FUMIGATION OF STORED GRAIN
WITH CARBON DIOXIDE

BY

DANIEL DELMAR MANN

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

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ABSTRACT

Stored grain is susceptible to infestation by stored-product insects. Synthetic chemical insecticides and fumigants are being restricted due to health and environmental concerns, and insect resistance to the chemicals is developing. Because insects die when exposed to elevated levels of carbon dioxide (CO_2), modified atmospheres may be a viable alternative to chemical control methods.

The visible bin openings of two full-size welded-steel hopper bins were modified to improve the gas-tightness of the bins. Mean CO_2 concentrations improved from approximately 10% before the bins were sealed to almost 50% following the final sealing technique. These improvements are significant because the amount of CO_2 used was constant for all experiments. The sealed bin retained approximately 79% of the CO_2 that was initially added.

For fumigation in a grain-filled bin, the addition of a large volume of gaseous CO_2 had to be offset by a release of air from the bin. Purging was found to be most practical if dry ice was allowed to sublimate inside a sealed box outside the bin and the gaseous CO_2 was ducted into the head space of the bin. Air was released through a purge valve at the bottom of the bin. For five experiments, purging efficiencies ranged from 69 to 92%.

Retention efficiencies ranged from 55 to 82% during 10-d fumigations, but only from 28 to 42% during 4-d fumigations. The extra dry ice added during the 4-d fumigations did not produce the desired increase in CO_2 concentration, and consequently, retention efficiencies declined. Mortality of caged adult rusty grain beetles, *Cryptolestes ferrugineus* (Stephens), was 100, 99.8, and 99.7% in three fumigations of 10-d duration and 95.3 and 79.8% in two fumigations of 4-d duration. Fumigations of 10-d duration should be promoted over fumigations of 4-d duration if only an initial application of dry ice is to be used.

Based on the published mortality data for *C. ferrugineus* exposed to elevated levels of CO_2, an equation was found that predicts the required exposure for any CO_2 concentration at a temperature

of 25°C. Because CO_2 concentrations decayed during fumigations, a procedure was developed to apply the equation cumulatively on short intervals. The lethal exposure time was calculated based on the CO_2 concentration observed during each interval. A ratio of the interval to the lethal exposure time was calculated and summed over all intervals to give the cumulative lethality index. When the cumulative lethality index equals 1.0, complete insect mortality should occur. Calculated cumulative lethality indexes compared well with the observed insect mortalities in this research.

Gas-tightness varies from bin to bin. Gas loss rate was related to the pressure decay time through a common factor of leakage area to allow a CO_2 concentration profile to be generated for any bin prior to the start of a fumigation. With knowledge of the CO_2 concentration profile, the length of time required to achieve complete mortality of *C. ferrugineus* can be calculated. Predicted rates of CO_2 loss compared well with observed rates of loss.

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LIST OF SYMBOLS

β	=	ratio of orifice opening to pipe diameter
η	=	empirical constant
η_r	=	retention efficiency (%)
ρ	=	density (kg/m^3)
ρ_{air}	=	air density (kg/m^3)
ρ_{co_2}	=	density of CO_2 (kg/m^3)
A_1	=	cross-sectional area of the bin (m^2)
A_2	=	cross-sectional area of the hole (m^2)
ABS	=	acrylonitrile-butadiene-styrene terpolymer
$A_{e(p)}$	=	predicted amount of CO_2 sorbed at equilibrium (mg/kg wheat)
a	=	cross-sectional area of the hole (m^2)
b	=	empirical constant
C_c	=	initial CO_2 concentration (%)
$(C_c)_i$	=	CO_2 concentration observed during interval i (%)
C_d	=	orifice coefficient
C_i	=	initial concentration of tracer gas (ppm or g/m^3)
C_f	=	concentration of tracer gas after time t_c (ppm or g/m^3)
C_o	=	O_2 concentration (%)
C_{th}	=	CO_2 concentration that would have been created by one domain volume of CO_2 gas, if all the introduced CO_2 gas stayed in the domain and none was sorbed by the grain (%)
CLI	=	cumulative lethality index
CV	=	coefficient of variation
$\overline{CV}$	=	average of CV values from all sampling times

$\overline{CV}_{20}$	=	average of CV values from all sampling times ≥20 h after the start of the experiment
C_w	=	weighted-volume average CO_2 concentration (%)
ΔC	=	concentration gradient across the opening (kg/m^3)
D	=	diffusion coefficient of CO_2 into air (m^2/s)
E	=	exposure time required to attain complete insect mortality at a given CO_2 concentration (h)
E_h	=	exposure time (h)
EPFT	=	equilibrium pressure flow test
e_1	=	purging efficiency with no mixing (%)
e_2	=	purging efficiency with free mixing (%)
e_3	=	combined purging efficiency (%)
Δg	=	mass of CO_2 lost (g)
IM	=	insect mortality (%)
M	=	molecular mass
M_{air}	=	molecular mass of air
MA	=	modified atmosphere
N	=	initial number of molecules inside the container
NDV of CO_2	=	volume of CO_2 gas used divided by the domain volume
ΔN	=	number of molecules transferring through the hole in a short time
n	=	number of moles of gas (mol)
$n_{½P_d}$	=	number of moles at pressure $½P_d$ above atmospheric (mol)
n_{P_d}	=	number of moles at pressure P_d above atmospheric (mol)
P	=	pressure (kPa)
P_{atm}	=	atmospheric pressure (kPa)

P_{bin} = pressure inside the bin (kPa)

P_d = initial decay test pressure (kPa)

PDT = pressure decay test

ΔP = pressure differential (Pa)

ΔP_i = initial pressure differential during a pressure decay test (kPa)

ΔP_f = final pressure differential during a pressure decay test (kPa)

P_1 = pressure inside the bin (kPa)

P_2 = pressure on the outside of the hole (kPa)

p = porosity

Q = airflow rate (m^3/s)

Q_L = average volume flow rate leaving the bin (m^3/s)

R = universal gas constant (8.314 $kPa \bullet dm^3 \bullet mol^{-1} \bullet K^{-1}$)

Re = Reynolds number

r = decay constant representing volume interchange rate (m^3/d)

RH = relative humidity (%)

T = temperature (°C)

T_K = temperature (K)

t_c = time for concentration to decay (d)

t_{exp} = experimental decay time (s)

t_h = duration of the experiment (h)

t_i = interval length (h)

t_p = pressure decay time [time for pressure to decay from an initial value to a value equal to one-half of the initial value] (s)

$t_{P_{bin}}$ = predicted decay time at a pressure of 1.5 kPa (s)

$t_{\frac{3}{4}P_{bin}}$ = predicted decay time at a pressure of 1.125 kPa (s)

$t_{\frac{1}{2}P_{bin}}$ = predicted decay time at a pressure of 0.75 kPa (s)

Δt = time interval (s)

V = volume (dm^3)

V_B = volume of stored commodity (m^3)

V_c = volume of the container (m^3)

V_G = volume of purge gas added (m^3)

V_{HS} = volume of head space (m^3)

V_L = volume of air leaving the bin (m^3)

v_1 = velocity of air inside the bin directly in front of a hole through the bin wall (m/s)

v_2 = velocity of air through a hole in the bin wall (m/s)

v_m = velocity of the molecules (m/s)

Δx = thickness of the boundary (m)

1. INTRODUCTION

Stored-product insects (hereafter referred to only as "insects") have been a concern since humanity began storing grain for future use because of the damage they cause to the stored grain. During the latter half of the twentieth century, a large number of synthetic chemicals were developed that were toxic to insects. These chemicals were perceived to be the ideal solution to the age-old problem of insects because they were effective and inexpensive. Recently, synthetic chemical insecticides and fumigants are being restricted or banned due to health (Garry et al. 1989) and environmental (Haines 1995) concerns, and insect resistance to the chemicals is developing (Price and Mills 1988; Fields 1992). Because insects continue to infest stored grain, alternate control methods must be developed.

Under aerobic conditions, insects survive by producing energy through respiration. When the insects are exposed to an environment deficient of oxygen (O_2), they can produce energy for short periods by glycolysis, but death will occur if the O_2-deficient environment is maintained. Insects also die when exposed to elevated levels of carbon dioxide (CO_2) because CO_2 has insecticidal action (Banks 1979). Controlling insects by altering the concentrations of atmospheric gases inside the storage environment is known as modified atmosphere storage of grain. Thus, lethal environments can be created without the addition of synthetic chemicals.

Modified atmosphere storage of grain is not a new concept. It is believed that the ancient Egyptians made use of this idea to protect their stored grain from insects. Lee (1960) reports that a flint sickle was found at the bottom of an ancient pit along the Nile river. It is believed that grain was stored in these underground pits because kernels of barley and an ancient wheat called "Emmer" have been discovered inside these pits. Respiration by the grain depletes the O_2 supply inside an airtight structure such as an underground pit. With a depleted O_2 supply, death of the insects occurs.

Recently, modified atmosphere storage of grain has received renewed attention around the world. The Australians have successfully fumigated grain in large, central storage facilities (Banks et al. 1980; Ripp 1984). Their greatest obstacle was that extensive sealing had to be done to the storage structures so that they would be able to maintain efficiently the modified atmosphere. The cost of extensive sealing of these storage structures was high. In western Canada, grain is typically stored in small storage structures on individual farms and farmers are responsible for ensuring the quality of their stored grain. For modified atmosphere fumigation to gain widespread acceptance in Canada, the cost of sealing a storage structure must be reduced so that it is feasible for an individual farmer.

An initial objective of this research was to identify an existing Canadian grain storage structure that can be sealed to allow efficient fumigation of insects using modified atmospheres. A practical method for sealing the storage structure is described.

Fumigation of insects by exposure to elevated levels of CO_2 is more appropriate for Canadian conditions than exposure to reduced levels of O_2 because the environment does not have to be controlled as precisely. Use of CO_2, therefore, reduces the cost of a modified atmosphere fumigation. Trial fumigations using dry ice as the source of CO_2 were conducted. The CO_2 environment inside the storage structure was created by ducting gaseous CO_2 into the head space and allowing air to escape from the bottom of the storage structure. Observed peak CO_2 concentrations were similar for fumigations of 10-d and 4-d duration, but mortality of caged adult *Cryptolestes ferrugineus* (Stephens) was higher following the 10-d exposures.

Although the trial fumigations were successful in my experimental bins, not all bins will be sealed to the same level of gas-tightness. A pressure decay test assesses whether a bin meets a minimum standard of gas-tightness. If the standard is not met, one option is to seal the bin better and then redo the pressure decay test. In some cases, additional sealing may be impractical or cost-prohibitive. For these situations, it would be beneficial if the fumigation exposure could be lengthened by an amount sufficient to result in mortality of the insects without the additional cost of sealing. This approach requires knowledge of the gas loss rate so that a profile of the CO_2 concentration can be generated. With knowledge of the CO_2 concentration profile and the mortality response of insects to CO_2, the required exposure can be predicted.

The following chapters present a review of the literature concerning fumigation with CO_2, a listing of the specific objectives of this research, a description of a method for sealing full-size welded-steel hopper bins, a description of several trial fumigations in the full-size bins, the observed mortalities of insects exposed to the trial fumigations, a novel procedure for evaluating the gas-tightness of a storage bin based on the pressure decay time, conclusions from this research, and recommendations for future research.

2. LITERATURE REVIEW

2.1 Problems with chemical control of insects

Insects are a major concern throughout the world because of the damage and contamination they cause to stored grain. In the past, it was thought that chemicals were the ideal solution for control of insects because they were fast-acting, effective, and inexpensive. Recently, problems have been identified which may jeopardize the future of chemical insecticides and fumigants.

The frequent and often improper use of chemicals has resulted in the emergence of resistant insect species (Price and Mills 1988; Fields 1992). The application of chemicals by untrained people often results in either insufficient dosages or insufficient exposures, allowing the most tolerant insects to survive. Among these tolerant insects are a few genetically pre-adapted for resistance to an insecticide. Under frequent chemical use, the resistant insects form most of the insect population. Consequently, the resistance is transmitted genetically to the offspring. Today, resistance to certain chemicals is so widespread that these chemicals have been rendered useless.

The application of chemical insecticides directly to grain can have serious consequences if toxic residues remain when the grain goes for processing (Taylor 1991). Society is no longer willing to accept potentially harmful chemicals on food products and has persuaded governments to ban many chemical insecticides that were previously used. Although most chemical fumigants do not leave residues on the grain like chemical insecticides (Monro 1969), their fumes are lethal to humans. Anyone exposed to these fumes is at risk of being poisoned or developing cancer (Garry et al. 1989). Fumigators are especially at risk because they must work directly with the fumigants. An increasing awareness of the dangers associated with fumigants has encouraged the search for new solutions.

An indirect, but harmful, consequence of one fumigant, methyl bromide, is that the earth's ozone layer is depleted by chemical reactions with methyl bromide (Haines 1995). Depletion of the ozone layer allows ultraviolet radiation to reach the earth. Although this may not directly affect our health now, it can have serious consequences to both us and our environment in the future.

In response to public pressure, governments have banned many chemical insecticides and fumigants used in the past. The remaining chemical control methods are under regulatory review and may be banned if found harmful to consumers, the environment, or both. If this happens, nonchemical control methods will be needed.

2.2 Modified atmospheres

2.2.1 Definition A modified atmosphere (MA) is produced by changing the intergranular gases inside a storage structure to create an environment lethal to insects. An MA can be created by either actively adding gases to the structure or by allowing the metabolic processes inside a sealed structure to alter the gaseous concentrations (Banks and Fields 1995). In the former case, a low-O_2 atmosphere can be created by adding a gas to displace oxygen (O_2) or a high-CO_2 atmosphere by adding carbon dioxide (CO_2). When metabolic processes alter the gaseous concentrations, also known as hermetic storage, lethal atmospheres are created slowly by the consumption of the O_2 inside the structure yielding a reduced O_2 concentration and an elevated CO_2 concentration. An MA can be considered a physical control method because nothing foreign is added to the storage environment (i.e., although the compositions of nitrogen (N_2), O_2, and CO_2 are changed, no new constituents are added to the atmosphere).

2.2.2 Low-O_2 atmospheres A low-O_2 atmosphere can be created either by adding pure N_2 or by ducting the output from a hydrocarbon burner into the storage structure. The addition of pure N_2 creates an atmosphere of almost 100% N_2 with only small amounts of O_2 and other rare gases. A hydrocarbon burner leaves small amounts of O_2, but the remaining atmosphere is composed of approximately 12% CO_2 in N_2 (Banks et al. 1991).

Under aerobic conditions, insects use O_2 to produce the energy needed for survival. When an organism is exposed to an atmosphere deficient of O_2, it can react in one or several of the following ways: 1) migration, 2) energy conservation, or 3) anoxic energy production (Adler 1994a). The desert locust, *Locusta migratoria* L., and the tobacco hornworm, *Manduca sexta* (Joh.), reduced their heat production to less than 5% of normal values after 4 and 5.5 h under anoxia, respectively, resulting in a tremendous saving of energy (Moratzky et al. 1992, cited by Adler 1994a). Insects are also able to produce energy without O_2 by a process known as glycolysis. Lactate, the source of energy from glycolysis, is acidic. If lactate levels rise due to prolonged glycolysis, the excessive quantity of positive (i.e., acidic) hydrogen ions could directly or indirectly stop the glycolysis process (Adler 1994a). With no energy production, the insect dies.

For a low-O_2 atmosphere to be effective, extremely low O_2 concentrations must be maintained. Lactate levels in *Ephestia cautella* (Walker) pupae rose quickly only when O_2 concentrations dropped below 3% — the point where energy metabolism changes from aerobic to anaerobic (Navarro and Friedlander 1975). Continued exposure to this low level of O_2 causes death. Banks et al. (1991) stated that 1% O_2 should be a typical target for a low-O_2 atmosphere, with 2% O_2 suggested as an upper limit (Bailey 1955). Although the speed of action may be faster if the O_2 concentration is reduced below 1%, it becomes harder to maintain such low levels of O_2 (Banks 1979).

2.2.3 Advantages and disadvantages of low-O_2 atmospheres One advantage of a low-O_2 atmosphere is that insects are unlikely to become resistant. Although insects can survive for short periods under anaerobic conditions by producing energy through glycolysis, they cannot recover unless returned to an O_2-rich environment. Donahaye (1991), however, showed that *Tribolium castaneum*

(Herbst) adults did develop a slight resistance to anoxia after 40 generations. The resistant strain was developed in an atmosphere of 99.5% N_2 and 0.5% O_2. Donahaye notes, however, that metabolism during exposure to these low O_2 concentrations was mainly by respiration. He speculated that this resistance could be due to more successful maintenance of energy or removal of the toxic end-products of glycolysis. Although Donahaye has shown the potential for resistance to low-O_2 atmospheres, it is unlikely that insects could adapt and survive under conditions of 0% O_2.

Low-O_2 atmospheres are difficult to maintain because even low rates of leakage through an imperfectly sealed structure will raise the O_2 concentration to nontoxic levels. The tendency will always be for O_2 to diffuse into a low-O_2 storage structure from outside because of the concentration gradient that exists across the membrane of the storage structure. Any small crack will allow O_2 to enter the structure. Because eliminating all leaks in large storage structures is impractical, a low-O_2 atmosphere will usually have to be maintained by continuous purging with a gas low in O_2.

2.2.4 High-CO_2 atmospheres A high-CO_2 atmosphere inside a storage structure is created by the addition of CO_2 with a corresponding reduction in both O_2 and N_2. The CO_2 can be supplied in either its solid, liquid, or gaseous state; but must be present in its gaseous state during a fumigation.

The observation that insects exposed to a high-CO_2 atmosphere containing substantial quantities of O_2 are killed suggests that CO_2 has some type of insecticidal action (Banks 1979). Nicolas and Sillans (1989) stated that mortality of insects exposed to high CO_2 concentrations was primarily caused by desiccation due to the opening of spiracles. Adult *T. castaneum* exposed to an atmosphere of 65% CO_2, 20% O_2, and 15% N_2 died due to desiccation and the exhaustion of energy reserves (Donahaye 1991). A CO_2-resistant strain developed by Donahaye (1991) was better able to control water loss and had greater energy reserves than nonresistant strains when exposed to the MA. In later work, Adler (1994b) exposed *Sitophilus granarius* (L.) pupae to atmospheres of pure CO_2 or pure N_2. Pupae exposed to pure CO_2 produced only one-third of the lactate produced by pupae exposed to pure N_2. His hypothesis was that the CO_2 dissolved in the body liquids of the pupae, forming carbonic acid and acidifying the body at the cellular level. The carbonic acid, when added to the lactate, supplied many positive hydrogen ions that could have directly or indirectly inhibited glycolysis, causing death. Insects tolerant to hypercarbia (i.e., an atmosphere of elevated CO_2) had greater body masses than non-tolerant insects (Donahaye 1991). A greater body mass correlates with more body liquids, suggesting a longer exposure to CO_2 before the same level of acidification is reached. Although all researchers do not agree upon the effects of CO_2 on insects, exposure to CO_2 does cause mortality even in the presence of adequate levels of O_2.

