Marketing Research Report No. 794

COMPARATIVE STUDY OF METHODS OF DISTRIBUTING METHYL BROMIDE IN FLAT STORAGES OF WHEAT: GRAVITY-PENETRATION, SINGLE-PASS, AND CLOSED-RECIRCULATION

Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture.

Buildings made by the Behlen Manufacturing Co. and the Butler Manufacturing Co. were selected for this study because they represented two common types of flat storage buildings with different aeration system designs—one using crosswise ducts, the other lengthwise ducts. Because of the significant differences between the grain-load characteristics in relation to the aeration system design in the two types of buildings, results from the single-pass and closed-recirculation fumigation cannot be directly compared. Valid comparisons can be made only between the three methods of application used within each type of building. Differences in the results from gravity-penetration fumigation have no relationship to the design or type of construction of either building, but resulted from the different physical condition of the two grain masses and the influence of related factors such as dockage, surface area, and grain load. Apparent comparisons in this report should not be used as criteria for the evaluation of one type of building against the other.

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PRECAUTIONS

To protect the ultimate consumer of food crops and animal products, the use of pesticides is regulated under the Federal Insecticides, Fungicides, and Rodenticides Act and the Federal Food, Drug, and Cosmetic Act. The rate and method of application and any resulting residues must comply with the requirements of these two acts. Products in violation of these two acts are subject to Federal action. If methyl bromide is used according to the instructions given in this publication, there should be no violation of the laws.

The established tolerances for grains, in parts per million, of inorganic bromides resulting from the use of the fumigant reported in this publication are:

Grain	*Tolerances* (p.p.m.)
Barley	50
Corn	50
Oats	50
Popcorn	240
Rice	50
Rye	50
Sorghum	50
Wheat	50

Methyl bromide is an odorless and invisible poisonous gas that requires special devices for detection. It should be used and handled with extreme care.

The directions and precautions on the label should be followed carefully. The correct gas mask and canister should always be worn when using methyl bromide.

PROTECT

Use Pesticides Safely

FOLLOW THE LABEL

U.S. DEPARTMENT OF AGRICULTURE

COMPARATIVE STUDY OF METHODS OF DISTRIBUTING METHYL BROMIDE IN FLAT STORAGES OF WHEAT: GRAVITY-PENETRATION, SINGLE-PASS, AND CLOSED-RECIRCULATION

By C. L. Storey, *entomologist,*[1] *Market Quality Research Division Agricultural Research Service*

SUMMARY

To evaluate the effectiveness of the three basic methods of fumigation—gravity-penetration, single-pass, and closed-recirculation—three identical flat-storage Behlen buildings and three identical flat-storage Butler buildings, each containing about 100,000 bushels of wheat, were treated with methyl bromide at the rate of 2 pounds per 1,000 cubic feet. Distribution of the methyl bromide and the resulting mortality of test insects were determined in more than 100 sample locations in each building.

Superiority of the closed-recirculation method is clearly demonstrated by the data on fumigant distribution and insect mortality. The difference in results justifies the expense of adding return ducts to existing aeration systems to permit recirculation of the fumigant. The effectiveness of the gravity-penetration and single-pass fumigations was limited by the lack of uniformity in distribution of the fumigant concentrations.

INTRODUCTION

Single-pass and closed-recirculation fumigations were conducted by Mid-West Grain Insects Investigations laboratory in various types of flat grain-storage buildings between 1953 and 1955 to demonstrate the feasibility of using aeration equipment to distribute grain fumigants.[2] Direct comparisons between the results obtained in these fumigation tests were impractical and often misleading because of the great variation in the storage buildings and aeration equipment employed. Now that identical flat grain-storage buildings are available, comparable tests can be made for proper evaluation of the three basic methods of fumigant distribution: gravity-penetration, single-pass, and closed-recirculation. Such data should help grain-storage owners decide whether the expense of adding equipment to permit more effective fumigation is warranted.

Cooperators in the 1960–61 fumigation studies presented in this report include the Dow Chemical Co., Midland, Mich.; the Behlen Manufacturing Co., Inc., Columbus, Nebr.; the Butler Manufacturing Co., Kansas City, Mo.; Consumers Cooperative Association, Kansas City, Mo.; Wamego Milling Co., Wamego, Kans.; Oak Hill Grain Co., Oak Hill, Kans.; Mingo Cooperative Elevator, Mingo, Kans.; and the Hart Grain Co., Kansas City, Mo.

GENERAL PROCEDURES

Three identical Behlen buildings and three identical Butler buildings were treated with methyl bromide applied at the rate of 2 pounds

[1] R. L. Ernst of the Market Quality Research Division's Mid-West Grain Insects Investigations laboratory in Manhattan, Kans., assisted in all of the tests.

[2] Phillips, G. L. EXPERIMENTS ON DISTRIBUTING METHYL BROMIDE IN BULK GRAIN WITH AERATION SYSTEMS. U.S. Dept. Agr. AMS–150, 60 pp., illus. January 1957.

per 1,000 cubic feet for an exposure period of 24 hours.[3] Each Behlen building had a capacity of about 137,000 cubic feet of air space and contained about 100,000 bushels of wheat. The Butler buildings each had a capacity of about 150,000 cubic feet of air space and contained about 100,000 bushels of wheat.

Two of the Behlen buildings contained identical aeration systems. These consisted of two 18-inch-diameter ducts extending across the width of the building about 23 feet from the ends. The third building contained three crosswise ducts, but the gravity-penetration method was used in this building. Tubeaxial aeration fans 22½ inches in diameter were used in the single-pass and closed-recirculation fumigations. Each fan was powered by a 220-v., 3-hp., 3-phase electric motor.

Each of the three Butler buildings had two aeration ducts extending down the length of the building about 15 feet from each side. The ducts consisted of a solid, half-round cover sitting on a 6-inch screen-covered angle-iron base, which allowed for air passage but excluded the grain. Total cross-sectional area of the duct system was 3.5 square feet. Tubeaxial aeration fans 21 inches in diameter were used in the single-pass and closed-recirculation fumigations. Each fan was powered by a 220-v., 3-hp., 3-phase electric motor.

In each of 20 locations, a tier of 5 probes was inserted into the grain. The probes, consisting of combination gas sample and test insect points, were placed at 2½-, 5-, 10-, and 15-foot depths and at the bottom. Fumigant concentrations at each location were determined with a thermal conductivity (T/C) instrument at intervals of 1, 4, 8, and 24 hours after release of the fumigant. A sample of wheat containing immature rice weevils, *Sitophilus oryzae* (L.), and a screen cage containing adult confused flour beetles, *Tribolium confusum* (Jacquelin du-Val), were placed inside a short section of perforated pipe attached to the bottom of each probe. Additional cages of test insects were placed on the grain surface and in the overhead space. Mortality counts of the adult test insects were made 2 weeks after the 24-hour exposure period. Emergence counts of the immature rice weevils were made 6 weeks after their exposure to the fumigant, and mortality estimates were based upon relative numbers of adult rice weevils emerging from treated and untreated samples.

