

# Sealing of welded-steel hopper bins for fumigation of stored grain with carbon dioxide

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<sup>2</sup>Cereal Research Centre, Agriculture and Agri-Food Canada, 195 Dafoe Rd., Winnipeg, MB, Canada R3T 2M9. Received 22 March 1996; accepted 1 May 1997.

Mann, D.D., Jayas, D.S., White, N.D.G. and Muir, W.E. 1997. Sealing of welded-steel hopper bins for fumigation of stored grain with carbon dioxide. *Can. Agric. Eng.* 39:091-097. Fumigation of grain with carbon dioxide (CO<sub>2</sub>) requires the maintenance of high CO<sub>2</sub> concentrations (20 to 60% by volume in air) for extended periods (> 4 d). Grain storage structures currently used on Canadian farms are not airtight and should be sealed if they are to be used for fumigation with CO<sub>2</sub>. Various sealing techniques were applied to two welded-steel hopper bins to improve their gas-tightness. Each sealing technique was tested by adding 136 kg of dry-ice pellets to a steel box connected to the empty bin by ABS piping. If the CO<sub>2</sub> displaced air, this would have created a CO<sub>2</sub> concentration of approximately 65% inside the empty bin. Carbon dioxide concentrations continually increased as the sealing improved, but never reached 65%. Uniformity of CO<sub>2</sub> within the bin in both the radial and vertical directions also improved as the sealing improved. Fumigating with CO<sub>2</sub> using this type of bin will be possible if either 1) the length of exposure at the lower CO<sub>2</sub> concentration is increased, or 2) additional dry ice is added to the bin to compensate for leakage.

La fumigation des grains avec du bioxyde de carbone (CO<sub>2</sub>) exige le maintien de fortes concentrations de CO<sub>2</sub> (20 à 60% par volume d'air) durant une longue période de temps (4 jours). Les structures d'entreposage des grains présentement utilisées sur les fermes canadiennes ne sont pas étanches et doivent être scellées si on veut y procéder à la fumigation avec du CO<sub>2</sub>. Plusieurs techniques de scellage ont été utilisées pour améliorer l'étanchéité de deux coffres à grains en acier soudé. Les deux coffres étaient reliés par un tuyau ABS. On a testé chacune des techniques en introduisant 136 kg de glace sèche dans un des coffres, l'autre demeurant vide. Si le CO<sub>2</sub> avait déplacé l'air, la concentration de CO<sub>2</sub> à l'intérieur du coffre vide aurait atteint 65%. Les concentrations de bioxyde de carbone à l'intérieur du coffre vide ont augmenté à mesure que l'étanchéité s'améliorait, mais n'ont jamais atteint 65%. L'uniformité de la distribution du CO<sub>2</sub> à l'intérieur des coffres s'est aussi améliorée dans les directions radiale et verticale, à mesure que l'étanchéité augmentait. La fumigation avec du CO<sub>2</sub> sera possible dans ce type de structure si 1) on augmente le temps d'exposition à des concentrations de CO<sub>2</sub> plus faibles ou 2) on ajoute plus de glace sèche à l'un des coffres pour compenser pour les fuites.

## INTRODUCTION

Grain storage managers throughout the world must control or eradicate stored-product insects to prevent quantitative or qualitative grain losses. For many years, chemical insecticides and fumigants have been widely used for this purpose. In recent years, however, concerns about toxic residues on the grain and potential health hazards to those who apply the

chemicals have encouraged the search for other solutions.

One alternative is to modify the atmospheric composition inside the storage structure to create an environment lethal to the insects. Controlled laboratory experiments have shown that a lethal environment for the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens), the most common pest in western Canadian grain (Sinha and Watters 1985), can be achieved by elevating the carbon dioxide (CO<sub>2</sub>) concentration (Ganapathy et al. 1993; Rameshbabu et al. 1991; White et al. 1988, 1990).

The main advantage of CO<sub>2</sub> is that it does not leave toxic residues on the grain. Although grain kernels do sorb CO<sub>2</sub> when exposed to high concentrations, desorption is complete with exposure to ambient air. Elevated CO<sub>2</sub> levels do not adversely affect seed germination or quality (White et al. 1990).