The optimum level of CO_2 for rapid insect mortality is 60% (Banks 1979; Jay and D'Orazio 1984), although it can be allowed to fluctuate. No advantage is gained by increasing the CO_2 levels above 60% (Fleurat-Lessard and Le Torc'h 1991, cited by Adler 1994b; Adler 1994b) because the mortality rates remain nearly constant. If CO_2 concentrations lower than 60% are used, the length of exposure must be extended beyond 4 d (Annis 1987).

2.2.5 Advantages and disadvantages of high-CO_2 atmospheres In contrast to a low-O_2 atmosphere, a high-CO_2 atmosphere does not have to be maintained as precisely because it can be effective over a range of concentrations. The subsequent addition of CO_2 during the fumigation may not be necessary if the rate of leakage is low. An initial CO_2 concentration of 70% declining to not less than 35% in 10 d at 20°C gives complete insect mortality under Australian conditions (Banks et al. 1980). If a structure exhibits this rate of leakage, a single application of CO_2 will be sufficient.

One disadvantage of a high-CO_2 atmosphere is the possibility that insects could develop a form of resistance. Because CO_2 levels do not have to be maintained precisely, as for low-O_2 atmospheres, there is an increased probability of carelessness when this method is used commercially.

If the CO_2 concentration dropped below 35% on the ninth day of a planned 10-d fumigation, it is unlikely that the fumigator would be concerned, though the most tolerant insects may still be alive. If these tolerant insects survive and reproduce, the potential for the development of resistance exists. Donahaye (1991) produced a strain of *T. castaneum* adults resistant to an atmosphere containing 65% CO_2, 20% O_2, and 15% N_2 at 95% relative humidity (RH) after exposure for 40 generations. Annis (1991) produced a strain of *S. oryzae* pupae resistant to various levels of CO_2 after seven selections of pupae for survival. The increased resistance was small compared with the observed variation in the dosage-mortality response. If CO_2 treatments are conducted in properly sealed bins with adequate lengths of exposure, however, all insects should be killed leaving little chance for the development of resistance (Annis 1991). Friedlander (1984) concluded that the build-up of tolerance will be difficult because multiple sites of action for CO_2 exist.

2.2.6 Hermetic storage Unlike low-O_2 or high-CO_2 atmospheres, hermetic atmospheres are created without the addition of atmospheric gases. A hermetic atmosphere is largely dependent on two factors: 1) the gas-tightness of the storage structure and 2) the respiration that occurs inside the structure. If a structure is sealed well, the movement of gases either into or out of the structure should be prevented. The respiration of the grain and insects inside the storage structure will eventually use up the available supply of O_2 and produce elevated CO_2 levels. If the O_2 concentration can be reduced below 1%, a low-O_2 atmosphere will be created.

Because hermetic storage is dependent upon respiration inside a sealed structure, the O_2 and CO_2 concentrations achieved depend on the moisture content of the grain and the number of insects in the grain (Champ and McCabe 1984). Grain respires more at elevated moisture contents (White et al. 1982). Similarly, a large population of insects respires more than a small population. With increased respiration, the O_2 will be used up more quickly with a corresponding increase in CO_2. If respiration continues until all O_2 is used up, the insects will die. Dry storage of cereals in hermetic storage can also result in significant levels of carbon monoxide, which will increase insect mortality (Whittle et al. 1994).

2.2.7 Advantages and disadvantages of hermetic storage The primary advantage of hermetic storage is that no gas must be added to the storage structure. Not only does this reduce the costs of eradicating insects, it also makes the MA technology useable in regions of the world where a supply of N_2 or CO_2 is not readily available.

Although additional gases are not needed, the storage structure must be sealed completely for hermetic storage to work. Besides being difficult to achieve, perfect sealing can also be expensive. One solution has been to use underground bunkers lined with plastic and covered with earth (Champ and McCabe 1984). Although these structures have been used successfully in many regions of the world for inexpensive storage, they are limited to dry areas having low water tables.

Hermetic storage is best-suited to long storage periods because it is dependent upon slow-acting respiratory processes (Adesuyi et al. 1980). Although hermetic storage may be suitable for storing excess supplies of dry, insect-free grain, it may not be practical for disinfestation of insects because the insects will continue to damage the grain until the slow-acting respiratory processes exhaust the O_2 supply, inhibiting the action of aerobic organisms.

2.2.8 Suitability of high-CO_2 atmospheres to Canadian conditions A unique characteristic of the Canadian grain handling system is that most grain is stored in small, on-farm structures until it is needed for export (Muir 1980). Individual farmers are responsible for their grain. An insect-disinfestation method that is effective on a small scale should be selected. A disadvantage of a low-O_2 atmosphere is that it requires the addition of gases throughout the fumigation. With CO_2, however, only an initial purge is required (Banks et al. 1980). Disinfestation with CO_2, therefore, would be easier for an individual farmer to conduct on a small scale.

Cost is another concern for farmers. When a fumigation is conducted in a central storage facility, the initial setup cost is spread over a large quantity of grain. When a fumigation is conducted on a farm, the individual farmer must absorb the entire cost. Although the cost of equipment necessary to produce a continuous supply of N_2 gas may be reasonable for a central storage facility, treatment with CO_2 is more economical for an individual farmer.

A final consideration is that most existing Canadian farm storage structures are not airtight. Although sealing is required for either low-O_2 or high-CO_2 treatments, less sealing is required when CO_2 is used because the concentrations can be allowed to fluctuate.

2.2.9 Sources of CO_2 Due to its physical properties, CO_2 can be supplied in either solid, liquid, or gaseous form. Solid CO_2 (dry ice) sublimates at temperatures above -78.5°C (Anonymous 1993), therefore, it readily changes to gaseous form at normal ambient temperatures. Liquid CO_2 exists only at high pressures. It must be contained in high-pressure cylinders and must be vaporized before it can be introduced into the storage structure (Wilson et al. 1984). At standard atmospheric conditions, CO_2 exists in gaseous form.

Although CO_2 can be used in any of its three physical states, solid CO_2 has one distinct advantage over the others. Achieving an accurate application of CO_2 with dry ice is easy because the mass can be accurately measured (White et al. 1993). When the source is either liquid or gaseous, a prediction of the quantity of CO_2 depends on the rate of flow, which is often not constant. Consistently adding the correct amount of CO_2 is easier when dry ice is used.

2.3 Factors influencing the effectiveness of a high-CO_2 atmosphere

2.3.1 Temperature Insect development occurs within a narrow band of temperatures between 13 and 35°C, depending on the species (Fields 1992). When an insect is within an environment of optimal temperature, its respiration rate will be the greatest (Person and Sorenson 1970). Fumigants, which enter the body of the insect through the respiratory tract, will be most effective when the respiration rate is high (Monro 1969). Modified atmospheric gases, which also enter the insect's body through the respiratory tract, will also be most effective when the respiration rate is greatest. Consequently, one would expect MAs to be most effective at high temperatures. This behaviour has been observed for *T. castaneum* (Storey 1975; 1977), *Rhyzopertha dominica* (F.) (Storey 1975), and *Sitophilus oryzae* L. (Person and Sorenson 1970) exposed to low-O_2 atmospheres. The higher the temperature, the shorter the exposure time required to achieve 95% mortality. AliNiazee (1971), in tests with *T. castaneum* and *T. confusum* J. du Val exposed to 100% CO_2, found that mortality increased as the temperature increased from 15.6 to 26.7°C. A similar trend was observed by White et al. (1988) who found that CO_2 concentrations had to be increased from 54% CO_2 at 20°C to >74% CO_2 at 10°C to maintain the same level of mortality of *Cryptolestes ferrugineus* (Stephens) after a 1 wk exposure.

Insects in low-O_2 atmospheres are more sensitive to temperature than insects in high-CO_2 atmospheres. Harein and Press (1968) observed mortalities of *T. castaneum* larvae exposed to 1% O_2 ranging from 14 to 100% as the temperature increased from 15.6 to 37.8°C. When exposed to ≈60% CO_2, mortalities ranged from 89 to 100%. Similarly, Zakladnoi (1976, cited by Banks and Fields 1995) observed little temperature dependence when insects were exposed to 100% CO_2, but definite dependence when exposed to 100% N_2. Although insects in low-O_2 atmospheres may be more sensitive to temperature than insects in high-CO_2 atmospheres, high-CO_2 atmospheres are most effective at high temperatures. Exposures should be lengthened with a decrease in temperature. Jay

(1980) suggested that the use of MAs to control *S. oryzae* is not necessary if the grain temperature is below 10.4°C because the cold alone will produce high mortality.

The length of exposure should be selected based on the coldest temperature within the grain bulk. For Canadian conditions, grain temperatures will be coldest near the bin wall during the winter (Muir et al. 1989; Leitgeb et al. 1990), so the length of a CO_2 fumigation should be based on the temperatures in these regions.

2.3.2 Relative humidity Although insect reproduction is reduced at low RHs, their short-term survival is unaffected (Howe 1965). When exposed to low O_2 concentrations due to either increased N_2 or CO_2, however, insects open their spiracles in an attempt to get more O_2. The result is water loss and eventual desiccation (Jay et al. 1971). The lower the RH, the greater the water loss and the sooner death will occur. This conclusion is supported by Jay et al. (1971) who exposed *T. castaneum*, *T. confusum*, and *Oryzaephilus surinamensis* (L.) to atmospheres containing ≈38% CO_2 with RHs ranging from 9 to 68%. For all three species, mortality increased as RH decreased. Similar results were obtained when the insects were exposed to <1% O_2 in N_2. Navarro and Calderon (1973), in studies with *E. cautella* pupae, reported critical water losses of ≈30% of the mass of the pupae confirming that desiccation caused death. Water loss increased as CO_2 concentration increased and RH decreased. At an RH of 95%, Navarro and Calderon (1974) found that mass loss was small, concluding that the toxic effects of the CO_2 were responsible for insect mortality.

Although there may be a positive effect of CO_2 on insects at low RHs, grain is seldom stored at extremely low RHs (i.e., low moisture contents), suggesting that there may be little practical benefit to be gained by a knowledge of the RH. In a bin of grain with low average moisture content, however, convection currents may cause moisture migration resulting in pockets of grain of elevated moisture content. The importance of RH (or moisture content), therefore, should not be underestimated because the length of exposure may need to be increased if the RH is above 70% in small pockets within the grain bulk (Banks and Fields 1995).

2.3.3 Sorption of CO_2 by grains When a gas and solid are present in the same environment, a physical mechanism of gaseous uptake by the solids occurs. This physical mechanism is composed of two processes: 1) adsorption and 2) absorption. In adsorption, the surface of the solid attracts and holds molecules of the gas with which it is in contact. Absorption occurs when gaseous molecules penetrate into the mass and internal structure of the solid. The term sorption includes both adsorption and absorption because they often occur simultaneously (Brunauer 1943).

Various cereal grains sorb CO_2 when exposed to high concentrations, although complete desorption occurred when the grains were allowed to stand in air (Mitsuda et al. 1973). Complete desorption of CO_2 is important because it means that no residues remain on the grain after a fumigation with CO_2. The concern, however, is that during the fumigation period, the kernels sorb some of the CO_2 required to kill the insects (Monro 1969). To achieve a successful fumigation, extra CO_2 must be added to the storage structure to compensate for the CO_2 that will be sorbed.

Although it is widely accepted that grains do sorb CO_2, the exact amounts sorbed with varying temperatures and moisture contents are not known. In tests with wheat, sorption of CO_2 decreased with increasing temperatures (0 to 30°C) while the moisture content was held constant at 14% (Cofie-Agblor et al. 1995). Sorption of CO_2 increased with increasing moisture content (12 to 18%) at a temperature of 20°C. These results were obtained for an initial CO_2 concentration of $99.2 \pm 0.76\%$ (volume basis). In later work, Cofie-Agblor et al. (1997) conducted tests with wheat and other types of grain exposed to initial CO_2 concentrations of 48.3 and 69.3%. Results obtained for wheat were similar to previous results (i.e., the uptake of CO_2 decreased with increasing temperature from 20 to 30°C for both initial CO_2 concentrations). Contrary to previous results, however, Cofie-Agblor et al.

(1997) observed decreases in CO_2 sorption with increasing moisture content from 12 to 18%. They speculate that the decline in CO_2 sorption may be attributed to the production of CO_2 at conditions of high temperature and moisture content. The production of CO_2 reduces the CO_2 partial pressure between the grain kernel and the airspace, reducing CO_2 diffusion into the kernels.

An important result of the work by Cofie-Agblor et al. (1997) is a relationship between the predicted amount of CO_2 sorbed at equilibrium and the temperature. For wheat of 14% moisture content and temperature between 20 and 30°C, the equations are:

$$A_{e(p)} = 326.6 - 2.4\ T \qquad (2.1)$$

at an initial CO_2 concentration of 48.3% and

$$A_{e(p)} = 458.1 - 4.2\ T \qquad (2.2)$$

at an initial CO_2 concentration of 69.3%

where: $A_{e(p)}$ = the predicted amount of CO_2 sorbed at equilibrium (mg/kg wheat), and

T = temperature (°C).

When the initial CO_2 concentration is not 48.3 or 69.3%, Cofie-Agblor et al. (1997) presented equations to predict sorption as a function of CO_2 concentration at temperatures of 20 and 30°C, respectively:

$$A_{e(p)} = 191.6 + 2.1\ C_c \qquad (2.3)$$

$$A_{e(p)} = 219.5 + 1.2\ C_c \qquad (2.4)$$

where: C_c = initial CO_2 concentration (%).

This work by Cofie-Agblor et al. (1997) yields useful information on the sorption of CO_2 by wheat under these limited conditions. For conditions outside the specified range, experienced guesses are the best current alternatives. Despite the incomplete data, sorption must always be considered because it is significant. Although equilibrium was not reached in all of their experiments (Cofie-Agblor et al. 1995), the proportion of initial CO_2 sorbed ranged between 12 and 14%. For a fumigation with CO_2 to be successful, extra CO_2 must be added to compensate for the significant amount of CO_2 sorbed.

2.3.4 Uniformity of CO_2 within the storage structure An MA must subject all insects within the storage structure to a lethal atmosphere. Although this does not require the atmosphere to be uniform throughout the structure, it does require a minimum value at all points within the structure. Rather than trying to find and maintain the region of lowest CO_2 concentration, it would be simpler if a uniform lethal concentration could be created within the entire storage structure.

Two factors commonly contribute to non-uniformity within a storage structure. First, gas density differences may exist within the storage structure causing a stratification of gases. Carbon dioxide is approximately 1.5 times as heavy as air and settles to the bottom of storage structures. Mechanical mixing is necessary if a gas heavier than air is added to air because the rate of natural mixing between the layer of air and layer of heavy gas will be slow (Monro 1969). Banks et al. (1991) agreed that CO_2 atmospheres in tall structures be recirculated to prevent the development of low concentrations in the upper parts of the structure. This phenomenon was observed when a methyl bromide fumigation was successful in the lower half of a ship's hold with insect survival in the upper half (Monro et al. 1952). Contrary to Banks et al. (1991), Monro (1969) did not recommend continuous recirculation and mixing throughout the fumigation. He stated that once a perfect mixture is attained, stratification of the heavier gas will take place so slowly that it will be unimportant for typical exposure periods with chemical fumigants.

A second factor that can lead to non-uniformity is a hole or leak in the membrane of the storage structure. Holes allow the exchange of gases between the inside and outside of the storage structure. Although *O. surinamensis*, *S. oryzae*, and *R. dominica* were not able to move from regions of low O_2 (0.9%) to regions of higher O_2 within a grain bulk, the insects that were close to a leak where O_2 concentrations were favourable survived the treatment (Navarro 1977, cited by Navarro et al. 1979). Similarly, it is possible that a leak would allow a reduction in CO_2 levels within the storage structure, permitting the survival of some insects.

Non-uniformity could be eliminated if structures could be made perfectly airtight. Because sealing to this level is often not practical, the common solution has been to recirculate the gases inside the structure to achieve more consistent mixing. This is especially necessary with single-application high-CO_2 atmospheres where no additional gas is added (Banks and Annis 1980). Noyes and Kenkel (1994) described a closed-loop fumigation system that enabled successful phosphine fumigations with the use of 50-75% of the usual amounts of phosphine, assuming a well-sealed structure. The reduction in gas use was attributed to thorough mixing between fumigant and air. Rather than being an added expense for a fumigation with CO_2, the recirculation may help to reduce costs by reducing the CO_2 required.

2.3.5 Stage and species of insect The effectiveness of a fumigation with CO_2 depends on both the species of insect and the developmental stages present in the grain. Different species of insects have biological differences that enable them to react differently to identical environmental conditions. Likewise, biological differences exist within developmental stages of a given species (i.e., egg, larva, pupa, and adult).

The key to a successful CO_2 fumigation is to identify the insect species and developmental stage present that is the most tolerant to CO_2. If the CO_2 treatment is adequate to kill the most tolerant pests, the less tolerant ones will also be killed. Unfortunately, researchers are unsure of the levels of CO_2 required to kill all developmental stages of all insects. A further problem is that recommended treatments are not always described using the same terms. For example, Jay and D'Orazio (1984) recommended a treatment of 60% CO_2 for 4 d while Banks et al. (1980) recommended an initial CO_2

concentration of 70% declining to not less than 35% in 10 d. Accurate comparisons can be made if the recommendation is given as a concentration-time (ct) product (Monro 1969; Anonymous 1989). If the gas concentration remained constant, the ct-product would be the product of the gas concentration and the length of exposure (Anonymous 1989). Often, however, the CO_2 concentration declines over time due to leakage. Here, the ct-product is equivalent to the sum of concentration-time products over short intervals, or the area under the concentration-time curve (Monro 1969).

