Navarro, S. and Donahaye, E. [Eds.](1993) Proc. Int. Conf. Controlled Atmosphere and Fumigation in Grain Storages, Winnipeg, Canada, June 1992, Caspit Press Ltd., Jerusalem, pp. 331-341.

EFFECT OF DELIVERY RATE OF CARBON DIOXIDE ON ITS DISTRIBUTION IN CONCRETE SILOS AND ITS SUBSEQUENT IMPACT ON THE QUALITY OF STORED CORN

Wu-Kang PENG[1] and Chieh-Wu CHEN[2]

[1] Department of Plant Pathology and Entomology, National Taiwan University, Taipei, Taiwan

[2] Hsiaokang Byproduct Factory, Taiwan Sugar Co., Kaohsiung, Taiwan

ABSTRACT

In Taiwan, infestation by pests is the major factor adversely affecting both the quantity and quality of stored corn. To prevent damage, five trials were conducted involving the application of carbon dioxide (CO_2) to concrete silos containing 600 tons of corn. Liquid CO_2 in a tank passed through a water bath at 20°C. The gas was introduced into the silos through an aeration duct near the base. It moved upwards through the grain mass, while the air was expelled from the silo. Throughout CO_2 delivery, the concentrations of CO_2 in the silos were measured hourly by a thermal conductivity CO_2 analyzer. The data show that 1.3 or 1.5 m^3/min were the optimum delivery rates for 600 tons of corn stored in concrete silos. Over 90% CO_2 was obtained after 30 hr on the surface of the corn, and the nearer the base, the higher was the concentration of CO_2. After delivery was completed, the silos were sealed for 95 days. The concentrations of CO_2 then decreased progressively, the higher the level of the silo, the lower the concentration. The increase in the average number of insects, and fatty acid values from the beginning to the end of the trials was less in the CO_2 treated silos than in the control. The rise in temperature of the corn in the treated silos was less than that in the control at the corresponding monitoring points.

INTRODUCTION

In Taiwan, approximately 4-5 million tons of corn have been imported annually, and are stored in concrete silos for the manufacture of animal feed. During storage, there is usually damage by insects, especially by *Sitophilus zeamais* Motschulsky, *Tribolium castaneum* (Herbst), *Cryptolestes ferrugineus* (Stephens), and other less important species. To control insect infestation, fumigants have been applied as necessary. However, increased public concern for possible contamination of foodstuffs with pesticide residue has led to development of a non-toxic chemical protective method, involving a change in the in-store atmospheric gas composition that would be lethal to the insects. This offers a residue-free and safe alternative method to chemical fumigants.

One way to achieve this is by introducing nitrogen (N_2) or CO_2 from an external source into the store. The other way is to store the commodity in an airtight facility until respiration by living organisms decreases the oxygen (O_2) concentration and raises the CO_2 concentration (Howe, 1943; Howe and Oxley, 1944). Bailey (1955) stated that in airtight storage, the O_2 concentration would have to be reduced to 2% before mortality of insects could become complete. AliNiazee (1971) reported that adults of *T. castaneum* and *T. confusum* exposed to various mixtures of N_2 or helium and O_2 were killed when the O_2 concentration was reduced to 1.7% or less. However, most of the adults exposed to various mixtures of CO_2 and O_2 were killed due to the effect of CO_2 itself. The use of CO_2 has become a preferred method of pest control. Lindgren and Vincent (1970) reported that the exposure times required to produce 95% mortality (LT_{95} values) became shorter as the concentration of CO_2 increased. Therefore, CO_2 concentration in the store may be a factor affecting the efficacy of insect control. Trials on the effect of different release rates of CO_2 on its distribution in concrete silos and its subsequent impact on the quality of stored corn were conducted and their findings are presented in this paper.

