaf volume. For example, a loaf volume of 750 to 800 cm$^3$ may be expected from approximately 170 g of flour (weight adjusted to 13% mc basis) with a protein content of 13%, and a loaf volume of 600 to 650 cm$^3$ from flour with a protein content of 10%. The quality of the flour, as determined by the Extensograph and Farinograph tests, also influences both loaf volume and loaf score.

### 11.5.2. Processing and end-product quality

Storage time and conditions have an influence on the technological milling and baking quality of wheat. One of the most difficult properties to maintain in stored wheats is consistency of flour performance. Historically, extended storage times lead to progressive increase in mixing requirement and consequent changes in baking procedures. The increase in mixing requirement is not associated with change in Farinograph water absorption, but is associated with a decrease in the bakery absorption, loss of loaf quality and increased ingredient cost Gras et al (2000).

The use of aeration cooling systems to achieve moderate storage conditions for milling wheat is not commonly practiced in Australia; however, such conditioning of wheat is well suited to maintain flour quality effectively constant for at least 12 months. Industrial milling and baking studies by Gras et al (2000) showed Farinograph development time and Extensograph extension (Rmax) were maintained at the same levels for 12 months for 12% mc wheat stored at 4 and 23°C for 12 months. At higher temperatures (35°C), Farinograph development time and Extensograph extension changed substantially after 4 ½ and 2 months storage respectively, and continued to increase with time. Similar negative relationship was recorded for test loaf volume (ml), with volume significantly decreasing over time at high temperatures.

Caddick (1999) assessed the effect of grain moisture content and temperature on physical dough properties, and noodle and bread-making quality of white-grained wheat over 12 months (Table 22). Southern-hard wheat (protein 13.5%) was conditioned to 12, 13, 14 and 15% mc and stored at 20 and 30°C. Storage conditions had various effects on different wheat quality attributes, i.e. extraction rate, Farinograph water absorption and dough development time, dough strength and starch pasting viscosity, without significant improvement or deterioration determined due to the effect of moisture content or temperature.

Table 22. Germination energy and end-product assessment of wheat stored at different moisture contents and temperatures for up to 12 months. End-product assessment by BRI Australia Limited, Sydney.

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Moist. Content (%)</th>
<th>Storage Time (months)</th>
<th>Germ. Energy (%)</th>
<th>Noodle Eating Quality</th>
<th>Noodle Colour Score</th>
<th>Noodle Quality Total (%)</th>
<th>Baking Quality Crumb Structure</th>
<th>Baking Quality Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>9.5</td>
<td>12</td>
<td>98.3</td>
<td>31</td>
<td>22</td>
<td>66</td>
<td>12</td>
<td>78</td>
</tr>
<tr>
<td>20</td>
<td>12</td>
<td>12</td>
<td>96.9</td>
<td>39</td>
<td>21</td>
<td>74</td>
<td>11</td>
<td>77</td>
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<td>30</td>
<td>12</td>
<td>12</td>
<td>93.3</td>
<td>39</td>
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<td>12</td>
<td>78</td>
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<td>20</td>
<td>13</td>
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<td>96.0</td>
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<td>6</td>
<td>95.4</td>
<td>38</td>
<td>19</td>
<td>71</td>
<td>12</td>
<td>78</td>
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<tr>
<td>30</td>
<td>14</td>
<td>6</td>
<td>86.9</td>
<td>41</td>
<td>18</td>
<td>73</td>
<td>12</td>
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<td>20</td>
<td>14</td>
<td>12</td>
<td>95.7</td>
<td>42</td>
<td>21</td>
<td>79</td>
<td>11</td>
<td>77</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>6</td>
<td>88.3</td>
<td>39</td>
<td>21</td>
<td>75</td>
<td>11</td>
<td>77</td>
</tr>
</tbody>
</table>
In general, the wheat assessed by Caddick (1999) maintained bread-making and noodle quality, with only slight deterioration in baking performance of flour derived from 13% mc wheat stored for a 12 month period. There was a marked improvement in noodle quality with increased moisture content and storage time, which was largely the result of improved elasticity and cooking colour. A well-balanced quality for both white noodles and bread was obtained for wheat at 14% mc and stored at 20°C for a 12 month period.