In western Canada, the most common stored-product insect is the rusty grain beetle, *C. ferrugineus* (Sinha and Watters 1985). Annis (1987) compiled the literature for 25 species of insects, one of which was *C. ferrugineus*. The concentrations recommended for successful treatment with CO_2 are (Annis 1987): 40% CO_2 for 13 d (ct-product = 12.48 x 10^3 %•h), 60% CO_2 for 4 d (ct-product = 5760 %•h), 80% CO_2 for 3 d (ct-product = 5760 %•h), and 100% CO_2 for 2 d (ct-product = 4800 %•h). These values are specified for adult *C. ferrugineus* only. Contrary to what might be expected, the ct-products are different. This suggests that the mortality depends on more factors than just the CO_2 concentration and exposure time. Rameshbabu et al. (1991) showed that the mortality of adult *C. ferrugineus* is a function of CO_2, O_2, exposure time, RH, and temperature according to Eq. 2.5:

$$IM = -23.65 + 0.26(C_c) + 0.32(C_o) + 0.85(E_h) + 0.53(T) - 0.44(RH) \qquad (2.5)$$

where: IM = insect mortality (%),

C_o = O_2 concentration (%),

E_h = exposure time (h), and

RH = relative humidity (%).

Rameshbabu et al. (1991) stated that exposure time was the most important variable followed by RH, temperature, CO_2, and O_2 in descending order. Consequently, even if the exposure time and CO_2 concentration remain constant, other variables could reduce the observed mortality. Caution should be employed, therefore, when using the ct-product to predict insect mortality.

Shunmugam et al. (1993) conducted experiments to determine the mortality of *C. ferrugineus* adults, pupae, larvae, and eggs exposed to CO_2 concentrations of 30, 40, and 60% at 30°C. At 60% CO_2, pupae were killed within 4 d, adults and eggs within 3 d, and larvae within 2 d. At 40% CO_2, adults were killed within 8 d, pupae within 4 d, eggs within 3 d, and larvae within 2 d. At 30% CO_2, adults were killed within 8 d, pupae within 4 d, and larvae and eggs within 3 d. The adult was the most tolerant developmental stage of *C. ferrugineus* except at 60% CO_2 (Shunmugam et al. 1993). A concentration of 60% CO_2 for 4 d kills all developmental stages of *C. ferrugineus*.

2.3.6 Gas-tightness of the storage structure By definition, an MA requires that the atmospheric composition inside the structure be altered. Due to the nature of gases, the atmosphere inside the structure will return to ambient, unless the structure can be made gas-tight to prevent the movement of gases.

Poor gas-tightness of a storage structure results in loss of the MA gases. Although perfect gas-tightness is an ideal objective, it is rarely achieved. The rate of gas loss is dependent on the degree of gas-tightness. Small, localized leaks may create pockets where the MA ceases to be lethal to insects. A low level of gas-tightness allows large quantities of MA gases to leak, possibly resulting in non-lethal concentrations throughout the structure. Less than perfect gas-tightness always leads to non-uniformity within the storage structure and inefficient gas use.

Gas loss occurs even when the structure is sealed well, although in these cases, leakage often depends on temperature and barometric pressure (Barker 1974; Meiering 1982). For intentionally ventilated structures, wind and the chimney effect determine the leakage rate (Blomsterberg and Harrje 1979; Peterson 1979). Most storage structures to be used with MAs lie between these two extremes, suggesting that all forces (i.e., temperature, barometric pressure, wind, and the chimney effect) contribute to the gas loss (Banks and Annis 1984).

The basic driving force behind gas leakage is a pressure difference across the leaks in an imperfectly sealed structure (Banks and Annis 1984). Although the pressure difference causes gas loss, the size, shape, and location of the holes will also contribute to the rate of gas loss. Several factors can create a pressure difference across the membrane of a structure. According to the ideal gas law (Eq. 2.6):

$$P = \frac{n\ R\ T_K}{V} \tag{2.6}$$

where: P = pressure (kPa),

n = number of moles of gas (mol),

R = universal gas constant (8.314 $kPa \cdot dm^3 \cdot mol^{-1} \cdot K^{-1}$),

T_K = temperature (K), and

V = volume (dm^3),

an increase in temperature will increase the pressure assuming the volume remains constant. Inside a storage structure, temperature variations can influence two distinct regions: the head space and the grain bulk. Temperatures within the head space can fluctuate substantially on a daily basis, but the daily fluctuation is much less in the grain bulk due to the low thermal diffusivity of grain (Muir et al. 1989). Gas loss from the head space can be substantial unless measures are taken to prevent temperature fluctuations by shading the roof or painting it white (Banks and Annis 1984; Barry 1984). Daily changes in the barometric pressure can also create pressure differences, although these differences are unlikely to cause treatment failures unless in conjunction with another factor (Banks and Annis 1984). Barker (1974) estimated that 2.5% of the interstitial air could be lost from 291 m^3 of wheat due to daily fluctuations in the barometric pressure. The wind can also create pressure differences, but the pressure differs from the windward to the leeward side. On the windward side, outside air will be forced into the structure while inside gas will be forced out on the leeward side. Gas loss due to wind, therefore, depends on the presence of leaks in opposite sides of the structure. Further, gas loss due to wind depends on the presence of a constant wind or pulsation and turbulence (Banks and Annis 1984). Finally, density differences caused by either composition or temperature can create pressure differences across leaks separated by a vertical distance. This phenomenon is known as the chimney effect.

Though most gas loss occurs because of a pressure difference, a small amount of gas loss occurs because of a composition difference across the membrane of the structure. A high concentration on one side may result in permeation through the fabric of the structure (insignificant for most storage structures) or molecular diffusion through holes in the membrane of the structure (Banks and Annis 1984).

Wind and temperature effects are the most significant factors affecting gas loss (Banks and Annis 1984). Their research, however, showed that gas loss caused by temperature was not dependent upon the size and type of leak in the structure. In fact, the gas loss by barometric pressure fluctuations and permeation were also independent of leak size and shape. Only leakage caused by the wind, the chimney effect, and diffusion were dependent on leak size. This suggests that gas loss can only be reduced, not eliminated, by sealing storage structures.

2.4 Sealing methods for various types of storage structures

2.4.1 The need for sealing Although gas loss may not be eliminated by sealing storage structures, it can be substantially reduced. The efficiency of an MA treatment depends on the quantity of gas used. When a small quantity is used, the treatment is considered efficient with a low associated cost of gas. If a large quantity of gas is required in a poorly sealed structure, the cost of gas is high. The main purpose of sealing is to reduce gas usage and the cost of an MA treatment.

2.4.2 Sealing methods for horizontal storage structures Horizontal, or flat, storage structures are common in Australia. Replacing all existing structures with ones specially designed to be airtight would not have been economically feasible (Banks and Annis 1980). Consequently, techniques were needed to seal existing structures.

Horizontal storage structures have been built using several different construction techniques. Some have concrete walls with roofs of sheet metal supported by a metal framework. Other structures have sheet metal walls and roofs supported by either a wood or metal framework (Woodcock 1984). Some of these storage structures have concrete floors (Woodcock 1984) and others have asphalt floors (O'Neil 1984). The variability suggests that no single sealing procedure can be used. Careful thought must be given to each structure that is to be sealed (Banks and Annis 1980).

A first source of gas loss is the floor. Woodcock (1984) suggested that the floor should first be cleaned thoroughly, large cracks filled, and the entire surface coated with a sealer that penetrates the concrete to fill the pores and hairline cracks. A similar procedure should be followed if the walls consist of concrete, with the exception that both inside and outside surfaces should be sealed for best results. The next step would be to seal the roof and walls if they are covered with sheet metal. Before sealing, the roof and walls should be carefully checked for damaged panels; loose nuts, bolts, and screws; and missing nuts, bolts, and screws. Once the sheet metal has been inspected and fixed, all seams and bolt-holes should be coated with a sealant. Other areas of concern are the various openings in the building membrane (i.e., doors, skylights, gable ends, and ventilation fans). If possible, they should be sealed without modification. Often, however, it is simpler to remove the existing piece and replace it with one designed to be airtight. Once all sealing is complete, a heat-reflective white coating should be applied over the entire external surface of the structure to reduce temperature fluctuations in the head space (Woodcock 1984).

Although many horizontal storage structures have been sealed effectively in Australia, certain disadvantages exist. Horizontal storage structures have large head spaces. Ripp (1984) described one structure that had a filling ratio of 0.6. When only 60% of the volume of the structure is filled with grain, much extra gas is required to fill the empty head space. Gas loss due to temperature fluctuations also increases as the head space increases. Another disadvantage of these large structures is that recirculation of the gases is required to ensure uniformity. Finally, much work is required to seal a single structure because the entire membrane of the building must be considered in great detail.

2.4.3 Sealing methods for concrete silos Because concrete silos are common throughout the world, there has been much interest in sealing these structures so that they can be used for fumigations and MA treatments. Although a concrete silo appears to be a continuous membrane (except for the in-loading and out-loading hatches), concrete is porous (i.e., many small cracks and openings exist). These fine, deep cracks may be the result of too much sand being used to make the concrete or sand particles being too large (Kamel et al. 1980). In other cases, cracks may develop in the concrete as the structure ages and the concrete dries and contracts (Banks and Annis 1980; Takada et al. 1980). Takada et al. (1980) further suggested that cracks could result from design problems (i.e., incorrectly predicted loads), construction problems, or changes in the operation of equipment used to fill and empty bins that could not have been anticipated at the time of construction. Another concern is that CO_2 is known to neutralize concrete (Takada et al. 1980). Commercial use of CO_2 in concrete silos was stopped in Australia until the effects of the CO_2 on the silo structure could be fully assessed (Banks et al. 1980).

Despite problems and concerns, concrete silos have been sealed effectively. Kamel et al. (1980) sealed the cracks in the wall of a concrete silo by applying an araldite epoxy resin over the entire surface of the walls. The resin can sometimes reopen when the structure is filled because the stored product applies an expansion pressure to the walls (Takada et al. 1980). They suggested sealing the silo while it is pressurized with air. A fine powder is sprayed into the atmosphere. As it moves through the cracks in the wall, it is deposited. Next, a liquid sealant is added to combine with the powder to form a paste. Several cycles may be required to reduce the size of the cracks. Finally, a third sealant is applied that completely seals the hole. With this procedure, the holes are sealed in their expanded state so that they should not reopen due to the outward pressure caused by the stored product. All other bin openings must be sealed as well.

2.4.4 Sealing methods for bolted-steel structures A bolted-steel structure can refer to horizontal storage structures covered with sheet metal, or cylindrical bins constructed of galvanized steel. Because I have already discussed horizontal storage structures, I will now consider cylindrical, bolted-steel structures, which are the most common storage structures on Canadian farms (Muir 1980). Because steel is not porous to gases in the same way as concrete, coating the entire inner surface with a sealant is not necessary. It is only necessary to coat the seams, bolt heads, and other leak-prone areas (Banks and Annis 1980). A further area of concern with bolted-steel bins is the region under the eave designed for natural ventilation. This region should be sealed by rivetting pieces of sheet metal to the wall and the ceiling and then coating with a sealant (Banks and Annis 1980). As with the other structures, bin openings such as doors, grain inlets, and grain outlets must also be sealed.

Alagusundaram et al. (1995) conducted experiments in unsealed, bolted-steel bins at the Glenlea Research Station near Winnipeg, MB, but found that the unsealed bins would not hold a lethal concentration of CO_2 for the fumigation period without the addition of extra CO_2. They stated that these bins would have to be rigorously sealed to achieve successful fumigations with CO_2. A more practical solution for Canadian farmers is to have a single, well-sealed bin that can be used for MA treatments rather than sealing all storage bins (Alagusundaram et al. 1995).

2.4.5 Sealing methods for welded-steel structures The advantage of a welded-steel structure for an MA treatment is that the sheets of steel composing the walls of the structure are connected with continuous welds. If care is taken to ensure high-quality welds, gas loss should not be possible through the membrane of the structure, except through the bin openings (i.e., door, grain inlet, and grain outlet). The sealing effort can be restricted to these easily identifiable locations. In Australia, some welded-steel bins sit on concrete floors. In these cases, sealing the joint between the wall and floor is necessary, and occasionally treating the entire floor with a sealant is necessary (Banks and Annis 1980). In Canada, most welded-steel bins are hopper-bottomed with the bottom cone welded continuously to the walls, eliminating the need to seal the floor.

Successful MA treatments in welded-steel structures have been reported in the literature (Banks et al. 1980). Welded-steel tanks are usually sealed better than bolted-steel tanks for use in a closed-loop phosphine fumigation system in the southwestern United States (Noyes and Kenkel 1994). This is to be expected because the potential for gas loss is restricted to small and easily identifiable areas assuming all welds are continuous and perfectly sealed.

2.4.6 Choosing a suitable structure for Canadian conditions Any structure can be sealed for an MA treatment if enough time and effort are expended. However, just because a structure can be sealed does not mean that it should be sealed. In Canada, most of the grain is stored on the farm (Muir 1980). Most farmers store their grain in either bolted- or welded-steel bins. Because welded-steel bins may be easier to seal, they should be considered first.

2.5 Methods for testing gas-tightness

2.5.1 Tracer decay test To conduct a tracer decay test, a tracer gas is added to the air inside a storage structure and the rate of change of the concentration of the tracer gas is measured over time

(Sharp et al. 1976). The theory behind a tracer gas test is that the high concentration of the tracer gas inside the structure, as opposed to outside the structure, will cause it to diffuse through any openings in the membrane. The rate of diffusion is proportional to the difference between inside and outside concentrations. The tracer gas concentration decays exponentially (Eq. 2.7) (Banks 1983):

$$C_f = C_i \, e^{-r \, t_c} \tag{2.7}$$

where: C_i = initial concentration of tracer gas (ppm or g/m^3),

C_f = concentration of tracer gas after time t_c (ppm or g/m^3),

r = decay constant representing volume interchange rate (m^3/d), and

t_c = time for concentration to decay (d).

The volume interchange rate, r, can be calculated from the slope of a semi-logarithmic plot of concentration against time.

The use of tracer gas tests is limited because of several disadvantages. First, the impermeability to diffusion can be influenced by outside factors such as convective air exchange caused by changes in internal pressure and external barometric pressure, or sorption of the tracer gas by various materials (Metlitskii et al. 1983). Another disadvantage is that tracer gases such as helium, CO_2, methyl chloride, and radioactive isotopes have densities that are significantly different from air, which prevents perfect mixing. Also, some gases cannot be used in containers filled with food products (Sharp et al. 1976).

2.5.2 Equilibrium pressure-flow test For an equilibrium pressure-flow test (EPFT), air is either introduced or withdrawn from a structure at a known rate. After a time, the pressure differential reaches equilibrium when the flow through the leaks is equivalent to the rate of flow supplied by the fan (Banks 1983). The flow rate and equilibrium pressure are recorded. This procedure is repeated for several flow rates. The flow can be related to the pressure differential by Eq. 2.8 (Banks 1983):

$$Q = b\ \Delta P^{\eta} \tag{2.8}$$

where: Q = airflow rate (m^3/s),

ΔP = pressure differential (Pa), and

b and η are empirical constants that can be obtained from the *ln* Q-*ln* ΔP plot of the results. The value of η cannot be controlled, so the value of b must be reduced to achieve a lower flow rate. A lower flow rate is achieved by improving the gas-tightness of the structure (i.e., further sealing).

An EPFT can be useful when an estimate of the actual leak size is required or a comparison of the gas-tightness of two structures is being made (Banks 1983), although it requires a flowmeter and takes 2 to 3 h. One important disadvantage of the EPFT is that air flows in the same direction (i.e., inward or outward) through all openings, whereas air flows in both directions (i.e., inward and outward) under normal conditions of a fumigation (Sharp et al. 1976).

2.5.3 Pressure decay test The most common method used to measure the gas-tightness of a storage structure is a pressure decay test (PDT). A positive or negative pressure is created inside the structure by either blowing air into or withdrawing air from the structure (Banks 1983). Once a set pressure differential is achieved, the air movement is stopped. The pressure decay with time is observed and recorded. Pressure decay follows Eq. 2.9 (Sharp 1982; Banks 1983):

$$\Delta P_i^{1-\eta} - \Delta P_f^{1-\eta} = \frac{b\ \rho_{air}\ R\ T_K\ (1-\eta)\ t_p}{M\ V} \tag{2.9}$$

where: ΔP_i = initial pressure differential during a pressure decay test (kPa),

ΔP_f = final pressure differential during a pressure decay test (kPa),

ρ_{air} = air density (kg/m^3),

t_p = time for pressure to decay (s), and

M = molecular mass.

The pressure decay time is important because it shows the gas loss that is occurring (i.e., as t_p increases, the gas loss decreases).

As with the EPFT, the PDT suffers from the disadvantage of air movement occurring in only one direction. Although the PDT can be conducted rapidly using simple equipment,(Banks 1983), b and η must first be found using the EPFT.

2.5.4 Current guidelines for the pressure decay test Due to its ease of use and short time requirements, the PDT is most often used for testing the gas-tightness of grain storage structures. Although most researchers agree that the PDT is the most suitable method for testing the gas-tightness of storage structures, there is some variation in the recommended maximum pressure and minimum decay time. Banks (1984), speaking for the Coordinating Committee on Silo Sealants in Australia, reported the agreement of a standard to describe the gas-tightness of concrete bins. The Committee suggested that a 5 min pressure decay time is adequate for three separate pressure decay ranges (i.e., 2500-1500 Pa, 1500-750 Pa, 500-250 Pa) for full bins. Although they do not recommend testing empty bins, they set a minimum decay time of 12 min for all three pressure decay ranges. The pressure decay range chosen should be as high as possible to minimize environmental effects (i.e., an increase in internal temperature increases the pressure inside the bin), within the structural limitations of the bin (Banks 1984). Another source stated that concrete silos and welded-steel structures can withstand a pressure differential of +1500 Pa (Anonymous 1989). The maximum allowable pressure difference depends on the type of structure and sealing methods used because Chantler (1984) warned against using a pressure difference of >300 Pa when testing existing silos on farms. It is my understanding that Chantler was referring mainly to bolted-steel structures sealed by coating the seams and bolt holes. It is not known whether it would be the structure or sealing material that would fail at these low pressures. Retro-sealed structures are more likely to fail than factory-sealed structures

(Andrews et al. 1994). This supports the argument that a pressure decay range should be selected based on the limitations of the structure under consideration, not solely on a published standard.

Though PDTs are most commonly used, a vacuum decay test should be used if a flexible enclosure (i.e., a stack of bagged grain covered with polyvinyl chloride (PVC) plastic) is to be treated with an MA (Banks 1983; Anonymous 1989). In this situation, a PDT does not give accurate results because the volume of the enclosure increases with increasing pressure. A vacuum test, however, shrinks the flexible membrane onto the stack of bags creating a constant volume, and yielding a relevant test.

