ENHANCED EFFECTIVENESS OF VACUUM OR CO_2 IN COMBINATION WITH INCREASED TEMPERATURES FOR CONTROL OF STORAGE INSECTS

S. NAVARRO[1], S. FINKELMAN[1], G. SABIO[2], A. ISIKBER[3], R. DIAS[1], M. RINDNER[1] and A. AZRIELI[1]

[1]Department of Stored Products, Agricultural Research Organization, The Volcani Center, P.O.Box 6, Bet Dagan 50250, Israel
[2] Bureau of Postharvest for Research and Extension, Department of Agriculture, Nueva Ecija, Philippines
[3] Department of Plant Protection, Faculty of Agriculture, University of Kahramanmaras Sutcu Imam, Kahramanmaras 46060, Turkey
Corresponding author:

ABSTRACT

Laboratory studies were carried out to identify the combinations that enhance the effectiveness of insect control based on vacuum or CO_2 in combination with increased temperatures as a quarantine treatment of storage pests. The roles of the commodity moisture content and the partial pressure of oxygen on the effectiveness of vacuum were described. For *T. castaneum, E. cautella* and *P. interpunctella* the egg stage was the most resistant to low pressure, the times needed to obtain LT_{99} were 22, 45 and 49 h, respectively. For *T. castaneum* the larva and adults were the most susceptible stages with an LT_{99} of 7 h; for *E. cautella* and *P. interpunctella* the adult was the most susceptible stage with LT_{99} times of only 6 h and 5 h. The effect of CO_2 at 45°C on reducing the exposure time for diapausing larvae of *T. granarium* showed that by increasing the CO_2 concentration to 90% the LT_{99} value decreased to about 10 h, whereas at 35ºC the LT_{99} value was 29 h. *Ephestia cautella* larvae were shown to be the most resistant stage to 90% CO_2 at 40°C, with an LT_{99} value of only 6 h. For *Oryzaephilus surinamensis* under the same conditions, the LT_{99} value was 9 h for the most resistant egg stage. These encouraging results led to the idea of developing a transportable flexible storage system to render the technology a practical tool for the control of insect pests. Experiments were carried out using a 15-m^3 capacity plastic container termed the "Volcani Cube™" or "GrainPro Cocoon™". Bioassays in field trials at 30°C demonstrated that complete mortality of test insects composed of all four developmental stages of *E. cautella* and *Tribolium castaneum,* was observed upon 3-days exposure to vacuum maintained between 23 and 75 mm Hg.

Keywords: methyl bromide alternatives, vacuum, CO_2, storage insects, transportable systems

Introduction

A significant development that has occurred over the past 10 years in post-harvest technologies has been the fast approaching phase-out of methyl bromide in developed countries by the year 2005 and worldwide by 2015 under the terms of the Montreal Protocol (UNEP, 1998). This has resulted in a significant increase in the number of publications dealing with alternatives to methyl bromide (Bell *et al*., 1996; Donahaye et al., 2001; International Conference on Alternatives to Methyl Bromide, 2002). In particular, the search for non-chemical methods of insect control has increased in intensity. Additionally, a public awareness has arisen with respect to pesticide residues in food and their harmful influence on the environment. Public pressure is increasingly being brought to bear on legislators to close every loophole that might enable the contamination of food with toxic materials. Consequently, future prospects for using new fumigants on stored food products remain very limited.

Many research groups are now in a "rethink" mode as a direct result of pressure from national and international legislative bodies and contract restrictions on grain purchase imposed by importing countries. These authorities are fast reducing the range of existing chemical options, while the development of new friendly chemicals, specifically for the stored product market has become prohibitively expensive. These constraints have led to a realization that prevention is better than cure. And so, the emphasis is rapidly shifting to integrated pest management (IPM) with chemical means of control as a last resort. However, in practice chemical control still plays a dominant role, with phosphine fumigation as the mainstay of the grain storage industry, even though, - as with methyl bromide - its use may also become increasingly more restricted in the future.