In a subsequent field study at The Rock (NSW), Caddick (1998a) showed for wheat stored at 12 and 13% mc for 10 months, there was no significant difference between the grain, flour, and technological processing parameters assessed. Average temperatures in the two 100 t concrete bins ranged from 28 - 30°C in mid-January, to 10 - 12°C late-October with greater variability around these temperature ranges within the outer peripheral layer.

Post-harvest maturation in wheat is apparently manifest by an increase in protein stability (i.e. increase in development time and Extensograph height), slight decrease in enzyme activity (i.e. lower maltose value and increased Viscograph height), and an overall improvement in bread-making quality. These improvements in technological processing appear to reach a maximum within 2 to 4 months post-harvest (Tipples, 1991) and need to be taken into account when considering the significance of the results of this study.

Reuss & Cassells (2005) assessed a range of dough rheology parameters for different varieties and grades of wheat collected during the 2002/03 and 2003/04 harvests, conditioned 10, 12 and 14% mc and stored at 15, 20, 25 and 30°C. Farinograph testing showed marked changes in Water Absorption, Dough Development Time and Stability with storage time, with substantial increases in DDT and peak value and reduced hydration capacity at 14% mc and 30°C. The influence of storage conditions on the change in Farinograph measurement however was not unambiguous. Extensograph testing showed similar trends, with changes in extensibility and Rmax (resistance to extension) of greatest magnitude at 14% mc and 30°C. At higher temperatures and moisture levels the change in both these extensibility measures was increased, with maximum extensibility showing the greatest change.

Wheat stored under moderate conditions (e.g. 12% mc and 25°C) is likely to improve with time. The time of maturation is important for the achievement of the optimal flour bread-making quality (Hruskova & Machova, 2002). Studies by Reuss & Cassells (2005), Gras et al (2000) and Caddick (1999, 1998a) show wheat is quite robust under moderate conditions, and there is no substantial loss in milling or baking performance up to 12 months storage. Lukow & White (1997) showed milling or baking parameters of red wheat stored under similar conditions improved during 15 months storage, although wheat strength was negatively affected.

The data of Reuss & Cassells (2005) and Caddick (1999) indicate sound wheat will retain processing and end-product at the industry’s 12.5% mc maximum receival limit for up to nine months storage when average grain temperature during storage approximates 30°C. Wheat received into storage at 13% mc is at greater risk of quality loss; however, wheat should retain processing and end-product up to six months, even in regions where frequent high temperatures prevail.

11.5.3. Germination as an index

For wheat, changes in technological processing potential are less affected by the loss in germination capacity (viability) due to storage influences. Caddick (1999) showed that a substantial loss of germination capacity (10 -15%) had no adverse affect on bread-making or noodle quality, as measured by the pan-bread and white noodle system of evaluation. Pomeranz (1988) supports these findings, concluding in his comprehensive review of the biochemical and functional changes in wheat during storage that substantial decreases in germination capacity (10 - 20%) were not reflected in bread-making potential.
The use of germination energy (GE) as a basis to establish safe storage recommendations for wheat therefore provides a substantial buffer against potential loss of processing and end-product quality during storage. Germination energy data shown in Figures 13 and 14 are from controlled studies by Reuss & Cassells (2005), Caddick (1999) and Caddick & Shelton (1998a) for storage temperatures of 20 and 30°C respectively. This is original data and is not produced in this form in any other publication.

At 20°C the storage potential of all wheat varieties used in these studies maintained GE for up to 52 weeks, including wheat conditioned and stored at 14% mc. The study of Reuss & Cassells (2005) extended storage time to 104 weeks and loss in GE was only significant for Sunvale wheat stored at 14% mc. All wheat varieties stored at 12% mc maintained GE above 95% for the 104-week period.

