Navarro S, Navarro H (2016) Emerging global technological challenges in the reduction of post-harvest grain losses. Pp. 259–265. In: Navarro S, Jayas DS, Alagusundaram K, (Eds.) Proceedings of the 10th International Conference on Controlled Atmosphere and Fumigation in Stored Products (CAF2016), CAF Permanent Committee Secretariat, Winnipeg, Canada.

Emerging global technological challenges in the reduction of post-harvest grain losses

SHLOMO NAVARRO*, HAGIT NAVARRO

Green Storage Ltd., Argaman St. 5, Rishon Letsion, 7570905, Israel

ABSTRACT

The grain industry is facing serious problems of storage shortage due to the unprecedented quantities to be stored in various climates. The modern grain industry in economically developed hot climate countries has been looking for storage solutions in large bulks. However, lack of experience particularly in hot climates and lack of adequate storage facilities may result in adverse results. In addition, even under ideal storage conditions, the grain industry is facing storage problems related to insect and mite contamination due to the restrictions placed on the use of chemical pesticides. Strict limitations have been placed on pesticide registration by regulatory agencies because of the adverse effects of pesticide residues in grain and the environment. Consumer demand for chemical-free and insect contamination-free products is a general trend with which the grain industry finds it difficult to conform. In addition, in many countries, insects in particular have been developing resistance to contact insecticides and to the conventionally used phosphine gas. This paper reviews the emerging global technological challenges in the reduction of post-harvest grain losses. Phosphine fumigation is a common treatment where three important points deserve attention: (*a*) sufficient gas tightness, the lack of which leads to insect resistance; (*b*) sufficient exposure time for complete control; and (*c*) prevention of gas from diffusing into the working area. In general, silos are not sufficiently gas tight unless they were specially constructed for fumigation or have been retro sealed. To prevent gas loss, adequate sealing is essential and before treatment, a pressure test for evaluating the sealing efficiency of the structures should be performed. For adequate distribution of phosphine gas, use of Closed Loop Fumigation (CLF) to circulate the fumigant is discussed. The most common non-chemical alternative for storage of cereals is the use of aeration systems during the winter and refrigerated aeration in the summer with the objective to achieve temperatures of less than 18°C to reduce insect activity. In temperate and cold climates, the most common non-chemical alternative to pesticides for cereal grain stored in bulk is the use of aeration systems during the winter that can effectively reduce the grain temperature. During summer, mechanical refrigeration, using large chilling units, provides an excellent solution for quality maintenance of grain. However, aeration using ambient air has a limited effectiveness in tropical climate areas.

Key words: Aeration, Bulk storage, CLF, Condensation, Gas distribution, Grain storage, Postharvest systems

Grain industry in developing countries has faced the need to store large quantities of grain in various climates (Naik and Kaushik, 2011). In the past, developing nations mostly characterized as being in hot climates and the storage of cereals characterized as bag storage. The modern grain industry in economically developed hot climate countries has been looking for storage solutions in large bulks. In hot climate countries, use of bulk storage has mostly been for only very short-term storage. Attempts to store in large bulks, particularly in metal silos resulted in significant losses due to condensation related mold activity, heating and insect damage. Storage sites built in hot climates still remain empty in a number of countries

---

[*] Corresponding author e-mail: *snavarro@013.net*

where adequate solutions to the condensation problems have not been met.

In many hot climate countries, phosphine is still the most widely used fumigant. One of the important aspects of phosphine fumigation that needs understanding is to perform the fumigation in sufficiently gastight structures— fumigation should be carried out only in gastight structures. Maintaining a metal silo just for fumigation of about up to 10 days under a hot climate is a technological challenge.

The most common non-chemical alternative in the cereal storage is the use of aeration systems during the winter and refrigerated aeration during the summer with the objective to achieve temperature of less than 18ºC for reducing insect activity (Navarro and Noyes, 2002). There is increased interest in refrigerated aeration for bulk-stored cereals to reduce the potential of commodity contamination by insects. However, aeration using ambient air in tropical climates has an extremely limited scope. Although most silo manufacturers from developed countries supply the silos with aeration equipment, the grain handlers find it difficult to use them in hot climate countries. There is an even worst situation when grain for feed is stored at high humidity in metal silos. Application of fungistatic agent to control fungi development encourages storage of higher moisture grain than the permissible limit, which in turn increases the danger of deterioration.

