SEALING OF GRAIN STORAGES FOR USE WITH FUMIGANTS AND CONTROLLED ATMOSPHERES

by

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Summary

There is an increasing trend towards the use of sealed storage for dry grain in Australia. Currently, about 2.9 Mt (12% of total permanent capacity in the central system) are sealed to a standard permitting use of fumigation or controlled atmospheres ('fumigable'). There is an active programme of conversion of existing storages to sealed systems both on farm and in the central system. Most new storage capacity is now built fumigable or designed to be easily modified to be so. Research during the past 10 years, summarised herein, has led to development of methods of sealing and testing of a wide variety of storage types. The disadvantages of sealed storage are discussed. Recent experience with the operation of large sealed storages (> 10,000 t capacity) has shown that, after a disinfestation using phosphine as a fumigant, wheat can be stored under Australian conditions for at least six months before a further insect control treatment is required. The sealed storage system appears to afford a significant protection against insect invasion of the grain from outside. It also ensures that fumigation can be carried out so that no significant insect population remains within the store to provide a nucleus for subsequent resurgence of infestation. A method is given for estimation of the total leak size remaining after sealing.

Introduction

Insect pests, if left uncontrolled, can do substantial damage to dry (< 12% m.c.) grain as stored in Australia and other warmer parts of the world. Since about 1961 grain stored in the central bulk handling system in Australia has been protected against insect attack with an organophosphate insecticide. The protectant has been applied directly to almost all grain received into the central system† from the grower. At first, malathion was used, but this has now been replaced by fenitrothion, often used in conjunction with the pyrethroid, bioresmethrin, to control organophosphate-resistant *Rhyzopertha dominica* (F.). Ambient air aeration has also been used and sometimes fumigation has been carried out if insects were detected in storage. Together with the normal practices of good warehousing and hygiene, these measures have been successful in reducing

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† Almost all wheat and much of the other grains in trade in Australia are handled through the central system, run by cooperatives or government instrumentalities.

the incidence of insect infestation in storage and found in Australian export grain to a very low level (Murray, 1979).

Several pressures are now forcing the reconsideration of widespread use of chemical protectants. These include risk of development of resistance to the insecticides now available, the continuing need for replacement materials, the risk of resistance to these replacements, cost increases, and market and consumer aversion to chemical residues on grain. In response to these pressures, there has been much recent research and development effort in Australia (Champ and Highley, 1981) into alternative insect control measures. There is also an increasing appreciation that the various measures available should be used when most appropriate and often in combination, rather than relying on a single technique (Evans, 1983).

The use of two related techniques, fumigation and CA storage, are being considered as replacements, at least in part, for contact pesticides. The recently-developed technique for surface application of phosphine formulations (Banks and Annis, in press (a); Snider and Allen, undated) has made fumigation a particularly attractive alternative. The process can be cheaper to use in some storages than contact pesticides (Love *et al.*, 1983), provides virtually residue-free grain and is convenient and rapid to apply. CA systems have now been developed in Australia to the stage where they can be applied commercially (Banks *et al.*, 1980).

Both fumigation and CA techniques use gases as active insecticidal agents. To use these gases effectively, the storages in which they are applied must be well sealed. For a 'fumigable' storage, suitable for use with both phosphine and CA, the loss rate from a storage should be less than 7% day^{-1} (Banks and Annis, in press (b)). In addition to being sealed, metal structures must be painted white externally to reduce solar heating, if the loss is to be reduced to this rate or less.

Unfortunately, few existing grain storages in Australia, either on farm or in the central handling system, are fumigable. This lack is a consequence of the success of protectants in providing insect pest control in low cost, unsealed structures and the belief that ventilation is required in both large and small storages under Australian conditions to prevent significant moisture-related grain deterioration, such as from excessive moisture migration. Unsealed stores can be made fumigable by covering with gas-proof sheets (Anon., 1974; Williams *et al.*, 1980(a)). However, this procedure is expensive and laborious with small and medium sized stores and is impractical for large capacity stores (> 50,000 t).