At 30°C losses in GE are most significant for wheat stored at moisture contents above 13%. Janz wheat at 15% mc rapidly lost GE and all seed was dead within 21 weeks. Wheat stored at 14% mc began to lose GE after 12 weeks storage and the loss of GE was rapid with all seed dead between 36 to 42 weeks for the different varieties. Janz wheat at 13% mc maintained GE above 80% for 52 weeks. All wheat at 10 and 12% mc maintained high GE for 104 and 52 weeks respectively.

The effect of storage conditions on the rate that GE is lost is influenced by initial seed condition and varietal influences. Weathered seed loses GE at an increased rate, and higher storage temperatures and moisture contents further accelerate this rate of loss. The placement of weathered or aged wheat into harvest bags will substantially increase the risk of loss of GE and loss of processing and milling quality.

These data show that wheat harvested and stored at the 12.5% mc industry receival standard will maintain GE for extended storage times (e.g. up to 52 weeks). Typically Australian wheat is harvested below 12% mc and the relativeness dryness of sound grain would provide a considerable buffer against loss of GE.
Assessing the limits of existing harvest bag technology under Australian conditions

Figure 13. Original data from Reus & Cossells (2005) and Caddick (1999) of Germination Energy of different wheat varieties and grades stored at 20°C
Assessing the limits of existing harvest bag technology under Australian conditions
Appendix 11.6

Barley and malting quality: influence of storage conditions

Maltsters use a range of indexes to quantify the malting performance of barleys. In Australia, most malt specifications are measured using recommended methods of the Institute of Brewing (Anon, 1997). The homogeneity of barley used to produce malt is of paramount importance and significantly influences the production efficiency in commercial malt-houses. Storage conditions and time therefore have an important influence in the delivery of a more homogeneous product.

The quality parameters used by Australian maltsters are described in section 11.6.1. An overview of the influence of storage conditions on malting performance is given in section 11.6.2, and the use of a viability index to gauge the loss in performance during storage is appraised in section 11.6.3.

11.6.1. Barley malt indexes

Micro-malting analysis provides maltsters and brewers an indication of the performance of a batch of malted barley. Sample replication is required to quantify (to a degree) variance within a batch. Malt quality has such a large variety of influences on the brewing process and beer that a single set of specifications is not likely to be universally acceptable. Historically, the established parameters: hot water extract (HWE), wort viscosity, wort \( \beta \)-glucan, \( \beta \)-glucanase, Kolbach Index (KI), Apparent Attenuation Limit (AAL), Diastatic Power (DP), \( \alpha \)-amylase, free amino nitrogen (FAN), wort colour, dimethyl sulphide and nitrosodimethylamine, are accepted internationally as malt specifications.

HWE expresses the specific gravity of an extract of malt under defined conditions. Malt with high HWE will have large amounts of fermentable substrates available during brewing, however it gives only a poor indication of actual brewing performance because of the difference between laboratory grinding and mashing and the process in an industrial brewery (Bamforth and Barclay 1993).

Wort viscosity is the measurement of laboratory wort with a viscometer. Worts with high viscosity increase lautering and filtration times and are therefore undesirable (Lewis and Young 1995). The viscosity of wort is increased by \( \beta \)-glucans, and therefore wort \( \beta \)-glucan and \( \beta \)-glucanase activity are important measurements of endosperm modification and consequently of malt quality.

Kolbach Index (KI) is the ratio of soluble to total nitrogen using an EBC mash regime. KI is an indicator of protein modification: more protein hydrolysis during malting means more soluble protein in the wort and therefore higher KI values (Bamforth and Barclay 1993). High quality malt should be within a specified KI range, as low KI values indicate insufficient modification (negatively influences wort gelatinisation, saccharification during mashing, flow rates during filtering, haze formation) while high KI values show excessive modification (leads to malt shattering and poor foam stability) (Palmer 1989).