Among the new gaseous application technologies that have successfully replaced fumigants are the manipulation of modified atmospheres (MAs) (Navarro, 2012). Bio-generated MAs, termed also hermetic storage, is based on the principle of generation of an oxygen-depleted, carbon dioxide-enriched interstitial atmosphere caused by the respiration of the living organisms in the ecological system of a sealed storage. For long-term storage systems, as well as intermediate storage of grain in bags or in bulk, suitable plastic structures have been developed and applied. These niche applications of MAs have resulted in very promising application treatments with market acceptability, serve as models for global challenges for new application methods.

The objective of this paper is to analyze the emerging global technological challenges in relation to the use of bulk storage of grain in hot climates with the scope of reduction of post-harvest grain losses.

TRANSITION FROM BAG TO BULK IN HOT CLIMATES

Increase in global food production in unprecedented quantities of cereals and oilseeds resulted in increased food storage, especially for storage of grain (Shukla, 2014). The positive impacts of public-private partnerships in this sector could have a positive impact given the inefficiencies in grain storage and the large proportion of post-harvest wastage, especially in the handling and storage of grain in developing countries.

While the economic efforts made by the World Bank and countries involved in these developments have been valuable in many sectors, there has been little use of private sector efficiencies in grain storage investment. Globally, only a few projects have been successfully implemented in this sector, with other projects being explored in various countries.

According to McKee (2013) over 99% of Indian government grain is still stored in 50-kg bags in state-owned warehouses or in the open air. According to some official estimates, storage losses were 10% or more in such facilities. McKee (2013) indicated that a movement is gaining momentum in India that will revolutionize both the modalities and technology of government grain storage.

Shukla (2014) in a brief overview of countries that included: India, Pakistan, Oman, Nigeria, Zambia and Philippines has reported on the trends in grain storage from bag to bulk. He indicated a significant shortage of adequate modern wheat (*Triticum aestivum* L.) storage capacity in India—estimated to be 10 million tonnes. The Punjab area, being the highest food producing state in India, has a storage shortage of 7 million tonnes. In another World Bank document, Shukla and Gupta (2014) indicated that many developing countries have little experience within the public or private sector of establishing, or operating and maintaining, large scale silo storage. Stringent requirements relating to running of silo projects have the potential to become a major barrier in such projects for the implementation of the construction and operation of silos.

In view of this transition of bag to bulk storage, several important technological aspects need consideration: (*a*) use of appropriate aeration and grain cooling methods where the climate permits use of cold ambient air; (*b*) preventing condensation inside the metal silos in hot climates; (*c*) retention of fumigants in the newly constructed metal silos; (*d*) use of Closed Loop Fumigation (CLF) to circulate the fumigant for insect control.

CONDENSATION IN LARGE BULKS

Because of its self-insulating properties, grain loaded into storage during summer harvest retains the initial harvest temperatures for several weeks in cool weather in autumn. For safe storage through the winter and spring months, grain temperatures must be lowered during the summer and autumn and maintained at low levels which will suppress insect and mold reproduction and growth.

As the ambient temperature drops during the cool season, the surface (and peripheral) layers of the grain become considerably cooler than the internal grain mass. Temperature gradients are established in the grain bulk which create convection currents that circulate air through the inter-granular spaces. The cold dense air settles along the outer walls and the warmer air (which contains more moisture than cool air) moves upwards towards the colder upper surface of the grain bulk. In this way, moisture carried by warm air may "migrate" to the cooler surface grain, where the aircools to reach high equilibrium relative humidity, even "dew point"and deposits excess moisture, slowly increasing the grain moisture content in the upper parts of the grain bulk.

Moisture migration is a slow convection air movement process that occurs in a grain mass when sufficient temperature differentials exist between the outside and middle of a grain mass which occur during a period of several weeks or months. Slow moving convection air causes moisture to slowly accumulate in the coldest grain layers. In extreme cases (particularly in the colder months), condensation of water may occur on the grain, or under the roof causing rapid mold (and sometimes bacterial) spoilage. One of the typical symptoms of this phenomenon is the "crusting" over of the grain surface or a ring of mould around the top layer where water has run down under the roof. Surface crusting should be taken as a warning sign indicating that action must be taken to prevent further damage. The more damaging aspect of moisture migration is not the amount of damaged grain, which is usually small in proportion to the grain bulk, but mixing of damaged with undamaged grain during bin unloading due to funnel flow. Mixing may reduce the quality of a significant part of the entire grain volume.