Widespread experience has proven that chemicals applied at commercial levels have the characteristic of developing resistance by insects. The wisdom of relying upon a single chemical such as phosphine, with the hope that resistance does not develop has been invalidated (Winks, 1987; Zettler, 1993). PH_3 is a very useful fumigant but it is slow acting and insects in various countries have developed resistance (Winks, 1987; Zettler, 1993).

Controlled atmospheres (CAs) technology can fulfill a specific niche where use of other fumigants is unacceptable such as treating organic foods. CAs are limited by the long exposure times required to produce complete mortality (Navarro and Jay, 1987), and are similar to those required for phosphine (PH_3) fumigations (Navarro and Donahaye, 1990). In cases where rapid disinfestation of commodities is required, the possibility of using CO_2 at temperatures raised to levels that will not adversely affect the commodity should be considered. It has been recognized that insecticide treatments, particularly those affecting the respiratory system are more pronounced at higher temperatures (Navarro and Calderon, 1980). Respiratory metabolism has also been observed to increase with temperature up to a maximum and then sharply declines at the upper lethal temperature (Chapman, 1982). A number of laboratory studies on the combined effects of high CO_2 and optimal elevated temperatures against insects have shown a corresponding increase in insect mortality with increase in temperature (AliNiazee, 1971; Adler, 1994; 1997; Bell et al., 1980; Donahaye et al., 1996; Navarro and Jay, 1987; Soderstrom et al., 1991).

Investigations on effects of low pressures on storage insects were carried out by Back and Cotton (1925), Bare (1948), and later on by Calderon *et al*. (1966), Calderon and Navarro (1968), and Navarro and Calderon (1969; 1972a; 1972b). Recently Mbata and Phillips (2001) investigated the effects of temperature and exposure time on mortality of three stored product insects exposed to low pressure. Insect mortality under low pressure is predominantly a result of oxygen deficit and not due to physical pressure effects (Navarro and Calderon 1979).

In a first attempt to use low pressures to preserve cacao beans quality, Challot and Vincent (1977) used polyethylene bags applying a low pressure of 600 mm Hg. Although 600 mm Hg may be effective in maintaining the product quality and prevent ingress of insects, storage insects can tolerate this pressure. For mortality of storage insects, low pressures below 100 mm Hg are required.

Gas tight flexible structures using the hermetic storage method have been developed and are in use on an industrial scale (Navarro *et al.,* 1988; 1990; 1994; Silberstein et al., 1998). These structures enable treatment with modified atmospheres or fumigation (Navarro *et al.,* 1995), and they are termed "Volcani Cubes™" or "GrainPro Cocoons™" (Navarro *et al.,* 1999). The use of these flexible storage facilities to maintain low pressures of 25-30 mm Hg was reported in two recent works (Phillips *et al*., 2000; Navarro *et al*., 2001).

The objective of this paper is to report on the mortality of different life stages of stored product insect pests exposed to increased temperatures and a constant low pressure or under CO_2 enriched atmospheres, and on the application of transportable systems for the environmentally friendly treatment of storage pests.

MATERIALS AND METHODS

Temperature, CO_2, and low-pressure combinations

For CO_2 treatments, concentrations varying from 60% to 90% of CO_2 in air at temperatures ranging from 30° to 45°C were tested. For low-pressure treatments, an absolute pressure of 50 (in the range 45 and 55) mm Hg at a temperature of 30ºC was tested.

Test insects

Diapausing larvae of Khapra beetle *(Trogoderma granarium)* were obtained by removing active larvae from cultures and placing them in groups of several hundred without food for one month at 28ºC (Lindgren and Vincent, 1960). Adults of *Tribolium castaneum*, *Oryzaephilus surinamensis, Ephestia cautella* and *Plodia interpunctella* were taken from laboratory cultures maintained at the Department of Stored Products, Volcani Center, Agricultural Research Organization, Bet Dagan, and mass reared on a standard artificial diet. Eggs, pupae and adults (1-2 days old) and larvae (4-15 days old) were taken from the same batch.