The probe placement pattern was slightly different for the Butler and Behlen buildings, but the same within each type of building. In general, the pattern was designed to measure gas concentrations and mortality of test insects in parts of the grain mass having high, low, and average rates of airflow. In each test the probes were placed (1) along the 4 sides of the building, (2) directly above the ducts, (3) in areas between the ducts, and (4) in areas between the ducts and the sides of the buildings.

After a 24-hour exposure period, the aeration equipment was operated to evacuate the fumigant. When it was safe to enter the building, the test insects were retrieved and taken to the laboratory for observation.

PROCEDURES AND RESULTS FOR EACH TEST

Gravity-Penetration

The two gravity-penetration tests were conducted in September 1960. After the probes had been placed and the building had been sealed, methyl bromide was released into the overhead space above the wheat surface. Fumigant application lines consisted of ¼-inch-ID polyethylene tubing fitted with plastic tees. Nozzles made from short sections of ¼-inch perforated pipe were attached to each side of the plastic tee as shown in figure 1. A total of 12 nozzles, in 3 rows of 4 nozzles each, were spaced to distribute the fumigant evenly throughout the headspace. A polyethylene sheet about 1 yard square was placed on the grain surface directly beneath each nozzle to prevent dripping of unvolatilized methyl bromide on the wheat surface.

The air during application of the fumigant was calm, and only a slight southwest wind blew during the entire 24-hour exposure period. Daytime temperatures were in the eighties. Grain

[3] The methyl bromide used in the fumigation tests is marketed under the trade name "Profume." Profume is composed of 98 percent of methyl bromide and 2 percent of chloropicrin which serves as a warning agent.

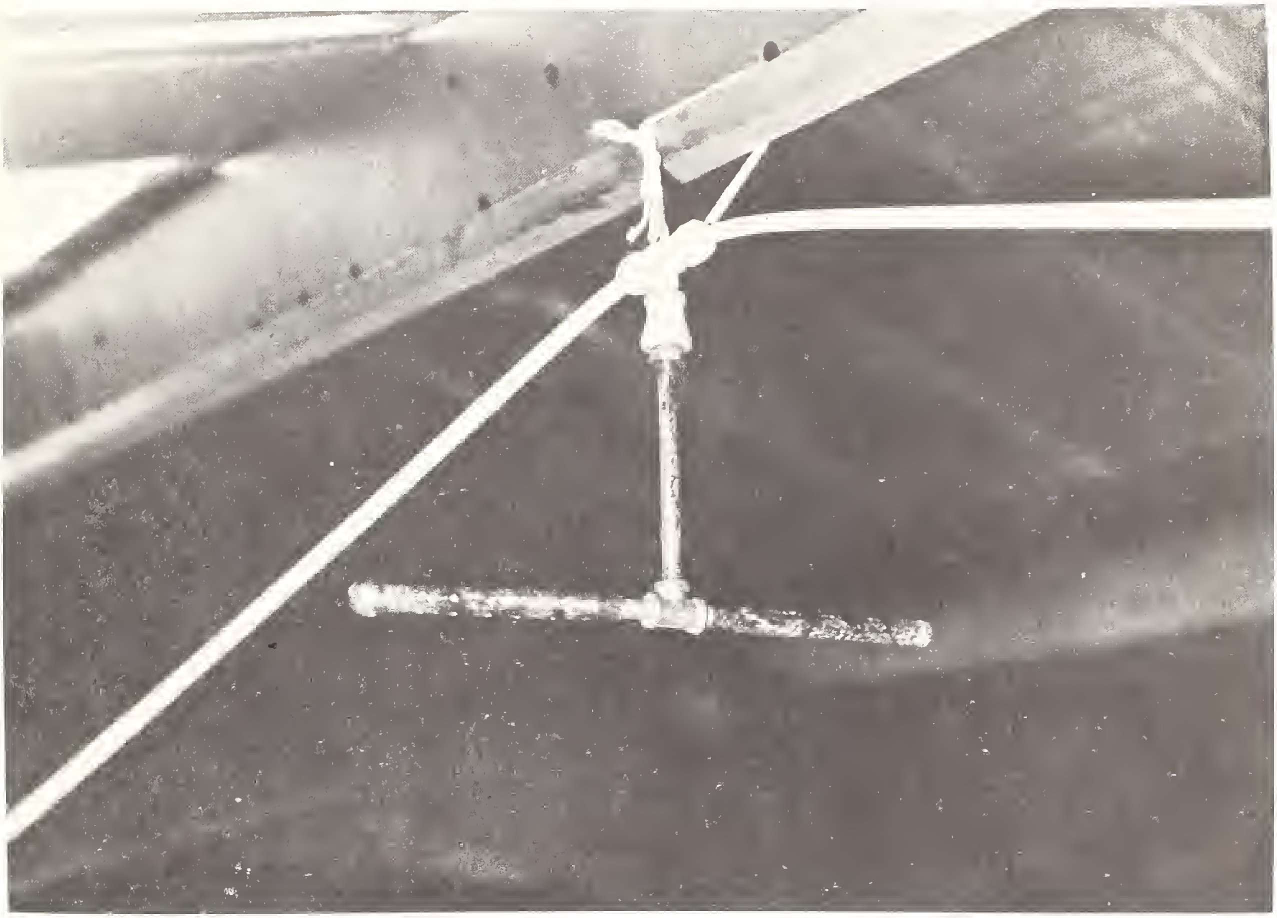

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FIGURE 1.—Fumigant application nozzle suspended above wheat surface.

temperatures in the Behlen building ranged between 75° and 101° F. and in the Butler building between 63° and 91° F. In general, the temperatures increased with depth of grain.

The wheat surface in the south end of the Behlen building was covered with a thick layer of dust which had filtered out from an overhead auger used to load boxcars. The grain surface in the Butler bin was in good condition and relatively free of dust.