Unlike chemical fumigants that are toxic to insects at low concentrations (at the parts per million level), CO<sub>2</sub> concentrations 10 000 times higher (at the parts per hundred level) are necessary for creating environments lethal to insects. These high CO<sub>2</sub> concentrations must be maintained for more than 4 d, the exact time depends on both the grain temperature and the species of insect that is to be eradicated. These requirements pose a problem because most storage bins used on farms in Canada are not airtight. As a result, CO<sub>2</sub> placed inside the bin leaks out rapidly. This problem can be solved in two ways: 1) continuously replenish the lost CO<sub>2</sub>, or 2) seal the bins to prevent leakage. Continuously replenishing the lost CO<sub>2</sub> is not an attractive solution because of the cost. There is incentive, therefore, to seal the bins so that a single application of CO<sub>2</sub> will be sufficient.

Sealing of large storage structures is not an easy task because all holes must first be found and then sealed. Alagusundaram et al. (1995a) reported that observed CO<sub>2</sub> concentrations were much lower than expected in bolted-metal bins because of leaks near bolt-holes and seams. Their recommendation was that bolted-metal bins would have to be rigorously sealed.

Australians have successfully sealed bolted-metal bins by using different types of sealants to coat the entire surface of the bin (Banks and Annis 1980). Also, Australian bin manufacturers now build structures that are more airtight (Chantler 1984). This significantly reduces the work required to seal

bins for CO<sub>2</sub> fumigation. Canadian bin manufacturers have not yet produced bins that are airtight, although welded-steel hopper bins have some potential because the bolt-holes and seams have been replaced with continuously welded seams. Assuming that all welding is done properly, the leakage area should be confined to the visible bin openings (i.e., bottom-cone opening, top-cone opening, access manhole in the roof, access manway in the bottom cone, and aeration-duct opening). Welded-steel hopper bins were selected for this project based on the assumption that leakage would be confined to these five openings.

## OBJECTIVES

The objective of this project was to develop and test practical methods for sealing welded-steel hopper bins so that they can be used to fumigate grain with CO<sub>2</sub>. Since it is anticipated that fumigation with CO<sub>2</sub> will be an alternative to fumigation with phosphine, the time required to complete a fumigation with CO<sub>2</sub> should be comparable to that required for a fumigation with phosphine. Fumigation with CO<sub>2</sub>, therefore, must kill the insects in approximately 4 d. For rusty grain beetles, *C. ferrugineus*, this will require a CO<sub>2</sub> concentration of approximately 65% by volume in air, with the exact concentration dependent on the grain temperature (Alagusundaram et al. 1995b; Jay and D'Orazio 1984). For complete effectiveness, the CO<sub>2</sub> concentration must be uniform throughout the bin, in both the radial and vertical directions. To make the fumigation as inexpensive as possible, the smallest possible quantity of CO<sub>2</sub> should be used.

For this research, the success or failure of each sealing technique was based on the maintenance of a uniform 65% CO<sub>2</sub> concentration throughout the bin for 4 d supplied by a single application of solid CO<sub>2</sub> (the mass of CO<sub>2</sub> was calculated assuming the ideal case of perfect purging of the air and no gas interchange after purging). Additionally, although not requirements, sealing the bin should require minimal work at minimal cost and should be possible when the bin is full of grain.

## MATERIALS AND METHODS

### Instrumentation of hopper bins

The storage structures used for this study were two welded-steel hopper bins (4.72 m in diameter, 104 m<sup>3</sup> in volume) (Model 16110E, STOR-KING, Winkler, MB), located at the Glenlea Research Station, approximately 20 km south of Winnipeg, MB. Both bins were instrumented identically with semi-rigid nylon tubing (3.2-mm outside diameter, 2.0-mm inside diameter) for gas sampling (Fig. 1). Previous work by Alagusundaram et al. (1996) suggested that CO<sub>2</sub> concentrations are likely to be uniform in the horizontal direction, therefore, sampling points were located along one radial plane only.

Sampling tubes were attached to three steel wires (points 0 through 10 to wire No. 1, points 11 through 14 to wire No. 2, and points 15 through 18 to wire No. 3) mounted vertically in the bin. The sampling tubes were led out of the bin through holes made in the aeration-duct cover which allowed us to take samples from ground level. The outlet ends of the sampling tubes were covered with rubber septa.

## Experimental procedure

Due to time limitations, we felt that replication was not necessary to evaluate the different sealing techniques. Applying knowledge gained in one sealing technique to the next attempt was more advantageous than repeating one that did not satisfy the criteria.