Eggs of tested species were used within 0-2 days of oviposition. The eggs were obtained by placing 500-1000 adults beetles in 500 g of wheat flour containing 5 g of brewers' yeasts. To obtain eggs from moths, *E. cautella* and *P. interpunctella* were placed on a mesh covered inverted jar, overnight and the females laid the eggs in a Petri dish. Two Perspex slides each with 50-drilled "wells" were used to individually place 100 eggs from each of the studied species. The slides were then covered with a cover glass to retain the eggs (Navarro and Gonen, 1970).

Exposure of insects to low pressures

Treatment chambers consisted of 3-L desiccators filled with 1 kg cocoa beans stabilized at an equilibrium relative humidity of 55 r.h. at 30^{o}C. For exposure, sets of 50 insects were confined in cages of 15-mm diameter and 50 mm length made of 100 mesh stainless steel.

Post fumigation procedures

Following treatment, larvae, pupae and adults were transferred to small jars (50 ml) and maintained at 28±1^{O}C and 65±5% R.H. The larvae were provided with food. The eggs were transferred to watch glasses and incubated under the same conditions as the other developmental stages. Mortality counts for larvae were carried out after two weeks of exposure; for pupae after one week, for adults after one day, and for eggs after 4-5 days of exposure. Mortality for larvae was based on those that failed to pupate, for pupae, those that failed to emerge as adults, for adults, those that were dead or moribund, and for eggs, those that failed completely to hatch.

RESULTS AND DISCUSSION

Effects of CO_2 and temperature

Table 1 shows the influence of CO_2 concentrations at different temperatures as expressed in LT_{99} mortality values for diapausing larvae of *T. granarium*. At 45°C, by increasing the CO_2 concentration to 90% the LT_{99} value decreased to 10 h, whereas at 35ºC the LT_{99} value was 29 h.

T. granarium is one of the most serious pests of stored cereal grains and oil seeds, and is subject to strict quarantine regulations in the US, Australia and several other countries. It is a member of the dermestid family and is a voracious feeder of grain products. The larvae can hide in cracks of the storage structure in a state of facultative diapause and can remain in this condition for years. It is particularly difficult to control with insecticides. Consequently, many quarantine treatments are mandatory when products such as rugs, spices and cereal products are imported from infested countries. In such situations, MB is still the only effective fumigant against this pest. Present distribution of *T. granarium* includes Western Africa through the Northern Indian subcontinent (Cuperus *et. al.,* 1992). Results shown in Table 1 may serve as guidelines to the possibility of applying slightly elevated temperatures for control of the most resistant diapausing larvae of *T. granarium.*

Table 1 - Influence of CO_2 concentrations expressed in LT_{99} (hours to obtain 99% mortality) values for *Trogoderma granarium* diapausing larvae at three different temperatures.

Temperature (°C)	CO_2 concentration (%)			
	60	**70**	**80**	**90**
35	38	29	-	29
40	24	28	20	-
45	15	17	15	10

A similar approach of applying various CO_2 concentrations at different temperatures was investigated for four developmental stages of *E. cautella*. Results in Table 2 summarize the effectiveness of the combination of CO_2 at temperatures in the range of 35ºC to 45ºC. Tests with *Ephestia cautella* showed that the pupa was the most resistant stage when exposed to 90% CO_2 with an LT_{99} value of 17 h at 35ºC, and only 3 h when exposed at 45ºC. The adult was the most sensitive stage of E. cautella requiring only 4 h of exposure to 90% CO_2 at 35ºC.

Results on the influence of various CO_2 concentrations at different temperatures on *O surinamensis* development stages are shown in Table 3. For this species as well, an increase in CO_2 concentration resulted in a decrease in the LT_{99} value. Generally, the eggs were the most resistant stage; at 40ºC and 90% CO_2 a six h exposure was required to obtain an LT_{99} value.

Table 2 - Influence of CO_2 concentrations expressed in LT_{99} (hours to obtain 99% mortality) values for *Ephestia cautella* various development stages exposed to CO_2 concentrations in air at three different temperatures.

