The future of hermetic storage of dry grains in tropical and subtropical climates

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Abstract

Oxygen (O_2) depletion and carbon dioxide (CO_2) enrichment of the intergranular atmosphere form the basis for suppressing and controlling insect infestations during hermetic storage of dry grain. Traditional methods and recent improvements are reviewed, and modern structures designed for hermetic storage at the commercial and farmer levels are described. Improvements needed to render the hermetic concept more widely acceptable are enumerated, and the development of hermetic storage within flexible plastic liners is evaluated on the basis of more than a decade of experience in hot climates. A preliminary model is employed to simulate the interdependent changes in gas concentrations, insect populations and amounts of grain consumed. A theoretical ingress rate of 0.05% O_2/day was found sufficient to arrest development of residual insect infestations. Potential niches for hermetic storage applications in developing and technologically advanced countries are identified. In tropical climates aeration for cooling of grain is not feasible, reinfestation is frequent and the available contact insecticides degrade rapidly because of high temperatures. The advantages of long-term hermetic storage in technologically advanced countries, and as a medium-term, user-friendly technology in developing countries, are stressed. In sharp contrast to the use of chemicals, hermetic storage is environmentally sound and poses no risk to storage operators, consumers or non-target organisms.

Historical

Underground pits

The considerable literature on sealed storage of grain termed 'air-tight storage' or 'hermetic storage' is well summarised by Hyde et al. (1973) and De Lima (1990). From this a clear picture emerges of underground storage in pits, from prehistoric times until the present day as a traditional method that is frequently sufficiently airtight to enable insects and other aerobic organisms in the grain mass to reduce oxygen (O_2) concentrations below those permitting insect development. These pits were excavated into the soil or rock, and are sometimes lined with supporting walls of brick or cement. However, the ideal situation of O_2 depletion and carbon dioxide (CO_2) accumulation as demonstrated in laboratory experiments of Oxley and Wickenden (1963) is rarely achieved. This is generally because of gas-exchange through the pit walls and roof, and the sorption of CO_2 by the grain itself and sometimes by the pit walls (Hyde and Daubney 1960).

Semi-underground structures

Large-scale construction for prolonged storage of grain surpluses in Argentina during the second world war consisted of below- and above-ground concrete lined trenches covered with flexible roofs (Anon. 1949). Later attempts at achieving hermetic storage were the Cyprus bins constructed in the 1950s (Hyde et al. 1973). These consisted of concrete lined conical pits surmounted by domed concrete-shell roofs. They were successfully used under hermetic conditions for a number of years. Improved versions of these structures were later constructed in Kenya for hermetic storage of the national grain reserve (De Lima 1990).

Above-ground small-scale structures

Another traditional method used by subsistence and small-scale farmers has been the storing of grain in sealed gourds, though these provide an incomplete hermetic seal unless treated with a sealing material (McFarlane 1970). A related method adopted in a number of tropical countries has been the adaptation of empty oil-drums and other metal drums for storage (Pattinson 1970; Sakho 1971). To prevent development of heavy infestations before control is achieved, these metal drums should be completely filled. This is because when only partially filled, the headspace volume may remain large (in relation to the grain mass) and developing populations may cause perceptible damage before O_2 concentrations are sufficiently reduced to arrest development.

Factors Affecting Insect Mortality in Hermetic Storage

The important role of low O_2 concentration rather than high CO_2 in causing mortality of stored-product insects in hermetic storage was demonstrated by Bailey (1965). Only later was the importance of the synergistic effect of concomitant O_2 depletion and CO_2 accumulation for insect control clearly demonstrated (Calderon and Navarro 1979; 1980). These synergistic and combined effects are essential for successful insect control, as shown by studies of the effects of incomplete airtightness upon insect populations (Oxley and Wickenden 1963; Burrell 1968). Furthermore, the lower the grain moisture content (m.c.) and corresponding intergranular humidity, the higher the mortality, due to the desiccation effect on insects caused by low O_2 (Navarro 1978), or elevated CO_2 concentrations (Navarro and Calderon 1973). The influence of temperature on insect respiration implies that, in warm climates, O_2 intake by insects is very intensive. Conversely, in temperate climates, insect metabolism is much slower, depletion of O_2 may be lower than its ingress, and insect control may not be achieved. This led Burrell (1980) to postulate that, for light infestations of cool grain, residual populations would provide an inoculum for reinfestation after the grain is removed from hermetic storage.

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Modern-day Hermetic Storage

Above-ground rigid structures

Documented data on successful application of hermetic storage to above-ground constructions are largely lacking. Many existing silos and warehouses have been modified to provide a high degree of hermetic seal especially in Australia (Delmenico 1993). However, the objectives have been to convert these storages for modified atmosphere (MA) treatments or improved fumigations, and not for hermetic storage as such.