2.6 Conducting a fumigation with CO_2

2.6.1 Types of fumigations When CO_2 is added to the storage structure only at the beginning of the fumigation, this is called a "one-shot" fumigation. For a "one-shot" fumigation to be successful, the CO_2 concentration must remain high for a period sufficient to kill the insects. Completely eliminating leakage is not practical, therefore, the structure should be sealed adequately so that leakage of CO_2 from the structure occurs slowly.

An important advantage of a "one-shot" fumigation is that it does not require the addition of CO_2 once the fumigation has started. The disadvantage is the need for accurate predictions before starting the fumigation. Consideration must be given to the amount of CO_2 that will be lost from the structure so that this extra amount can be supplied initially. Otherwise, if leakage occurs faster than predicted, the CO_2 concentration may decline to low levels before all insects have been killed.

The alternative to a "one-shot" fumigation is a "maintenance" fumigation. A supply of CO_2 is continuously or periodically added to the structure to compensate for that lost through leakage. A "maintenance" fumigation may be required if the storage structure has not been sealed well and the rate of gas loss is high. "Maintenance" fumigations are most often used with low-O_2 atmospheres because the O_2 concentration must be kept constant at extremely low levels. Even low rates of leakage render a low-O_2 MA ineffective. A high-CO_2 atmosphere, however, is effective over a range of CO_2 concentrations. Thus, maintaining an exact atmospheric composition is not necessary.

2.6.2 Purging the bin For either a "one-shot" or "maintenance" fumigation, the first step is to replace the air inside the structure with the MA gases. This procedure is known as purging. The goal of purging is to force the air out of the structure with minimal loss of MA gas. An ideal situation would be to cover the exit valve with a membrane capable of allowing the air to pass through, but holding in the MA gas. For a fumigation with CO_2, this would require a membrane that held CO_2 while O_2 and N_2 were allowed to pass through. Unfortunately, to the best of my knowledge, no such membrane exists.

Without a membrane to separate gases, the best alternative is to prevent the mixing of MA gases with the air during purging. With no mixing, the exit valve can be closed when the gas front reaches the exit valve (the gas concentration can be monitored at the exit valve). If no mixing occurs, the CO_2 directly displaces the air. In this case, Eq. 2.10 gives the efficiency of purging (Banks 1979):

$$e_1 = C_c \left[\frac{p\ V_B + V_{HS}}{V_G} \right] \tag{2.10}$$

where: e_1 = purging efficiency with no mixing (%),

p = porosity,

V_B = volume of stored commodity (m^3),

V_{HS} = volume of head space (m^3), and

V_G = volume of purge gas added (m^3).

The rate of addition of purge gases affects the purging efficiency (Narasimhan et al. 1993; Peng and Chen 1993). If the rate of introduction of purge gas is too fast, the front will not move uniformly and turbulence will be created (Peng and Chen 1993). Consequently, mixing of the CO_2 and air will occur. Narasimhan et al. (1993) found that a purge rate of 2.05 kg•h^{-1}•t^{-1} was too high for proper displacement of the air. Banks (1979) calculated the purging efficiency assuming free mixing throughout the storage atmosphere (Eqs. 2.11a & b):

$$e_2 = -100 \left[\frac{(p\ V_B + V_{HS}) \ln \left(1 - \frac{C_c}{100}\right)}{V_G} \right] \tag{2.11a}$$

$$e_2 = 100 \left[\frac{p\ V_B + V_{HS}}{V_G} \right] \ln \frac{(21)}{(C_o)} \tag{2.11b}$$

where: e_2 = purging efficiency with free mixing (%).

The choice of equation depends on whether CO_2 or O_2 concentration was measured. A further argument for limiting the purge rate is the finding of Shejbal et al. (1973a) that faster rates of gas movement through the grain reduced insect mortality.

Even if mixing does not occur in the grain bulk, it is likely that free mixing will occur in the head space. The head space should be minimized to achieve the highest possible purging efficiency (Bailey and Banks 1974). Assuming complete displacement in the grain bulk and free mixing in the head space, the efficiency of purging is (Banks 1979) (Eq. 2.12):

$$e_3 = 100 \left[\frac{p\ V_B + V_{HS} \ln \frac{(21)}{(C_o)}}{V_G} \right] \tag{2.12}$$

where: e_3 = combined purging efficiency (%).

Purging a structure can be done in two ways: from bottom to top (bottom purge), or from top to bottom (top purge). In the bottom purge, the CO_2 is added at the bottom of the structure while the air is vented out the top. The opposite is true for the top purge. Banks (1979) reported purging efficiencies > 70% for the bottom purge and ranging from 60 to 93% for the top purge (both using CO_2). Thus, either method can be used effectively.

Shejbal et al. (1973a; 1973b) and Shejbal and Di Maggio (1976) created low-O_2 atmospheres by the addition of N_2 into the head space of structures. Because the density of N_2 is less than that of air, downward purging with N_2 may reduce density-related mixing and thus increase the purging efficiency (Banks 1979). Using the same reasoning, purging from the bottom with CO_2 may be more efficient because CO_2 is more dense than air. Banks and Annis (1980) stated that CO_2 has a tendency to layer horizontally because of its density. It is more likely that CO_2 layers horizontally because the grain kernels offer less resistance in the horizontal direction than in the vertical direction (Kumar and Muir 1986). Regardless of the reason, it is important to note that the CO_2 first layers horizontally.

Determining which purging method has been used most often in the literature is difficult because, while some authors explicitly state bottom purging (Chakrabarti et al. 1993; Narasimhan et al. 1993; Peng and Chen 1993) or top purging (Jay et al. 1970; Jay and Pearman 1973), others are less clear (Le Du 1968, cited by Banks 1979; Banks and Sharp 1979a) about which method was used.

2.6.3 Recirculation of the gases Although a "one-shot" fumigation with CO_2 requires the addition of CO_2 only at the beginning of the fumigation, the gaseous composition inside the structure does not remain static throughout the treatment period. Leakage out of the structure and settling of the CO_2 to the bottom of the structure because of its density creates non-uniformity within the structure. If left uncorrected, this could lead to the survival of insects in some parts of the structure. Mixing the internal gas is the solution to this problem (Banks and Annis 1980). Mixing of gases occurs when the storage atmosphere is recirculated and is often accomplished with a pump and ductwork located outside the bin from top to bottom (Banks and Annis 1980; Guiffre and Segal 1984). Because CO_2

settles to the bottom of structures, drawing the atmosphere from the bottom and forcing it into the head space is usual (Banks 1979; Banks and Annis 1980; Barry 1984; Guiffre and Segal 1984).

Although there is agreement on the need for recirculation of gases from bottom to top, there is disagreement over the required rates of recirculation. Banks and Annis (1980) found that a recirculation rate of about 0.1 volume/d was adequate for bins and a shed. Later, Banks et al. (1991) stated that a recirculation rate of 1.0 volume/d is necessary in tall structures. This difference may be due to the height of structures because the density effects may be more pronounced over large heights.

The greatest concern in the design of a recirculation system should be that it is airtight. The pump and ductwork must be considered as part of the structure's membrane. Leakage from the recirculation system is no different than leakage from any other part of the structure.

2.6.4 Maintaining a high-CO_2 atmosphere If a "maintenance" CO_2 fumigation is to be used, one must know how much CO_2 to add. The rate of addition of CO_2 to the structure should be equivalent to the rate of leakage of CO_2 from the structure. Knowledge of the leakage rate from the structure, therefore, is necessary for an efficient "maintenance" CO_2 fumigation.

A "maintenance" fumigation can be conducted in two ways. First, liquid or gaseous CO_2 can be added to the structure, preferably to the head space. It is twice as effective to add CO_2 to the head space as opposed to the bottom (Chakrabarti et al. 1993). They speculated that trying to force CO_2 up against the column of grain would increase the pressure in the bottom of the bin, possibly resulting in more leakage. Practically, if the CO_2 concentration is lowest in the top of the structure, it makes sense to add CO_2 directly to the top. Second, a CO_2 concentration can be maintained with the use of dry ice placed in an insulated box inside the storage structure. Banks and Sharp (1979a) placed pellets of dry ice into an insulated box placed on top of a stack of bags in a freight container sent by ship. Because the box was insulated, the dry ice sublimated slowly, providing a release rate of 3 kg/d of gaseous CO_2. Alternately, large dry ice blocks could be used without an insulating box (Anonymous 1989). Due to their low surface area to volume ratios, sublimation is slow, providing an ideal source of CO_2 for a "maintenance" fumigation. Jay and D'Orazio (1984) placed blocks of dry ice into railcars containing flour to be transported from Ohio to Georgia. After the 10-d trip, they observed 95.2 to 99.1% mortality of *T. confusum*, showing that the blocks had sufficiently maintained the CO_2 concentrations for an effective treatment. Alagusundaram et al. (1995) placed dry ice blocks inside insulated boxes and observed that CO_2 concentrations in bolted-metal bins were maintained for long durations with no need for replenishment.

2.6.5 Ventilating the bin The final step in a CO_2 fumigation is to ventilate the grain to remove the CO_2. Removing the CO_2 before entering the structure is necessary because high concentrations of CO_2 are toxic to humans. The system used for recirculation can be used to ventilate the grain by drawing gases out the bottom and venting it to the atmosphere rather than back into the head space (Barry 1984). Structures equipped with aeration equipment may be ventilated using this equipment. Simply unloading the grain and exposing it to the external atmosphere may also be sufficient.

Although ventilating the structure before entering is necessary, ventilating is not necessary immediately after the fumigation treatment is completed. If the grain is to be stored for an extended period, leaving the structure sealed may be advisable. The residual CO_2 concentration should ensure the death of all insects that may still be alive and prevent a reinfestation by survivors. Further, the sealed structure should provide a barrier against incoming insects.

2.7 Considerations for a successful CO_2 fumigation

2.7.1 Sublimation loss during transport If dry ice is to be used to create a high-CO_2 atmosphere, consideration must be given to the loss that occurs while the dry ice is being transported from the supplier to the farm. Dry ice sublimates (i.e., changes from the solid to the vapour state without forming the intermediate liquid state) at -78.5°C. Therefore, at ambient temperatures, the dry ice continuously sublimates during transport.

One way to reduce the loss of CO_2 during transport is to enclose the dry ice in insulated containers to reduce the rate of sublimation. Dry ice is available in either blocks or small pellets. If dry ice blocks are transported, the need for insulation will be minimal due to the low surface area to volume ratio (Anonymous 1989). I am not aware of any research that has investigated the problem of gas loss during transport.

Even if an insulated container is used to transport the dry ice, sublimation still occurs. To guarantee successful CO_2 fumigations, compensation should be made for the CO_2 that will be lost during transport. To purchase the correct amount of extra dry ice, the rate of sublimation must be known. Although a theoretical relationship for the rate of sublimation would be ideal, Ducom (1994) described a simple experimental procedure that will give an estimate of the sublimation rate. He placed known amounts of Methyl isothiocyanate on an electronic balance and monitored the loss in mass over time at 20°C. A similar procedure could be used with dry ice at several temperatures and in various insulated containers.

2.7.2 Safety Although CO_2 is a naturally-occurring component of the atmosphere (0.03% by volume), at concentrations necessary for fumigation of insects it is extremely lethal to humans. Many countries have set a hygienic standard (i.e., the concentration to which a person can be continuously exposed) of 0.5% (Anonymous 1989). Concentrations up to 5% CO_2 cause headaches and a noticeable increase in the rate of breathing (Anonymous 1989; Anonymous 1993). At concentrations up to 15% CO_2, breathing becomes increasingly more difficult, often resulting in unconsciousness. Concentrations higher than 15% CO_2 cause rapid circulatory insufficiency leading to coma and death.

Usually, there are no long-term health effects from an exposure to a high-CO_2 concentration if the person is removed from the high concentration within a short time (Anonymous 1989). First aid in a situation where someone has been exposed to a high CO_2 concentration consists of moving the person to fresh air. If the person is unconscious, he or she should be given assisted resuscitation and supplemental oxygen, if available (Anonymous 1993).

A dangerous characteristic of dry ice is its extremely cold temperature (i.e., -78.5°C). At this temperature, care must be taken to protect the skin. Gloves should be worn whenever handling dry ice and tongs may be useful when handling the small pellets. If continuous contact with the skin occurs, frostbite or cryogenic "burns" could result (Anonymous 1993). First aid in these situations consists of flushing the affected areas with lukewarm (not hot) water, followed by consultation with a physician if blistering of the skin or deep tissue freezing has occurred.

A required method to warn people of the danger near a structure is to post a warning sign. Otherwise, a person unaware that a CO_2 fumigation is being conducted may enter a structure and be overcome by the high levels of CO_2. Every effort should be made to create signs that are highly visible and easily readable, night or day.

A final consideration is for ventilation of the CO_2 before entering the structure. Ventilation should continue until the concentration of CO_2 in the head space is below 0.5% (Anonymous 1989). The grain will continue to desorb CO_2 for some time after ventilation has stopped, therefore, the CO_2 concentration should always be checked before entering the bin.

2.8 Additional benefits of a CO_2 fumigation

2.8.1 Prevention of growth of fungi Although the main purpose of MAs is insect control, they may be effective at stopping the growth of fungi. Fungi are dependent on a supply of oxygen for their growth (Briggs 1978, cited by Tipples 1995). Lacey et al. (1991), however, stated that the concentration of O_2 must be reduced below 0.14% before linear growth is decreased by half for some species of fungi. Richard-Molard (1988) supported this conclusion that no mould growth is observed, even on moist grain, when the O_2 concentration is below 1%, although he stated that spores may survive even under these conditions. The maintenance of such a low O_2 concentration is not practical.

Fungal growth can be slowed by the presence of CO_2 (Tipples 1995). Similarly, fungal growth and mycotoxin production in grains are adversely affected by the presence of CO_2 (Hocking 1990). In separate work, Dharmaputra et al. (1991) reported that CO_2 reduced the production of aflatoxin on maize. Sabio (1993) observed reduced microbial infection in beans exposed to an elevated CO_2 atmosphere compared with those stored in control. High-CO_2 atmospheres may prevent the growth of fungi, although MA treatments used for insect control are insufficient for fungal control (Lacey et al. 1991). A further problem is that an MA does not kill fungi; in the best scenario it will only prevent its growth while the atmosphere is maintained. Control of moulding, therefore, requires maintenance of the MA throughout the storage period (Lacey et al. 1991).

2.8.2 Physical exclusion of insects from a sealed structure A beneficial side-effect of sealing a structure for an MA treatment is that insects should no longer be able to enter the structure. The work done to seal the structure effectively makes a physical barrier that can exclude insects. Banks (1987) made the analogy that physical exclusion is similar to using a chemical protectant in a chemical control system. Physical exclusion, therefore, should provide long-term protection from insects once those inside the structure have been killed.

Physical exclusion of insects is widely used on a small scale for packages of processed food products, but little work has been done to apply this idea on a large scale possibly because sealing a large grain storage structure completely is difficult. Imperfections in a 2000 t capacity storage structure may total 1000 mm^2 (Banks et al. 1980). A 20 x 10^3 t structure may have leaks totalling

8000 mm^2 (Banks and Ripp 1984). Because adults of some common insects can penetrate through a square metal mesh with openings of 0.7 mm (Cline and Highland 1981), so-called "sealed" structures probably have many openings that are large enough to permit the entry of insects. Further, Barrer (1983) showed that several species of insects can find holes in structures. Despite evidence suggesting that the level of sealing attained for large storage structures should not provide protection against insects, Banks and Ripp (1984) summarized cases over four harvest seasons where grain was stored for more than five months following a phosphine fumigation where protection from reinvasion was obtained. In only two cases were insects found on out-loading; in both cases the storage structure had not been sealed to meet the PDT standard. These favourable results were observed despite conditions favourable for insect development within the grain bulk and ambient temperatures favourable for insect flight (Banks and Ripp 1984). In the Phillippines, Sabio (1993) observed that insect infestation in bagged soybeans inside sealed plastic enclosures was nil in comparison to the control stacks. A plastic enclosure sealed to meet PDT specifications protected rice for up to six months under humid tropical conditions where the pressure for an insect invasion was high (Annis et al. 1984, cited by Banks 1987).

Sufficient evidence exists to suggest that physical exclusion can be an important factor in the protection of stored grain. Unfortunately, sealing for insect exclusion is often not stressed as a reason for modifying a storage structure (Banks and Ripp 1984), although it can be an important component of an integrated pest management system (Bridgeman and Collins 1994). Similarly, Banks (1987) suggested that physical exclusion is a natural complement to a control process such as fumigation or MA treatment that does not leave residual protection.

2.9 Factors affecting grain quality

2.9.1 Sorption of CO_2 Of the three MA gases (CO_2, O_2, and N_2), only CO_2 is sorbed by grains in appreciable amounts (Mitsuda et al. 1973). Fumigants are usually completely dissipated upon ventilation, although occasionally, a small amount of the fumigant will react chemically with the stored commodity and will not be desorbed (Monro 1969). Mitsuda et al. (1973) observed that CO_2 desorbed completely from rice, wheat, corn, peanuts, soybeans, and their flours when the grains were allowed to stand in air. With complete desorption of CO_2, no residue is left after a CO_2 fumigation. This is in contrast to other fumigants like methyl bromide or phosphine which can leave residues (Bond 1984).

2.9.2 Direct contact with dry ice Grain is not usually stored at extremely low temperatures. It is unknown what the effect will be if dry ice is placed directly in contact with grain during a CO_2 fumigation. The germination of wheat exposed to -80°C for 7 d was unaffected, except at a moisture content of 23% (Dell'Aquila and Di Turi 1995). Loss of viability was the result of the moisture content more than the temperature because germination was decreased for all sub-freezing temperatures at 23% moisture content. There are many examples of the use of dry ice either directly on the grain surface (Banks 1979; Banks and Sharp 1979a; Carmi et al. 1991; Hamel 1991), on wheat flour (Jay and D'Orazio 1984), and on bagged grain under plastic enclosures (Banks and Sharp 1979b); but only Banks and Sharp (1979a) mentioned the quality of the stored product. They stated that there was no indication of damage caused by condensation. The fact that condensation has never been reported as a problem with the use of dry ice may be due to the small quantity of grain that comes in direct contact with the dry ice. Although Dell'Aquila and Di Turi (1995) exposed wheat to -80°C in air, to my knowledge there have been no studies on grain when the cold temperature is caused by direct contact with dry ice.