Results of the T/C analysis and mortality counts of test insects obtained in the Behlen and Butler buildings, respectively, are summarized in tables 1 and 2. At the 1-hour sampling period, the average concentrations generally decreased with grain depth in the Behlen building, but were more erratic in the Butler building. In subsequent readings, the fumigant concentrations in the Behlen building were higher in the upper 10 feet of grain than at the lower depths. Distribution data obtained in the Butler building indicated that much of the methyl bromide moved rapidly through the grain mass to the bottom levels and remained there during the 24-hour exposure period. There was a wide range in gas concentrations throughout the grain in the gravity-penetration fumigations. Very few zero readings were obtained in the Behlen building, but in the Butler building there were many zeros at all sampling levels each time concentration data were obtained. Average mortalities of the test insects correlated well with the gas concentration data. Mortality was complete in test insect cages placed on the wheat surface and in the overhead space above the wheat surface. However, examination of wheat

TABLE 1.—*Average mortality of test insects and the total amount of methyl bromide recorded in each sampling level in fumigations of Behlen flat-storage buildings by the gravity-penetration, single-pass, and closed-recirculation methods*

Sampling level and depth in grain	Method of fumigation [1]	Total methyl bromide recorded per sampling level								Average mortality at each sampling level [2]			
		1-hour		4-hour		8-hour		24-hour		Adult confused flour beetles		Immature rice weevils	
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
		Oz.	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Overhead	All methods									100.0		100.0	
Surface	All methods									100.0		100.0	
2½ ft	Gravity-penetration	62.0	14–196	30.1	5–78	26.5	8–59	15.0	9–26	89.5	0–100	94.2	9–100
	Single pass	17.7	0–46	13.4	0–25	9.8	1–18	5.9	0–12	82.9	3–100	94.9	13–100
	Closed-recirculation	25.6	10–72	15.5	4–29	11.3	3–22	4.5	0–11	100.0		99.4	88–100
5 ft	Gravity-penetration	54.9	16–190	28.5	3–83	25.0	7–57	15.2	9–26	80.3	0–100	88.7	9–100
	Single-pass	15.9	0–47	10.7	0–29	8.9	0–20	5.1	0–13	75.9	0–100	90.7	17–100
	Closed-recirculation	29.2	11–140	15.6	4–38	11.8	3–23	5.0	0–16	100.0		100.0	
10 ft	Gravity-penetration	43.7	8–164	33.0	1–83	30.7	6–69	16.3	8–29	75.3	0–100	80.1	1–100
	Single-pass	17.4	0–44	12.4	2–38	9.4	0–22	6.6	0–18	75.6	0–100	91.8	17–100
	Closed-recirculation	25.5	13–50	15.2	3–26	11.5	4–19	6.2	0–16	96.2	24–100	99.8	96–100
15 ft	Gravity-penetration	21.6	4–60	16.4	0–70	21.9	1–59	14.2	5–26	67.6	0–100	78.4	1–100
	Single-pass	18.5	1–44	13.9	2–27	10.3	0–22	7.9	0–20	81.8	3–100	98.1	65–100
	Closed-recirculation	23.9	13–35	15.0	4–27	11.0	3–18	7.8	1–19	99.7	94–100	100.0	
Bottom	Gravity-penetration	25.0	2–320	17.7	0–240	18.4	0–154	13.6	0–70	45.8	0–100	51.8	0–100
	Single-pass	20.1	5–37	16.9	3–42	12.2	3–30	9.1	1–19	89.9	0–100	99.7	94–100
	Closed-recirculation	24.0	12–35	17.8	3–51	15.9	3–97	11.1	0–56	99.5	91–100	100.0	

[1] Dosage: 2 pounds of methyl bromide per 1,000 cubic feet.

[2] Exposure time: 24 hours.

TABLE 2.—*Average mortality of test insects and the total amount of methyl bromide recorded in each sampling level in fumigations of Butler flat-storage buildings by the gravity-penetration, single-pass, and closed-recirculation methods*

Sampling level and depth in grain	Method of fumigation [1]	Total methyl bromide recorded per sampling level								Average mortality at each sampling level [2]			
		1-hour		4-hour		8-hour		24-hour		Adult confused flour beetles		Immature rice weevils	
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
		Oz.	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Oz.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Overhead	All methods									100.0		100.0	
Surface	Gravity-penetration									100.0		100.0	
	Single-pass									72.7	0–100	90.2	11–100
	Closed-recirculation									100.0		100.0	
2½ ft	Gravity-penetration	20.6	0–84	14.4	0–56	10.3	0–30	4.2	0–17	45.8	0–100	64.4	0–100
	Single-pass	12.9	0–63	8.4	0–19	6.1	0–18	5.4	1–10	73.8	0–100	88.3	0–100
	Closed-recirculation	22.2	8–47	14.1	9–40	13.1	7–28	6.8	0–16	100.0		99.9	98–100
5 ft	Gravity-penetration	11.8	0–68	13.0	0–48	8.9	0–27	4.7	0–18	45.3	0–100	58.2	0–100
	Single-pass	14.4	0–104	9.5	0–42	6.9	0–19	5.4	1–12	75.8	0–100	91.0	0–100
	Closed-recirculation	22.9	9–50	15.4	10–66	14.8	8–44	7.2	0–18	100.0		100.0	
10 ft	Gravity-penetration	20.9	0–138	11.2	0–62	6.9	0–28	5.3	0–20	42.7	0–100	56.4	0–100
	Single-pass	23.7	0–280	12.3	0–96	8.8	0–37	6.6	0–17	85.0	0–100	92.6	0–100
	Closed-recirculation	23.0	8–48	13.6	9–24	13.2	4–30	7.5	0–14	100.0		100.0	
15 ft	Gravity-penetration	4.9	0–25	5.7	0–24	4.0	0–21	4.5	0–19	42.3	0–100	60.4	0–100
	Single-pass	17.7	0–104	11.6	0–74	8.4	0–35	6.9	0–16	85.0	0–100	90.8	0–100
	Closed-recirculation	21.8	8–33	12.5	4–18	12.0	8–16	6.6	0–13	100.0		100.0	
Bottom	Gravity-penetration	27.6	0–130	43.9	0–146	36.3	0–142	15.2	0–86	65.3	0–100	75.9	0–100
	Single-pass	18.4	0–180	15.7	0–160	13.1	0–108	9.3	0–50	85.2	0–100	90.4	0–100
	Closed-recirculation	20.7	9–34	13.3	4–46	14.7	3–70	6.7	0–26	100.0		100.0	

[1] Dosage: 2 pounds of methyl bromide per 1,000 cubic feet.

[2] Exposure time: 24 hours.

samples taken below undisturbed dusty surface areas in the Behlen building revealed a high rate of survival in the natural insect populations. No live insects were found in surface areas free from dust.