MATERIALS AND METHODS

Each concrete silo used in five trials was surrounded by 4 silos of 10 m diameter (Fig. 1), each containing 600 tons of corn. All silos were equipped with built-in thermal detector cables (Fig. 1, T) connected to a control room. The sensors on the cables were set at depths of approximately 5, 10, 15, and 20 m from the top of the silos. The temperature at each monitoring point was recorded daily at 15:00 hr. Before the silo was filled with corn, 3-mm diameter plastic tubing was installed in each silo at depths of 0, 5, 10, 15 and 20 m from the top of the silo as well as in the head-space above the corn (Fig. 1, C). To check the concentration of incoming CO_2 during delivery, an additional gas sampling point was placed near the connection of the aeration duct with the silo (Fig. 1, B). All tubing was led outside the silos to a pump that pumped the gas samples from the silos into a thermal conductivity type CO_2 analyzer. Liquid CO_2 in a tanker was obtained from a commercial source. The truck together with the gas were weighed at the beginning and the actual amount of CO_2 used was obtained by subtracting the weight when the delivery had been completed. The method of applying CO_2 to the silo was by purging from the bottom (Jay, 1980). The tanker was connected by a high pressure hose, 5.0 cm in diameter, to an electrically-heated water bath (vaporizer), that was controlled automatically at 20°C (Fig. 1, H). After evaporation, the CO_2 passed a flowmeter and moved into the silo through the aeration duct near the base. The concentration of CO_2 during delivery was measured hourly. After delivery was completed, the supply of CO_2 was disconnected and the outlet was covered by a steel plate. To prevent possible leaks at the discharger, the manhole was made gastight by silicone sealant. The concentrations of CO_2 maintained in the silos were measured every 3-5 days. Corn samples were taken by a suction type sampler after the silos were loaded, at depths of 0, 3.7, 7.4, and 11 m from the grain surface, as well as at the discharger at the base (Fig. 1, D). Three sampling points at each level were selected. Four samples, each containing 800 ml of corn, were taken at each point. One was used for the fatty acid analysis by the AACC approved method (AACC, 1987). The insects in the other three samples were identified and counted.

RESULTS AND DISCUSSION

The concentrations of CO_2 in the silos during CO_2 delivery at rates of 1.0, 2.0 and 3.8 m^3/min are given in Tables 1-3. In the first trial, the release rate was 3.8 m^3/min (Table 1). The CO_2 percentages increased rapidly. Approximately 55% CO_2 was obtained at 10 m after the first hour, and 85% was measured in the head-space after 4 hr. When the delivery rate was reduced to 2.0 m^3/min in trial 2, the CO_2 concentration in the headspace rose more slowly and only 50–55% CO_2 was reached 7 to 11 hr after the purge had been initiated. Delivery was interrupted during the night between hours 11 and 23. After delivery was resumed at hour 23, a 50% CO_2 concentration was maintained for a considerable time at depths of 5 m and below.

Table 1 indicates that when CO_2 was delivered at 3.8 or 2.0 m^3/min, atmospheres at the top of the silo contained high concentrations of CO_2 for a short time only. It also implies that if CO_2 is delivered continuously at these rates, the atmosphere will be expelled through the top of the silo, rendering it an uneconomical process. Therefore, delivery was interrupted after 4 and 27 hr respectively.

Table 2 shows that at a rate of 1.0 m^3/min in Trial 3, only approximately 40% CO_2 was recorded below 15 m. In this trial, delivery was continuous but the front moved up very slowly.

Table 3 shows that when CO_2 was delivered at 1.3 m^3/min, 94% CO_2 was obtained at 20 m after the first hour. The front moved up slowly but homogeneously. At hour 29, 90% CO_2 was obtained at the surface of the corn. In the fifth trial, when the rate was increased to 1.5 m ^{3}/min, the front moved up faster than at 1.3 m^3/min, with the CO_2 concentration reaching 92% on the surface of the corn after 25 hr. The concentration of CO_2 below 10 m was 100%. The concentrations of CO_2 in the last two silos were regarded as sufficiently lethal to the pests, and the rates were regarded as optimal for this type of silo. After the continuous delivery for 27 or 30 hr had been completed, the silos were sealed. McGaughey and Akins (1989) showed that in circular corrugated steel bins filled with wheat to a depth of 1.5 m, the O_2 concentration dropped to zero when purged with CA at a rate of 14 m^3 /hr. The slower the rate, the longer it took.