Apparent Attenuation Limit (AAL) measures the ability of brewing yeast to decrease the specific gravity of laboratory wort. AAL depends on the types and quantity of carbohydrates in the wort, the availability of free amino acids during fermentation, the thermostability of amylases, and a number of factors that flocculate yeast (Eglington et al 1998, Kihara et al 1998). High AAL directly relates to brewing yield.

Diastatic Power (DP) measures the ability of malt to degrade starch. It is determined by measuring the amount of sugars released from a starch solution containing ground malt. The enzymes responsible are \( \alpha \) and \( \beta \)-amylase, limit dextrinases and \( \alpha \)-glucosidase. \( \alpha \)-amylase activity is commonly measured as a good indicator of aleurone activity during malting (Bamforth and Barclay 1993). High Diastatic Power levels are essential to assist in the conversion of the solid adjuncts such as corn and rice grits commonly used in overseas breweries.
11.6.2. Malting quality

The extract available in the brewhouse from a tonne of malt is a key economic driver in beer production. The availability of the hydrolytic enzymes provided by the malt is especially important in brewing processes that include the addition of complex carbohydrate adjuncts to the wort (Woonton et al, 2002). Barley breeding has focused on increasing enzyme systems in new barley releases and this has led to improvements in extraction efficiencies with higher levels of hydrolytic and proteolytic enzymes. However, improvements in DP, KI and AAL can readily be lost due to poor storage management.

Malt with high enzyme levels and good modification is capable of producing high hot water extract values. Woonton et al (2002) showed the activity of malt hydrolytic enzymes α-amylase and β-glucanase increased significantly in germinated Franklin barley following storage under room conditions (i.e. 22-27°C and 38-44% RH) for up to 12 months. Overall malt quality improved, with increased DP, KI and AAL and decreased wort-β-glucans. Reuss et al (2005, 2004) supported these finding for different barley varieties stored at 10% mc and 15-25°C. At higher moisture contents the activity of malt hydrolytic enzymes increased and then levels were maintained at 15-20°C, gradually declined at 25°C, or rapidly declined at 30°C.

Variatel differences were shown in activity of the enzymes α-amylase, β-amylase and β-glucanase in the barleys used in the study by Reuss et al (2005, 2004). In barleys that exhibited dormancy, enzyme activity increased with storage. Increased activity was predominantly associated with α-amylase and β-glucanase. β-amylase measurements showed no clear trends, which reflected the fact that β-amylase is deposited in the endosperm during grain development, while α-amylase is very actively synthesized during germination (Fincher and Stone 1993).

Diastatic Power (DP) is influenced by both temperature and moisture content. Reuss et al (2005) and Caddick (unpublished data) showed storage of barley at 10% mc maintains DP for 12 months at temperatures up to 30°C. Barley stored at 12% mc and 25°C generally maintained DP for up to 12 months. As moisture content and storage temperature increases above the moderate conditions, the rate of quality loss over time increases and the more severe the storage conditions, the faster the rate of quality loss. Caddick (unpublished data) showed at 35°C, the loss in malting potential was significant, especially at 12, 13 and 14% mc. 14% mc barley rapidly lost malting performance and within three months storage was characterised by very hazy wort with high levels of β-glucans and low DP (50% reduction).

Kolbach Index (KI) and Apparent Attenuation Limit (AAL) appear strongly related to germination energy in barley. Reuss et al (2005, 2004) showed KI increased where the germination remained high. Loss of GE resulted in decreased KI and generally increased haziness in the wort extract with increased levels of β-glucan. The reverse was generally observed for changes in AAL, with loss in GE resulting in increased AAL. The magnitude in changes in KI, DP and AAL observed by Reuss et al (2005, 2004) generally reflected increasing harshness of storage conditions, with high temperatures and moisture contents resulting in greater change in these parameters.