In contrast, the sealing of both bagged stacks and bulk grain in warehouses in China using plastic liners is part of a grain preservation regime termed 'Triple-Low'. This is an integrated approach to insect control consisting of obtaining reduced O_2 concentrations by metabolic activity within the grain bulk, in combination with phosphine and low temperature treatments (Wang et al. 1993; Xu and Wang 1993). This procedure is claimed to provide effective protection.

Above-ground flexible structures

In the early 1970s, above-ground structures were designed in England for emergency storage using flexible plastic liners supported by a weldmesh frame. These liners were made of butyl rubber, sometimes laminated with white EPDM, and consisted either of a wall-floor section, plus a roof section attached after loading, or both sections welded into a single unit. These silos were recommended for both conventional storage and hermetic storage of dry grain (Kenneford and O'Dowd 1981). However, under tropical and subtropical climates the liners were found to deteriorate, and gas permeability increased to a level where the liners could no longer be used for hermetic storage (Navarro and Donahaye 1976; O'Dowd and Kenneford 1982).

In Israel, the manufacture of PVC liners that conform to prerequisite specifications of durability to climate, gas-permeabilities, and physical properties, enabled the development of three storage systems based on the hermetic principle. These are:

- Bunker storage for conservation of large bulks of 10000–15000 t capacity (Navarro et al. 1984; Navarro et al. 1993).
- Flexible silos supported by a weldmesh frame of 50–1000 t capacity for storage of grain in bulk or in bags (Calderon et al. 1989; Navarro et al. 1990).
- Liners for enclosing stacks of 10–50t capacity termed storage cubes, and designed for storage at the farmer-cooperative and small trader level (Donahaye et al. 1991).

The problem of applying present-day technology to provide hermetic storage for subsistence farmers lies in the need to provide an easily sealable low-cost container of 50–100 kg capacity. The high surface area to volume ratio necessitates a liner with a very low permeability to gases. The most recent attempt to address this problem has been through the 'Joseph bag', which is made of a plastic-metal foil laminate, sealable by means of a hot-iron (Murray 1990).

Underground flexible structures

The main approach to achieving lower levels of O_2 and higher accumulations of CO_2 has been by lining pits with plastic liners in order to improve the hermetic seal (Donahaye et al. 1967; Dunkel et al. 1987). With a similar approach, small-scale underground storages have been developed for farmer storage of maize and dry beans in Brazil (Sartori and Costa 1975; Sartori 1987).

Experience Gained Using Flexible Liners

Our accumulated experience of hermetic storage using several types of flexible liners for above-ground storage, in-the-open, under tropical and subtropical conditions (Calderon et al. 1989; Donahaye et al. 1991; Navarro et al. 1968; Navarro and Donahaye 1993; Navarro et al. 1984, 1990, 1993), is summarised in the following sections.

Structural durability

The use of PVC-based sheeting without mesh reinforcement produces a material of suitable strength and elasticity for storing grain. This material was formulated to have a high resistance to solar UV irradiation. Rodent penetration has been recorded on only exceptional occasions involving minor damage. Our hypothesis that rodents find it difficult to gain a tooth-hold on the smooth surface has been corroborated by laboratory studies using wild-caught roof rats and house mice (Navarro, Moran, Dias and Donahaye, unpublished data).

Liners have been used continuously for over 10 years, and though they have lost some plasticity, permeability to gases decreases as the plasticisers evaporate. This characteristic renders the liners more effective with time in retaining gas concentrations, e.g., for 0.83 mm PVC, the initial permeability (expressed throughout as a measure given at a gradient from 21% O_2) decreased from 87 to 50 mL O_2/m^2/day after 4 years of exposure under Mediterranean climate (unpublished data).

Insect control

At a liner thickness of 0.83 mm and a gas permeability level of 87 mL O_2/m^2/day, there is a possibility of insect survival close to the grain-liner interface. This is especially so at the top layer of the structures where moisture content tends to be higher than the remaining parts of the bulk. However, after the minimum O_2 concentration is reached, survival is usually well below 1 insect/kg, and would require multiple sampling to detect a single insect (Navarro et al. 1984, 1993). This residual infestation is more of a problem on return to aerobic conditions and the commodity should be consumed without additional prolonged storage. This residual infestation is less serious than the danger of reinfestation by insects from the surroundings under storage by conventional methods. For grain destined for export and where freedom from insects is mandatory, a final treatment using phosphine may be undertaken if necessary. In future, this treatment may be superfluous if higher degrees of gas retention achieve complete elimination of residual infestation.

Moisture migration

Diurnal temperature fluctuations, accentuated by solar radiation on liners, followed by rapid cooling at night, cause successive moistening and drying cycles at the upper grain surface. This may result in gradual moisture accumulation, particularly during the transient seasons between summer and winter when temperature fluctuations are greatest, so that initially dry grain may rise to above critical levels enabling limited microfloral spoilage to occur. This is particularly accentuated along the peaks of bunkers where warm air rising on convection currents tends to concentrate the moisture condensation in confined areas. For bunkers of 12000–15000 t capacity constructed in recent years, the condensation phenomenon has been alleviated and almost eliminated by levelling the peaked apex (with a ridge of less than 2 m) to a slightly convex, wide apex of bunker cross-section (with a ridge of more than 6 m) that is just sufficient to permit rain-water run-off. This configuration appears to enable the dispersal of moisture migration over a much larger area. Differences in the intensity of moisture increase between bunker peaks with narrow ridges and peaked apices, and apices with a broad ridge are demonstrated in Figure 1. Although comparative results for concurrent storages are not available, results shown in this Figure 1 form a summary of observations made over 4 intermittent years at the same storage site in Israel.