2.9.3 Exposure to modified atmospheres A measure of grain quality is often achieved by determining the viability of seeds. There is little evidence to suggest that either low-O_2 or high-CO_2 atmospheres cause a reduction in viability. White and Jayas (1993) compiled a review of the studies made on the effects of MAs to the quality of grain (i.e., germination, milling, and bread making). They concluded that MAs have no detrimental effects on dry grain. Grain stored in a low-O_2 atmosphere (i.e., anaerobic conditions) for over a year did not decrease in quality (Tipples 1995). Some fumigants cause partial or total loss of germination, but CO_2 does not affect germination (Anonymous 1989). If grain must be stored without loss of germination, it should be stored in an MA with low O_2 (Briggs 1978 cited by Tipples 1995; Anonymous 1989).

Climatic conditions (i.e., temperature and moisture content) are more harmful to the grain than MAs (Fleurat-Lessard et al. 1994). Storing grain under high-CO_2 atmospheres when the climatic conditions within the storage structure are not favourable (i.e., high temperatures or high RH) may be beneficial because the grain deterioration will be slowed (White and Jayas 1993).

2.10 Summary

Modified atmospheres of both low-O_2 and high-CO_2 have been used successfully in both laboratory and commercial situations. Because most grain is stored by Canadian farmers in small bins on farms, an MA treatment should be suitable on a small scale. Low-O_2 atmospheres are difficult to achieve without the addition of gases throughout the fumigation period — a procedure that requires a continuous supply of gas and equipment for its delivery. "One-shot" fumigations with CO_2 can be much simpler, especially if dry ice is used as the source of CO_2. For Canadian farmers, fumigation using dry ice as the source of CO_2 is most practical.

Although factors such as temperature, RH, life stage and species of insect, and uniformity of CO_2 within the storage structure influence the concentration of CO_2 and length of exposure necessary for complete control of all insects, the greatest concern is the amount of CO_2 lost from the storage structure during the fumigation period. The most obvious source of gas loss is due to leakage from the structure. With appropriate sealing, the gas loss can be reduced, but seldom eliminated. The most popular method used for testing the gas-tightness of a storage structure, the PDT, has limited practical value because it does not show the rate of gas loss from a structure. The guideline for the PDT should be changed to yield the expected rate of gas loss so that extra CO_2 can be added to compensate for that which will be lost during the fumigation period. The modified guideline would be applicable to structures sealed to different degrees of gas-tightness.

A less obvious source of gas loss is due to sorption by the grain within the structure. Although the CO_2 sorbed by the grain has not been physically removed from the storage structure, it is no longer a part of the interstitial airspace within the structure. Because the insects are killed by the CO_2 in the air within the structure, the CO_2 sorbed by grain is, in effect, a loss. If sorption is not compensated for, the fumigation may be unsuccessful.

A third source of CO_2 loss occurs at the start of a fumigation when the air is purged from the storage structure. If the air could be purged from the structure without being mixed with the incoming CO_2, the CO_2 loss would be nil. In reality, some mixing occurs, and therefore, some CO_2 will be lost. It is necessary, therefore, to determine a suitable purging procedure and quantify the amount of CO_2 lost during purging. Purging is likely to be complicated by the use of dry ice as the CO_2 source because sublimation of large quantities of dry ice does not occur instantaneously. Consequently, the CO_2 is not all present at once and purging occurs over a long period. To help predict purging, knowledge of the sublimation rate of dry ice would be useful.

An understanding of these sources of CO_2 loss is important if a "one-shot" fumigation is to be done with introduction of CO_2 only at the beginning of the fumigation. The amount of CO_2 added should be increased by the amount predicted to be lost by one or more of these factors.

There is little or no detrimental effect on grain quality by the presence of high CO_2 concentrations. Germination has been shown to decrease at cold temperatures if the grain has a high moisture content. There is no indication, however, what the result would be if grain kernels came into direct contact with dry ice.

Although the main goal of a fumigation with CO_2 is to kill insects, there are two additional benefits to be gained from this procedure. First, fungal growth is slowed by the presence of CO_2. The benefit, however, remains only as long as the atmosphere of elevated CO_2 is maintained. Second, although sealing generally does not eliminate all holes, a sealed structure should provide an effective barrier against the entry of insects. Several researchers have stated that sealed structures prevent entry of insects, but, to the best of my knowledge, there has been no experiment conducted to confirm this reasonable assumption. If a sealed structure can prevent the entry of insects, preventing insect infestations by sealing structures immediately after harvest may be possible. This could eliminate the need for control of insects in stored grain.

3. OBJECTIVES

In the literature review, I discussed many factors relevant to CO_2 fumigation. Despite the complex relationships discussed, the success of a CO_2 fumigation is dependent upon a simple premise: the stored-product insect must be exposed to a lethal environment. The primary objective of this research, therefore, was to achieve a lethal CO_2 environment in a full-size farm bin.

Specific objectives were:

1. to design and evaluate a system to seal a full-size bin to minimize CO_2 leakage and permit feasible CO_2 fumigations,
2. to identify a suitable purging method that minimizes purging losses and yields lethal CO_2 environments,
3. to evaluate the efficacy of the designed sealing system by determining the mortality of insects exposed to the CO_2 environment, and
4. to devise a guideline for conducting CO_2 fumigations in bins sealed to varying levels of gas-tightness.

4. SEALING A WELDED-STEEL HOPPER BIN

4.1 Objectives for preparation of the storage bin

Existing bolted-metal storage bins in North America are not suited for fumigation with CO_2 because holes in the bin membrane must be found, and then sealed (Alagusundaram et al. 1995). Due to the difficulties associated with bolted-metal bins, two welded-steel hopper bins (4.72 m in diameter, 104 m^3 in volume) (Model 16110E STOR-KING, Winkler, MB), at the Glenlea Research Station, approximately 20 km south of Winnipeg, MB were used for this research.

Based on the assumption that leakage through the welded seams of the hopper bins is negligible, leakage would be confined to the seams of the visible bin openings. These bins had five visible openings: 1) the bottom-cone opening for grain unloading, 2) the top-cone opening for grain filling, 3) the access manhole in the roof, 4) the access manway in the bottom cone, and 5) the aeration-duct opening. The objective of the first series of experiments was to develop a suitable method for sealing the five visible bin openings. A design constraint was that the method should be compatible with existing welded-steel hopper bins because sealed bins are not yet available for sale in North America.

4.2 Criteria for evaluating each sealing method

To be an ideal replacement for phosphine, CO_2 should kill the insects in the same length of time as phosphine. At grain temperatures in the range of 16-25°C, phosphine released from aluminum phosphide tablets kills *C. ferrugineus* in 4 d (Detia Degesch Manual, Laudenbach, Germany). To kill all life stages of *C. ferrugineus* in 4 d, a CO_2 concentration of approximately 65% is required, with the exact concentration dependent on the grain temperature and moisture content (Jay and D'Orazio 1984; Alagusundaram et al. 1996). Any sealing method that maintains a 65% CO_2 concentration for 4 d will be considered acceptable. In addition, the CO_2 must be uniform throughout the bin, in both the radial and vertical directions. Lethal concentrations can be maintained by continuously or periodically adding CO_2 throughout the duration of the fumigation (Jay et al. 1970; Alagusundaram et al. 1995). Management of a CO_2 fumigation could be simplified, however, if only an initial application of CO_2 was required.

Various sealing methods were evaluated based on the maintenance of a uniform 65% CO_2 concentration throughout the empty bin for 4 d supplied by a single application of dry ice (the mass of dry ice was calculated assuming perfect replacement of air by the CO_2).

4.3 Instrumentation of the welded-steel hopper bins

Both bins were instrumented identically with semi-rigid nylon tubing (3.2-mm outside diameter, 2.0-mm inside diameter) for sampling CO_2 concentrations inside the bin (Fig. 4.1). Because CO_2 concentrations are likely to be uniform in the horizontal direction (Alagusundaram et al. 1996), sampling points were located along only one radius at four heights. The sampling tubes were attached to three 21gauge copper 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 top and bottom ends of each wire were tied to eye-bolts fastened to the top and bottom cones of the bin. All sampling tubes were led out of the bin through holes made in the aeration-duct cover, which allowed the collection of gas samples while standing on the ground. The outlet ends of the sampling tubes were covered with rubber septa.

A pressure relief valve (Fig. 4.2), attached to the bin through a hole in the aeration-duct cover, was used as a precaution against the bin pressurizing and rupturing. The pressure relief valve was constructed of acrylonitrile-butadiene-styrene terpolymer (ABS) pipe (76-mm inside diameter) and filled with a mixture of water and windshield washer anti-freeze (methyl alcohol). All holes created for the installation of the instrumentation in the bins were sealed with a silicone sealant.

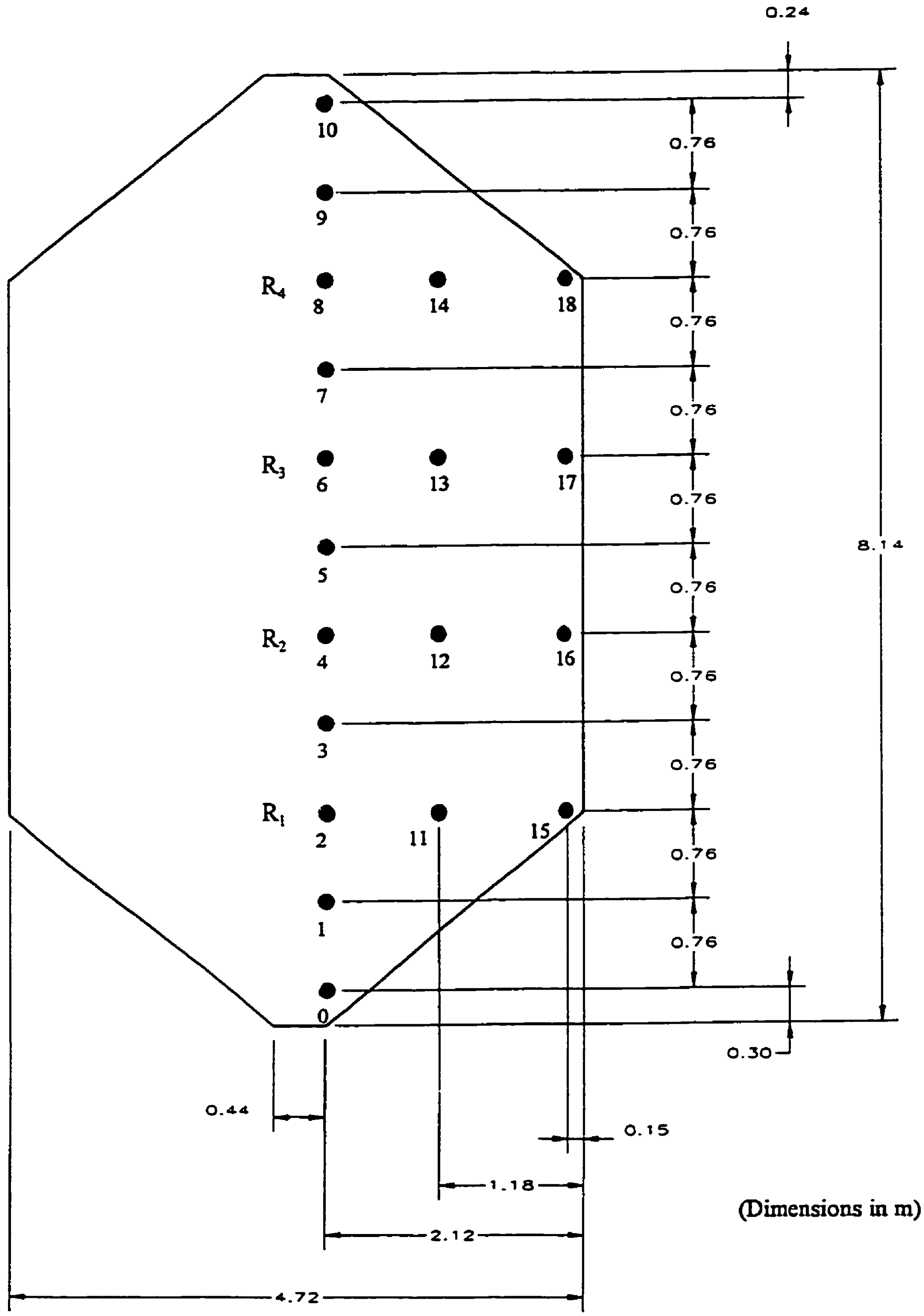
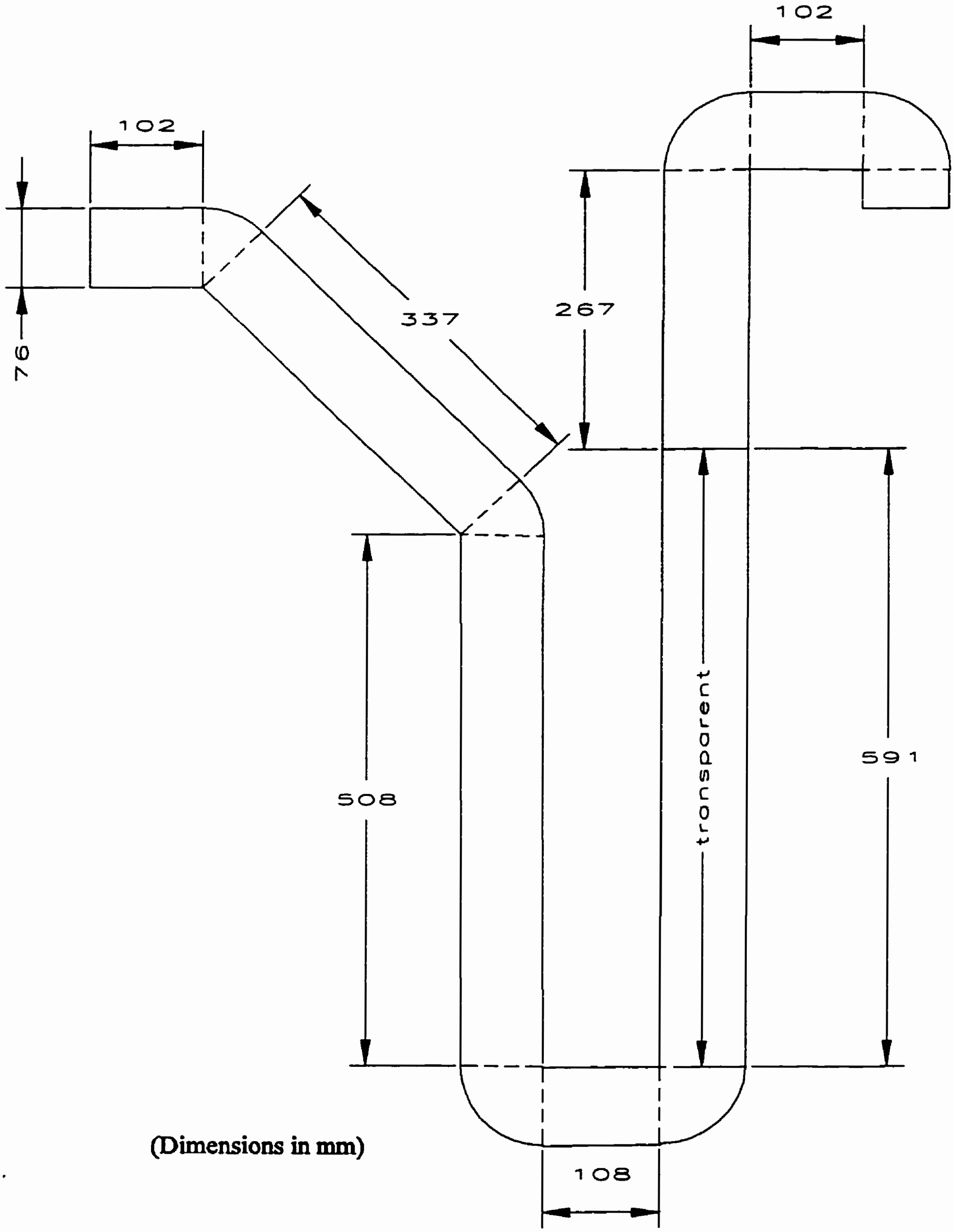


Fig. 4.1 Locations of sampling points in the instrumented welded-steel hopper bins.



(Dimensions in mm)

Fig. 4.2 The pressure relief valve, constructed of ABS pipe, was attached to the aeration-duct cover as a precaution against the bin pressurizing and rupturing.

4.4 Apparatus for introduction of dry ice into the bin

A box-and-duct apparatus (Fig. 4.3) was designed to use dry ice (solid CO_2) as the source of fumigant. A 0.575 m x 0.575 m x 0.575 m box was constructed using 18-gauge cold-rolled sheet metal to hold the dry ice pellets outside the bin at ground level. The pellets sublimated inside the holding box and the gaseous CO_2 was ducted to the top of the bin inside a 50-mm inside diameter ABS pipe and into the bin through a hole in the roof.

Vertical CO_2 stratification occurs inside large bins (Banks et al. 1991; Peng and Chen 1993; Alagusundaram et al. 1995). This problem can be solved by recirculating the gases within the bin from bottom to top. For this purpose, a second duct was connected from the aeration-duct cover to the holding box. A vacuum pump (Model 0440-V119-A, Gast Mfg. Corp., Benton, MI) was used to recirculate the interstitial gases. Automotive heater hose (19-mm inside diameter; 3-mm wall thickness) was used to connect the vacuum pump with the ABS pipe. Plastic or brass ball valves were fitted into the lines at various locations to control the recirculation circuit.

4.5 Procedure for evaluating the permeability of the recirculation duct

Once connected to the bin, the box-and-duct apparatus became part of the storage structure and had to be considered when the bin was being sealed. The holding box was assembled with continuous welds, therefore, leakage from the box was assumed negligible. All ABS joints were glued with an ABS solvent and connections between the heater hose and the ABS pipe and between the heater hose and the vacuum pump were clamped tightly using hose clamps. With the assumption of no leakage at any joints, the only potential for leakage was through the duct material itself. It was expected that the loss of CO_2 through the wall of either the ABS pipe or the heater hose would be negligible, but this was not known. A simple experiment was conducted to provide assurance that CO_2 was not escaping through the walls of the duct material.