This paper describes progress in Australia towards the modification of a substantial proportion of the grain storage system to be fumigable. Some of the research work that made this possible is reviewed. Problems that have arisen with the conversion to and operation of sealed stores are discussed. Further data is given on the degree of protection that a sealed store provides against insect invasion.

The work with sealing of storages in Australia in the early part of the 1970's was directed towards providing facilities for methyl bromide recirculation and modifying existing structures for use with CA systems.

The development of the surface application technique for phosphine fumigations in flat storage provided the impetus towards much more widespread use of sealing and a recognition of its potential as an important factor assisting pest control. Although the use of sealing for insect exclusion was and is recognised, this has not been stressed as a reason for storage modification.

The use of sealed storage against insects is not new. A variety of purpose-built structures have been used (e.g. underground and semiunderground structures, (Hyde *et al.*, 1973)). Some existing leaky concrete silo bins have been sealed (e.g. Burns Brown and Heseltine, 1951; Takada *et al.*, 1980). Plastic sheeting and locally available materials (bitumens, waxes, mud and straw) are widely used for sealing storages in China (Lu, in press). However, the programme described here is the first in which a wide variety of storage types have been converted to fumigable structures using modern sealants and in a way that allows those structures to be operated with a modern bulk handling system.

Sealed Storage Capacity in Australia

In 1975, most of Australia's storage capacity in the central system was unsealed. Some silo bins were sealed and equipped with ductwork for treatment with methyl bromide under recirculation and a small proportion (< 10%) of the total storage capacity was in the form of easily sealed welded steel structures, although at that time these had not been converted to sealed systems. After about 1979, almost all new capacity constructed, both as silo bins and flat storage, was designed to be gastight or to be easily sealable. Table 1 gives the capacity of sealed and unsealed storage in 1975, 1980 and at the present time. It can be seen that there has been a substantial move towards sealed systems since 1975. In the last three years there has been a significant contribution to the total from sealing existing stores, rather than sealed construction *de novo*. This trend is continuing. In particular, there is a large current sealing programme for existing 'flat' storage (> 25,000 tonnes capacity each) in Western Australia with a projected increase of 0.6 Mt sealed capacity in 1984. It has been

Table 1. Progress in provision of sealed storages in the Australian central bulk handling system

Date	Total storage (Mt)	Sealed storage (Mt)
Dec. 1975	20	0.4
Dec. 1980	23	1.3
Oct. 1983	24	2.9

Data sources: Australian Wheat Board and Bulk Grain Handling Authorities.

predicted that three-quarters of the storage in the Australian central bulk handling system will be in the form of sealed storage by the year 2000 (Bengston, 1981).

About one quarter of the Australian grain storage capacity is in the form of small structures on farm (Nicholls and Morse, 1974). Very little of this is yet permanently sealed. Generally, fumigation is carried out in these structures sealed by temporary methods (Williams *et al.*, 1980(b)). However, there is an active conversion programme for existing storage in one state (Western Australia) and most (ca. 90%) of the new farm storage capacity sold there during 1983 was sold in the form of gastight bins.

Research into Matters Associated with Sealing

The recent, rapid progress towards a substantial capacity of sealed storage in Australia has only been possible because of the research and development of techniques associated with sealing carried out there over the last decade. In particular, development of an objective means of assessment of the degree of sealing of a structure has been an important advance. This is usually carried out by a pressure test.

Hitherto, the use of pressure tests to measure the degree of sealing of grain storages has been restricted to silo bins equipped for methyl bromide recirculation (e.g. as in Japan (Akiyama, in press)). In Australia, pressure testing techniques have now been developed so that they can be applied to a wide variety of types and sizes of storage (Banks, in press (a)). Storages of up to 260,000 tonnes capacity have been tested successfully (B.E. Ripp, unpublished results).