Temp. (°C)	35				40				45			
CO_2 (%)	**60**	**70**	**80**	**90**	**60**	**70**	**80**	**90**	**60**	**70**	**80**	**90**
Eggs	23	23	17	9	16	12	8	5	9	5	3	2
Larvae	60	27	20	12	17	9	6	6	5	4	2	2
Pupae	56	37	17	17	36	10	8	4	7	4	4	3
Adults	20	14	6	4	6	5	3	2	3	2	2	2

Table 3 - Influence of CO_2 concentrations expressed in LT_{99} (hours to obtain 99% mortality) values for *Oryzaephilus surinamensis* various development stages exposed to CO_2 concentrations in air at three different temperatures.

Temp. (°C)	Life Stage	CO_2 concentrations (%)			
		60	**70**	**80**	**90**
30	Eggs	-	-	38	22
	Adults	21	-	22	9
35	Eggs	29	25	21	9
	Adults	26	11	8	4
40	Eggs	15	7	6	6
	Larvae	8		2	2
	Pupae	-	-	-	5
	Adults	12	11	6	3

Effects of low pressures and temperature

The response of four developmental stages of three storage insects to 55 mm Hg is shown in Table 4. For *T. castaneum, E. cautella* and *P. interpunctella* the egg stage was the most resistant to low pressure, the times needed to obtain LT_{99} being 22, 45 and 49 h, respectively. For *T. castaneum,* the larva and adults were the most susceptible stages with an LT_{99} of 7 h. For *E. cautella* and *P. interpunctella* the adult was the most susceptible stage with only 6 h and 5 h.

Temperature plays an important role in the exposure time needed to achieve mortality of insects. At 18°C and at 55 mm Hg times needed to achieve LT_{99} for eggs, larvae, pupae and adults of *E. cautella* were 149, 44, 26 and 77 h, respectively (Finkelman et al., 2002), while at 30°C these times were shortened to 45, 10, 7 and 6 h (Table 4). For *T. castaneum* the temperature effect was even more marked; at 18°C the times needed to achieve LT_{99} were 93, 37, 72 and 30 h, respectively, while at 30°C the times were shortened to 22, 7, 13 and 7 h.

The only other information available on the effects of low pressure on *E. cautella*, and *T. castaneum* is that provided by Calderon et al. (1966) who reported that at 10-12 and 16-20 mm Hg and at 25°C, adults of *E. cautella* were very sensitive, and less than 1 h exposure was required to obtain 99% mortality, while for *T. castaneum* adults 2.7 h were necessary. Mbata and Phillips (2001) reported on the eggs of *P. interpunctella* as the most resistant stage compared to the larvae and the pupa, with LT_{99} values for eggs exposed to 32.5 mm Hg at 25°C as 28 h. An increase in temperature to 33°C resulted in a decrease in LT_{99} for eggs to an exposure time to 6 h.

Navarro and Calderon (1979) compared the influence of low pressure on *Ephestia cautella* pupae with that of low oxygen concentrations, and deduced that the partial pressure of oxygen has a decisive effect on insect mortality, while no significant function could be attributed to the low pressure itself. At 50 mm Hg the partial pressure of oxygen is equivalent to 1.4%, this being similar to the target oxygen concentration under a modified atmosphere obtained by nitrogen flushing. Table 5 shows the various units used in the literature for describing the equivalent values of various low pressures and equivalents in oxygen % at normal temperature and pressure of the atmosphere. In the process of evacuation, the main significant effect is the reduction in the partial pressure of the oxygen. The drop in the partial pressure of oxygen concentration is proportional to the atmospheric pressure and is almost linear. However, the commodity moisture largely dictates the humidity within the treated enclosure. Humidity response is linear if the treated enclosure is empty and no other gas then air is present in the enclosure. To demonstrate the effect of commodity moisture, Fig. 1 was prepared and tested for cocoa beans of 6.2% moisture content. According to Gough (1975), the equilibrium relative humidity (ERH) of cocoa beans is 60%. Although an evacuation process may reduce the humidity of the enclosure for a short time, the commodity gives off moisture to the interstitial space until the commodity moisture equilibrates with the humidity of the atmosphere of the interstitial space. For cocoa beans with a fill ratio of 63% in desiccators, this equilibration process lasted less than one hour at 30°C.