Single-Pass

The single-pass tests were conducted in late September and early October 1960. After the probes had been placed, the aeration fans were reversed so that they would force air up through the wheat mass instead of in the downward direction normally used in cooling grain. Reversing the normal direction of air movement produced a slight increase in air pressure within the wheat mass over the outside atmospheric pressure. Negative air pressure within the wheat during normal downward air movement introduces fresh air along wall seams. Positive air pressure within the wheat when the fans are reversed forces mixed air and fumigant out through any leaks, insuring penetration of the methyl bromide to the building walls. In addition, when air moves upward through the grain, the airflow is somewhat more uniform in the long duct systems used in flat storages.

With each of the fans operating, static pressure readings were made with a manometer from each sample location within the wheat mass. It was estimated from these readings that a minimum fan operation time of 20½ minutes in the Behlen buildings and about 25 minutes in the Butler buildings would be required for a single air change in the center of the buildings, where the rate of airflow was lowest. The highest rate of airflow was recorded directly above one of the aeration ducts at a point nearest to the fan outlet. A single air change in this part of the wheat mass took 4½ minutes in the Behlen building and 5 minutes in the Butler building. Because of the wide range between the fastest and slowest air change times, it was decided that fan operations of 20½ and 25 minutes, the air change time at the slowest rate of airflow, would result in too great a loss of fumigant pushed out of the building. To reduce the loss of fumigant from that part of the wheat mass having a high rate of airflow, and still distribute the fumigant in parts of the wheat mass where the rate of airflow was low, a fan operation time was selected by averaging the ten slowest air change times found in the 20 sample locations. The average air change time was approximately 13½ minutes in the Behlen building and 14½ in the Butler building.

Before the fumigant was released in the Behlen building, the overhead ventilators were sealed from inside the building because the 30-degree pitch of the roof made access to the outside of the ventilators rather difficult and dangerous. The access doors in each end of the building were left open during operation of the fans and then sealed after the fans had been stopped. Before the fumigant was released in the Butler building, the access doors in each end were sealed. The overhead ventilators were left uncovered while the fans were operating and then sealed after the fans had been stopped.

With both fans operating, 90 percent of the total dosage of methyl bromide was released directly into the aeration duct. After the fans had been stopped, the remaining 10 percent of the total dosage was released into the overhead space through a single line equipped with 4 nozzle outlets spaced down the length of the center of the building.

During the application of the methyl bromide, an attempt was made to determine the concentrations of fumigant pushed out through the open access doors or the ventilators during the time the fans were operating. Methyl bromide was first detected at the north door of the Behlen building 9 minutes after release of the fumigant. After 10 minutes, the reading was 5 ounces per 1,000 cubic feet and increasing. After 12 minutes, the reading was 31 ounces per 1,000 cubic feet and still increasing. The final reading, taken at the time the fans were stopped, was 38 ounces per 1,000 cubic feet. At the south access door, no methyl bromide was detected until 13 minutes after release of the fumigant; and the reading when the fans were stopped was only 8 ounces per 1,000 cubic feet. The lower readings at the south door may have been caused by a moderate southwesterly wind which blew during the test and could have obscured or diluted the readings. Fumigant concentrations at the ventilators in the Butler building were first detected 9 minutes after release of the fumigant. At 10 minutes, the reading was 10 ounces per 1,000 cubic feet and increasing. The final reading, taken when the fans were stopped, was 20 ounces per 1,000 cubic feet and still increasing.

Grain temperatures ranged from 42° to 81° F. in the Behlen building and from 63° to 88° in the Butler building. In general, the temperatures increased with depth of the grain.

In both tests, the wheat surface was in good condition and relatively free of dust.

Results of the T/C analyses and mortality counts of test insects for each building are in tables 1 and 2. At the 1-hour reading, average methyl bromide concentrations were more similar at each level in the Behlen building than in the Butler building. The gas concentration relationships that existed at the 1-hour reading at the 5 levels remained unchanged throughout the 24-hour exposure period. At each sampling level the concentrations dropped by 50 percent or more during the 24-hour exposure period; however, the range in concentrations was not as great in the single-pass method as it was in the gravity-penetration method. Again, there were fewer zero readings in the Behlen building than in the Butler building. The highest loss in the total fumigant concentrations occurred at the 5-foot level in the Behlen building and at the 10-foot level in the Butler building. The least reduction occurred at the bottom level in both buildings. There is little evidence to indicate any marked settling of the fumigant after its initial distribution in the Behlen building, but the concentration data from the Butler building suggest that some settling did occur.

As a basis for comparison, the 20 gas-sampling tiers in each building were grouped according to their position in the wheat mass in relation to the aeration ducts. The groups consisted of all the sampling tiers (1) directly above the aeration ducts, (2) along walls parallel to the ducts and in the corners, (3) midway between and along the length of the ducts, and (4) midway between the ducts and walls (only in the Behlen building). Average estimated times for a single air change and average test insect mortality for each group are in tables 3 and 4. The estimates of air change times were based on the movement of air through a 1-foot-square column of wheat extending from the surface of the grain to the building floor and across to the nearest aeration duct. These estimated air change times represent only the air movement through the longest possible air path. As would be expected, the shortest air change times were at the tiers nearest the ducts and the longest at the tiers located in the deepest parts of the wheat mass midway between the ducts.

The average mortality of test insects correlated well with the concentrations of methyl bromide at the different levels. Mortality was complete in the insect cages in the overhead

TABLE 3.—*Average estimated air change times based on static pressure readings and average test insect mortality obtained in a single-pass fumigation of a Behlen flat-storage building*

Group	Average mortality		Average air change time
	Adult confused flour beetles	Immature rice weevils	
	Percent	*Percent*	*Minutes*
Group I:			
Above ducts	83.2	92.5	7.4
Group II:			
Corners and walls parallel to ducts	85.7	99.9	12.1
Group III:			
Between ducts	84.7	95.8	14.2
Group IV:			
Between ducts and walls	75.1	95.8	9.6

TABLE 4.—*Average estimated air change times based on static pressure readings and average test insect mortality obtained in a single-pass fumigation of a Butler flat-storage building*

Group	Average mortality		Average air change time
	Adult confused flour beetles	Immature rice weevils	
	Percent	*Percent*	*Minutes*
Group I:			
Above ducts	100.0	100.0	7.9
Group II:			
Corners and walls parallel to ducts	75.2	88.8	13.5
Group III:			
Between ducts	69.4	83.6	16.4

space of both buildings and on the wheat surface in the Behlen building. There was considerable survival in the cages on the wheat surface in the Butler building. In both buildings, 20 of 100 insect sample locations within the wheat mass had less than 90 percent mortality of adult confused flour beetles. Mortality of immature rice weevils was less than 90 percent in 8 of 100 locations in the Behlen building and in 13 of 100 locations in the Butler building. Survival of more than 10 percent of the test insects was most common in the upper levels. Survival was least at the lower levels.