In addition to discoloration, mustiness, and decreases in germination, the potential for production of mycotoxins in micro flora damaged grain should also be considered. This is the most significant aspect of micro flora damage that has received worldwide attention by mycologists and nutritionists since the mid-sixties.

An important objective of grain aeration, especially in subtropical and temperate climates in which diurnal or seasonal temperature fluctuations occur, is to maintain uniform grain temperatures. Thus, a major purpose of aeration is not only cooling grain to lower temperatures, but the prevention of "moisture migration" by maintaining uniform temperatures throughout the grain mass.

Moisture migration occurs in warm, subtropical climates, as well as in cooler temperate climates in which ambient temperatures may fluctuate widely between day and night, and may be much colder than the stored grain during winter. Moisture migration can be prevented by the elimination of temperature gradients throughout the grain bulk by aeration with ambient air during cool weather at low aeration rates. Grain temperatures should be measured throughout the aerated bulk at frequent intervals (i.e. bi-weekly or monthly) to check grain temperature uniformity.

Under-roof condensation is a different natural process than moisture migration within the grain bulk. Condensate that drips on the grain involves moisture in humid air which accumulates in the head-space above the grain bulk which condenses on the undersurface of the bin roof. This natural condition which is acute in hot climates is the primary factor limiting the introduction of bulk handling technology in tropical developing countries.

For example, there have been several attempts to adopt metal silos or bins for storage of paddy (rice) in the Philippines. However, headspace moisture condensation caused grain spoilage accompanied by insect infestation and hot spots, even during short storage durations of three months (de Padua, 1974). Similar occurrences of headspace moisture condensation in metal silos have been reported in other ASEAN countries (Abdulkadir and Joyosuparto, 1979; Shamsuddin, 1979). Experimental work carried out on storage of paddy (*Oryza sativa* L.) in the Philippines demonstrated that moisture condensation in metal silos could be significantly reduced by using aeration systems to maintain uniform grain temperatures and ventilate bin headspaces (NAPHIRE, 1990). By using aeration equipped bins, low moisture paddy could be successfully stored for one year without significant loss in quality.

Roof headspace exhaust fans operated by humidistat control would be desirable for controlling headspace humidity in steel bins or silos in tropical or subtropical climates. Repeat 24 h cycle timers may be a simple alternative to humidistat control. The timer could be set to turn roof exhaust fans on and off at the times each day when bin roofs normally cool and headspace relative humidity rises.

In subtropical and temperate climates, if grain bulks are stored at high temperatures and are not cooled before cold weather, moisture may condense on the underside of the bin roof. Warm grain (10–11% mc (is OK in my experience), stored in metal bins can cause condensation during the night even in relatively warm weather in sub-tropical and temperate climates. This condition occurs when heat from the roof radiates to the cold night sky, chilling the roof metal until headspace air reaches dew point or below, causing moisture to condense on metal roof panels and drip on surface grain. Proper aeration can minimize the risk of headspace moisture condensation. Cooling the surface grain by aeration will tend to lower headspace dew point temperatures, reducing condensation.

RETENTION OF FUMIGANTS IN SILOS

Phosphine fumigation

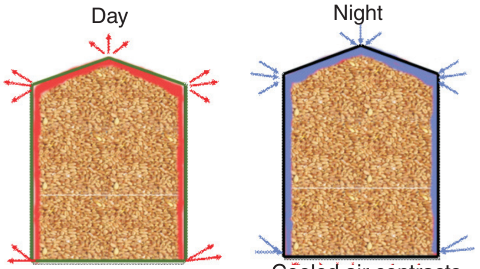
It is a common treatment where three important points deserve attention: sufficient gastightness, the lack of which leads to insect resistance; insufficient exposure time for complete control; and prevention of gas from diffusing into the working areas.

In general, silos are not sufficiently gastight unless they were specially constructed for fumigation or retro sealed. For fumigation, adequate sealing is essential and before a treatment, a pressure test for evaluating the sealing efficiency of the structures should be performed (Navarro, 1998).