For dry grain kept in 'storage cubes' in subtropical climates, moisture migration is not a pronounced phenomenon. However, for maize or paddy stored in the tropics, moisture migration is accentuated because the initial grain moisture is closer to its critical level. For this purpose, the solution to moisture migration has been under examination by placing an insulating layer between the liner and the upper layer of bagged grain. Preferably this consists of a layer of bagged agricultural wastes such as rice hulls, or straw, or if these are not available a 'felt-fibre' layer with insulating properties appears promising.

Development of a Predictive Model

In view of the complexity of the grain bulk ecosystem prevailing under hermetic conditions, we propose to use a simulation model to rapidly analyse numerous situations, and describe the critical limits of the different factors. The model is in a preliminary phase of development to simulate the interdependent changes in gas concentrations, dynamics of insects population and amounts of grain consumed. The model has been set to run numerical experiments to investigate the influence of degree of gastightness of the structure expressed as the rate of O_2 ingress through the storage membrane, size of the grain mass, volume of the treated structure, initial number of insects/kg of grain, respiration rate of the mixed insect population, and birth and death rates of the species on changes in O_2 concentrations in the storage, changes in insect population, and amounts of grain consumed.

The preliminary version of the model is the first approximation of the system built to study the influence of the physical characteristics of the storage structure as well as initial infestation. The main state variables that define the dynamics of the system are O_2 concentration, and number of insects and loss in grain weight. The model was written using the modelling package STELLA (Pytte and Doyle 1984) available for Macintosh® personal computers. Values of structural membrane permeabilities were based on laboratory measurements. Birth and death rates were estimated from field observations obtained from storages under aerobic and hermetic conditions. At present the main assumptions of this preliminary version of the model used in the exercise are as follows:

- Oxygen is distributed uniformly throughout the grain mass and no gas stratification occurs.
- CO_2 effect on insects and CO_2 sorption by grain are ignored.
- Temperature of the grain mass is uniform, and therefore moisture migration due to temperature gradients is ignored.
- Influence of wind on the structure is negligible.
- Influences of changes in temperature and barometric pressure are ignored.
- Insect distribution is homogenous in the grain mass.
- The storage structure is cube shaped.
- No head-space volume exists, the volume of the structure is occupied by the grain mass with an interstitial air space of 45% and a bulk density of 750 kg/m^3.

Calculated changes in oxygen concentration in hermetic storages

Influence of different initial insect populations

For this exercise a fixed O_2 ingress rate equivalent to about 0.24%/day was chosen for a structure with a volume of 10 m^3. For these values, changes in oxygen concentrations in