The testing procedure normally followed after completing each sealing attempt consisted of the following steps:

- 1) Dry ice was placed inside a steel box connected by ABS piping to the empty bin.
- 2) At specified intervals, we manually collected gas samples for analysis using a calibrated gas chromatograph (Model 8430, Matheson Gas Products, East Rutherford, NJ) equipped with a thermal conductivity detector and operated at 40°C using helium as a carrier gas.
- 3) The running time for each experiment was planned to be 4 d. Often, however, the leakage was so rapid that it was meaningless to run the experiment for 4 d. In these cases, the experiment was stopped prematurely to allow the start of the next experiment.
- 4) The bin was opened and allowed to ventilate so that the gas concentrations inside the bin would return to atmospheric level.

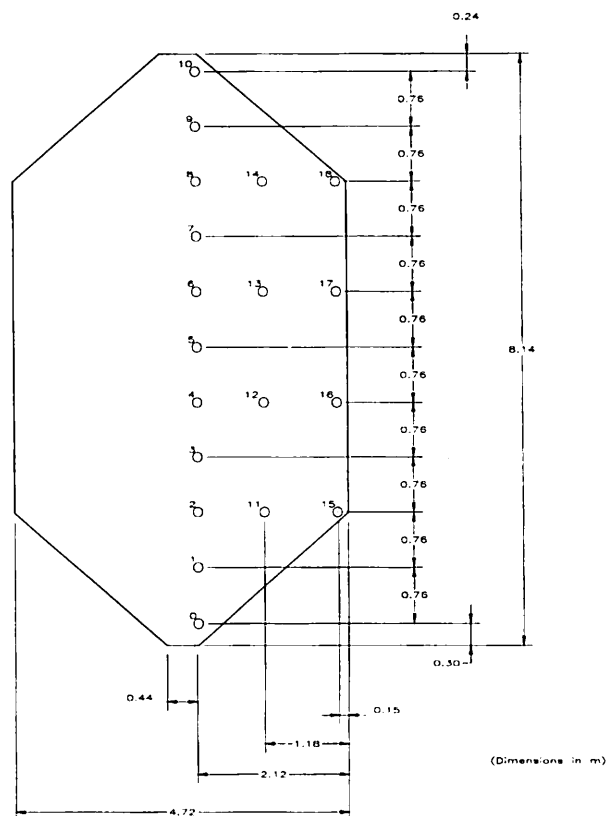


Fig. 1. Locations of sampling points in the instrumented welded-steel hopper bins.

For these experiments, no grain was placed in the bin. Grain is known to sorb CO<sub>2</sub>, but the exact amounts are not known. Rather than assuming a sorption rate that could be wrong, the absence of the grain eliminated this variable from consideration. A grain bulk also has different airflow resistance characteristics in the horizontal and vertical directions. With no grain inside the bin, there was no interference with the movement of gas in all directions to any leaks. A further advantage to be gained by an empty bin was the reduced time required for ventilation between experiments.

### Apparatus for introducing CO<sub>2</sub> into the bin

A box and duct system was used to introduce the CO<sub>2</sub> into the bin (Fig.2). A 0.575 m x 0.575 m x 0.575 m box of 18 GA sheet metal was constructed to hold the pellets of solid CO<sub>2</sub>. The duct system (constructed of 50-mm diameter ABS pipe) ran up from the box along the side of the bin and through a hole in the roof. Another duct ran from the aeration-duct cover to a recirculation pump (0.25 kW) and then to the box. Ball valves were fitted into the lines at various points so that the recirculation circuit could be opened or closed.

The solid CO<sub>2</sub> (136 kg) was placed into the box, the lid closed, and the pellets allowed to sublimate. In some trials, when the recirculation pump was not run, the CO<sub>2</sub> would flow upward in the ABS duct due to the increased pressure inside the box. In most trials, however, the recirculation pump forced the movement of the gases through the box, increasing the rate of sublimation. The recirculation pump also effectively moved the gases in the bin, providing more uniform CO<sub>2</sub> concentrations.

A pressure relief valve (Fig. 3) was attached to the bin as a precaution against the bin pressurizing and rupturing. All holes created by instrumentation were sealed with a silicone sealant.