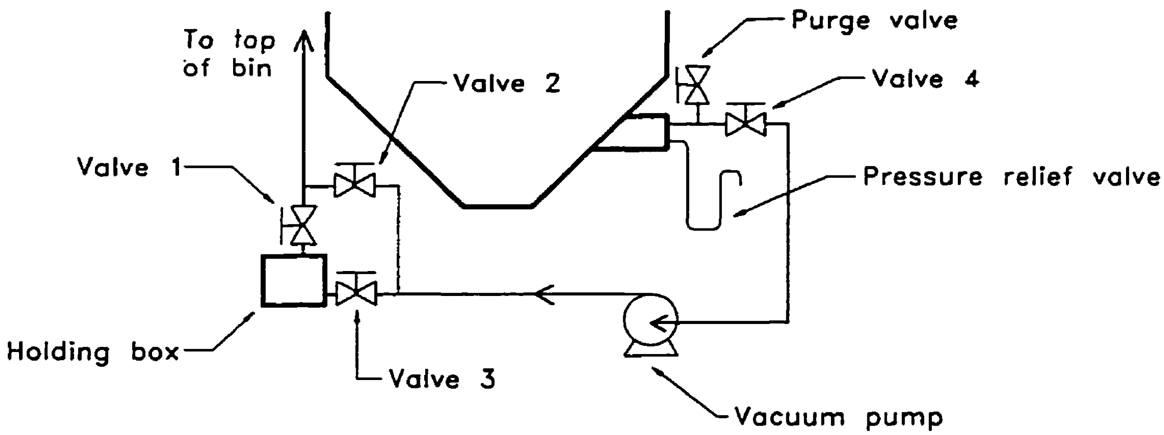


Fig. 4.3 The box-and-duct apparatus used for introducing CO_2 into the bin from ground level. Dry ice was placed into the holding box and, after sublimation, was ducted into the bin with ABS pipe. Valves 1 to 4 were used to control the flow of gases.

A 1 m length of the duct material was fitted with ball valves at either end and instrumented with one nylon sampling tube and one type T copper-constantan thermocouple at the midpoint. One end of the test length was connected to a cylinder of gaseous CO_2. The sampling tube was covered with a rubber septum and the thermocouple was connected to a digital temperature indicator.

With both valves open, gaseous CO_2 was purged through the test length (either heater hose or ABS pipe). The valve on the CO_2 tank was then closed. Immediately thereafter, the ball valves at either end of the test length were closed. At 15 min intervals, for a duration of 4 h, the temperature inside the test length was recorded and a gas sample was collected and analyzed (Appendix A) using a calibrated gas chromatograph (Model 8430 Matheson Gas Products, East Rutherford, NJ) equipped with a thermal conductivity detector and operated isothermally (oven and detector) at 40°C using helium as a carrier gas. The column was stainless steel (2 m long) and packed with Porapak Q. This gas chromatograph was used for all experiments described in this thesis. The procedure was repeated three times for each duct material.

The number of moles of CO_2 and, therefore, the CO_2 concentration inside the test length decreased (solid lines in Figs. 4.4 and 4.5). The total volume of gas inside the test length was 2.0 x 10^{-3} m^3 for the ABS pipe and 0.3 x 10^{-3} m^3 for the heater hose. Approximately 10.0 x 10^{-6} m^3 of gas were withdrawn from the test length each time a sample was taken. Consequently, after 17 samples had been taken, 170 x 10^{-6} m^3 of gas had been removed. This corresponded to approximately 9% of the volume inside the ABS pipe and 57% of the volume inside the heater hose. After adjustment for the moles of CO_2 removed with each sample, the dashed lines (Figs. 4.4 and 4.5) are relatively constant, suggesting that the quantity of CO_2 lost through the walls of the ducts was negligible. For further tests, I assumed that the ABS pipe and the heater hose were impermeable to CO_2 and concluded that the recirculation system was not a likely source of CO_2 loss from the bin.

4.6 Experimental procedure for evaluating a sealing method

Initially, the bins had visible holes around several of the factory covers (i.e., the cover for the top-cone opening had been designed to allow the escape of air through the top during aeration or near-ambient drying of the stored grain). Modifications were required to make the bins airtight.

To evaluate the effectiveness of each sealing method, the bin was filled with gaseous CO_2 and the rate of concentration decay was measured. Grain is known to sorb CO_2 (Mitsuda et al. 1973), but because the exact amounts are not known I could not have differentiated between the CO_2 lost due to leakage and that due to sorption. To eliminate this unknown interaction of CO_2 with grain, I decided to evaluate empty bins. An additional benefit to be gained by the absence of grain was reduced ventilation time between experiments. It was important that the concentration of CO_2 before addition of CO_2 be at or near atmospheric levels so that a true indication of CO_2 retention by the bin was observed. With empty bins (experiments S1.1 to S13.2), complete ventilation was achieved in a matter of minutes while several hours would have been required if the bins had been full of grain.

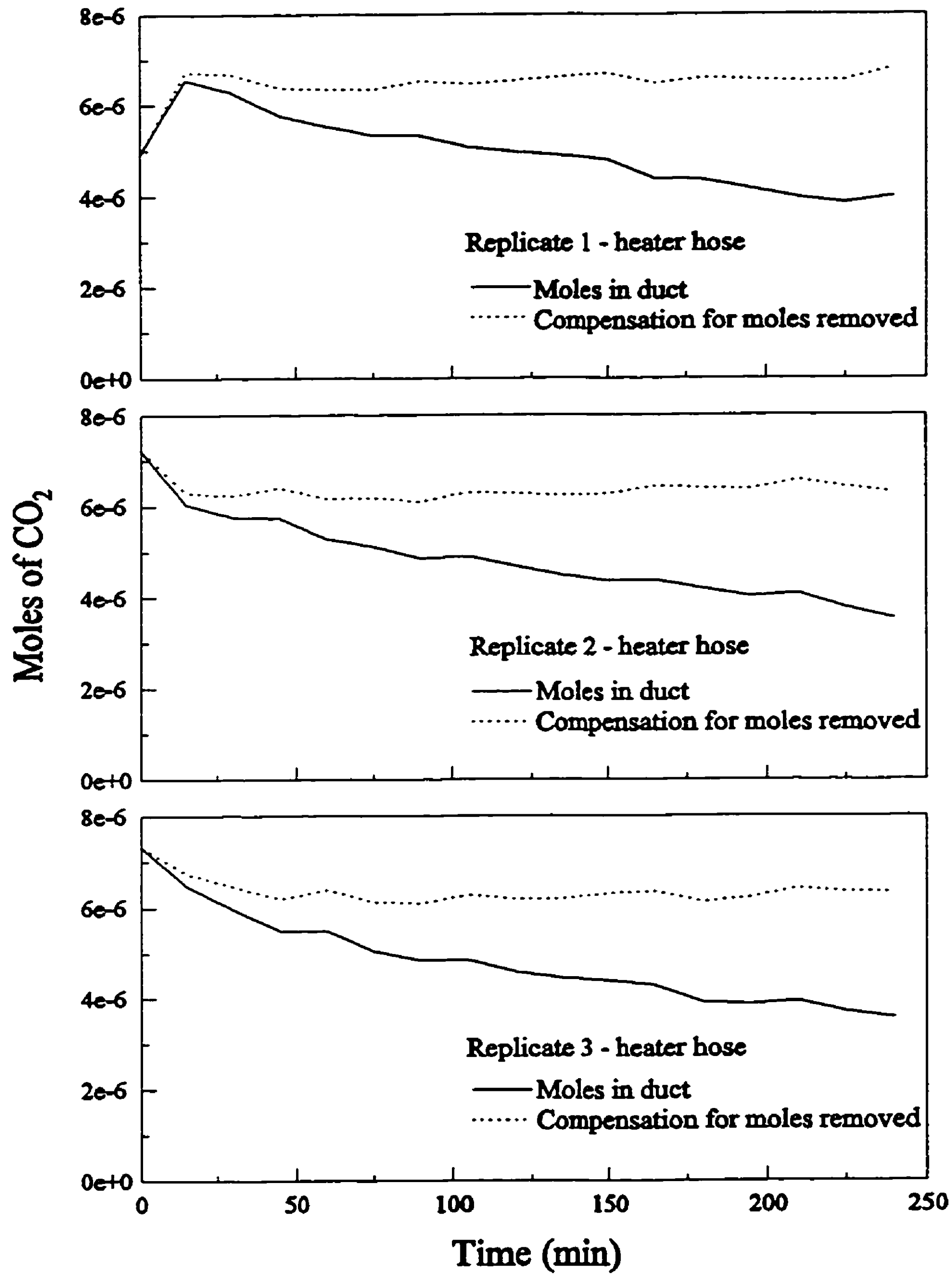


Fig. 4.4 Moles of CO_2 remaining inside a 1 m length of heater hose as a function of time. The solid lines represent the experimental observations and the dashed lines represent the number of moles adjusted for those removed by sampling.

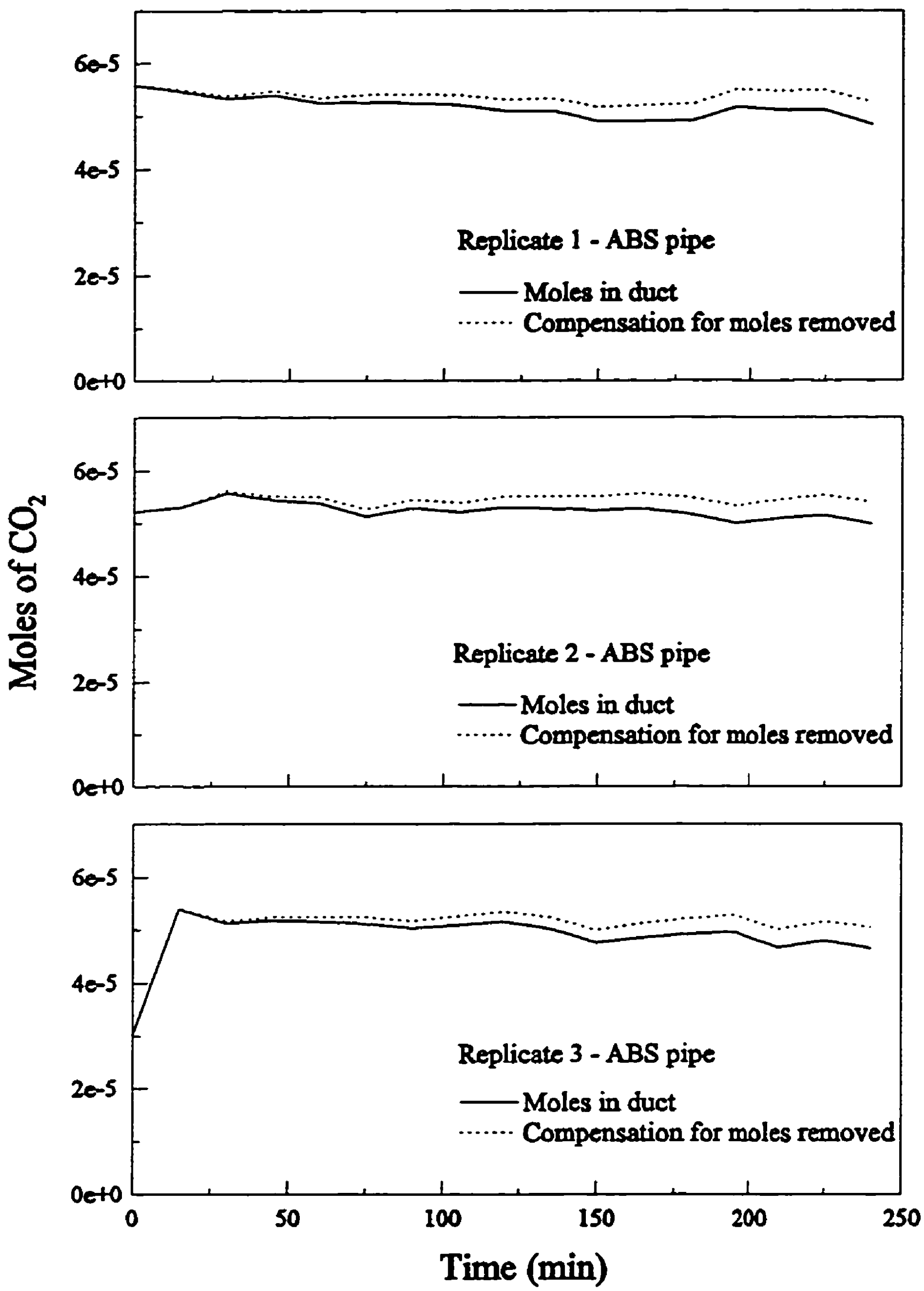


Fig. 4.5 Moles of CO_2 remaining inside a 1 m length of ABS pipe as a function of time. The solid lines represent the experimental observations and the dashed lines represent the number of moles adjusted for those removed by sampling.

The procedure followed after completing each method of sealing consisted of four steps:

1. dry ice was placed inside the holding box;
2. at specified intervals, gas samples were collected for analysis using the calibrated gas chromatograph. Before collecting the 10-mL samples, the sampling lines were purged with a syringe by withdrawing a volume of gas equivalent to the volume of the length of sampling line. The gas samples were temporarily stored in gas-tight syringes and were analyzed within of 30 min of being collected;
3. the running time for each experiment was planned to be 4 d. Often, however, the leakage was so rapid that running the experiment for 4 d was meaningless. In these cases, the experiment was stopped prematurely to allow the start of the next experiment; and
4. the bin was opened and allowed to ventilate so that the gas concentrations inside the bin would return to atmospheric levels.

Although beneficial for these experiments, empty bins would not be used in an actual CO_2 fumigation. Consequently, once the potential sealing methods had been identified, a small number of experiments (S14.1 to S15.3) were conducted with the bins half-filled with wheat to ensure that the sealing methods would work for grain-filled bins and to identify concerns for future experiments (see Section 4.8.3 for a description of the concerns which were identified).

4.7 Description of the sealing methods

Many sealing methods were tried with varying degrees of success. Because some sealing methods were not effective and experimental time was limited, replication was not considered a priority. Rather than repeating an unsuccessful method, useful information gained from it was applied to the next method. A summary of the experiments is given in Appendix B.

Experiments S1.1 to S2.3 (Table 4.1), with no sealing done to the bins, were used as a frame of reference to evaluate the impact of each subsequent sealing method. These four experiments were grouped under the heading of *No sealing* (Table 4.1) for further analysis.

The next set of five experiments (S3.1 to S5.3) were grouped as *Method #1* (Table 4.1) for further analysis because the basic sealing method remained constant. The bottom-cone opening was sealed by placing an inflated bicycle tire tube between the sliding gate and the bin floor. Before inflation, the tire tube was fastened in place using duct tape and the sliding gate was closed. The tire tube was then inflated using a foot pump. All other bin openings were sealed by placing rubber gaskets around the perimeter of the openings and closing the factory lids. This method was impractical because the tire tube was difficult to insert and the rubber deteriorated so that holes were present after only five tests (an elapsed time of approximately 2 wk).

Experiments S6.1 to S10.1 were grouped as *Method #2* (Table 4.1). Of these five experiments, no two were identical as improvements were made constantly. Again, the bottom-cone opening was treated differently than the other openings. A trough-shaped steel lid was constructed to enclose the entire sliding-gate mechanism. Gas leakage was evident at the corners of the lid during experiment S6.1, therefore, the corners of the trough-shaped lid were modified for the remaining four experiments (S7.1 to S10.1). The trough-shaped lid was more practical than the bicycle tire tube because it could be added to the bin from the outside even if the bin was full of grain, however, the lid was difficult to close and did not eliminate the leakage from the bottom of the bin. The other factory lids were modified so that they could be clamped shut, but this did not eliminate all gas loss. During this group of experiments, I realized that the top-cone opening was also a prominent source of gas loss. For experiments S9.1 and S10.1, a plastic-wrapped Styrofoam disk was inserted inside the factory lid to fill the space designed for air escape.

In the next group of experiments (S11.1 to S12.3, grouped as *Method #3* in Table 4.1), a modified flat lid was much easier to close than the trough-shaped lid and eliminated any detectable leakage from the bottom of the bin. Besides changes to the lid for the bottom-cone opening, the rubber gasket was replaced with closed cell neoprene/EPDM rubber (Jacobs and Thompson Division, Weston, ON) on the other bin openings. These factory lids were clamped shut as before.

With the success of the lid design used in *Method #3* for sealing the bottom-cone opening, all five openings were sealed using the same method. Two experiments (S13.1 and S13.2) were done with all five openings sealed identically.

Table 4.1 Description of the basic sealing ideas associated with each group of experiments.

Experiments	Group Name	Description of Basic Sealing Idea*
S1.1, S2.1, S2.2, S2.3	*No sealing*	No modifications to bin, but holes created by instrumentation were filled with a silicone sealant.
S3.1, S4.1, S5.1, S5.2, S5.3	*Method #1*	**Opening in bottom cone**: An inflated bicycle tire tube was duct-taped between the sliding gate and floor of the bin.
S6.1, S7.1, S8.1, S9.1, S10.1	*Method #2*	**Opening in bottom cone**: A trough-shaped, sheet-metal lid was fitted over the sliding-gate housing, enclosing the entire sliding-gate mechanism.
S11.1, S12.1, S12.2, S12.3	*Method #3*	**Opening in bottom cone**: A flat, sheet-metal lid was clamped against angle iron welded around the sliding-gate housing, enclosing the entire sliding-gate mechanism.
S13.1, S13.2	*Method #4*	**All five bin openings**: 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 experiments within the group. Minor variations existed among experiments (Appendix B).

4.8 Evaluation of the sealing methods

4.8.1 Uniformity of CO_2 in the radial direction The uniformity of CO_2 in the radial direction was assessed using the coefficient of variation (CV), which is a ratio of the standard deviation (S.D.) to the mean (expressed as a percentage) (Appendix C). A CV value was calculated for each of the four levels (R_1 = points 2, 11, and 15; R_2 = points 4, 12, and 16; R_3 = points 6, 13, and 17; R_4 = points 8, 14, and 18) at each sampling time (Figs. 4.6 to 4.9). Small CV values correspond to low levels of variation, or in this research, a high degree of uniformity. Before sealing the bins, radial uniformity was poor for all four levels throughout the duration of the tests (Fig. 4.6). As the different sealing methods were tried, the observed trend was toward smaller CV values (Figs. 4.7 to 4.9). Statistical analysis confirmed that the CV values changed significantly with improved sealing (ANOVA: One-way, α=0.05). Further analysis showed that CV values decreased significantly from *No sealing* to *Method #1* and from *Method #2* to *Method #3*, but not from *Method #1* to *Method #2* (Student's t-test, α=0.05). Consequently, I concluded that radial uniformity improved with increased sealing and that *Method #3* was the best sealing method.