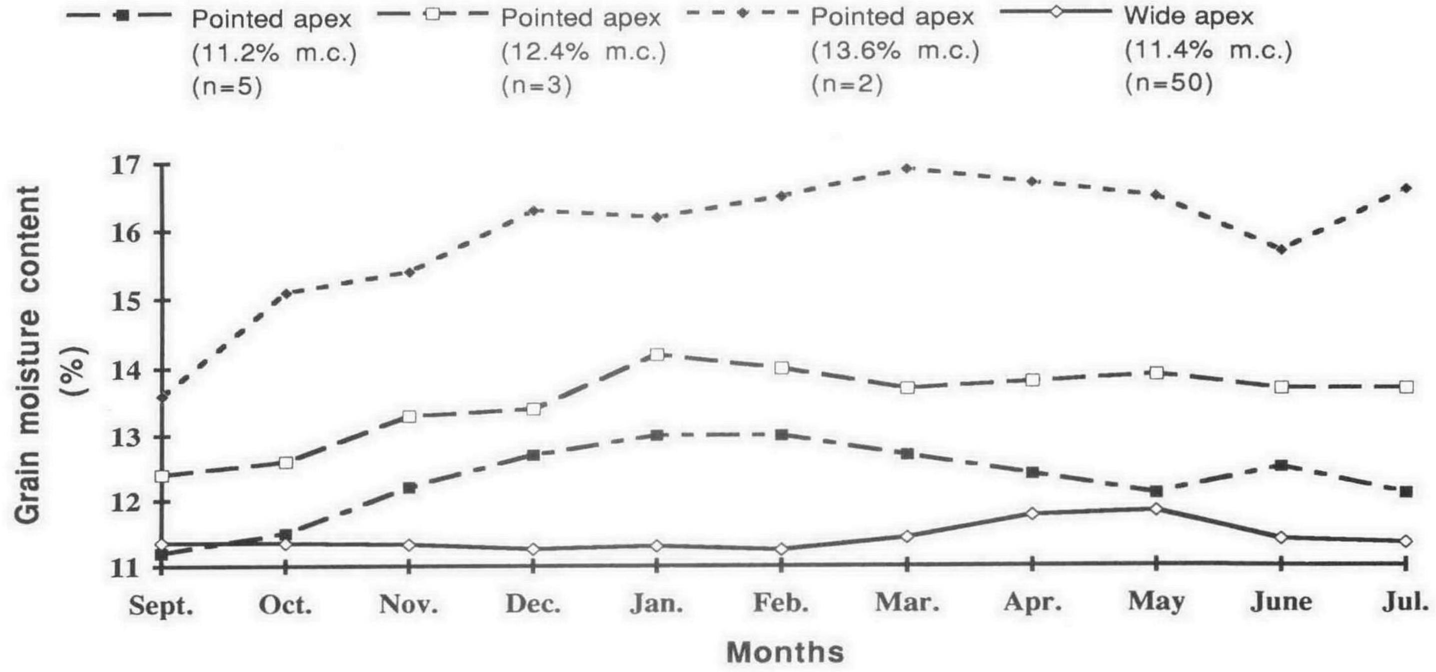

Fig. 1. Seasonal changes in moisture content of wheat as recorded at the top layers (0 –20 cm) of bunkers with pointed apices and narrow ridges (observations made over one season), and bunkers with wide apices and broad ridges (observations made over three seasons) (initial moisture contents [m.c.] given in brackets, n = number of samples taken from a specific location).

response to different initial insect populations are illustrated in Figure 2. Accordingly, a cyclic change in concentrations is obtained as a result of O_2 ingress and the ability of insects to survive at low O_2 levels. These theoretical cyclic changes in O_2 concentrations were also observed in different laboratory and field studies (Oxley and Wickenden 1963; Hyde et al. 1973; Navarro et al. 1990).

Under the conditions governing the numerical experiment, the model calculates that there is a residual insect population even after an extended storage period of one year. This is shown by the continuing fluctuations in O_2 levels before a steady-state is reached (Fig. 2). This result is corroborated by field observations that a residual population may remain when the grain is re-exposed to normal atmospheric air, though under the hermetic conditions and restricted O_2 supply their reproductive capacity is limited (Burrell 1980; Navarro et al. 1993). There are only limited data in the literature regarding respiration of mixed population of insects (Birch 1947; Calderwood 1961; Carlson 1966 1968; Chaudhry and Kapoor 1967; Keister and Buck 1974; Park 1936). Furthermore, the respiration of these species under low O_2 tension is not well documented (Donahaye 1992; Navarro 1974). To determine the changes in O_2 levels under different hermetic conditions, more information is needed on the contribution of different species to O_2 consumption at low O_2 tensions.

Influence of membrane permeability levels

To clarify the importance of membrane permeability in a specific situation, the model was run with an initial infestation of 2 insects/kg at different levels of O_2 ingress rates for a 10 m^3 cube containing grain as above. Results obtained with O_2 ingress rates of 0.05, 0.12, and 0.24% O_2/day, at an initial infestation level of 2 insects/kg, are shown in Figure 3. The calculated line for the 0.05%O_2/day ingress rate differs significantly from the lines with higher ingress rates. At the 0.05%O_2/day ingress rate, after a minimum O_2 level is reached the increase in O_2 concentration follows the O_2 ingress rate of a structure without insects. This exemplifies the importance in reducing the O_2 ingress rate levels below which the residual insect population can be eliminated from the grain. These levels of gastightness are easily obtained in the laboratory, but difficult to achieve at commercial levels, especially with existing large rigid structures.

Calculated grain losses in hermetic storages

Influence of different initial insect populations

Aerobic metabolism of insects associated with respiration involves the utilisation of carbohydrates which constitute the largest component of cereal grains. In the model, the dry-matter loss was calculated on the basis of O_2 required for oxidation of carbohydrates utilised in the process of insect metabolism. The model was run with the same parameters as used in Figure 2, and its results are shown in Figure 4. Calculated weight losses obtained with a gas ingress rate of 0.24% O_2/day at the three infestation levels indicate that losses over a 1-year period range between 0.050 and 0.058% of initial weight. Observed weight loss (count and weight method) due to insect activity in a 15500 t capacity bulk storage held under sealed conditions over a 15-month period was 0.15% (Navarro et al. 1984). The differences between field results and the model estimate may partly derive from difficulties in obtaining accurate evaluation of the field trial. The experimental field values and the calculated values from the model indicate that although insect activity causes weight losses, these losses are within the lower range of commercially acceptable biological losses. Furthermore, these levels in some cases may fall within the accuracy range of commercial scales.