Table 1: Percentage of CO_2 in the silo during delivery at rates of 3.8 and 2.0 m^3/min.

	time (hr)												
	1	2	3	4	5	7	9	11	23	24	25	26	27
Depth (m)	Rate of delivery: 3.8 m^3/min												
0	0	0	30	85	-								
5	0	67	67	75	-								
10	55	62	62	65	-								
15	45	50	50	55	-								
20	47	47	47	48	-								
entrance*	100	100	100	100	-								
Rate of delivery: 2.0 m^3/min													
0	0	0	0	0	0	50	50	55	0	2	9	20	41
5	0	0	0	70	67	70	70	60	40	48	55	58	61
10	0	0	53	62	57	58	60	51	47	49	53	55	57
15	1	50	50	56	51	53	51	45	45	48	50	50	50
20	39	48	45	50	45	48	46	41	41	45	45	45	45
entrance*	100	100	100	100	100	100	100	100	100	100	100	100	100

*entrance of CO_2 near the base of silo.

Table 4 in this study shows the change in CO_2 concentration in the last two trials during 51 days after delivery. The concentrations declined daily, especially over the first few days. The decline was more marked near the surface of the corn. Also, the lower concentrations were found at the higher levels of the silos. The purge and maintenance method would have been helpful to maintain CO_2 concentrations in the silos. If automatic timers and electrically-operated valves had been used (Jay *et al.*, 1970), the cost of maintenance of CO_2 concentration would have been cheaper and the application more convenient.

Table 2: Percentage of CO_2 in the silo during delivery at a rate of 1.0 m^3/min.

	time (hr)												
Depth (m)	1	3	5	7	9	22	24	26	28	30	32	34	35
0	0	0	0	0	0	0	0	0	0	1	1	1	1
surface*	0	0	0	0	0	0	0	0	0	1	1	1	1
5	0	0	0	0	0	0	0	0	0	1	1	1	1
10	0	0	0	18	44	2	3	1	0	1	1	1	1
15	0	0	42	44	44	31	43	45	40	42	47	43	45
20	33	37	37	38	40	38	40	40	40	40	41	40	40
entrance**	100	100	100	100	100	100	100	100	100	100	100	100	100

*surface of corn mass.
**entrance of CO_2 near the base of silo.

Table 3: Percentage of CO_2 in the silo during delivery at rates of 1.5 and 1.3 m^3/min.

	time (hr)															
Depth (m)	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	30
	Rate of delivery: 1.5 m^3/min															
0	0	0	0	0	0	0	0	0	7	25	43	55	65	70	-	-
surface*	0	0	0	0	0	0	0	28	47	55	55	85	92	93	-	-
5	0	0	0	0	0	8	86	94	97	98	95	97	97	97	-	-
10	0	0	0	97	100	100	100	100	100	100	100	100	100	100	-	-
15	0	91	100	100	100	100	100	100	100	100	100	100	100	100	-	-
20	97	98	100	100	100	100	100	100	100	100	100	100	100	100	-	-
entrance**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	-	-
	Rate of delivery: 1.3 m^3/min															
0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	15	23
surface*	0	0	0	0	0	0	0	0	0	9	30	60	77	85	90	90
5	0	0	0	0	0	0	0	61	89	90	90	93	93	94	95	95
10	0	0	0	40	97	99	100	100	100	100	100	100	100	100	100	100
15	0	76	98	100	100	100	100	100	100	100	100	100	100	100	100	100
20	94	99	100	100	100	100	100	100	100	100	100	100	100	100	100	100
entrance**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

*surface of corn mass.
**entrance of CO_2 near the base of silo.

Table 5 shows the levels of insect infestation in the corn before treatment, and 95 days after treatment. In the control silo, the corn contained an average of 0.1 insects/800 ml at the beginning and 6.8 insects/800 ml at the end of the period. Over the same period, the number of insects in the corn in the treated silos of trials 4 and 5 increased from 1.5 to 2.7, and from 0.2 to 1.8 insects/800 ml respectively. It was also found that a smaller number of insects were present in the lower layers than at the upper layers. This was due to the fact that a higher percentage of CO_2 were maintained in the lower layers, and the lowest concentrations were recorded at the surface (Table 4).

Table 4: Changes in CO_2 concentration (%) in the silo after delivery.