Rigid metal chambers have been in use for the implementation of vacuum fumigation in agricultural commodities (Bond, 1984). A recently developed technology based on high-pressure CO_2 treatments also makes use of rigid chambers (Adler *et al*, 2000). However, these structures are expensive and their lack of transportability h restricts the implementation of this environmentally sound method. Based on the encouraging data obtained herein, to render the technology a practical tool, the possibility was recently investigated of using CO_2 or low pressures to control storage insects in a transportable system (Phillips *et al*., 2000).

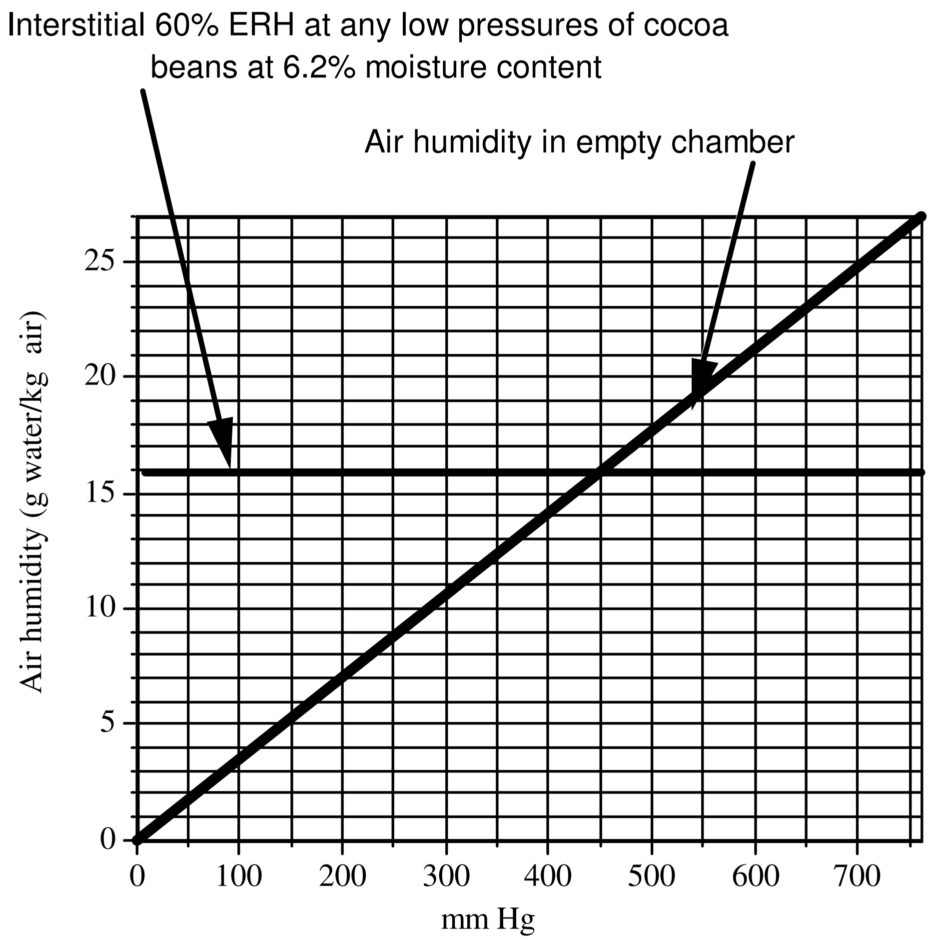
Table 4 - The influence of 55 mm Hg on exposure time expressed in LT_{99} (hours to obtain 99% mortality) values of three storage insect pests at 30°C.