The average insect mortalities in the various groups were directly related to air change times in the Butler building; that is, the faster the air change time the higher the mortality. In the Behlen building the average mortality was highest in the areas having an intermediate air change time. Several factors in addition to air change time can affect the distribution of the fumigant and the resulting mortality of insects in a single-pass fumigation. For example, the highest rate of airflow and most rapid air change time in the Behlen building was recorded directly above one of the aeration ducts at a point nearest to the fan outlet (group I); however, mortality of test insects in this sample tier was only 1.2 percent of the confused flour beetle adults and 54.8 percent of the rice weevil larvae. The mortality of test insects in the other sampling tiers of group I was nearly 100 percent.

The low mortality of test insects and low concentrations of fumigant were the direct result of poor timing in the application of the fumigant. The fumigant cylinder attached to the aeration duct was exhausted in about 10 minutes. During the final 3½ minutes of fan operation, fresh air coming into the aeration duct diluted the methyl bromide, particularly in that part of the wheat having the highest rate of airflow and most rapid air change time. All of the fumigant had been applied in the second duct about 12½ minutes after the cylinder was opened. Dilution of the fumigant concentrations that resulted from the additional 1 minute of fan operation in the second duct was not sufficient to lower the mortality of the test insects. The mortality of test insects in the sampling tier that had the next highest air change time that would be affected by dilution with fresh air was also rather low (adults 44.2 percent and larvae 87.4 percent). This tier of probes was in group IV. If these two sampling tiers were eliminated from their respective groups, the resulting average test insect mortality would have been directly related to the average rates of airflow and air change times, the longest air change times producing the highest mortalities among the test insects.

Another factor that may affect the average mortality of test insects in a particular sampling tier is the application of part of the total dosage into the overhead space after the fans are stopped. Higher mortalities of insects in the overhead, surface, and 2½-foot levels may be obtained in a sampling tier even though the airflow or fan operation time was inadequate to push enough fumigant to the upper part of the grain mass.

Closed-Recirculation

The closed-recirculation tests were conducted October 19, 1960, and September 7, 1961. The recirculation system in the Behlen building is shown in figures 2 and 3, and in the Butler building in figures 4 and 5. When all overhead ventilators and access doors were sealed, the entire dosage of methyl bromide was released through nozzles suspended above the wheat surface. The nozzle arrangement was similar to that used in the gravity-penetration fumigation. The recirculation system consisted of a fan to draw the gas from the overhead space, down through a duct on the outer wall of the building, and force it through the aeration ducts on the floor and up through the grain again into the overhead space.

Static pressure readings made before the fumigant was released indicated that a fan operation time of about 29 minutes would be required for a single air change at the lowest measured airflow in the Behlen building and 13.5 minutes for a single air change in the Butler building. Three or more air changes are generally preferred in closed-recirculation fumigations to insure good distribution of the fumigant. In these tests, however, the fan operation time was limited to 1 hour in both buildings to minimize the loss of fumigant by leakage

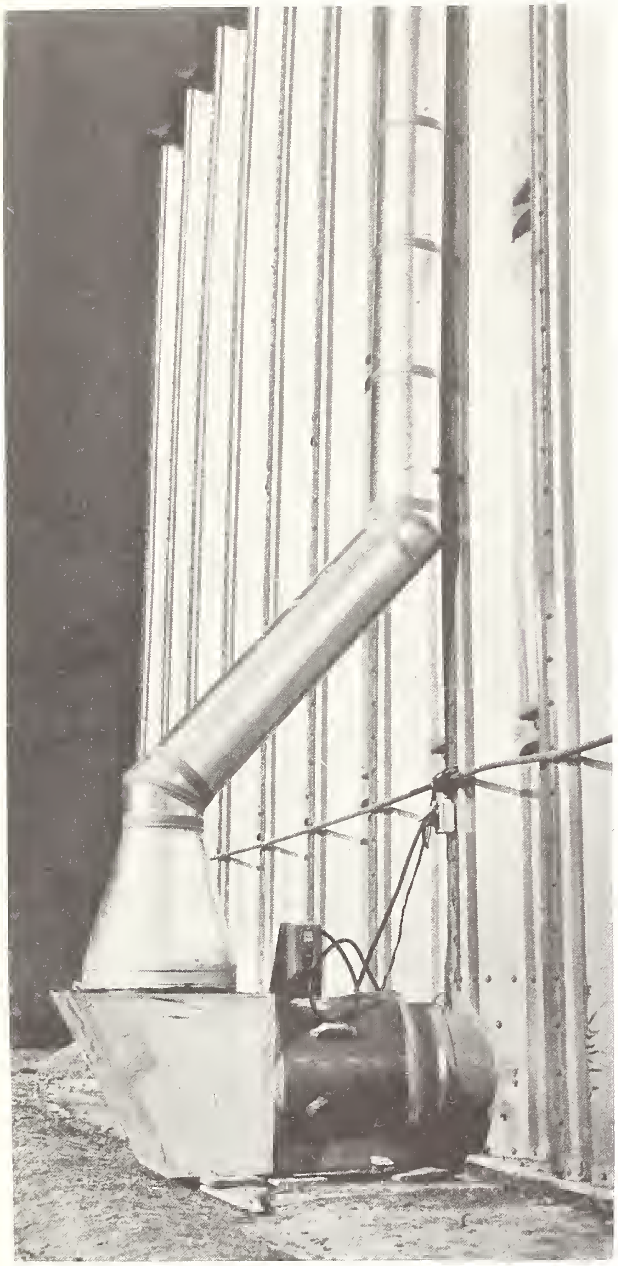

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FIGURE 2.—Side view of fan, junction box, and return duct of recirculation system attached to aeration duct of Behlen building.

around return duct joints and at the eaves of the roof, which were not sealed.

Placement of the probes and fumigant sampling techniques used in the closed-recirculation fumigation were the same as used in the gravity and single-pass fumigations.

The wind during application of the fumigant and during each recirculation fumigation was moderate. Daytime temperatures were in the lower fifties for the Behlen building test and in the midseventies for the Butler building test. Grain temperatures in the Behlen building were in the midfifties at the bottom, from 50° to 75° near the surface, and from 36° to 50° at the 10-foot level. In the Butler building the grain temperatures were higher but varied little. They were about 80° at the bottom and increased gradually to about 90° near the surface level.