### Methods of sealing

With the goal of attaining a sealed bin, many sealing methods were tried with varying degrees of success. The trials have been divided into five groups based on the general sealing principle used. Although the trials within each group have differences, a common principle links them (Table I). Several of the sealing methods were important in helping to identify the points of leakage, but were not practical as a solution. For example, an inflated bicycle tire tube fastened between the sliding gate and the bin floor (Method #1, Table I) proved

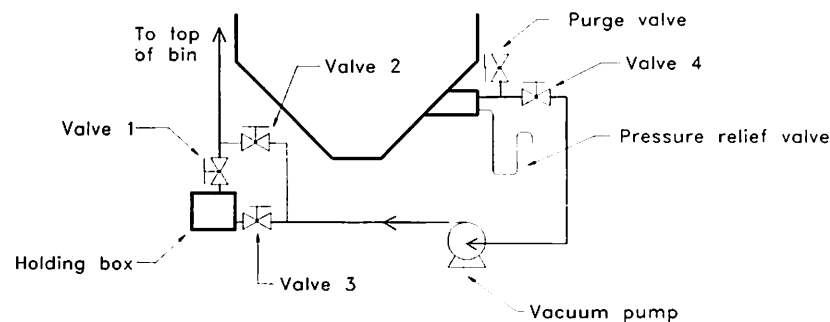


Fig. 2. The box and duct apparatus used for introducing the CO<sub>2</sub> into the bin from ground level.

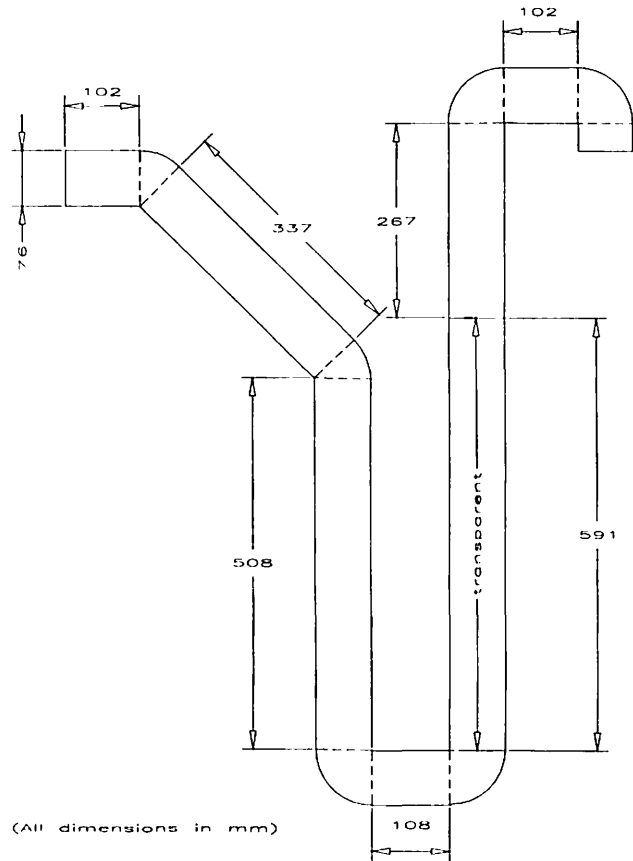


Fig. 3. The pressure relief valve attached to the aeration-duct cover as a precaution against the bin pressurizing and rupturing.

that CO<sub>2</sub> was leaking around the sliding gate, but it was not a practical sealing method because the tire tube had to be put in place while the bin was empty and the rubber deteriorated so that holes were present after only five tests. The trough-shaped steel lid constructed to enclose the sliding gate mechanism (Method #2, Table I) was more practical because it could be added to the bin from the outside even if the bin was full of grain. The lid, however, was difficult to put on, and it did not eliminate leakage from the bottom of the bin. After modification, a new flat lid (Method #3, Table I) was easier to install and seemed to eliminate leakage from the bottom of the bin. In Methods #1-3, our priority was to seal the opening in the bottom cone. Our attempts on the other openings consisted of attaching rubber gaskets around the openings with the lids clamped down tightly. Finally, for the trials of Method #4 (Table I), all five bin openings were sealed using the procedure employed in Method #3 for the opening in the bottom cone.

## RESULTS AND DISCUSSION

### Uniformity of CO<sub>2</sub>

**Radial direction** To assess the uniformity of CO<sub>2</sub> in the radial direction, the coefficient of variation (CV), which is a ratio of the standard

**Table I: Description of the basic sealing idea associated with each group of trials**

Group	Number of trials	Description of basic sealing principle*
No sealing	4	No modifications to bin, but holes created by instrumentation were filled with silicone sealant.
Method #1	5	<b>Opening in bottom cone:</b> An inflated bicycle tire tube was duct-taped between the sliding gate and floor of the bin.
Method #2	5	<b>Opening in bottom cone:</b> A trough-shaped, sheet-metal lid fit over the sliding-gate housing enclosing the entire sliding gate mechanism.
Method #3	4	<b>Opening in bottom cone:</b> A flat, sheet-metal lid was clamped against angle iron welded around the sliding-gate housing enclosing the entire sliding gate mechanism (Figs. 5 & 6).
Method #4	2	<b>All five bin openings:</b> The idea used in Method #3 was used to seal all five of the bin openings.