Radial uniformity also appeared to improve with time (Figs. 4.7 to 4.9). I speculated that large CV values occurred during the initial hours of the tests before equilibrium had been reached, but decreased after equilibrium was reached. Based on observation of the plotted CV values (Figs. 4.7 to 4.9), I decided that variation was greatest during the first 20 h of all tests. To enable comparison, $\overline{CV}$ and $\overline{CV}_{20}$ values were calculated for each of the four levels by averaging the CV values associated with each sealing method. All CV values were used to calculate $\overline{CV}$, but only those CV values occurring 20 h or more after the start of the experiment were used to calculate $\overline{CV}_{20}$. Contrary to my expectation, $\overline{CV}_{20}$ values were not significantly (Student's t-test, α=0.05) different than $\overline{CV}$ values in 14 out of 16 cases (Table 4.2).

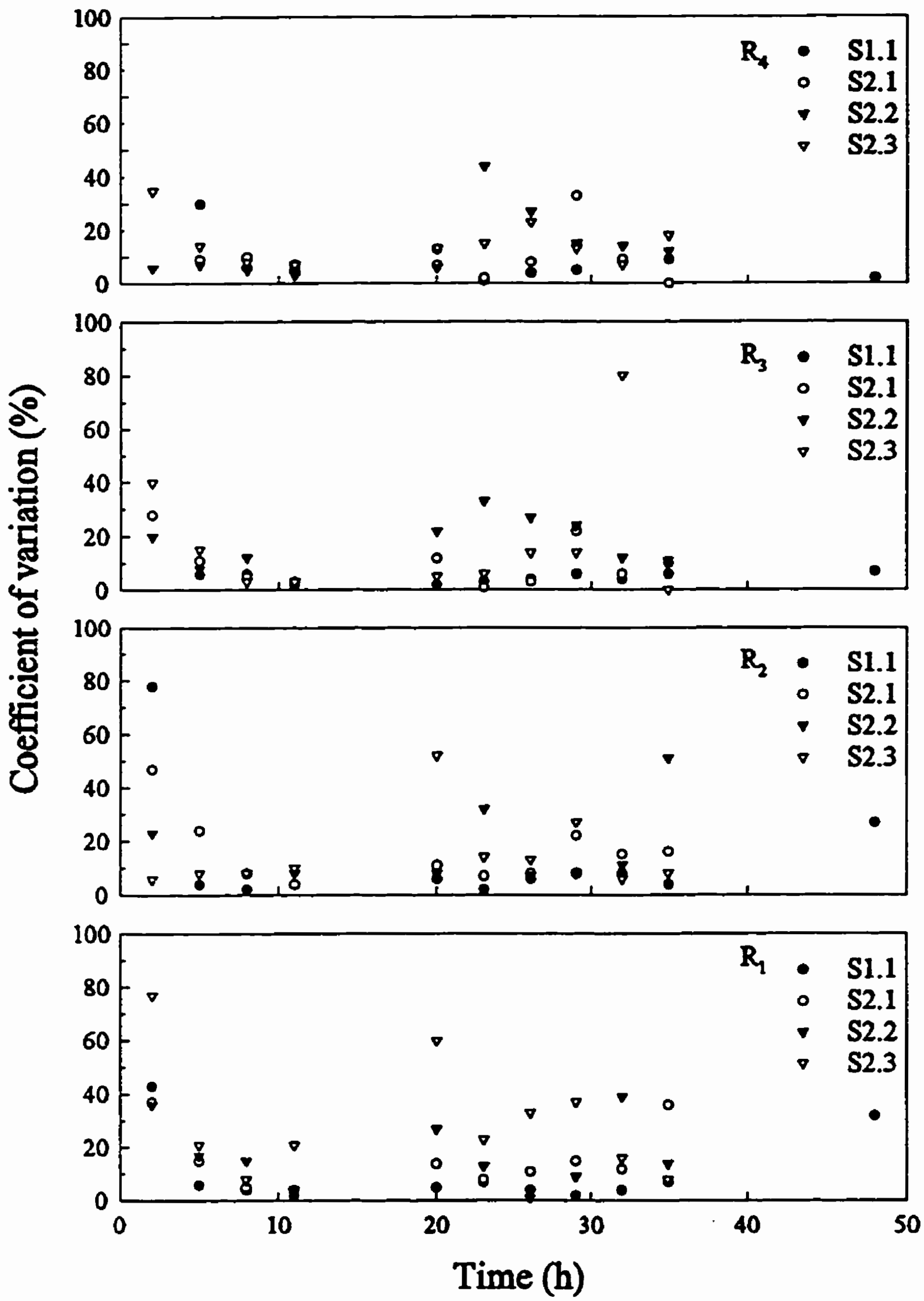


Fig. 4.6 Radial uniformity of CO_2 concentrations within empty bins for each of the four levels, represented by the coefficient of variation. These four experiments (S1.1 to S2.3)were conducted with no sealing done to the bins.

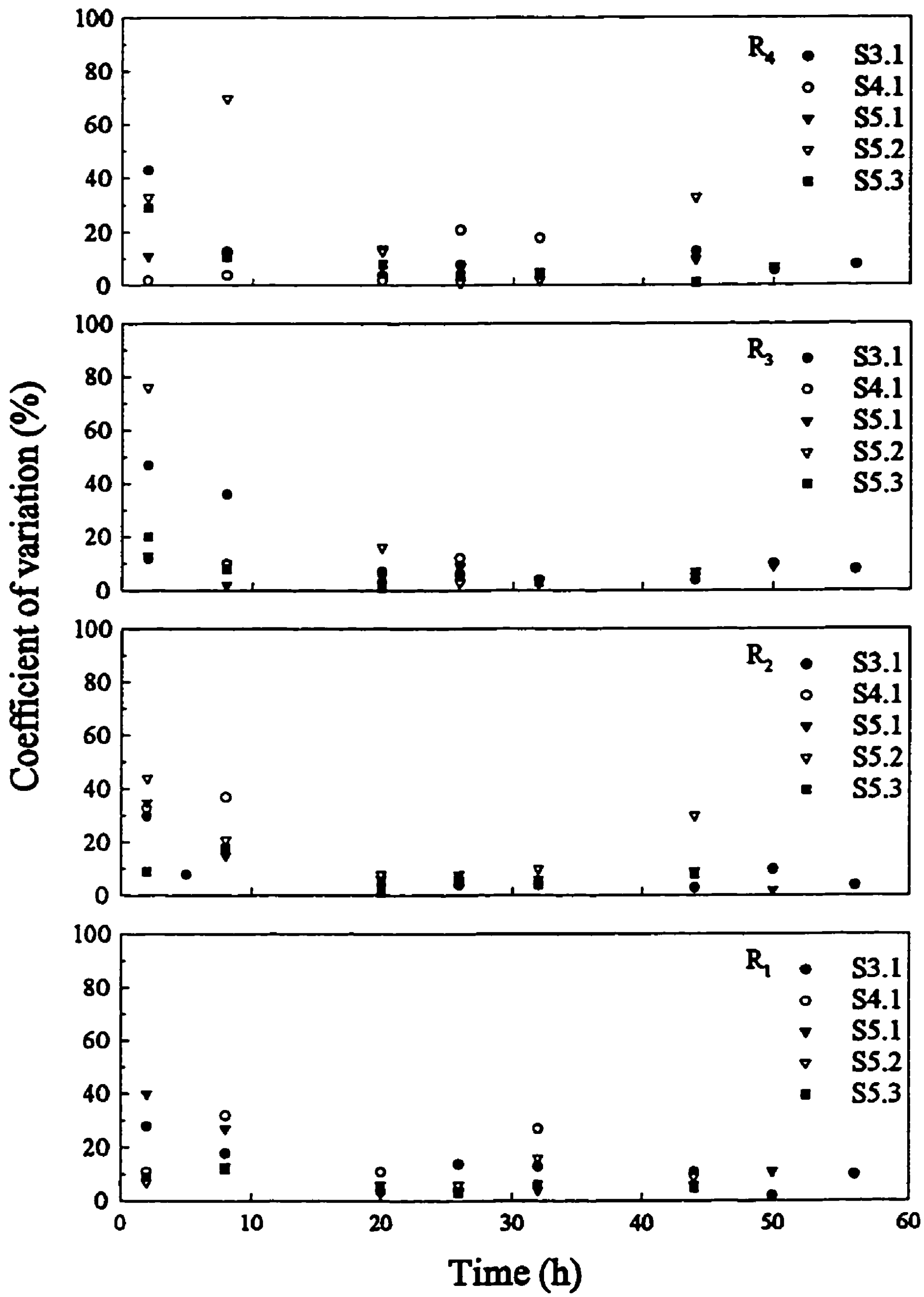


Fig. 4.7 Radial uniformity of CO_2 concentrations within empty bins for each of the four levels, represented by the coefficient of variation. These five experiments (S3.1 to S5.3) were conducted with the bin sealed according to *Method #1* (Table 4.1).

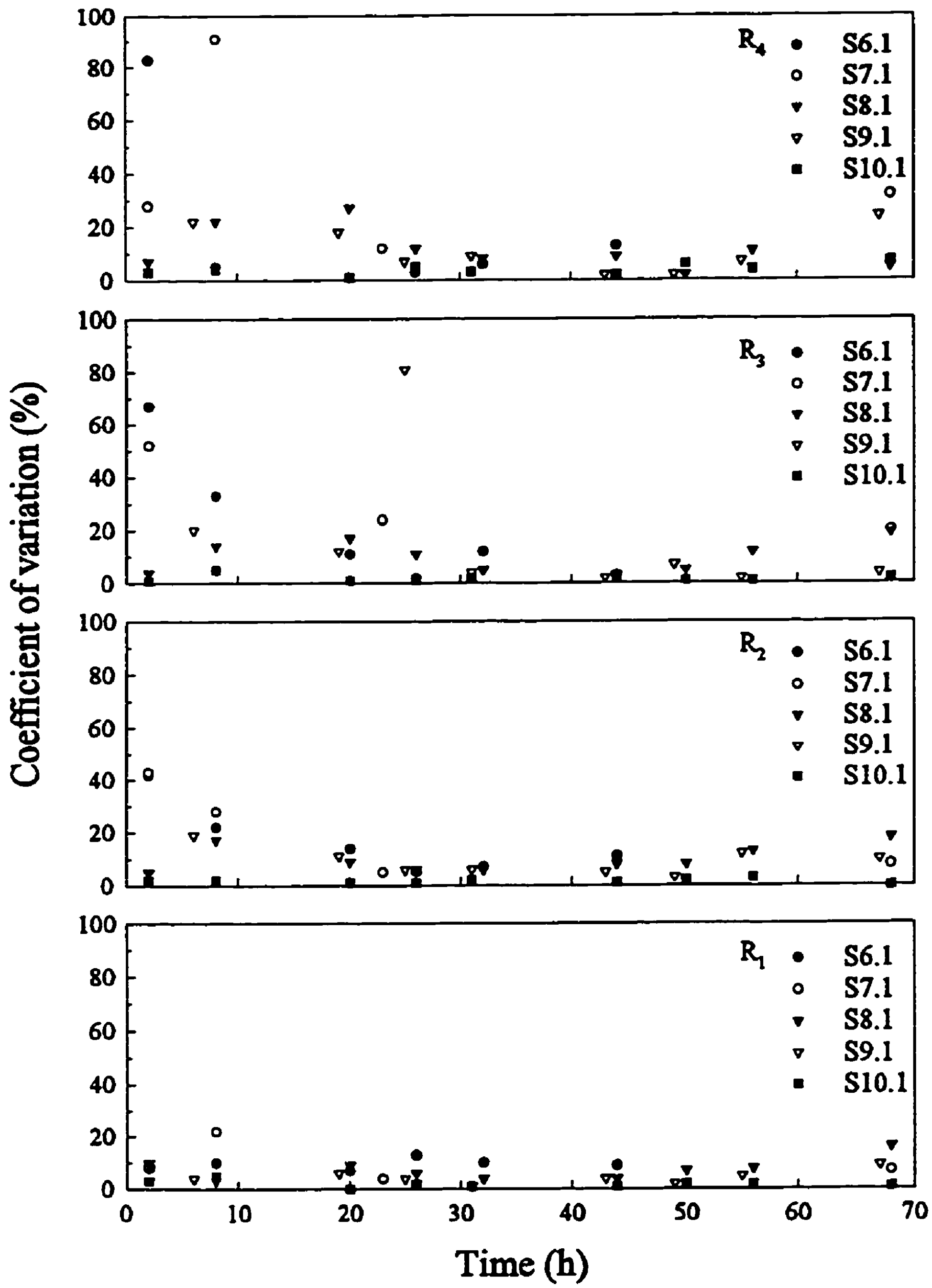


Fig. 4.8 Radial uniformity of CO_2 concentrations within empty bins for each of the four levels, represented by the coefficient of variation. These five experiments (S6.1 to S10.1) were conducted with the bin sealed according to *Method #2* (Table 4.1).

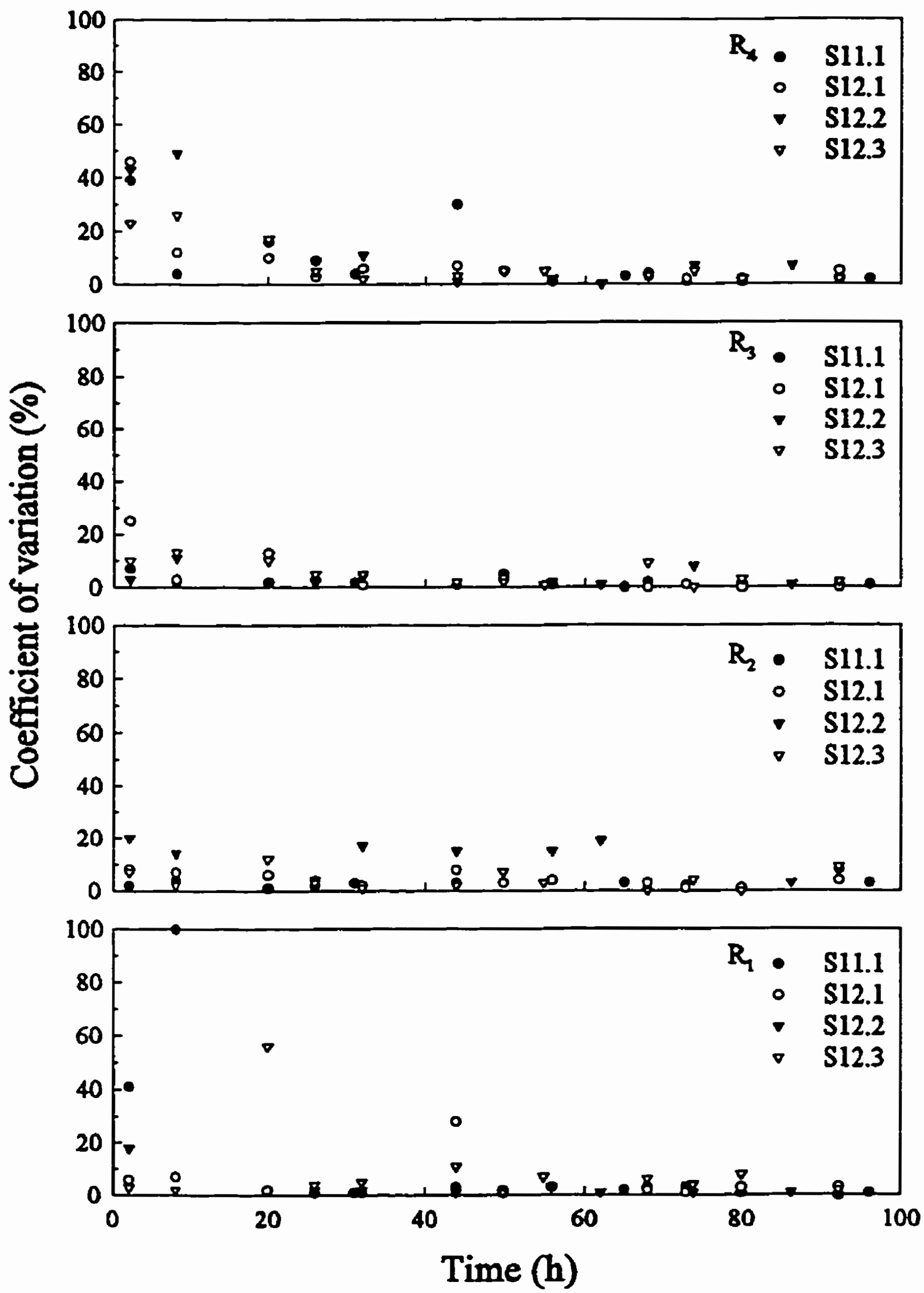


Fig. 4.9 Radial uniformity of CO_2 concentrations within empty bins for each of the four levels, represented by the coefficient of variation. These four experiments (S11.1 to S12.3) were conducted with the bin sealed according to *Method #3* (Table 4.1).

Table 4.2 Average CV values (%) for each of the four levels calculated as the average of CV values from all sampling times ($\overline{CV}$) and from all sampling times ≥ 20 h after the start of the experiment ($\overline{CV}_{20}$) of all experimental trials in empty bins associated with each sealing method.

	No Sealing		*Method #1*		*Method #2*		*Method #3*	
Level	$\overline{CV}$ (%)	$\overline{CV}_{20}$ (%)	$\overline{CV}$ (%)	$\overline{CV}_{20}$ (%)	$\overline{CV}$ (%)	$\overline{CV}_{20}$ (%)	$\overline{CV}$ (%)	$\overline{CV}_{20}$ (%)
R_4	18	12	13	9	14	8	10	5*
R_3	16	13	12	7	11	7	4	3
R_2	15	15	13	8*	10	7	5	5
R_1	18	17	12	9	6	5	8	5

* The $\overline{CV}_{20}$ value is significantly different than the corresponding $\overline{CV}$ value (Student's t-test, α=0.05).

When the bins were sealed using *Method #3*, the $\overline{CV}$ values were ≤ 10% for all four levels compared with $\overline{CV}$ values between 15 and 18% before any sealing had been done (Table 4.2). Based on these results, I concluded that there was a reasonable degree of radial uniformity in empty bins. The degree of radial uniformity would be even greater if R_4 was ignored. Because the gaseous CO_2 entered the bin at the top closest to R_4, there was little time for the gas to disperse. When the readings during the initial 20 h were ignored (while the most rapid sublimation was occurring), the $\overline{CV}_{20}$ value of 5% for R_4 agreed closely with the $\overline{CV}$ values calculated for the other three levels. The experiments for *Method #4* were conducted after preliminary analysis had shown this radial uniformity, therefore, CO_2 readings were taken along the centreline of the bin only.