Sealing silos before grain loading is not generally considered practice except in Australia where the standards for sealing for insect control were established (Standards Australia, 2010). Silo designs are engineered to hold the grain in storage and prevent damage from external effects like rain, winds, and to certain extent rodents and birds. Engineers engaged with designing silo structures are very seldom requested to consider the possibility of designing a silo that can hold the fumigant gas. Newly constructed silos in developing countries in Asia and Africa should consider the option of silo gastightness design according to the climatic constraints of the geographical location of the silos. Such options need to be based on research, education, experience and know-how. The planned large-scale facilities will be challenged by those external climatic factors for their ability to maintain the storability of the grain in those silos for the designed length of time.

In some countries, grain immediately after it is received in the pit is dosed using a phosphine dosimeter for applying pellets. The recommended dosage is about 5 g phosphine/tonne at temperature above 15°C. This dosage is appropriate provided the gas is well distributed and retained in the bin.

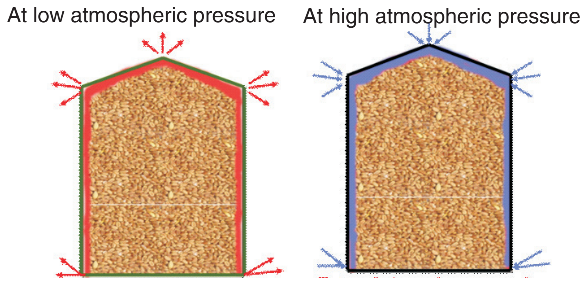
In some cases, the dosimeter for phosphine is located at the base of the elevator. Although in principle the general rule is to keep a minimum dosage of 2 g/tonne for 7 days but for several considerations including lack of gastightness, this dosage is in practice considerably increased to 5 g/tonne. With a nominal dosage of 2 g/tonne, the expected initial concentration in the enclosure, after the gas is completely released may be as high as 1,000 ppm. However, this concentration is theoretical, and may only be attained in extremely gastight conditions. Phosphine release from tablets or pellets is a matter of time, under ideal conditions, only 75% of the maximum theoretical concentration is released after 24 h and 85% after 48 h at 25°C (Ducom and Bourges, 1992). Meanwhile, gas loss due to leakage counteracts to reduce the gas concentration. Most grain storage structures suffer from a lack of sufficient gastightness. Those leaks lead to increase of gas loss due to the exposure of the structures to changing day and night temperatures. During the day, the energy absorbing surface causes expansion of the air that contains the gas and thus it is released to the atmosphere (Fig. 1a) and during the night, the air-gas mixture contracts due to cooling and in this way the gas concentration is diluted (Fig. 1b). The same effect occurs due to changes in atmospheric pressure, when the pressure is low it causes gas loss (Fig. 2a) and during high pressure (Fig. 2b) air infiltration into the bin causes a reduction of fumigant concentration (Navarro, 1997).



Heated air expands
(a)

Cooled air contracts
(b)

Fig. 1. Effect of temperature changes on gas loss; during the day (*a*) on expansion and at night (*b*) on contraction causing reduction of fumigant concentration



Inside atmosphere moves out
(a)

External atmosphere moves in
(b)

Fig. 2. Effect of atmospheric pressure changes on gas loss; during the low pressure (*a*) on gas loss and during high pressure (*b*) on air infiltration into the bin causing reduction of fumigant concentration

Gas tightness of structures for gaseous treatments

Rigid structures can withstand the positive pressures exerted on them during the test for gastightness without changes in volume. Rigid structures may be constructed of concrete, metal or a combination of the two. For modified atmosphere (MA) treatments, the structures must be equipped with a pressure relief valve in order to avoid structural failure under extreme and sudden pressure variations.

A general precaution for rigid structures: In conducting the pressure tests, care should be taken to carefully monitor the pressure applied, especially within the rigid structures, so as not to exceed the pressure limits this structure can withstand. A small blower used to pressurize the structure can eventually produce enough pressure to cause structural damage. This is particularly important in large stores. It is always advisable to seek the advice of a civil engineer regarding the structural soundness of the storage before conducting pressure tests.

Gas permeation through the rigid structure membrane

Gas loss through the structural membrane during gaseous treatments is an important phenomenon. Concrete walls, plaster and plastic liners permit gas permeation and gas exchange. Pressure tests, as described below are not capable of measuring the degree of such losses.

Comparative results with variable pressure test **:** In variable pressure test, the structure is pressurized to a value above atmospheric, using a fan. The air supply is then shut off and the pressure is allowed to fall by natural leakage to a new value. The time taken to fall from the high (positive or negative) pressure serves as a measure of the degree of sealing. Time elapse to half the pressure is usually considered for comparisons of gastightness level.