		Days after treatment											
Depth (m)	At end of delivery	1	3	5	7	10	12	14	17	22	29	35	51
		Rate of delivery: 1.5 m^3/min											
0	70	1	1	1	1	1	1	1	1	1	1	3	4
surface*	93	14	2	1	1	1	1	1	1	1	1	4	4
5	97	33	5	2	1	1	1	1	1	2	2	4	5
10	100	77	25	14	10	5	4	4	4	3	3	4	6
15	100	95	60	35	22	15	13	9	8	6	4	4	6
20	100	99	90	71	55	39	34	27	22	17	12	9	6
entrance**	100	100	95	83	69	51	44	36	29	20	15	8	7
		Rate of delivery: 1.3 m^3/min											
0	23	1	1	1	1	1	1	1	1	1	1	2	3
surface*	90	5	1	1	1	1	1	1	1	1	2	2	3
5	95	7	2	1	1	1	1	1	1	1	2	2	3
10	100	45	10	5	4	1	1	1	1	1	2	3	4
15	100	90	32	17	10	7	5	5	4	4	3	3	4
20	100	98	73	45	31	21	17	15	12	8	7	5	4
entrance**	100	100	87	60	40	27	22	17	14	9	7	2	4

*surface of corn mass.
**entrance of CO_2 near the base of silo.

The mortality of insects depends on the concentration of CO_2 to which they are exposed (Harein and Press, 1968; Lindgren and Vincent, 1970). When fumigants such as methyl bromide are used in combination with CO_2, the susceptibility of insects increases (Williams, 1985; Donahaye and Navarro, 1989). If an additional amount of CO_2 could be applied to the surface of the corn just before the delivery is completed, to maintain the CO_2 concentration for a longer period, or, if ether phosphine or methyl bromide could be applied at the surface, the efficacy of insect control, especially at the surface, could be improved greatly.

Table 5: Number of live insects, fatty acid value and moisture content of the corn (800 ml) sampled before CO_2 delivery, and in storage for 95 days after treatment.

Location* of samples	No. live insects		Fatty acid value***		Moisture content (%)	
	before	after	before	after	before	after
Rate of Delivery: 1.5 m^3/min						
0	0.5	6.5	8.6	14.1	14.5	14.7
3.7	0.4	0.7	9.1	10.8	14.4	13.8
7.3	0	0.9	11.2	11.6	14.2	13.6
11	0	0.5	11.9	12.0	14.4	13.7
bottom**	0	0	10.3	12.5	14.0	13.7
Average	0.2	1.8	10.2	12.2	14.3	13.9
Rate of Delivery: 1.3 m^3/min						
0	0.1	8.1	7.1	17.7	13.9	14.1
3.7	0	0.3	8.5	14.2	14.1	13.9
7.3	6.2	2.6	7.6	14.3	13.0	14.2
11	0.9	1.6	7.3	12.3	14.1	13.9
bottom**	0.4	0.7	7.8	13.9	14.1	13.7
Average	1.5	2.7	7.7	14.5	13.8	14.0
Control						
0	0	18.8	8.3	32.8	14.0	13.5
3.7	0	4.5	8.0	29.2	14.4	13.8
7.3	0	2.9	8.7	13.2	14.4	13.7
11	0.1	2.6	10.4	13.0	14.5	14.0
bottom**	0.3	5.1	11.8	11.2	14.4	13.3
Average	0.1	6.8	9.4	19.9	14.3	13.7

*meters below the surface of corn.
** bottom of silo.
*** mg KOH/g oil.

The temperatures recorded from the corn in the silos (trials 4 and 5) after the delivery are given in Table 6. Over the first 40 days, the temperatures remained almost unchanged. However, they started to rise after day 50. The temperatures measured on day 95, when compared with those at the beginning, show that in the CO_2 treated silos, the increase in temperature was less than that in the control at the corresponding points.

CO_2 is about 1.5 times heavier than air. When CO_2 was delivered from the bottom of the silo, the air in the intergranular airspace was displaced by CO_2, and moved gradually upwards, and was finally expelled outside the silo. When CO_2 was delivered at a rate of 2 m^3/min, or faster, the gas moved too fast to distribute evenly. The CO_2 front was not uniform in the corn bulk as it moved up the silo, and a turbulence occurred near the front within the silo. Therefore, CO_2 and air mixed rapidly, and both were expelled to the outside air. This phenomenon could be more serious if the delivery rate is increased.

Table 6: Temperature of the corn (^oC) measured after CO_2 delivery.