Developmental stage	*Tribolium castaneum*	*Ephestia cautella*	*Plodia interpunctella*
Eggs	22	45	49
Larvae	7	10	12
Pupae	13	7	10
Adults	7	6	5

Table 5 - Units used to express atmospheric pressure and their equivalent partial pressure of oxygen expressed in mmHg and in percentage.

mmHg (≈torr)	atm	kg/cm^2	inches Hg	kPa	mbar	mm Hg oxygen	% oxygen
760	1.00	1.03	29.92	101,325	1,013	159	20.9
600	0.79	0.82	23.62	79,993	800	125	16.5
500	0.66	0.68	19.68	66,661	667	105	13.8
400	0.53	0.54	15.75	53,329	533	84	11.0
300	0.39	0.41	11.81	39,997	400	63	8.3
200	0.26	0.27	7.87	26,664	267	42	5.5
100	0.13	0.14	3.94	13,332	133	21	2.8
50	0.07	0.07	1.97	6,666	67	11	1.4
0	0.00	0.00	0.00	0	0	0	0.0

Fig. 1 - Linear relationship between atmospheric pressure (mm Hg) and air humidity (g/kg) 30°C.



The transportable system was made of flexible PVC, which has been in use commercially for hermetic storage of grain and other commodities to control insect disinfestation by naturally obtained modified atmospheres (Navarro *et al.,* 1999). Experiments were carried out using a 15-m3 capacity plastic container termed the "Volcani Cube™" or "GrainPro Cocoon®". The pressure was maintained between 25 and 29 mm Hg for 17 days. Bioassays in field trials demonstrated that complete mortality of test insects composed of mixed ages of *E. cautella Plodia interpunctella*, and larvae of *T. castaneum,* was observed following the 3-days exposure to vacuum (Phillips et al. 2000). For the disinfestation of durable commodities, these flexible storage containers can be considered as an alternative to treatments with methyl bromide and other toxic fumigants. Currently, cocoa beans are treated in the Ivory Coast with phosphine for five days and this treatment has replaced the conventional methyl bromide fumigation (Finkelman et al., 2002). The option of low pressure therefore is a promising solution that can provide the required insect control in less time and without the need to use environmentally harmful chemicals.

Acknowledgements

We thank Dr. E. Donahaye for reading the manuscript and making useful suggestions. This work was funded in part by a grant from the United States-Israel Science and Technology Foundation, Israel Agricultural Research Organization Project No. 5288.

References

Adler, C. S. (1994). A comparison of the efficacy of CO_2-rich and N_2-rich atmospheres against the granary weevil *Sitophilus granarius* (L.) (Coleoptera: Curculionidae). In: E. Highley, E. J. Wright, H.J. Banks, and B.R. Champ (Eds.), Proc. 6th Int. Work. Conf. Stored-Product Protection. Canberra, Australia. pp. 11-15

Adler, C. S. (1997). Rapid disinfestation through the combination of controlled atmospheres and heat. In: E. J. Donahaye, S. Navarro, and A. Varnava (Eds.), Proc. Int. Conf. Controlled Atmospheres and Fumigation in Stored Products. Printco Ltd., Nicosia, Cyprus. pp. 89-93.

Adler, C., Corinth, H. G. and Reichmuth, C. 2000. Modified atmospheres, pp. 105-146. In B. Subramanyam and D. W. Hagstrum [eds.l Alternatives to pesticides in stored product IPM. Kluwer, Boston, MA.

AliNiazee, M. T. (1971). The effect of carbon dioxide gas alone or in combinations on the mortality of *Tribolium castaneum* (Herbst) and *T. confusum* du Val (Coleoptera: Tenebrionidae). J. stored Prod. Res. **7**: 243-252.

Back, E. A. and R. T. Cotton. 1925. The use of vacuum for insect control. *J. Agric. Res.* 31: 1035-1041.

Bare, C. O. 1948. The effect of prolonged exposure to high vacuum on stored tobacco insects. *J. Econ. Entomol*. 41: 109-110.

Bell, C. H., Price, N. and Chakrabarti, B. (eds.). 1996. The methyl bromide issue. Wiley, Chichester, England.

Bell, C. H., Spratt, E.C., and D.J. Mitchell (1980). The effect of nitrogen and carbon dioxide on eggs of *Ephestia cautella* (Walker) and *E. kuehniella* Zeller (Lepidoptera: Pyralidae). Bull. ent. Res. **70**: 293-298.