To minimize the thermal influence, tests should be carried out preferably before sunrise and in still weather. A pressure of 250 Pa may be taken as an upper limit, but for some structures even this pressure may cause poor seals to open. Welded steel cells and concrete silos may be able to stand 500 Pa, but higher pressures are usually unnecessary.

Comparative tests with variable pressure tests were carried out to determine the infiltration of O_2 and loss rate of CO_2, PH_3, and methyl bromide from exposed (EX) and shaded (SH) empty structure of 7.5 m^3 capacity in relation to half-life pressure decay time (min) (Table 1). The suggested maximum infiltration rate for modified atmospheres is 0.5% O_2/d increase. The suggested maximum loss rate for CO_2 is 2%/d. PH_3 loss should not exceed 100 ppm/d. Methyl bromide loss of 1.0 g m^{-3}/d was considered acceptable. For methyl bromide, the shaded structure was tested in October and the exposed structure was tested in November, when ambient temperatures were lower than in October (Navarro and Zettler, 2001).

For controlled atmosphere storage in Australia, with structures of 300 to 10,000 tonnes capacity, a decay time of 5 min for an excess pressure drop of 2500–1500 Pa or 1500–750 Pa or 500–250 Pa was regarded satisfactory (Banks et al., 1980). According to Banks and Annis (1980), this range of pressures was chosen so that it is the highest usable without unduly stressing the storage fabric of the store. They commented also that above 10,000 tonnes capacity, pressure testing is difficult to carry out satisfactorily, as it requires very stable atmospheric conditions. From analysis of the data presented by Banks et al. (1980), it would appear that for storages with capacities in the range of 1,600–1,900 tonnes in MA with an initial CO_2 concentration of about 60–85% for an average decay time of 11 min, the daily decay rate was about 4% CO_2. With similar range of initial CO_2 concentration

Table 1 Infiltration of O_2 and loss rate of CO_2, PH_3, and MB from exposed (EX) and when shaded (SH) empty structure of 7.5 m^3 capacity in relation to half-life pressure decay time (min). The suggested maximum infiltration rate for modified atmospheres is 0.5% O_2/d increase. The suggested maximum loss rate for carbon dioxide is 2%/d. PH_3 loss should not exceed 100 ppm/d. MB loss of 1.0 g m^{-3}/d was considered acceptable. For methyl bromide the shaded structure was tested in October and the exposed structure was tested in November, when ambient temperatures were lower than in October (Navarro and Zettler, 2001)

Minutes for half-life pressure decay	Infiltration rate (% O_2/d)		Loss rate (% CO_2/d)		PH_3 loss (ppm/d)		MB loss in (g m^{-3}/d)	
	EX	SH	EX	SH	EX	SH	EX	SH
1	1.60	1.15	6.65	5.00	220	145	1.95	2.05
2	1.35	1.05	5.45	4.20	190	120	1.70	1.85
3	1.15	0.95	4.40	3.45	175	100	1.45	1.55
4	0.95	0.70	3.30	2.70	155	75	1.15	1.25
5	0.80	0.50	2.20	1.95	130	52	0.93	1.10

in a structure of 150 m^3 capacity, daily gas loss was correlated to different levels of pressure decay times (Navarro et al., 1998). Their comparison resulted in a pressure decay time of 3 min for a daily decay rate of about 4% CO_2.

The influence of hermetic storage on controlling insects was examined using small scale 15, 30 and 52 m^3 capacity sealed plastic structures for outdoor storage of wheat, paddy and corn (*Zea mays* L.) (Navarro et al., 1995). Pressure decay rates were compared with daily CO_2 decay rates. Within these structures, successful insect control was obtained with <1% CO_2 daily decay rate which was equivalent to 5 min half-life pressure decay time. Similarly, comparative data were obtained using hermetic bunker storages of about 19,000 m^3 capacity, where successful results were obtained when the half-life pressure decay was about 9 min (Navarro et al., 1984).

According to Banks and Annis (1984), daily ventilation rates tolerable in various insect control processes are estimated as 2.6% for hermetic storage, 5% for N_2 based MA, 7% for CO_2 based CA, and 10% for phosphine fumigation. Based on the proportion of ventilation rates, this would account for ventilation rates for fumigation using phosphine being two fold of N_2 based MA , and the latter being as much as twice at hermetic storage.