	5 metres			10 metres			15 metres			20 metres		
Days after delivery	S_1*	S_2	S_0	S_1	S_2	S_0	S_1	S_2	S_0	S_1	S_2	S_0
0	19	21	19	20	20	18	20	20	18	21	21	21
1	19	21	19	20	20	18	20	20	18	21	21	21
5	19	20	19	20	19	18	20	20	18	21	22	22
10	19	20	19	20	20	18	20	20	18	21	22	22
20	18	20	19	19	19	17	19	19	18	21	20	21
30	18	20	19	19	19	18	19	19	18	21	21	21
40	19	20	19	20	19	18	20	19	18	21	21	21
50	21	22	21	21	21	19	20	20	19	22	22	23
60	22	24	23	22	22	20	21	21	20	23	23	24
70	23	25	24	23	23	21	22	22	21	23	23	24
80	24	27	27	24	24	22	23	22	22	24	24	25
90	26	30	32	25	26	24	24	23	24	24	24	26
95	27	33	35	27	27	27	25	24	25	25	25	27
Temp. difference**	+8	+12	+16	+7	+7	+9	+5	+4	+7	+4	+4	+6

*S_1 , S_2 are the CO_2 treated (1.5, 1.3 m^3/min), and S_0 is the control silo.

**Temperature difference between end of delivery and after 95 days.

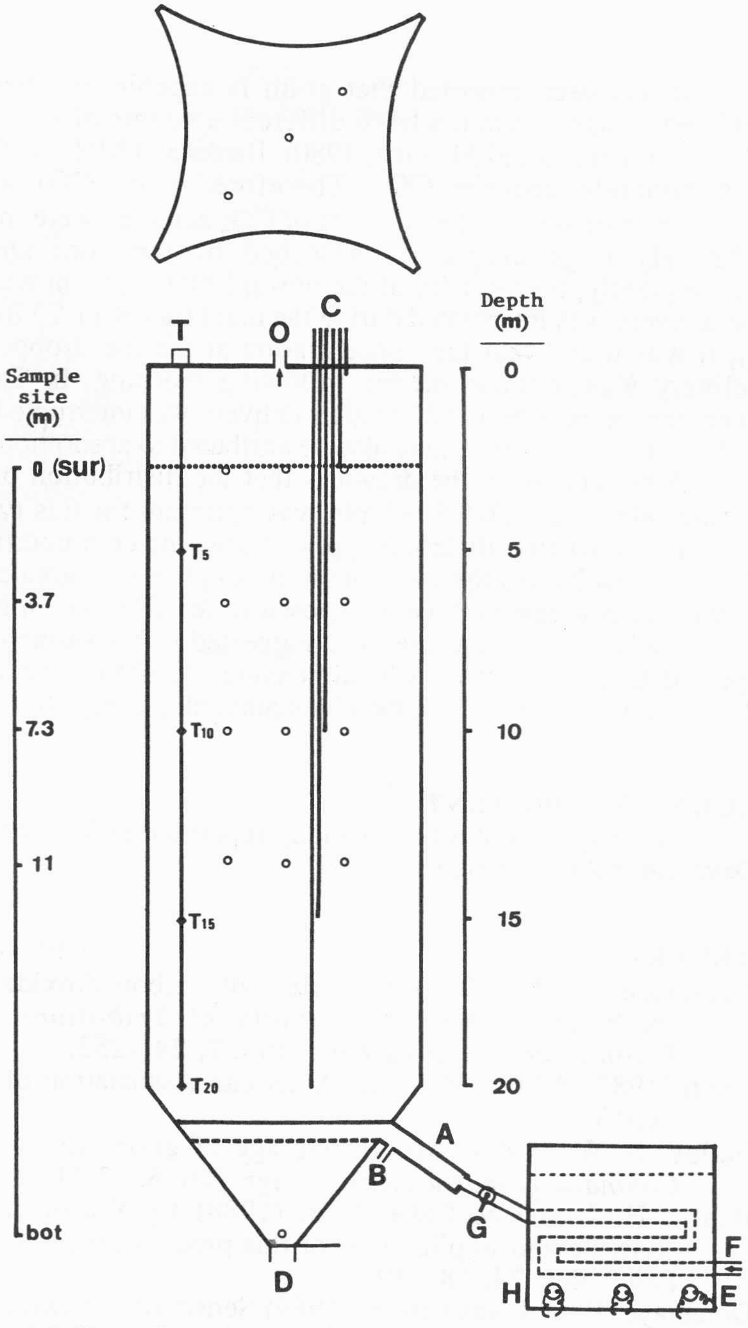

Fig. 1: The experimental silos and accessory equipment. (A is the aeration duct used for introduction of CO_2; B and C are gas sampling tubes; D is the silo discharge outlet; E and H are the electrical water heater; O is the outlet duct; T is the temperature monitoring cable. Corn samples were taken at 0, 3.7, 7.4, and 11 m below the surface of the corn bulk as well as at the bottom from the discharge outlet).