Bond, E. J. 1984. Manual of fumigation for insect control. FAO Plant Production and Protection Paper 54. Food and Agriculture Organization of the United Nations, Rome, Italy

Calderon, M. and Navarro, S. 1968. Sensitivity of three stored-product species exposed to different low pressures. *Nature* (Lond.) 2I8: 190.

Calderon, M., Navarro, S. and Donahaye, E. 1966. The effect of low pressures on the mortality of six stored-product insect species. *J. Stored Prod. Res*. 2: 135-140.

Challot, F. and Vincent, J. C. 1977). Stockage du cacao sous vide dans des conteneurs en polyethylene. *Café Cocoa Thé*, vol. XXI (2), 129-136.

Chapman, R. F. (1982). The tracheal system and respiration in terrestrial insects. In: The Insects Structure and Function. 3rd Ed. Harvard Univ. Press, Cambridge, Massachusetts. pp. 529-553.

Cuperus, G.W., Johnson, G. and Morrison, W.P. 1992. IPM in wheat and stored grain. In: *Successful Implementation of Integrated Pest Management for Agricultural Crops*. (Edited by Leslie A. and Cuperus, G.), Lewis Publishers, Boca Raton, Fl., 33-55.

Donahaye E., Navarro S., Rindner M., and Azrieli, A. 1996. The combined influence of temperature and modified atmospheres on *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) *J. stored Prod. Res*. 32, 225-232

Donahaye, E., Navarro, S. and Leesch, J. (2001) (Eds.) *Proceedings of an International Conference on Controlled Atmosphere and Fumigation in Stored Products*, Fresno, CA, 2000. Executive Printing Services, Clovis, CA, (in print).

Finkelman, S., Navarro, S., Rindner, M., Dias, D., Azrieli, A., 2002 Effect of low pressures on the survival of cacao beans insects stored at 18° C. Journal of Stored Products (In press).

Gough, M.C. (1975) A simple technique for the determination of humidity equilibria in particulate foods. Journal of stored Products Research, 11, 161-166.

International Conference on Alternatives to Methyl Bromide, 2002. Proceedings of International Conference on Alternatives to Methyl Bromide. March 5-8, 2002, Sevilla, Spain, 420pp. (Pre-publication copy).

Lindgren, D.L. and Vincent, L.E. 1960. Response of quiescent Khapra beetle larvae to fumigation and low temperatures. *J. Econ. Entomol*. 53, 698-699.

Mbata, G. N. and Phillips, T. W. 2001. Effects of temperature and exposure time on mortalirty of three stored product insects exposed to low pressure. *J. econ. Entomol.* 94 (5) :1302-1307.

Navarro S. and Jay, E. 1987. Application of modified atmospheres for controlling stored grain insects. In *Proc. British Crop Protection Council*, No. 37 Stored Products Pest Control. Univ. of Reading. 229-236.

Navarro S. and M. Calderon (1980). Integrated approach to the use of controlled atmospheres for insect control in grain storage. In Controlled Atmosphere Storage of Grains. J. Shejbal (Ed.). Proc. Int. Symposium, 12-15th May 1980, Rome: pp. 73-78.

Navarro, S. and Calderon, M. 1969. The effect of low pressure on egg mortalities of three stored product insect species. Report of the Stored Prod. Res. Lab. 83-87.(in Hebrew with English summary).

Navarro, S. and Calderon, M. 1972a. Exposure of *Ephestia cautella* (Wlk.) (Lepidoptera, Phycitidae) to low pressures: effects on adults. *J. stored Prod. Res.* 8: 209-212.

Navarro, S. and Calderon, M. 1972b.. Effects of low pressures on water loss and mortality of *Ephestia cautella* (Wlk.) pupae. Report of the Stored Prod. Res. Lab. 47-53. (in Hebrew with English summary).

Navarro, S. and Calderon. M. 1979. Mode of action of low atmospheric pressures on Ephestia cautella (Wlk.) pupae. *Experientia* 35: 620-621.