Development and introduction of pressure testing into routine commercial use has greatly assisted the adoption of sealing as a technique. A pressure test value is used to set a verifiable specification for contracts for sealing work and to assess how successful a particular attempt at sealing a structure has been.

The standard used as an informal guide to the gastightness required for a fumigable structure is given in Table 2. This degree of sealing can be shown theoretically to be the minimum which reduces the losses of gas from a storage caused by wind and the chimney effect to an acceptable level (Banks and Annis, in press (b)). In practice, it restricts the ventilation rate of a structure adequately for fumigation and CA use. The standard given in Table 2 corresponds (Banks, in press(b)) to a similar degree of sealing to that required in Japan (Akiyama, in press) to achieve Grade "A" (highest) certification for fumigation.

Testing of Sealing Processes

In the early 1970s, when creation of a significant capacity of fumigable structures was being considered, there were no techniques available at an acceptable cost for the sealing of the various storage types (silo bins, flat storage and farm bins) that had been adequately tested for routine commercial application. However, there were many newly-developed

Table 2. Target gastightness standard for storages between 300 and 10,000 tonnes capacity (Banks, in press)

Pressure decay range (Pa)†	Minimum decay time (minutes) in full storage*
2500 - 1500 or	
1500 - 750 or	5
500 - 250	

† Range to be used is the highest that is structurally acceptable.

* Decay time for an empty bin, equivalent to that in a full bin, depends on the ratio of headspace to grain when the store is full. It is between about 9 - 12 minutes.

sealant materials available. These appeared potentially useful as substitutes for and improvements on materials used previously (e.g. bitumens and rubber-based paints (Burns Brown and Heseltine, 1951), epoxies (Sergeev *et al.*, 1969)).

As a result largely of development work in Australia by CSIRO and under the aegis of an industry committee (the Coordinating Committee on Silo Sealants) it is now known that a variety of modern sealant materials are suitable. The development work included Australia-wide full scale trials on sealing storages with a variety of potentially suitable sealant materials and techniques. Specifically, it was found (Banks, in press(b)) that some thickened modified acrylic emulsions (e.g. Flexacryl (Taubmans: Sydney), Siloseal (Gardner Bros: Sydney)), synthetic rubber emulsions (e.g. Wastolan (VAT Baustofftecknik: Hamburg)) and PVC-based materials (e.g. Envelon (Dominion Plastics: Shepparton)) were particularly useful as sealants. When combined with polyurethane foam sealants for large gaps and, when reinforced with fibreglass tape if the leak to be sealed was subject to movement, these materials can be applied so as to seal almost any permanant storage structure in use in Australia to a high standard of gastightness (Banks *et al.*, 1979; Banks and Annis, 1980; Williams *et al.*, 1980(a)).

Costs of Sealing

Table 3 gives some typical costs for sealing of some structures to the specification in Table 2. It can be seen that the cost of sealing is only a small fraction of the total cost of large storages. The cost of sealing old concrete cells is relatively high, as it has been usually found necessary to seal the whole of the concrete surface to prevent leakage both through cracks and the porosity of the concrete itself. There is a substantial saving in cost of sealing on a 'per tonne' basis with size.

The data in Table 3 follows ($r^2 = 0.984$) the equation $y = 59\ x^{-0.3}$ (y is cost per tonne in \$A, x is the storage capacity in tonnes).

Table 3. Typical Australian construction costs for three storage types, with additional costs of sealing and modification when the storage is initially built unsealed.

Storage	Construction ($\$A\ t^{-1}$)	Sealing ($\$A\ t^{-1}$)	Modification† ($\$A\ t^{-1}$)
Farm bin (bolted metal, cylindrical 25 t)	125	20	8
Silo bin (Concrete, cylindrical 2700 t)	125	6.70	0.55
Flat storage (metal roof, concrete walls, rectangular, 27000 t)	55	2.80	0.70
Flat storage (metal roof, concrete walls, rectangular, 300,000 t)	-	1.16	1.16

† Replacement of hatches with gastight systems, recirculation ductwork and fans, pressure relief valves, exhaust fans, electrical work as required.