\* Refers to the basic sealing idea common to all trials within the group. Minor variations existed among trials.

**Table II: Average CV values (%) for each of the four radii calculated as the average of CV values from all sampling times (CV) and from all sampling times  $\geq 20$  h after the start of the experiment (CV<sub>20</sub>) of all experimental trials associated with each sealing method**

Radius	No sealing		Method #1		Method #2		Method #3	
	$\overline{CV}$	$\overline{CV}_{20}$	$\overline{CV}$	$\overline{CV}_{20}$	$\overline{CV}$	$\overline{CV}_{20}$	$\overline{CV}$	$\overline{CV}_{20}$
R <sub>1</sub>	18	17	12	9	6	5	8	5
R <sub>2</sub>	15	15	13	8	10	7	5	5
R <sub>3</sub>	16	13	12	7	11	7	4	3
R <sub>4</sub>	18	12	13	9	14	8	10	5

**Table III: Average CV values (%) calculated as the average of CV values from the eleven points along the centerline of the bin from all sampling times (CV) and from all sampling times  $\geq 20$  h after the start of the experiment (CV<sub>20</sub>) of all experimental trials associated with each sealing method**

Sealing method	$\overline{CV}$	$\overline{CV}_{20}$
No sealing	54	54
Method #1	30	19
Method #2	18	11
Method #3	13	8
Method #4	8	8

deviation (S.D.) to the mean (expressed as a percent), was calculated for each of the four radii (R<sub>1</sub> = points 2, 11, and 15; R<sub>2</sub> = points 4, 12, and 16; R<sub>3</sub> = points 6, 13, and 17; R<sub>4</sub> = points 8, 14, and 18) (Fig. 1) at each sampling time. Then, for

each sealing method, the average CV (CV) was calculated for each of the four radii by averaging the CV values associated with that sealing method (Table II). Large CV values existed during the initial hours of most tests, but smaller values were observed as the test progressed and the variation within the bin decreased. For this reason, CV<sub>20</sub> values were calculated as the average of CV values occurring 20 h or more after the start of the experiment.

The general trend observed in this experiment was a decrease in CV<sub>20</sub> values with increased sealing. The CV<sub>20</sub> values ranged from 3 to 5% for Method #3. Based on these results, we concluded that the CO<sub>2</sub> concentrations were uniform in the radial direction. The trials for Method #4 were conducted after preliminary analysis had shown this uniformity, therefore, CO<sub>2</sub> readings were taken along the centerline of the bin only.

**Vertical Direction** The mean, standard deviation (S.D.), and coefficient of variation (CV) of the eleven sample points along the centerline of the bin were calculated for each sampling time of each trial. From these values, CV and CV<sub>20</sub> values (Table III) were calculated. The CV<sub>20</sub> values in the vertical direction were large when no sealing was done to the bin, but decreased as the amount of sealing increased. For the third and fourth sealing methods, the CV<sub>20</sub> values were sufficiently low (8%) to conclude that the CO<sub>2</sub> concentration was uniform in the vertical direction.

#### Concentration of CO<sub>2</sub>

For each sampling time, the CO<sub>2</sub> concentration inside the bin was estimated as the mean of the eleven sample points along the centerline of the bin. The general trend was for the CO<sub>2</sub> concentration to increase with increased sealing (Fig. 4), but the objective of 65% CO<sub>2</sub> for 4 d was not reached suggesting that some leakage was occurring. A bin would never be sealed perfectly, and therefore, assuming that no leakage will occur is unrealistic. The mass of CO<sub>2</sub> added to the bin was calculated based on the assumption of 100% retention. Be-

cause 100% retention did not occur, two possible alternatives can be tried. First, the length of exposure can be increased. For example, rather than maintaining 65% for 4 days, main-