Results of the T/C analyses and mortality of test insects for each building are in tables 1 and 2. It should be noted that there were no zero readings in either building through the first 8 hours. At the 1-hour reading in the Behlen building, the average concentrations of methyl bromide detected at each level were fairly similar, indicating that the distribution of the fumigant at the completion of the air circulation time was reasonably uniform throughout the wheat mass. At the 4-, 8-, and 24-hour sampling intervals, more methyl bromide was found at the bottom level than at any of the other levels. However, nearly equal amounts of methyl bromide were recorded at the 2½-, 5-, 10-, and 15-foot levels during the 4- and 8-hour readings. At the 24-hour readings more than twice as much methyl bromide was found at the bottom level as was found at the 2½- and 5-foot levels combined. The loss in total methyl bromide concentration detected at a single level between the 1- and 24-hour readings was highest at the 5-foot level (about 83 percent) and lowest at the bottom level (about 54 percent).

Mortality of test insects was complete in the overhead, surface, and 5-foot locations. Excellent kills of test insects were obtained at each of the remaining levels. Only one sample of larvae at the 2½-foot level and one sample of adult insects at the 10-foot level had less than 90 percent mortality.

At the 1-hour reading in the Butler building, the total amounts of methyl bromide at each sampling level were very similar. The largest amount, which was at the 10-foot level, was only 47 ounces more than the lowest amount, which was at the bottom level. While the average concentrations detected in later samples de-

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FIGURE 3.—Overhead view of Behlen building and recirculation system.

creased, the fumigant remained uniformly distributed through the wheat mass.

Mortality of the confused flour beetles was complete in all the sample locations. Only one rice weevil emerged from the wheat samples. It was found at the 2½-foot level in a probe tier near the center of the building. In the other sample locations, mortality of the rice weevil larvae was complete.

Average estimated times for a single air change and average test insect mortality for each group of sampling tiers in the closed-recirculation tests are in tables 5 and 6.

TABLE 5.—*Average estimated air change times based on static pressure readings and average test insect mortality obtained in a closed-recirculation fumigation of a Behlen flat-storage building*

Group	Average mortality: Adult confused flour beetles	Average mortality: Immature rice weevils	Average air change time
	Percent	*Percent*	*Minutes*
Group I:			
Above ducts	100.0	99.9	11.0
Group II:			
Corners and walls parallel to ducts	99.7	100.0	20.2
Group III:			
Between ducts	100.0	99.4	23.1
Group IV:			
Between ducts and walls	94.5	100.0	15.3

TABLE 6.—*Average estimated air change times based on static pressure readings and average test insect mortality obtained in a closed-recirculation fumigation of a Butler flat-storage building*

Group	Average mortality: Adult confused flour beetles	Average mortality: Immature rice weevils	Average air change time
	Percent	*Percent*	*Minutes*
Group I:			
Above ducts	100.0	100.0	5.2
Group II:			
Corners and walls parallel to ducts	100.0	100.0	12.0
Group III:			
Between ducts	100.0	99.9	10.3

Comparisons of the sampling tier groups yield little information. The average mortality of test insects was extremely high regardless of the average air change time. It is interesting to note, however, the variations that occurred in average air change times between similar groups in the single-pass and closed-recirculation fumigations (table 7). Variations in air change times between the single-pass and closed-recirculation fumigations in the Behlen building reflect both the decreased rate of airflow resulting from the addition of the smaller diameter return duct and the increased depth of wheat that occurred in the closed-recirculation fumigation. The increase in average air change time between Group I (above ducts) single-pass and Group I closed-recirculation was only 3.6 minutes. The difference between Group III (between ducts) in the single-pass and closed-recirculation fumigations was nearly 9 minutes or an increase of about 60 percent in the fan operation time required for a single air change. In the Butler building fumigations, the times required for a single air change in each group in the closed-recirculation fumigation was less than was required in the single-pass fumigation. This was due to a combination of factors including shallower grain depths, particularly over the ends of the ducts and along the side walls, and larger diameter return ducts.

Three sample points in one of the probe tiers in Group III in the Behlen recirculation test and two sample tiers in Group III of the Butler single-pass test were eliminated from the comparison made in table 7 and from the statistical analysis data discussed later. Fumigant concentrations at each of the sampling locations withheld far exceeded the average concentrations associated with other locations within their respective groups. It is suspected that the abnormally high concentrations resulted from dripping of unvolatilized methyl bromide from the application nozzles. The polyethylene sheet used to catch the unvolatilized methyl bromide apparently was not alined with the nozzle outlets above those tiers.

In comparing these 1-hour readings, it should be noted that in the single-pass fumigations the fans ran about 15 minutes and the fumigant distribution was measured nearly 45 minutes

TABLE 7.—*Comparison of the range of methyl bromide concentrations and the average concentrations obtained in the 1-hour readings in each airflow group of the single-pass and closed-recirculation fumigations*

Building and probe tier group	1-hour methyl bromide concentrations					
	Single-pass			Closed-recirculation		
	Range	Average	Air change time	Range	Average	Air change time
Behlen buildings	*Ounces*	*Ounces*	*Minutes*	*Ounces*	*Ounces*	*Minutes*
Group I: Above ducts	3–37	18.3	7.4	11–35	22.9	11.0
Group II: Corners and walls parallel to ducts	0–44	16.4	12.1	10–35	22.5	20.2
Group III: Between ducts	1–36	13.9	14.2	15–31	24.2	23.1
Group IV: Between ducts and walls	0–47	25.1	9.6	11–35	27.2	15.3
Butler buildings						
Group I: Above ducts	5–26	14.5	7.9	12–35	24.0	5.2
Group II: Corners and walls parallel to ducts	0–24	9.2	13.5	8–30	19.7	12.0
Group III: Between ducts	0–18	4.7	16.4	15–50	23.5	10.3

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FIGURE 4.—Recirculation system in a Butler building at the Hart Grain Company, Woodston, Kans.

after they had stopped, whereas fumigant concentrations in the closed-recirculation were determined immediately following the 1-hour recirculation period.