Influence of membrane permeability levels

The model was run with an initial fixed infestation of 2 insects/kg at O_2 ingress rates of 0.05, 0.12, and 0.24% O_2/day for a 10 m^3 cube containing grain. Results in Figure 5 show that an O_2 ingress rate of 0.05%/day is sufficient to arrest the theoretical weight loss at a level of 0.018% over a 1-year storage period, whereas for higher O_2 ingress rates, the weight loss continues to rise in proportion to the O_2 ingress rate. At an ingress rate of 0.05% O_2/day insect development is arrested and therefore the possibility of a residual surviving insect population is eliminated. This low O_2 ingress level, is difficult to obtain in rigid structures, but is achievable in practice using flexible liners. It could serve as a guideline for the sealing specifications of structures appropriate to the hermetic storage method. With a permeability level of 81 mL O_2/m^2/day using a flexible liner 0.83 mm thick, a structure with a capacity of more than 10 m^3 would meet this requirement. As far as rigid structures are concerned the main drawbacks in obtaining this level of gastightness lie in their constructional limitations. When a silo is not used at its full capacity, there remains a headspace volume which renders the structure more sensitive to the influence of ambient temperature and barometric fluctuations. Even when the structure is extremely gastight, if a breather-bag is not used, gas exchange through the pressure relief valve to compensate for pressure changes due to temperature and barometric fluctuations cannot be avoided.

The size factor in hermetic storages

Experience shows that hermetic storage works best for large structures. This is obvious from the low surface area/volume ratio in large bulks compared with small bulks. Although the factor of O_2 ingress rate can be reduced by suitable modern technologies, in practice it is a goal difficult to achieve. Therefore, depending on the commercially available membrane permeabilities, engineers should aim at designing hermetic structures of sufficiently large dimensions. This is in sharp contrast to the objective of using hermetic storage at farm level in developing countries where low-permeability liners must be preferred.

To emphasise the importance of the size of the structure in hermetic storage, the model was run assuming a permeability level of 200 mL O_2/m^2/day for structures of different dimensions ranging from 1 to 1000 m^3 (Fig. 6). The model demonstrates that a tenfold increase in the volume of the bulk causes approximately a twofold decrease in the initial O_2 ingress rate.

The model is still being developed and we intend to publish a full description elsewhere.

The Need for Future Research and Development

Although the principle of hermetic storage is simple, there are still a number of aspects that require clarification or improvement in order to render it more acceptable as a storage alternative. Of these, we believe the following to be the most important.

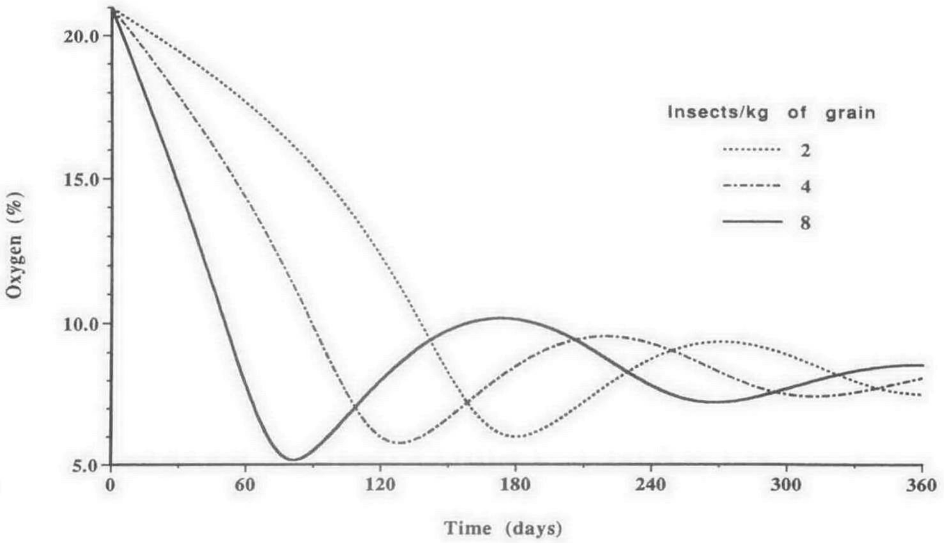

Fig. 2. Calculated oxygen concentrations in a 10 m^3 grain mass containing different infestation levels of insects having an oxygen intake of 157 μL/insect/day using a sealed liner with an oxygen ingress rate of 0.24%/day.