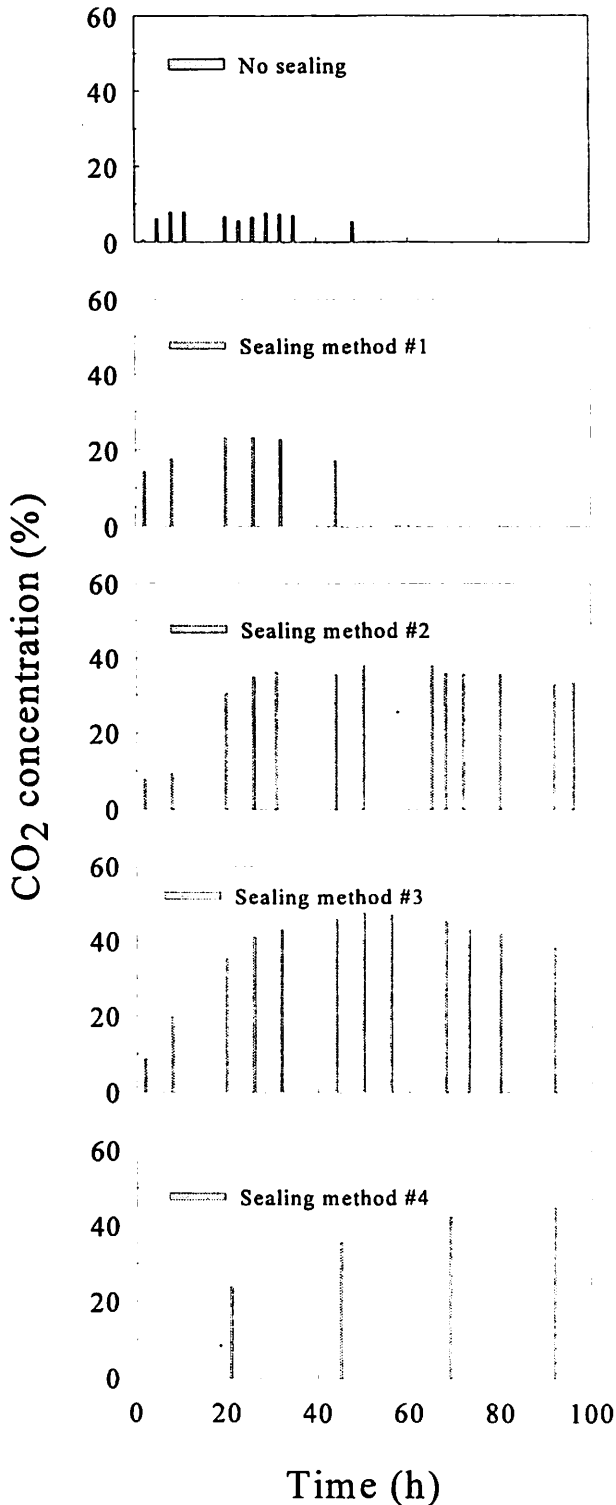


Fig. 4. The mean CO<sub>2</sub> concentrations (i.e., averages of the 11 sample points along the centerline of the bin) at each sampling time for a typical experimental trial from each sealing method.

taining 40% for 13 d may be possible (Annis 1987), although a farmer may not be able to hold the grain for this extended period. A second alternative is to add an additional amount of CO<sub>2</sub> to compensate for the CO<sub>2</sub> that will leak out. This requires a prediction of how much extra CO<sub>2</sub> to add to the bin.

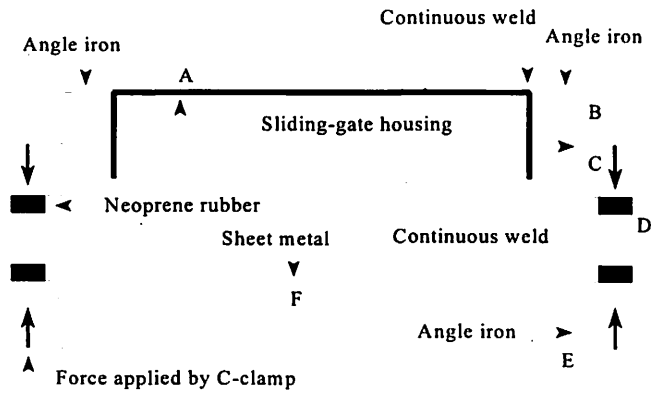


Fig. 5. Schematic of the sealing technique used to seal the opening in the bottom cone of the hopper bin (Methods #3 and #4).