Little correlation is evident in the Behlen fumigation between the range and average methyl bromide concentration detected in each group of probes and the average air change time required for each group. In the Butler fumigations the highest average methyl bromide

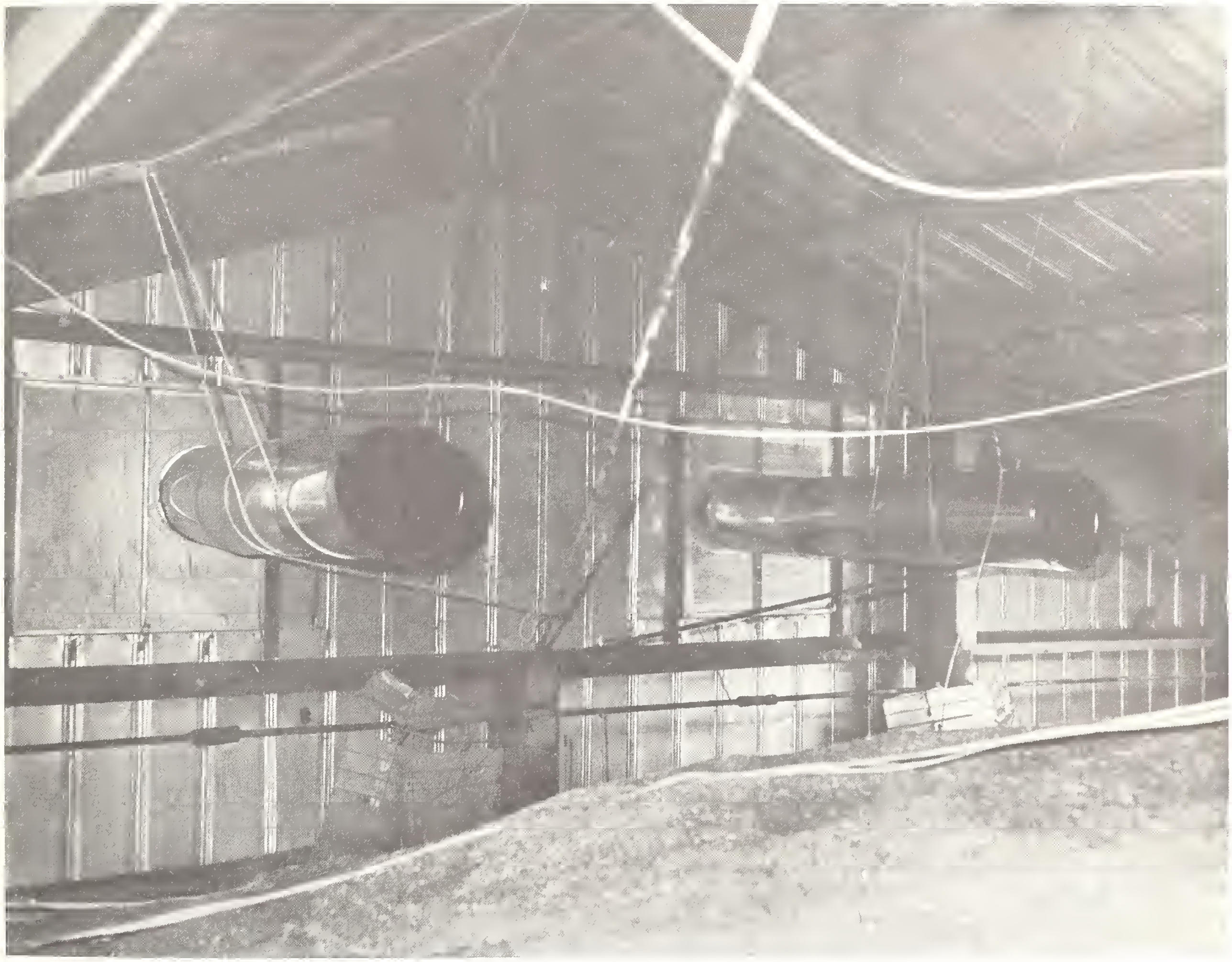

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FIGURE 5.—View of the return ducts from inside a Butler building at Woodston, Kans.

concentrations were detected in the groups having the fastest air change time, and the lowest average methyl bromide concentration was found in the groups having the slowest air change time. Significantly more methyl bromide was found in the closed-recirculation fumigations than was detected in the single-pass fumigations. In addition, the methyl bromide was more uniformly distributed between the probe tier groups in the closed-recirculation fumigations. This comparison demonstrates the ability of the closed-recirculation method of fumigant application to distribute the fumigant fairly uniformly even in grain-storage facilities having a wide range of air change times in various parts of the grain mass.

GENERAL DISCUSSION

One important measure of the efficiency of a method of fumigation is the uniformity of adequate fumigant concentrations distributed by that method throughout the grain mass within a reasonable length of time. Using the homogeneity of variance method of statistical analysis, the methyl bromide concentrations at the various sampling locations in each of the three Behlen and three Butler building fumigations were reduced to single comparable figures.

A summary of the estimates of variance for gas concentration data from the three Behlen building fumigations is in table 8 and from the three Butler building fumigations in table 9.

TABLE 8.—*Estimates of variance for gas concentration data obtained by fumigating wheat stored in Behlen flat-storage buildings with methyl bromide*

Fumigation method and sampling interval [1]	Estimate of variance for each sampling level [2]				
	2½-foot	5-foot	10-foot	15-foot	Bottom
Gravity-penetration:					
1 hour	2,568.39	2,401.72	2,851.07	227.58	52.70
4 hour	450.16	465.77	765.67	257.43	73.61
8 hour	139.80	153.15	318.61	197.27	141.20
24 hour	19.12	18.73	24.47	44.47	94.80
Single-pass:					
1 hour	198.56	212.73	199.62	144.36	90.79
4 hour	65.50	75.43	105.29	66.03	77.67
8 hour	25.46	34.83	63.19	42.01	40.90
24 hour	20.41	17.36	30.47	39.25	26.68
Closed-recirculation:					
1 hour	95.77	95.34	81.51	87.24	75.06
4 hour	56.51	60.04	53.39	64.26	75.94
8 hour	39.28	37.92	32.40	35.84	423.56
24 hour	7.73	11.47	12.61	17.81	145.77

[1] Dosage: 2 pounds of methyl bromide per 1,000 cubic feet.
[2] The homogeneity of variance method was used in summarizing the data. To compare any one estimate of variance with any other estimate of variance, divide the greater by the smaller. If the quotient equals or exceeds 2.52, the divisor or smaller variance indicates a significantly more uniform distribution of the fumigant under that particular circumstance.