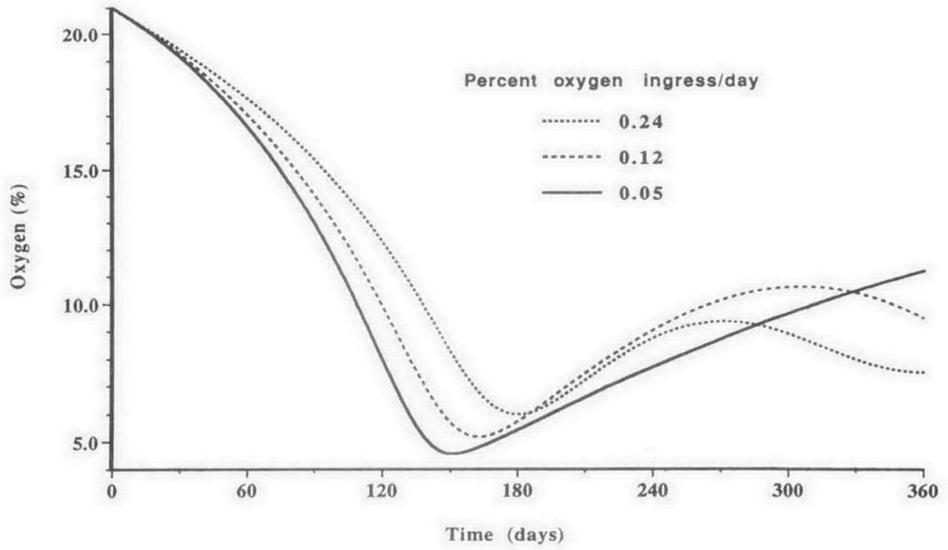

Fig. 3. Calculated oxygen concentrations in a 10 m^3 grain mass containing a fixed level of initial infestation of 2 insects/kg, having an oxygen intake of 157 μL/insect/day using a sealed liner at different oxygen ingress rates.

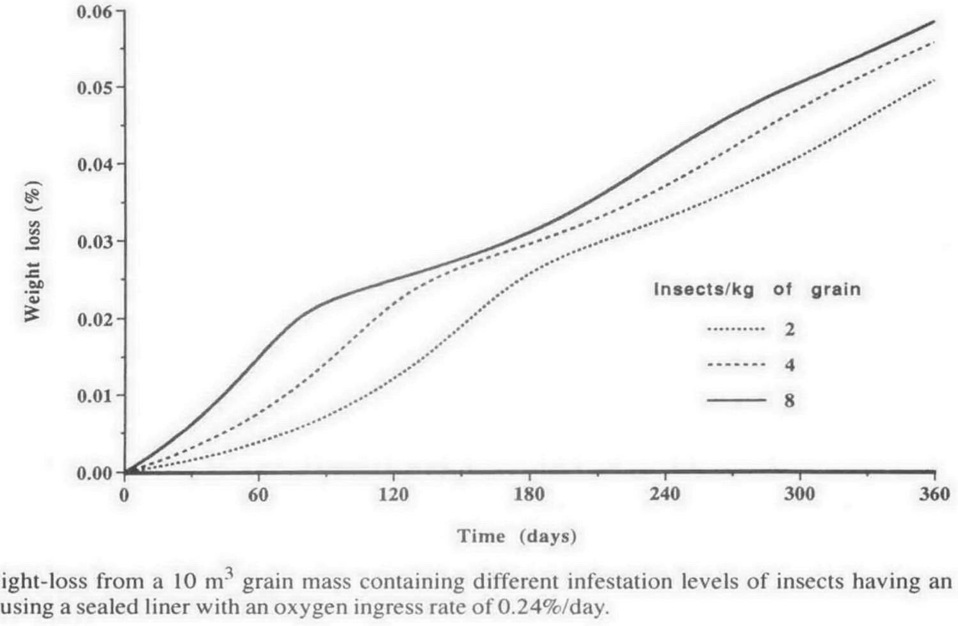

Fig. 4. Calculated weight-loss from a 10 m^3 grain mass containing different infestation levels of insects having an oxygen intake of 157 μL/insect/day using a sealed liner with an oxygen ingress rate of 0.24%/day.

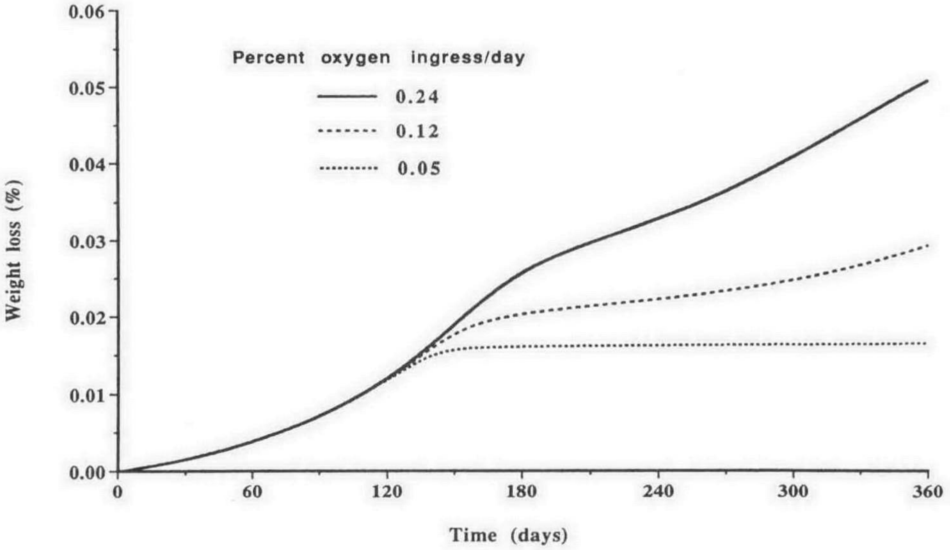

Fig. 5. Calculated weight-loss from a 10 m^3 grain mass containing a fixed level of initial infestation of 2 insects/kg, having an oxygen intake of 157 µL/insect/day using a sealed liner at different oxygen ingress rates.