There is considerable variation in the levels of β-glucans between the different barley varieties. Time in storage appears to have a predominant influence on wort viscosity and β-glucan levels and to a lesser degree on wort colour and clarity. Reuss et al (2005, 2004) and Caddick (unpublished data) showed wort viscosity and β-glucan levels increase with time, even at lower moisture levels. Storage at high temperature and moisture levels increases the levels of β-glucans and wort viscosity. Colour of wort also changes and wort derived from barley stored under severe conditions is generally extremely hazy and darkened. For commercial brewing practices, significant increases in wort viscosity and β-glucan levels lead to increase filtration and lautering times, an undesirable outcome.
The data of Reuss et al (2005) and Caddick (unpublished data) show that the storage of dry barley (≤ 11% mc) provides a substantial buffer against loss of malting quality at temperatures above 30°C. The storage of barley above 11% mc increases the risk of quality loss, and storage at the industry’s 12% mc maximum receival limit poses substantial risk where extended periods of hot weather prevail post-harvest.

11.6.3. Germination as an index

Germination energy is a useful indicator to assess ageing and overall changes in barley malting quality. Loss of germination is the result of the break-down of cellular structure and function, and enzyme and biochemical systems are modified. Barley quality is essentially based on the ability of the seed to germinate rapidly and uniformly during malting and the production of high levels of hydrolytic and proteolytic enzymes during this process to maximise extraction efficiency of the substrate during beer production.

The MBIBTC specify a minimum germination capacity of 98% for stored barley (Anon, 1998) and generally maltsters will not receive barley for processing when the GE is below 96%. Barley with high and uniform vigour is paramount in malting and any substantial loss of vigour during storage is detrimental to the overall malt process. The loss of vigour precedes loss in viability, and barley can potentially maintain high viability, but exhibit low and poor uniformity of vigour.

The germination energy data of Reuss et al (2005, 2004) and Caddick (unpublished data) shown in Figures 15 and 16 provides a useful basis for establish recommendations for safe storage limits for malting barley at a range of moisture content and temperatures. This is original data and is not produced in this form and any other publication.

These data show that cool and dry storage conditions are necessary to maintain GE and malting quality for extended storage times (e.g. up to 52 weeks). Reuss et al (2005) showed that storage at moisture contents greater than 10% and temperatures greater than 20ºC can lead to a loss in barley quality. As shown in Figure 15, short-term storage at 30ºC and 14% mc rapidly resulted in barley that could not be malted and all seed was dead at 24 weeks.

The effect of storage conditions on barley and malt quality is further complicated by initial seed condition, varietal influences, post-harvest maturation and the presence of dormancy and water-sensitivity. It is difficult to differentiate between these influences. All barleys have aged to some degree at harvest and any estimate of a Damage Index will be subject to cumulative errors in each measured index.

To meet the requirements of Australian maltsters, barley must overcome postharvest dormancy and be able to germinate vigorously. Barley undergoes significant changes associated with dormancy decay during postharvest storage. These changes promote germination of the grain, resulting in increased enzyme production and improved malt quality.

Barley with dormancy and water sensitivity was shown by Reuss at al (2004) to have a degree of protection against germination loss during storage. Dormancy and water sensitivity is gradually removed during storage at rates largely determined by temperature and moisture content. Reuss et al (2004) and Caddick & Shelton (1998b) showed that dormancy can be removed within weeks by heating grain to temperatures up to 40ºC. Figure 16 shows Schooner barley in premium condition stored at 35°C maintained GE close to 100% up to 52 weeks at 10% mc and above 96% for 26 weeks at 12% mc. These data show that malting barley can be exposed to relatively harsh storage conditions and maintain GE within limits.
Figure 15. Original data from Reuss et al (2005) and Caddick (unpublished) showing loss of Germination Energy of different barley varieties stored at 30°C up to 52 weeks.
Figure 16. Original data from Caddick (unpublished) showing loss of Germination Energy of Schooner barley stored at 35°C to 52 weeks.