It has been reported that grain is capable of adsorbing CO_2, and different kinds of grain adsorb different amounts of CO_2 (Mitsuda *et al* ., 1973; Yamamoto and Mitsuda, 1980). Banks and McCabe (1988) also found that concrete adsorbs CO_2. Therefore, when CO_2 was delivered at 1.0 m^3/min or slower, the amounts of CO_2 supplied were insufficient, with a relatively large proportion adsorbed by the corn and the concrete. Consequently, the velocity of the upward moving front was reduced. When the delivery was interrupted during the night (hours 11-23 in trial 1, see Table 1), it was found that the concentration at the top dropped to zero before delivery was resumed on the following morning. In Table 2, the same phenomenon occurred at 22 hr after delivery was interrupted between hours 9 and 22. This occurrence may also be attributed to absorption.

A conclusion to be drawn is that the distribution of CO_2 in the silo during release at 1.3-1.5 m^3/min was optimum for this type of silo. But it must be noted that different types of silos or commodities could lead to different results. As the gas front moves upwards, a greater volume of corn as well as concrete surface is exposed to the CO_2, and a greater amount of CO_2 is adsorbed. Therefore, it is suggested that a variable delivery rate be applied to suit different silo dimensions to obtain the most satisfactory distribution pattern of CO_2, thereby maintaining the quality of the stored corn.

ACKNOWLEDGMENT

This experiment was financially supported by Taiwan Grains and Feeds Development Foundation.

REFERENCES

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

Anon (1987) AACC Methods. American Association of Cereal Chemists (AACC).

Bailey, S. W. (1955) Airtight storage of grain: its effect on the insect *Calandra granarius. Aust. J. Agr. Res.* **6,** 33-51.

Banks, H. J. and McCabe, J. B. (1988) Uptake of carbon dioxide by concrete and implications of this process for grain storage. *J. stored Prod. Res.* **24,** 183-192.

Donahaye, E. and Navarro, S. (1989) Sensitivity of two dried fruit pests to methyl bromide alone, and in combination with carbon dioxide or under reduced pressure. *Trop. Sci.* **29,** 9-14.

Harein, P. K. and Press, A. F. (1968) Mortality of stored-peanut insects exposed to mixtures of atmospheric gases at various temperatures. *J. stored Prod. Res.* **4,** 77-82.

Howe, R. W. (1943) An investigation of the changes in a bin of stored wheat infested by insects. *Bull. Entomol. Res.* **34,** 145-158.

Howe, R. W. and Oxley, T. A. (1944) The use of carbon dioxide production as a measure of infestation by insects. *Bull. Entomol. Res.* **35,** 11-12.

Jay, E. G. (1980) Methods of applying carbon dioxide for insect control in stored grain. USDA AAT-S-13, 7 pp.

Jay, E. G., Redlinger, L. M. and Laudani, H. (1970) The application and distribution of carbon dioxide in a peanut (groundnut) silo for insect control. *J. stored Prod. Res.* **6,** 247-254.

Lindgren, D. L. and Vincent L. E. (1970) Effect of atmospheric gases alone or in combination on the mortality of granary and rice weevils. *J. econ. Entomol.* **63,** 1926-1929.

McGaughey, W. H. and Akins, R. G. (1989) Application of modified atmospheres in farm grain storage bins. *J. stored Prod. Res.* **25,** 201-210.

Mitsuda, H., Kawai, F., Kuga, M. and Yamamoto, A. (1973) Mechanisms of carbon dioxide gas adsorption by grains and its application to skin-packaging. *J. Nutr. Sci. Vitaminol.* **19,** 71-83.

Williams, P. (1985) Toxicity of methyl bromide in carbon dioxide enriched atmospheres to beetles attacking stored grain. *Gen. Appl. Entomol.* **17,** 17-24.

Yamamoto, A. and Mitsuda, H. (1980) Characteristics of carbon dioxide gas adsorption by grain and its components. In: *Controlled Atmosphere Storage of Grains,* (Edited by Shejbal, J.), pp. 247-258. Elsevier Sci. Publ. Co., Amsterdam, Holland.