Data Sources: Cooperative Bulk Handling Ltd, State Wheat Board (Queensland) and various sealing contractors.

New construction designed to be sealed costs little more than unsealed systems. For instance, concrete cells of 2000 - 3000 t capacity are now built to exceed the sealing specification given in Table 1 by the State Wheat Board, Queensland (H. Giddins, pers. comm.) without significant premium compared with unsealed ones. A 25 t capacity farm bin of bolted steel plates with cone bottom costs about \$2500 brought sealed and \$2225 unsealed in Western Australia.

Engineering Modifications Required for Sealed Storage

To seal a storage to a high level of gastightness, it is necessary not only to ensure that the fabric of the store itself is well sealed, but also that the hatches and other penetrations through the fabric are sealed or sealable. This is done in practice either by providing a temporary seal, such as with silicone rubber sealant, or modifying the items so that they can be closed easily to give a gastight system. Sealed systems must be fitted with relief valves in order to protect the structure from damage from excessive pressure forces. In some cases, locally made (Banks *et al.*, 1979) or commercial flap valves are used (e.g. Protectoseal: Bensenville, Illinois). Simple liquid-filled valves (Fig. 1) are also in use and are made commercially for small storages (5-50 tonnes capacity, Acrifab: Perth). Large sealed flat storage may require provision of enhanced natural or forced ventilation to remove dust and fumes during grain handling (see below). These necessary modifications may contribute substantially to the overall cost of converting a simple storage to a sealed structure (Table 3).

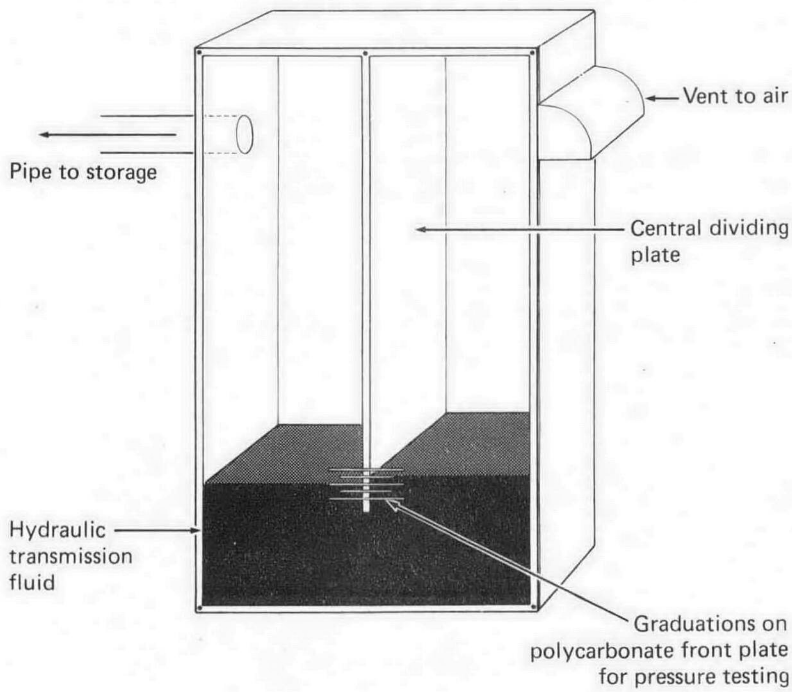

Fig. 1. Pressure relief valve as fitted to some sealed storage in Australia.

Detection of Leaks

It is inevitable that, when attempting to seal a storage, some leaks remain. Sometimes, these are sufficient to prevent the structure reaching the target sealing level. Methods of detecting these leaks are still under investigation and no completely satisfactory method has yet been developed. Soap testing has been found one of the most useful of the methods so far tried. For this, the structure is pressurised to say, 300 Pa, and then sprayed with soap or detergent solution. Leaks are easily seen by the bubbles formed. The method has been successfully applied to large storages (25,000 tonnes capacity).