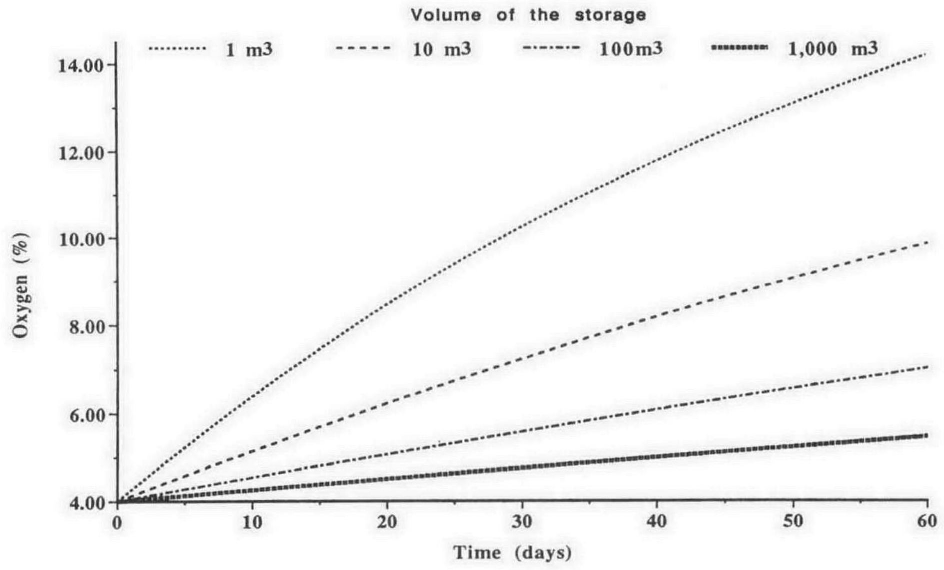

Fig. 6. Calculated rates of oxygen ingress into grain bulks (without infestation) of different volumes confined within a sealed liner with an oxygen permeability of 200 mL/m^2/day.

Influence on grain quality

The review of Banks (1981) reveals that most studies on grain quality have been carried out using modified atmospheres (MA). He concludes that for low moisture content grains, low O_2 and high CO_2 concentrations do not have a detrimental effect on germination, milling and baking properties of wheat, or organoleptic properties of rice, though for intermediate and high moisture grains, quality is affected. Our studies on long-term hermetic storage of wheat (Navarro et al. 1984, 1993) also clearly indicate that both germination and baking properties of wheat are well preserved, and milling properties of dry paddy are not affected (Donahaye et al. 1991). For maize seed, Moreno et al. (1988) found that at 14–14.5% m.c., hermetic storage did not have a detrimental effect on germination. Nevertheless, confusion has arisen in the past because of moisture migration in hermetic storage structures and the consequential deterioration of moistened grains. This has had a negative effect on consumer acceptance that needs to be redressed both by experimentation on moisture migration and grain quality parameters in hermetic storage, and by explanation of the findings at all professional levels.

Degree of sealing

Sealing methodologies have been well developed and published (Alexander 1984; Lloyd 1984; Sutherland and Thomas 1984; Woodcock 1984; Newman 1990). However, in practice, sealing of rigid structures has been limited mainly to Australia, and elsewhere many new silos are being built to low standards of sealing that do not permit application of hermetic storage or MA treatments. The future approach to silo construction should take a more professional attitude to silo sealing. It should be noted that a high level of sealing is essential in the modern approach to fumigation for reduction in emissions (especially when using methyl bromide because of its association with ozone depletion), and also to eliminate the possibility of development of phosphine-resistant insect populations.

Headspace

A major problem in rigid structures is the volume of headspace above the grain bulk. This is not only a limiting factor in determining the rate at which O_2 concentration decreases, but also accentuates pressure differences between the interior and exterior of the silo as a result of daily temperature and barometric fluctuations of the ambient. Pressure-relief valves provide a satisfactory solution for MA storage. However, the use of breather-bags to unify internal and external pressures appears to be more desirable for hermetic storage since it reduces the gas exchange. To the best of our knowledge breather-bags have not been employed in silo bins, except for 'Harvestores' used for silage. Experimental data on the use of such breather-bags under tropical and subtropical climates would be very useful when considering the application of hermetic storage to reduce the intensity of air ingress into the storage system.