Navarro, S. and Donahaye, E. 1990. Generation and application of modified atmospheres and fumigants for the control of storage insects. pp. 152-165. In Champ, B.R., Highley, E., and Banks, H.J. (1990). Fumigation and controlled atmosphere storage of grain: Proceedings of an International Conference, Singapore, 14-18 February 1989. ACIAR Proceedings No. 25, 301 p.

Navarro, S., and Gonen, M. 1970. Some techniques for laboratory rearing and experimentation with *Ephestia Cautella* (WLK) (Lepidoptera, Phycitidae). *J. stored Prod. Res.* 6, 187-189.

Navarro, S., Donahaye, E. and Fishman Svetlana 1994. The future of hermetic storage of dry grains in tropical and subtropical climates. In: *Proc. 6th Int. Working Conf. on Stored-Product Protection* (Edited by Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R.) Canberra, Australia, 17-23 April 1994, CAB International, Wallingford, Oxon, UK, 130-138.

Navarro, S., Donahaye, E. and Silberstein, B. 1988. Apparatus and method for storing grain. Israel Patent No. 87301.

Navarro, S., Donahaye, E., Caliboso, F. M. and Sabio, G.C. 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., R., D., Azrieli, A., Rindner, M., Phillips, T., Noyes, R., Villers, P., DeBruin, T., Truby, R. and Rodriguez, R. 2001.. Application of vacuum in transportable system for insect control. (eds) Donahaye, E.J., Navarro, S. and Leesch, J. *Proc. Int. Conf. on Controlled Atmospheres and Fumigation in Stored Products*, Fresno, CA 29 Oct. 3 Nov. 2000 (in press).

Navarro, S., Donahaye, E., Rindner, M. and Azrieli, A. 1990. Airtight storage of grain in plastic structures. *Hassadeh Quarterly,* 1(2), 85-88.

Navarro, S., Donahaye, J.E., Rindner, M., Azrieli, A. and Dias, R. 1999. Protecting grain without pesticides at farm level in the tropics. In: *Quality assurance in agricultural produce. Proc. 19th Asean/1st APEC Seminar on Postharvest Technology,* (Edited by Johnson, G.I., Le Van To, Nguyen Duy Duc and Webb, M.C.), Ho Chi Minh City, Vietnam 9-12 Nov. 1999. ACIAR Proceedings No. 100. 353-363.

Phillips, T. W., G. N. Mbata, R. T. Noyes, P. Villers, R. Trubey, R. Raudales, S. Navarro, J. Donahaye, and T. deBruin. 2000. Application of vacuum to control postharvest insect pests, pp.83-1- 82-2. In G. L. Obenauf and R. Obenauf (eds.), *Proceedings, 2000 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions*, 6-9 November 2000, Orlando, FL. Methyl Bromide Alternatives Outreach, Fresno, CA.

Silberstein, B., Navarro, S. and Donahaye, E. 1998. Application of Modified Atmospheres for the Control of Storage Pests in Sealed Plastic Storage Structures. In: *Plastics in Packaging; CIPA International Congress*, March 1997, Tel-Aviv, pp 69-77.

Soderstrom, E. L., Brandl, D. G., Hartsell, P. L., and B. Mackey (1991). Fumigants as treatments for harvested citrus fruits infested with *Asynonychus godmani* (Coleoptera: Curculionidae). J. econ. Ent**. 84** (3): 936-941.

UNEP 1998. United Nations Environment Programme, Montreal Protocol on Substances that Deplete the Ozone Layer, 1998: Assessment of Alternatives to Methyl Bromide. Methyl Bromide Alternatives Committee. Nairobi, Kenya

Winks, R. G. 1987. Strategies for effective use of phosphine as a grain fumigant and the implications of resistance. *Proc. 4th Int. Wkg. Conf. Stored Products Protection*. Tel Aviv, Israel. Sept. 86 [Eds. E. Donahaye and S. Navarro] pp. 335-344.

Zettler, L. H. 1993. Phosphine resistance in stored-product insects. In: Navarro, S. and Donahaye, E. ed., *Proceedings International Conference on Controlled Atmosphere and Fumigation in Grain Storages*, Winnipeg, Canada, June 1992 , Jerusalem, Caspit Press Ltd., 449-460.