Problems Associated with Sealed Storage

There are several disadvantages and problems associated with sealed storages for grain. Some are inherent in the process (e.g. difficulty of access), others are potentially capable of resolution by changes in design or technique (e.g. provision of aeration).

1. *Cost.* The cost of converting existing unsealed facilities to a sealed system may be substantial (although small compared with total construction cost). Since this cost is largely associated with pest control only, it must be allowed for in any cost comparison between methods requiring sealed stores and those which can be carried out in unmodified buildings (e.g. as done in Love *et al.*, 1983). The amortised cost of conversion may be the main cost component of some pest control processes.

2. *Industrial safety.* Atmospheres within a sealed storage may be dangerous to humans, either because of the presence of residual fumigants or low oxygen concentrations. In the past there have been deaths associated with entry in sealed stores containing inadequate oxygen (e.g. Ronicke, 1939; Lillevik and Geddes, 1943). It is necessary to inform those who work with sealed storage of the hazards involved and to prevent entry while the storage atmosphere is hazardous.

3. *Removal of airborne dust, fumes and residual gases.* In most flat storage in Australia, at least part of the grain is moved by front-end loaders during outloading. During grain movement, the dust concentration in the air may become excessive in storages that have been sealed, since there is no natural ventilation from the eave vents normally present. Fumes from the grain-moving vehicles may also build up. It has been found necessary to instal sealable natural ventilation or forced ventilation to alleviate this problem.

   Sealable ventilation is also necessary for removal of residual fumigation gases or controlled atmospheres so that the storage atmosphere is safe to enter. The necessity for this ventilation is inconvenient and may add significantly to the cost of operation of large sealed storage.

4. *Inspection.* If a grain bulk in a sealed store is to be inspected, the seal must be broken and the storage atmosphere rendered safe for the inspectors. This is inconvenient and brings a risk of entry of insects into the potentially insect free system. It is yet to be determined how often it is necessary to inspect grain held in a sealed store. It is certainly less than required for an unsealed system. Fumigation and CA treatments can both be carried out very effectively in well-sealed structures and the seal appears to provide some protection against reinvasion (see below). The likelihood that insect infestation may develop in a

properly treated sealed store is low compared with an unsealed structure. In the latter case fumigations may be only partially effective. There may be regions of the grain bulk in which contact pesticide, if applied, has become ineffective through degradation, imperfect application technique or insecticide resistance and the unsealed system provides little barrier to insect invasion.

5. *Moisture migration.* There appears to be a potential problem of moisture migration in sealed storage. If insect infestation is left unchecked, the lack of ventilation, particularly in the headspace, could result in the accumulation of moisture in parts of the grain bulk and consequent grain damage through the well-known processes of insect-induced moisture migration. It appears that under Australian conditions (< 12% m.c. grain, diurnal ambient temperature range often > 20°C) moisture migration generally does not occur to an extent sufficient to cause damage in the absence of insects. However, it does occur when grain is taken from a drier into a sealed storage without adequate cooling (F. Boland, pers. comm.). Significant moisture migration has been noted in only one instance in recent long term storage of grain in sealed flat storage (see Table 4) and in no case has there been moisture-related damage and loss.

6. *Aeration.* It is difficult and inconvenient to reconcile the need for a sealed system for pest control with the use of aeration. Dry wheat stores well in sealed systems in Australia, even though it may be held at > 30°C for many months. However barley for malting, paticularly the cultivar Clipper, does not retain adequate germination levels under these conditions and cooling would extend the storage life of the grain substantially. Closed circuit systems are currently under consideration for the cooling of barley by aeration for quality preservation while retaining the advantages of the sealed system for insect control.