PHOSPHINE RECIRCULATION

Phosphine has been used as a fumigant in pellets or tablets and traditionally probed 1 or 2 m deep in the grain. During conventional fumigation, grain surfaces are either plastic tarped or roof openings are sealed. In steel bins, about 75% of the dosage is surface probed and 25% is placed in base aeration ducts. In silos, automatic dispensers drop a calculated number of pellets or tablets per 35 m^3 onto grain conveyed by belt conveyors or elevator legs during grain transfer to storage units. This is now an illegal use of phosphine in Australia – it has been removed from the label (C. Newman *Personal information*).

Because phosphine gas is explosive in sealed compartments at concentrations above 17,900 ppm, researchers have been reluctant to test phosphine in recirculation systems like those used for methyl bromide. Compared to conventional probe/ tarp fumigation methods, or automatic pellet dispensing into concrete silos to fumigate while turning grain, 'closed loop fumigation' (CLF) is performed without removing the grain from the silo (Noyes et al., 1998). Aeration fans, vents, conveyors, and down spouts are primary openings to be sealed prior to use of CLF. In dosing for CLF, fumigant can be spread on grain surfaces, or added to a small percentage of grain conveyed from one bin into another bin with dosage added to conveyors during transfer of a portion of the grain (2 to 5% of bin capacity) into the treated bin.

Recirculated phosphine achieves uniform distribution throughout the grain bulk much faster and more predictably than was possible with conventional probe fumigation that relied on diffusion and convection air currents. A 0.075 kW (0.10 HP) recirculation blower that delivers 353 m^3/h through the grain in an 8,100 tonne welded steel storage bin was used. The flow rate of 0.043 $m^3/h/tonne$, created one gas exchange per 12 hours, and proved satisfactory to mix and achieve relatively uniform gas distribution with 4 to 6 air exchanges in 2 to 3 days (Cook, 1980). The rate of 0.36 $m^3/h/tonne$ is about 1.4 hours per air exchange or 17 air changes per day. Cook (1980) preferred to use between 0.090 and 0.048 $m^3/h/tonne$, which are equivalent to 5.6 to 10.4 hours per air exchange, or 2.3 to 4.3 air changes per day.

CONCLUSION

- There is an increasing economic development accompanied by demand for bulk storage of grains particularly in hot climate areas.
- The transition from bag to bulk increased the demand for bulk storage in warehouses, but also in metal silos.
- Long term bulk storage of grain in hot climates needs additional research, development, technological know-how and experience to prevent grain losses.
- Large bulks should be equipped with appropriate aeration and grain cooling systems and where the climate permits, use of cold ambient air should be implemented.
- In hot climates, preventing condensation inside the metal silos poses a technological challenge.
- In newly planned silos, provisions should be made for appropriate gastightness necessary for the retention of fumigants. Such gastightness should not obviate the possibility of implementing aeration technology. Sealable aeration vents have been designed and are in use in Australia.
- For effective fumigation of large bulks, in addition to proper gastightness, they should be equipped with closed loop fumigation to circulate the fumigant for insect control.

REFERENCES

Abdulkadir A, Joyosuparto S (1979) A study on the performance of silo in RPC Tambun. (*In*) Proceedings of Workshop on Grains Postharvest Technology, January 16–19, 1979, Jakarta, Indonesia, pp 342–353.

Banks HJ, Annis PC (1980) Conversion of existing grain storage structures for modified atmosphere use. In: Shejbal J (ed). Controlled Atmosphere Storage of Grains, Elsevier, Amsterdam. pp. 461–473.

Banks HJ, Annis PC, Henning RC, Wilson AD (1980) Experimental and commercial modified atmosphere treatments of stored grain in Australia. (In) Shejbal J (ed) Controlled Atmosphere Storage of Grains. Elsevier, Amsterdam pp 207–224.

Banks HJ, Annis PC (1984) Importance of processes of natural ventilation to fumigation and controlled atmosphere storage. (*In*) Ripp B E et al. (eds), Controlled Atmosphere and Fumigation in Grain Storages, Elsevier, Amsterdam, pp 299–322.

de Padua DB (1974) Postharvest rice technology in Idonesia, Malaysia, Philippines and Thailand - A state of the art survey. International Development Research Center, 66 pp.

Ducom P, Bourges C (1992) Comparison of rate of release of phosphine from some commercial formulations generated under 75% relative humidity and four temperatures. (In) Navarro S, Donahaye E (eds) Proc. Int. Conf. Controlled and Fumigation in Grain Storages, Winnipeg, Canada, June 1992, Caspit Press Ltd., Jerusalem, pp 293–297.