#### Description of sealing method #4

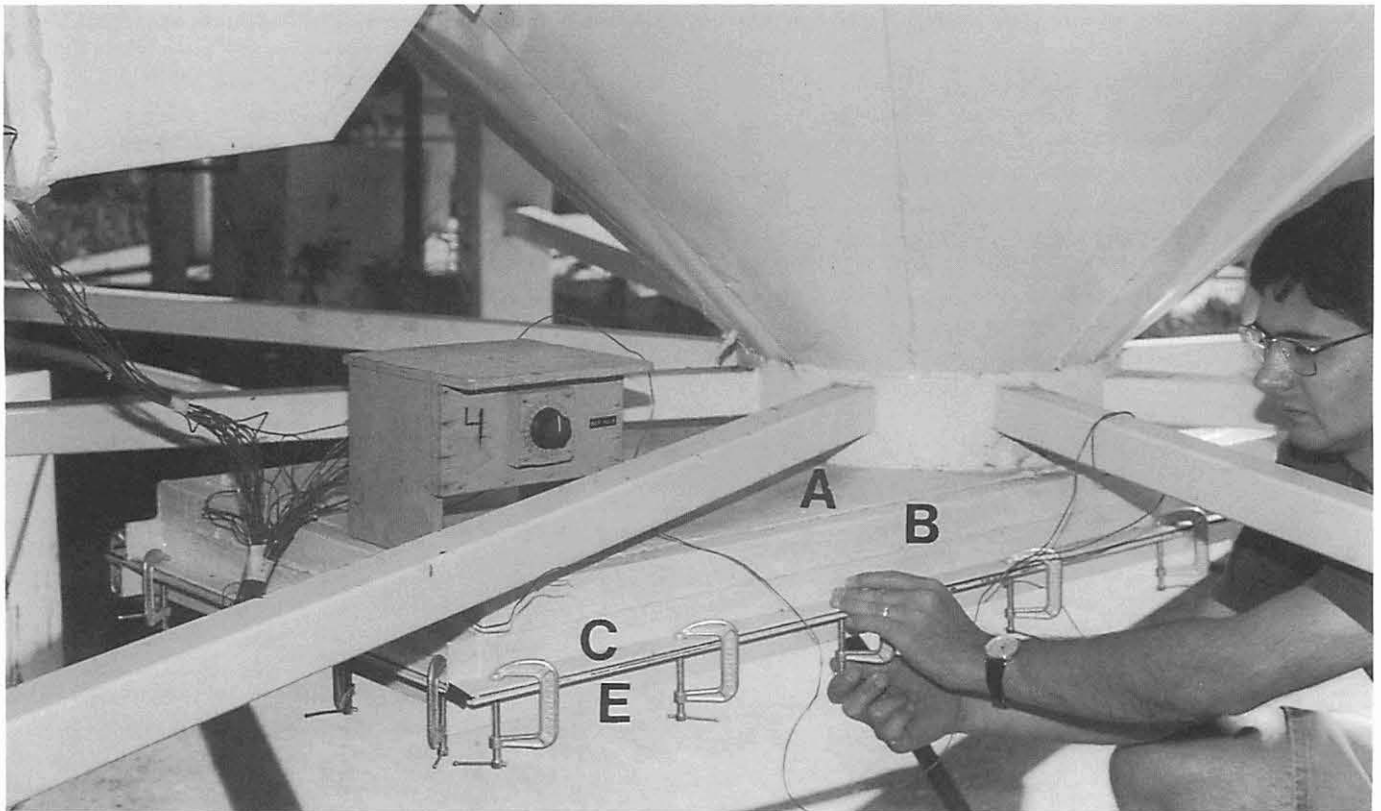
Based on the experimental results of uniformity and maximum CO<sub>2</sub> concentration, we concluded that sealing method #4 was the most successful. A schematic diagram of the sealing technique as applied to the opening in the bottom cone of the hopper bin is shown in Fig. 5. The modifications must not interfere with the moving parts of the sliding gate mechanism, so the entire mechanism was enclosed by welding pieces of angle iron (B) onto the sliding-gate housing (A) (Fig. 5). A size of angle iron was selected that would provide sufficient clearance for the components of the roller mechanism. The second piece of angle iron (C) extended lower than the sliding gate mechanism. All four sides were constructed in the same way with the pieces of angle iron welded together using continuous welds to prevent leakage. A hole drilled through the angle iron allowed us to connect or disconnect the crank. When disconnected, the hole was plugged with a rubber stopper.