Degree of Insect Protection Afforded by Sealed Systems

Entomologically, one of the most interesting questions concerned with sealed storage is: to what extent does a system sealed to the level given in Table 2 protect a commodity from insects outside the system? It is known that many stored product insect species, notably *R. dominica* and *T. castaneum*, are capable of passing through holes of < 2 mm^2 (Cline and Highland, 1981) and also of locating small imperfections in grain storages distant from obvious sources of infestation (Barrer, 1983). Furthermore it can be shown (Appendix I) that the total leak area corresponding to the standard in Table 2 may be as much as 0.4 mm^2 x the rated capacity (tonnes) for a typical large Australian flat storage. Thus, for a 20,000 t capacity store, the total equivalent leak size is about 8,000 mm^2 and presumably includes many holes large enough to admit most important stored product pests. Yet, under Australian conditions, a grain bulk in a large sealed storage, once disinfested by fumigation or CA treatment, remains sensibly insect-free for a long period. This occurs despite conditions apparently favourable for insect pest multiplication in the grain bulk and ambient temperatures for several months apparently high enough to permit dispersal by flight.

Table 4. Recent treatments of wheat in sealed flat storage in Australia.

Storage Site	Tonnage	Pressure test 150-75 Pa decay or similar (mins)	Treatment (date)	Infestation * before treatment	Outturn condition (period of unloading)
Burracoppin	27,000	8	0.3g PH_3 t^{-1} (2.iii.1982)	R.d., T.c. and others	No infestation (x.1982)
Cunderdin	27,000	7	0.3g PH_3 t^{-1} (2.iii.1982)	R.d., T.c. and others	No infestation (viii-ix.1982)
Harden	16,000	3	1.7g PH_3 t^{-1} (29.ii.1980)	T.c., O.s.	No infestation (xi-xii.1980)
Harden	16,500	3	attempted CO_2 treatment (8.iii.1981) 1.7g PH_3 t^{-1} (5.vi.1981)	R.d., Cr., T.c.	No infestation (30.ix-4.xii.1981)
Harden	15,600	3	0.9g PH_3 t^{-1} (5.iii.1982)	none found	No infestation, slight crusting (26.x.1982-28.i.1983)
Jandowae	4,500	0.4	1.5g PH_3 t^{-1} (5.xii.1980)	none found	One T.c., some psocids (v.1981)
Jandowae	4,900	0.8	1.5g PH_3 t^{-1} (21.xii.1981)	none found	Some T.c. and Cr. present (vi-vii.1982)
Jandowae	4,800	0.9	1.9g PH_3 t^{-1} (19.xi.1982)	none found	No infestation found. Refumigated (iv.1983)
Narromine	18,000	1	1.3g PH_3 t^{-1} (6.iv.1982)	R.d., T.c., O.s., Cr., S.g., moths	No infestation (1.vi.-24.ix.1982)
Southern Cross	27,000	6.5	0.3g PH_3 t^{-1} (2.iii.1982)	R.d., T.c. and others	No infestation (vii.1982)
17 storages in Western Australia	17,700-34,000 each (total 405,000 t)	> 8	0.3g PH_3 t^{-1} (i-iii.1983)	One third of storages noticably infested (T.c., R.d., S.o., O.s.)	No infestation (†)

* Cr. = *Cryptolestes* spp., O.s. = *Oryzaephilus surinamensis*, R.d. = *Rhyzopertha dominica*, S.g. = *Sitophilus granarius*, S.o. = *Sitophilus oryzae*, T.c. = *Tribolium castaneum*.

† All storages outloaded > 5 months after treatment. Seven of the storages held grain for > 7 months after treatment.

Table 4 lists the treatments carried out in large sealed flat storage in Australia over the last four harvest seasons where the grain was stored for more than five months subsequent to treatment. In all cases, phosphine fumigation was used as the initial disinfesting treatment. In only two cases were insects detected during inspection on outloading. Both of these cases were for a shed that had not been sealed to the specified level (Table 2).