TABLE 9.—*Estimates of variance for gas concentration data obtained by fumigating wheat stored in Butler flat-storage buildings with methyl bromide*

Fumigation method and sampling interval [1]	Estimate of variance for each sampling level [2]				
	2½-foot	5-foot	10-foot	15-foot	Bottom
Gravity-penetration:					
1 hour	747.62	384.20	967.78	54.24	1,649.04
4 hour	249.83	185.52	278.59	60.98	2,827.08
8 hour	107.48	79.25	63.99	35.52	2,003.27
24 hour	25.92	27.82	25.38	26.05	415.43
Single-pass:					
1 hour	96.54	82.21	71.40	83.28	49.36
4 hour	43.73	41.65	36.29	59.01	38.17
8 hour	27.46	39.29	28.87	36.00	75.54
24 hour	6.36	7.19	8.83	14.70	23.36
Closed-recirculation:					
1 hour	41.88	38.81	41.56	41.17	47.61
4 hour	7.53	5.93	5.67	11.32	12.15
8 hour	8.01	17.00	12.45	6.95	13.43
24 hour	7.23	8.13	7.14	10.05	10.80

[1] Dosage: 2 pounds of methyl bromide per 1,000 cubic feet.
[2] The homogeneity of variance method was used in summarizing the data. To compare any one estimate of variance with any other estimate of variance, divide the greater by the smaller. If the quotient equals or exceeds 2.60, the divisor or smaller variance indicates a significantly more uniform distribution of the fumigant under that particular circumstance.

The distribution of the methyl bromide after 1 hour at each sampling level in the closed-recirculation and single-pass fumigations is compared with the distribution after 8 hours in the gravity-penetration fumigation in the Behlen buildings (fig. 6) and in the Butler buildings (fig. 7). The 8-hour sampling interval was used in the comparison because of the longer period of time required to obtain maximum dispersal of the fumigant vapors throughout the grain mass by gravity-penetration. As shown by these graphs, the distribution of the methyl bromide

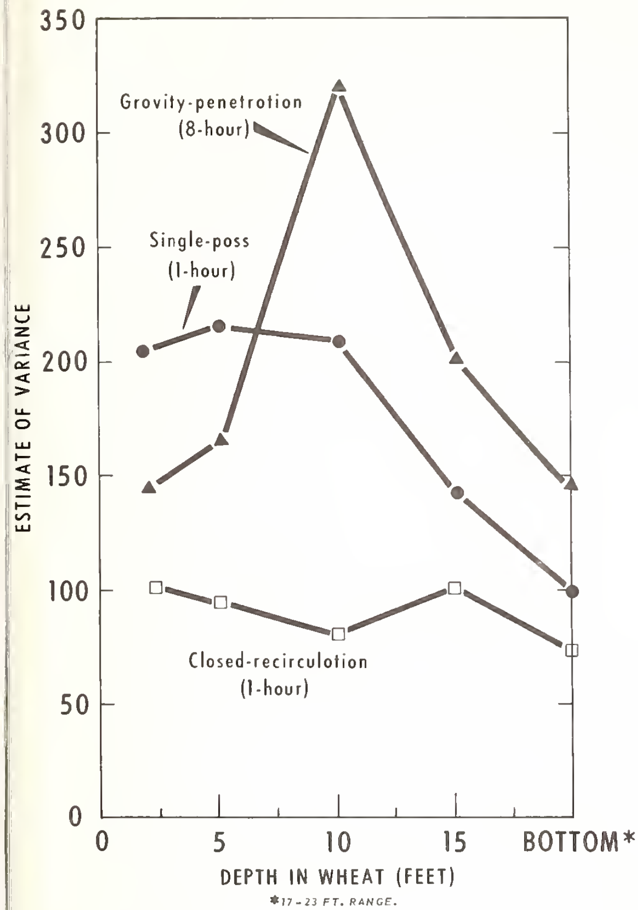

FIGURE 6.—A comparison of the estimates of variance of methyl bromide distribution in wheat stored in Behlen flat-storage buildings resulting from three methods of applying the fumigant.

TABLE 10.—*Average mortality of test insects within the grain mass in each of the three Behlen and three Butler buildings*

Method of fumigation	Mortality	
	Adult confused flour beetles	Immature rice weevils
	Percent	*Percent*
Gravity penetration:		
Behlen building	76.9	83.6
Butler building	48.3	63.1
Single-pass:		
Behlen building	85.7	96.7
Butler building	81.0	90.6
Closed-recirculation:		
Behlen building	99.2	99.7
Butler building	100.0	99.9

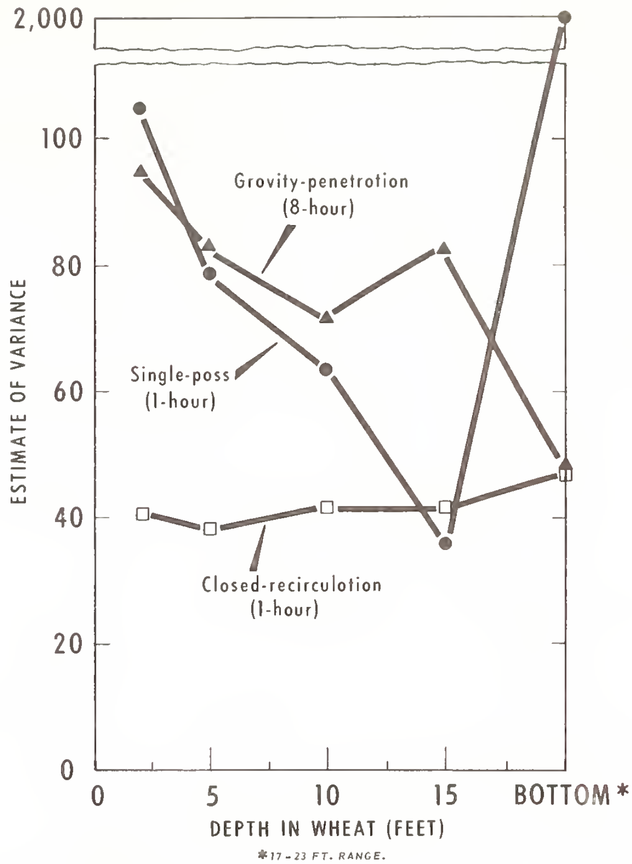

FIGURE 7.—A comparison of the estimates of variance of methyl bromide distribution in wheat stored in Butler flat-storage buildings resulting from three methods of applying the fumigant.

1 hour after the closed-recirculation fumigations was considerably more uniform than the distribution 1 hour after the single-pass fumigations or 8 hours after the gravity-penetration fumigations.

Uniform distribution of the methyl bromide concentrations and overall mortality of the test insects were closely related. The average mortality of test insects within the grain mass in each test is given in table 10.

CONCLUSIONS

In these tests, the closed-recirculation method of fumigation brought about a more uniform distribution of the methyl bromide and a higher mortality of the test insects than single-pass or gravity-penetration methods. It also eliminated the loss of fumigant caused by the difficulty of coordinating the timing of the fan operation and the fumigant application required in the single-pass method.

The improved fumigant distribution and higher test insect mortality justifies the expense of adding return ducts to existing aeration systems to permit recirculation of the fumigant.

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