Moisture condensation

A phenomenon that discourages the use of hermetic storage in hot climates is moisture migration and condensation, and this is especially accentuated in metal silos. In conventional storages, engineers rely on designing well-ventilated headspaces to reduce the intensity of this phenomenon, and even incorporate aeration systems with exaggeratedly high airflow rates regardless of their efficacy in the tropics. In subtropical climates with a cool season, aeration systems were shown to effectively overcome this problem by equalising grain temperatures (Navarro and Calderon 1982). For this reason, when applying MA storage in metal structures the integration of aeration was proposed by Navarro and Calderon (1980). However, the efficacy of this approach was never adequately documented.

For metal silos in hot climates, moisture condensation is intensified when insect infestation causes grain heating. The most disturbing effect of moisture migration, especially in rigid constructions, is the difficulty in removing the damaged layer, usually at the top of the bulk.

So far, two approaches are known to reduce the intensity of this phenomenon: equalising grain temperatures, and insulation of the roof. Equalising grain temperatures by aeration is limited to climates with a cool season. Comparative data on the efficacy of aeration and the effect of insulation in preventing moisture migration in metal silos in the tropics are lacking.

For small-scale applications using flexible liners, the influence of insulation materials in reducing the intensity of moisture migration in subtropical (Israel) and tropical (Philippines) climates has been investigated by Donahaye and Navarro (unpublished data). A model describing moisture migration by natural convection has been proposed (Nguyen 1986). However, more experimental data are required to support the development of predictive models for hermetic storage.

Flexible liners

One approach to hermetic storage has been through the use of flexible liners. All liners have the advantage that they follow the contours of the grain-bulk surface and, with no headspace, gas exchange is restricted to the intergranular air volume. However, liner materials need improvement. Although liners with zero permeability to gases are available, other factors such as physical characteristics, durability, resistance to penetration by pests (rodents and insects), amenability to jointing and welding, and cost of manufacture are all critical to the choice of liner. Integration of all these characteristics into a single liner is still an objective of the future.

Monitoring

Standard inspection procedures based on temperature and grain sampling may be employed. However, since the objective is to retain the hermetic seal, attention should be paid not to leave the inspection port open for more than the minimum time required. It is most desirable to support sampling evaluation of storage condition by measurement of O_2 and CO_2 concentrations. For large-scale operations modern and reliable electronic monitoring equipment is available. However, these instruments are expensive and clearly are not suitable to the small-scale farmer in developing countries. Yet the use of Orsat-like manometric gas analysis apparatus relies too heavily upon equipment maintenance. Affordable and reliable instrumentation for hermetic storage monitoring has still to be developed.

Hermetic Storage as a Future Alternative?

The need for alternative methods of prevention and control of insect infestations in stored products has become acute over the last few years. This is because conventional measures using insecticides are being questioned by environmental agencies and pressure-groups, and the choice of available permissible materials is decreasing. Of the two remaining fumigants in general use, a decision has been made by the U.S. Environmental Protection Agency to phase-out methyl bromide by the year 2001 due to its destructive effect on ozone in the stratosphere (USEPA 1993). This is coupled with mounting evidence of development of insect resistance to phosphine (Zettler 1993) indicating that even phosphine may not be economically effective in years to come. Modern, safer and acceptable technologies such as aeration, refrigerated aeration and modified atmospheres are still expensive and require adequate infrastructure. In sharp contrast to the use of chemicals, hermetic storage is an environmentally friendly technology, involving no hazard to the storage operators, consumers or non-target organisms, and as such, its application should enjoy a high level of consumer acceptance.

In developing countries

Hermetic storage may provide an answer to the need for a less costly method of storage for food security of the rural populations. This could be achieved by supplying a storage solution at the farmer level, and thereby affording the farmer protection from seasonal fluctuations in grain prices. The basic advantage of hermetic storage in developing countries is its simplicity, obviating the need for insecticidal admixture procedures or fumigations, both of which require high levels of expertise not usually possessed by the small-scale farmer. Furthermore, it is generally the only MA option since MA-generators or gas cylinders are neither affordable nor obtainable.

In technologically advanced countries

In spite of the trend towards improved sealing of existing silos in some countries (Newman 1990; Delmenico 1993), the objective has been either to obtain increased fumigation efficiency, or to convert structures for storage under modified atmospheres. The relatively slow rates of O_2 depletion in the hermetic storage process, especially when the initial population is low, renders it inappropriate to apply this method to short-term storage systems. Neither is it practical for application in rigid horizontal storage structures where the headspace is always relatively large. Clearly, it is best suited to long-term storage projects such as national grain reserves, buffer stocks and storage of grain surpluses.

The conversion of rigid structures to sealed storages should be considered for long-term large-scale storage projects. The evidence that the method is effective at the high temperatures prevailing in tropical climates is best documented by De Lima (1990). In tropical climates aeration for cooling of grain is not feasible, reinfestation is frequent and the available contact insecticides degrade rapidly because of high temperatures. Under these conditions hermetic storage may provide an advantageous solution.

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