The period of storage possible after CA treatment has been discussed by Banks *et al.*, (1980). Annis *et al.*, (in press) found that a plastic tent enclosure sealed to a standard equivalent to that in Table 1 protected stored rice for a least six months under humid tropical conditions after CO_2 treatment. Under humid tropical conditions the insect invasion pressure can be expected to be high, so this observation provides a severe test of the protection afforded by a sealed system.

From these uncontrolled field observations, we conclude that a substantial period of protection can be expected in large sealed storages sealed to the level given in Table 2. It appears that at least six months safe storage is assured under Australian conditions. Grain placed in storage at harvest in Australia, without insecticidal treatment, generally becomes infested after two or three months to a level where insects can be easily found. It can thus be assumed that, even in those instances in Table 4 where insects were not detected, they were nevertheless present initially, although in small numbers only. It can thus be inferred from data given in Table 4 that the treatments carried out in those sealed stores were effective to the level where no significant insect populations remained. If this were not so, a resurgence of infestation would have been noted during the long storage period subsequent to treatment.

Conclusion

This paper has described some of the Australian developments and experience with sealed storage of dry grain. Although a few technical problems still remain, generally the process has been found to be industrially acceptable, being cost-competitive with existing measures in many cases and permitting highly effective pest control and residue-free storage. It remains to be seen whether this process can be applied effectively in other countries. We believe that, in some form, sealed storage will be found appropriate in many situations where dry grain is held for a few weeks or more and that the advantages gained by the capability created for cheap and highly efficient pest control will outweigh the inconvenience and cost of sealing of many kinds of stores.

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APPENDIX I. Estimation of Total Hole Size in a Storage Sealed to a Certain Level from Pressure Test Data

With isothermal expansion, the decay of pressure, p, in a pressure test, from an initial pressure, p_o, with time, t, follows the equation (Sharp, 1982):

$$p_o^{1-n} - p^{1-n} = (1-n)bkt \qquad (1)$$

where $k = \frac{\rho R T}{V M}$

(ρ is the density of the gas entering the storage, R, the universal gas constant, T, the absolute temperature, V, the contained gas volume, and M, the molecular weight of the gas entering (usually air)). The empirical parameters b and n are derived from the equation

$$Q = b\Delta p^n \qquad (2)$$

describing the variation of flow, Q, through a leak or combination of leaks with pressure difference, Δp, across the system. If the leaks act as orifices, as assumed here, n = 0.5 and

$$b = \gamma A \sqrt{\frac{2}{\rho}} \qquad (3)$$

(γ is the orifice coefficient for the leak and A is the orifice cross-sectional area (derived from Kreith and Eisenstadt (1957))). By substitution in equation (1) for b and assuming n = 0.5, an expression can be obtained for the leak area, A, corresponding to a particular pressure test specification.

Thus:

$$A = \frac{(p_o^{0.5} - p^{0.5})VM}{RTt\gamma} \sqrt{\frac{2}{\rho}} \qquad (4)$$

With T = 25°C; γ = 0.6, a typical value for an orifice, $\rho = 1.1 \text{ g m}^{-3}$, appropriate for air, with a decay time of 5 minutes for 150 to 75 Pa, a typical pressure test for large sealed flat storage corresponds to:

$A = 0.31\ V \text{ mm}^2$ with V in m^3

With the design of flat storage frequently used in Australia (30° pitch roof, such as described in Banks *et al.* (1979)), the rated capacity, C, in tonnes, is related to the contained gas volume within the storage, V, when the store is filled with wheat, by

$$V = 1.3\ C$$

Thus $$A \approx 0.4\ C\ \text{mm}^2$$

In practice $0.7 < n < 1.0$ for well sealed storages (H.J. Banks and P.C. Annis, unpublished data) and thus the calculation based on $n = 0.5$ gives a high estimate of the true overall leak size. Nevertheless it does give some guide to the magnitude of the holes contributing to leakage and thus is of value when considering the size of imperfections which could be present in a partially sealed system.