McKee D (2013) Grain Storage trends in India, http://www.davidmckee.org/2013/06/15/grain-storage-trends-in-india/. Accessed 11 June 2016.

Naik SN, Kaushik G (2011) Grain Storage in India: An Overview. http://vigyanprasar.gov.in/Radioserials/Grain%20Storage%20in%20India%20by%20Prof.%20S.%20N.%20Naik,%20IIT%20Delhi.pdf.Accessed 11 June 2016.

NAPHIRE (1990) Study of the Physics of Bulk Storage for Paddy: Terminal Report. National Postharvest Institute for Research and Extension (NAPHIRE), Philippines, 135 pp.

Navarro S, Zettler L (2001) Critical limits of sealing for successful application of controlled atmosphere or fumigation. (In) Donahaye EJ, Navarro S and Leesch JG (eds) Proc. Int. Conf. Controlled Atmosphere and Fumigation in Stored Products. Fresno, CA. 29 Oct.-3 Nov. 2000, Executive Printing Services, Clovis, CA, USA, pp 507–520.

Navarro S (2012) The use of modified and controlled atmospheres for the disinfestation of stored products. Pest Science **85**(3): 301–322.

Navarro S (1997) Sealing efficiency assessment in modified atmosphere storages. (In) Donahaye EJ, Navarro S and Varnava A (eds) Proc. Int. Conf. Controlled Atmosphere and Fumigation in Stored Products, 21–26 April 1996, Printco Ltd, Nicosia, Cyprus, pp 371–384.

Navarro S (1998) Pressure tests for gaseous applications in sealed storages: Theory and practice. (In) Proc. 7th Int. wkg. Conf. Stored-Product Protection. Zuxun J, Quan L, Yongsheng L, Xianchang T, Lianghua G (eds) 14–19 October, Beijing, China, Sichuan Publishing House of Science and Technology, Chengdu, Sichuan Province, Vol. I, pp 385–390.

Navarro S, Noyes R (2002) (Editors) The Mechanics and Physics of Modern Grain Aeration Management. CRC Press, Boca Raton, FL, 647 pp.

Navarro S, Donahaye E, Caliboso FM, Sabio GC (1995) Application of modified atmospheres under plastic covers for prevention of losses in stored grain. Final Report submitted to U.S. Agency for International Development, CDR Project No. C7-053, August 1990 – November 1995, 32 pp.

Navarro S, Donahaye E, Rindner M, Azrieli A (1998) Control of nitidulid beetles in dried fruits by modified atmospheres. (In) Adler C, Scholler M (eds) Integrated protection of stored products. IOBC wprs Bulletin 21(3). International Organization for Biological and Integrated Control of Noxious Animals and Plants, Dijon, pp 159–164.

Navarro S, Donahaye E, Kashanchi Y, Pisarev V, Bulbul O (1984) Airtight storage of wheat in a P.V.C. covered bunker. (In) Ripp, BE et al. (eds) Controlled Atmosphere and Fumigation in Grain Storages, Elsevier, Amsterdam, pp 601–614.

Noyes RT, Phillips TW, Cuperus GW, Bonjour EL (1998) Advances in recirculation fumigation technology in the U.S.A. (In) Proceedings of 7th International Working Conference on Stored Product Protection, Beijing, PR China, 14–19 October 1998. pp 454–462.

Shamsuddin I (1979) Bulk storage and handling of paddy in Malaysia. (In) Proceedings of Workshop on Grains Postharvest Technology, 16–19, January 1979, Jakarta, Indonesia, pp 434–443.

Shukla S (2014) Global Trends in Public-Private Partnerships in Grain Storage. World Bank Group, Public-Private Partnership. https://olc.worldbank.org/sites/default/files/PPP%20in%20Grain%20Storage-%20Combined%20ppt%20July%2029%20webinar.pdf. Accessed 11 June 2016.

Shukla S, Gupta N (2014) Grain storage; public-private partnership. https://library.pppknowledgelab.org/World%20Bank%20Group/documents/2409/downloadAccessed 11 June 2016.

Standards Australia (2010) AS 2628-2010Sealed grain-storage silos - Sealing requirements for insect control. http://infostore.saiglobal.com/store/details.aspx?ProductID=1391029. Accessed 11 June 2016.