A flat piece of sheet metal (F) was used to cover the opening, with strips of closed cell neoprene/EPDM (D) (Jacobs and Thompson Division, Weston, ON), attached to the bottom of the angle iron (C) and the top perimeter of the sheet metal (F), providing the seal. Small C-clamps spaced approximately 150-200 mm apart applied the force necessary to ensure an adequate seal (Fig. 6). An angle iron frame (E) placed beneath the sheet metal ensured that the force from the C-clamps was distributed evenly along the length of the seam.

Sealing of the other four openings was simpler because only a single piece of angle iron had to be welded to the bin. Three of the four openings were circular, which required the angle iron to be shaped before it was welded to the bin. Apart from these two differences, all five openings were sealed the same way.

#### Work requirements of sealing method #4

The work required to seal a bin depends on the number of openings in that individual bin. The experimental bins had five openings that had to be sealed. Other bins may have as few as two openings (one at the top for entry of the grain and



**Fig. 6.** Photograph of the sealing technique as applied to the opening in the bottom cone of the hopper bin (Methods #3 and #4). The entire sliding gate mechanism is enclosed. (In the figure, A is the sliding-gate housing, B is the first angle iron welded to the sliding-gate housing, C is the second angle iron welded to the first angle iron, and E is the bottom angle iron.)

one at the bottom for removal of the grain). Welding the angle iron onto the bin required the most time.

Although some modifications were made to the bin, the work was all done from the outside. One should be careful if grain is in the bin while welding because grain dust is explosive. Consequently, modifying an empty bin is preferable. Once the welding has been done and the lids cut to size, clamping the lids shut should require less than 1 h. Once the initial bin modifications have been made, sealing the bin is a quick and easy task.

Though sealing an existing bin is possible, it would be better if the manufacturer would make these modifications. For example, we sealed the opening in the bottom cone by welding two pieces of angle iron together (Fig. 5). If manufacturers constructed this at the time of manufacture, there may be better ways to achieve the same shape. The quality of work would also be more consistent if done at the time of manufacture.

For existing bins, bin manufacturers may find it advantageous to design "modification kits" which bin owners could purchase. This would also help to achieve a more consistent quality of work.

#### **Cost of sealing method #4**

Because the bin was sealed in different stages throughout the summer, the time spent welding and sealing is not known. Consequently, no labour or welding cost was included in this analysis. The cost analysis was based only on the four com-

ponents required to seal the bin: angle iron, sheet metal, neoprene/EPDM rubber, and C-clamps.

For each experimental bin, approximately 22 m of angle iron, sold in 6.1 m lengths, were used. With a unit cost of Can\$ 12.20/length for 25 mm x 25 mm x 3 mm angle (Russel Steel, Winnipeg, MB), the total cost for angle iron was Can\$ 48.80.

Sheet metal is sold in 1.22 m x 2.44 m sheets. One sheet of 18 GA steel was sufficient to make all five lids. The sheet metal costs Can\$ 45.00/sheet (Russel Steel, Winnipeg, MB).

Approximately 19 m of neoprene/EPDM rubber were used for each bin. This rubber is sold in 15.24 m rolls, so two rolls were required. At Can\$ 17.26/roll (Wearing Williams Limited, Winnipeg, MB), the total cost was Can\$ 34.52.

To ensure an adequate seal, approximately 50 C-clamps were used on the five openings. The C-clamps vary in price depending on their size. Small clamps can be used since they are spaced close together and they do not have to exert a large force. With a price of approximately Can\$ 3.00/clamp, the total was Can\$ 150.00.

The total cost of materials required to seal the experimental bin was approximately Can\$ 320.00 including taxes (1995 prices including 14% sales tax). This cost, however, varies with the number and size of the openings in an individual bin. This does not include the cost of the holding box and recirculation duct.

## CONCLUSIONS

With each successive sealing attempt, the experimental results improved, but the stated objective of a 65% CO<sub>2</sub> concentration for 4 d was not attained. In the latter attempts, CO<sub>2</sub> concentrations > 45% were observed. Although the desired CO<sub>2</sub> concentrations were not achieved, uniformity in the radial (CV values from 3 to 5%) and vertical (CV values = 8%) directions was high during the latter sealing attempts. Based on these results, sealing method #4 was selected as the best sealing method. The time required to initially modify the hopper bin is not known, but subsequent sealing can be done in < 1 h. The cost associated with sealing our experimental bin was approximately Can\$ 320.00.

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