Four additional experiments were done in bins half-filled with wheat to test the influence of grain on radial uniformity. For experiment S14.1, the bin was sealed according to *Method #2*, but for experiments S15.1 to S15.3, the bins were sealed according to *Method #3*. Because there was no visible difference in CV values between the two sealing methods (Fig. 4.10), the four experiments were grouped for further analysis. As done previously, $\overline{CV}$ and $\overline{CV}_{20}$ values were calculated for each of the four levels (Table 4.3). The results were consistent with those from the empty bins because there were no significant differences (Student's t-test, α=0.05) between $\overline{CV}$ and $\overline{CV}_{20}$ values.

To enable comparison between empty and half-filled bins, all radial CV values for *Method #3* in the empty bins were averaged to yield a value of 7%. The average of all radial CV values from the wheat-filled bins was significantly (Student's t-test, α=0.05) greater at an average of 10%. Although uniformity was poorer in the wheat-filled bins, I have concluded that a $\overline{CV}$ value of 10% represents an acceptable amount of variation. Consequently, I have assumed that CO_2 concentrations were uniform in the radial direction in both empty and half-filled bins.

Table 4.3 Average CV values (%) from all sampling times ($\overline{CV}$) and all sampling times ≥20 h after the start of the experiment ($\overline{CV}_{20}$) for each of the four levels and the bin centreline for the four experiments conducted in bins half-filled with wheat.

Location	$\overline{CV}$ (%)	$\overline{CV}_{20}$ (%)
R_4	16	10
R_3	7	5
R_2	9	8
R_1	9	9
Centreline	24	18

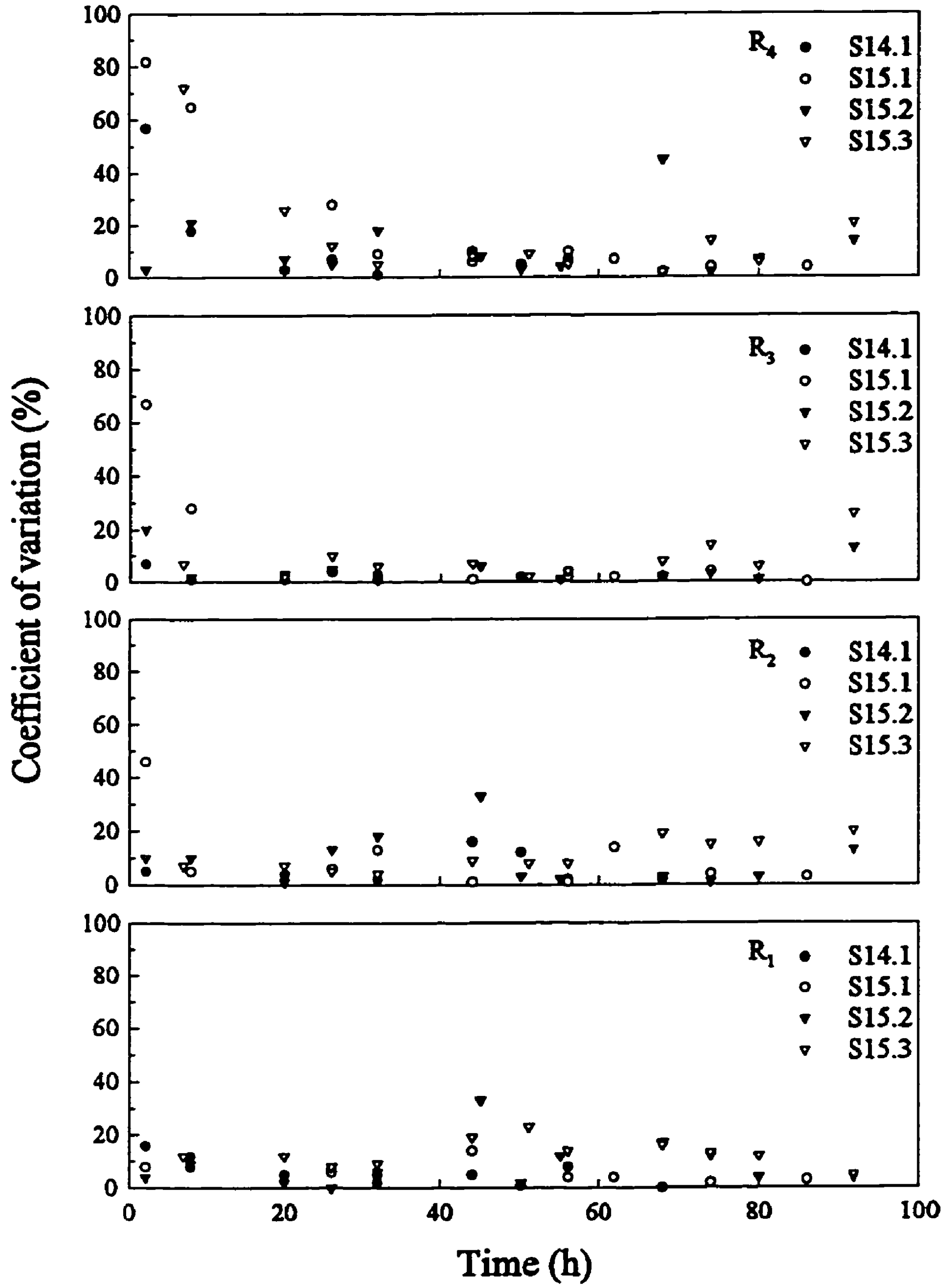


Fig. 4.10 The radial uniformity of CO_2 concentrations within bins half-filled with wheat (experiments S14.1 to S15.3) for each of the four levels, represented by the coefficient of variation.

4.8.2 Uniformity of CO_2 in the vertical direction The mean, standard deviation (S.D.), and coefficient of variation (CV) of the CO_2 concentrations measured at the eleven sampling points along the centreline of the bin were calculated for each sampling time of each experiment (Appendix C). Without sealing, vertical uniformity of CO_2 was poor (Fig. 4.11), but improved with sealing. Vertical variation decreased significantly (Student's t-test, $\alpha=0.05$) from experiments with no sealing to those sealed according to *Method #1*, but did not decrease significantly (Student's t-test, $\alpha=0.05$) during the next two increments (i.e., *Method #1* to *Method #2* and *Method #2* to *Method #3*). The variation decreased significantly (Student's t-test, $\alpha=0.05$), however, from *Method #3* to *Method #4*, possibly because all bin openings were sealed using the flat lids. From these results, I concluded that vertical uniformity improved with sealing.

Based on examination of Fig. 4.11, it appeared that vertical uniformity improved with time. As done in the radial direction, $\overline{CV}$ and $\overline{CV}_{20}$ values were calculated (Table 4.4). Significant (Student's t-test, $\alpha=0.05$) improvements in vertical uniformity were observed for the second and third sealing methods when readings taken during the initial 20 h were ignored. This comparison was not possible for *Method #4* because no samples were taken during the initial 20 h. Variation during the initial 20 h possibly occurred because the CO_2 was ducted into the bin at only a single location, and subsequently, had a large vertical distance to move. Based on these results, I concluded that the $\overline{CV}_{20}$ values were a better approximation of vertical uniformity than the $\overline{CV}$ values. With $\overline{CV}_{20}$ values of 8% for the third and fourth sealing methods, I concluded that the CO_2 concentration was uniform in the vertical direction when the bins were sealed according to either of these methods.

The presence of grain had an influence on vertical uniformity. Unlike the empty bins where vertical $\overline{CV}_{20}$ values were significantly (Student's t-test, $\alpha=0.05$) lower than $\overline{CV}$ values, there was no significant difference (Student's t-test, $\alpha=0.05$) between vertical $\overline{CV}$ and $\overline{CV}_{20}$ values in the wheat-filled bins (Fig. 4.12 and Table 4.3). In a direct comparison between the empty and wheat-filled bins, the $\overline{CV}$ value of 13% for *Method #3* in an empty bin (Table 4.4) was significantly (Student's t-test, α=0.05) lower than the $\overline{CV}$ value of 24% observed in the wheat-filled bin (Table 4.3). This large amount of vertical variation is cause for concern because it could result in insect survival in the top portions of the grain bulk.

Table 4.4 Average CV values (%) calculated as the average of CV values from the eleven points along the centreline of the bin from all sampling times ($\overline{CV}$) and from all sampling times ≥ 20 h after the start of the experiment ($\overline{CV}_{20}$) of all experimental trials in empty bins 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

* The $\overline{CV}_{20}$ value is significantly different than the corresponding $\overline{CV}$ value (Student's t-test, α=0.05).

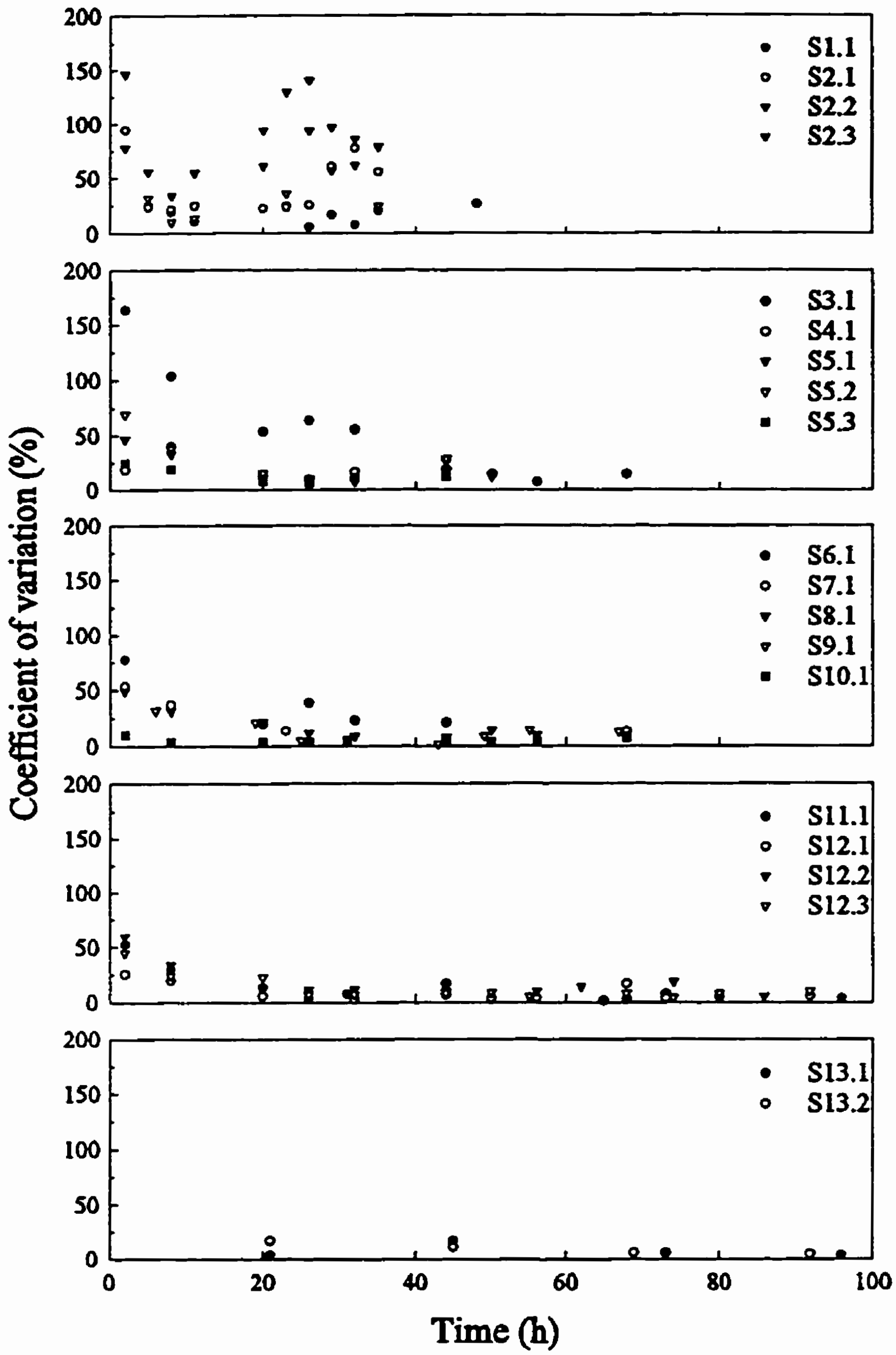


Fig. 4.11 Vertical uniformity of CO_2 concentrations within empty bins, represented by the coefficient of variation. The plots represent *No sealing*, *Method #1*, *Method #2*, *Method #3*, and *Method #4* from top to bottom, respectively.

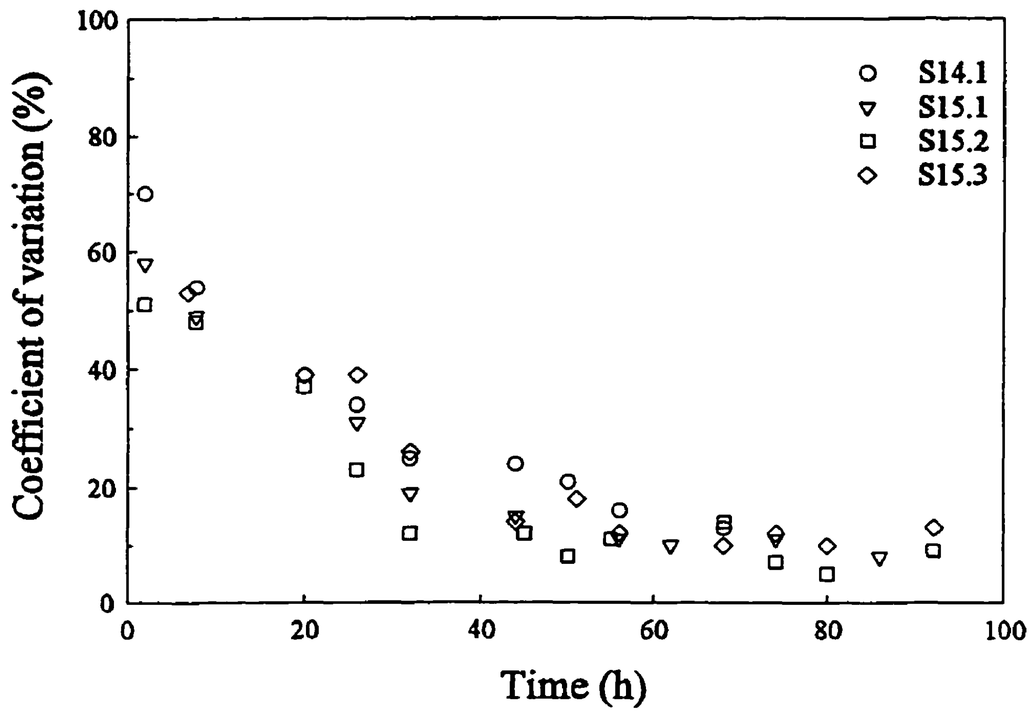


Fig. 4.12 The vertical uniformity of CO_2 concentrations within bins half-filled with wheat (experiments S14.1 to S15.3), represented by the coefficient of variation.

Testing the effectiveness of forced recirculation was not an objective of this work, but experiments were done both with and without forced recirculation, enabling a limited comparison to be made. Forced recirculation had a significant (Student's t-test, α=0.05) influence on radial $\overline{CV}$ values in only 4 out of 12 instances (Table 4.5). In two instances, the $\overline{CV}$ values decreased with forced recirculation, but in the other two cases, the $\overline{CV}$ values increased. This unexpected increase may be the result of a small sample size because only one experiment without recirculation (S11.1) was compared with three experiments with forced recirculation (S12.1, S12.2, and S12.3). Experiment S11.1 possibly displayed unusually low variation.

In the vertical direction, forced recirculation had a significant (Student's t-test, α=0.05) influence in only one of four instances (Table 4.6) with $\overline{CV}_{20}$ values used to make the comparison. Forced recirculation improved uniformity when the least amount of sealing was done (*Method #1*), but had no effect once sealing was improved.

According to my data, forced recirculation does not improve uniformity in well-sealed bins, although this research was not planned to test forced recirculation. Some sample sizes were small and other uncontrolled factors may have influenced the results. Additional research should be done to confirm these results.

Table 4.5 Comparison between $\overline{CV}$ values (%) obtained with and without forced recirculation for each of the four levels of each sealing method.

Sealing Method	Level	$\overline{CV}$ (%)	
		No Recirculation	Forced Recirculation
Method #1	R_4	11	11
	R_3	14	11
	R_2	13	13
	R_1	15	10
Method #2	R_4	20	8
	R_3	16	6*
	R_2	14	6*
	R_1	7	5
Method #3	R_4	9	10
	R_3	2	5*
	R_2	3	6*
	R_1	12	6

* Indicates that the pair of $\overline{CV}$ values are significantly different (Student's t-test, α=0.05).

Table 4.6 Comparison between $\overline{CV}_{20}$ values (%) obtained from the eleven sample points along the centreline of the bin for all trials with no recirculation and $\overline{CV}_{20}$ values (%) obtained from the eleven sample points along the centreline of the bin for all trials with forced recirculation.

Sealing Method	$\overline{CV}_{20}$ (%)	
	No Recirculation	Forced Recirculation
Method #1	28	12*
Method #2	15	8
Method #3	7	9
Method #4	6	10

* Indicates that the pair of $\overline{CV}_{20}$ values are significantly different (Student's t-test, α=0.05).

4.8.3 Mean concentration of CO_2 in the bin For each sampling time, the CO_2 concentration inside the bin was estimated as the mean of the CO_2 concentrations measured at the eleven sample points along the centreline of the bin (Appendix C). For the first experiments (i.e., S1.1 to S2.3), some error was associated with this estimate because vertical uniformity was poor. As the uniformity improved, the error decreased yielding an adequate estimate of the CO_2 concentration inside the bin.

The observed trend was for the mean CO_2 concentration to increase with improved sealing (Fig. 4.13), but the objective of 65% for 4 d (96 h) was not achieved. A CO_2 concentration approaching 50% was observed for experiments S12.1 to S12.3 compared with a peak of approximately 10% without any sealing. Because all concentrations were generated with an identical initial application of 136 kg of dry ice pellets, the modifications to the bins were successful at improving the gas-tightness of the bins. The quantity of dry ice added, however, should have created a CO_2 concentration of approximately 65%. I can conclude, therefore, that loss of CO_2 remained a problem throughout all of these experiments.

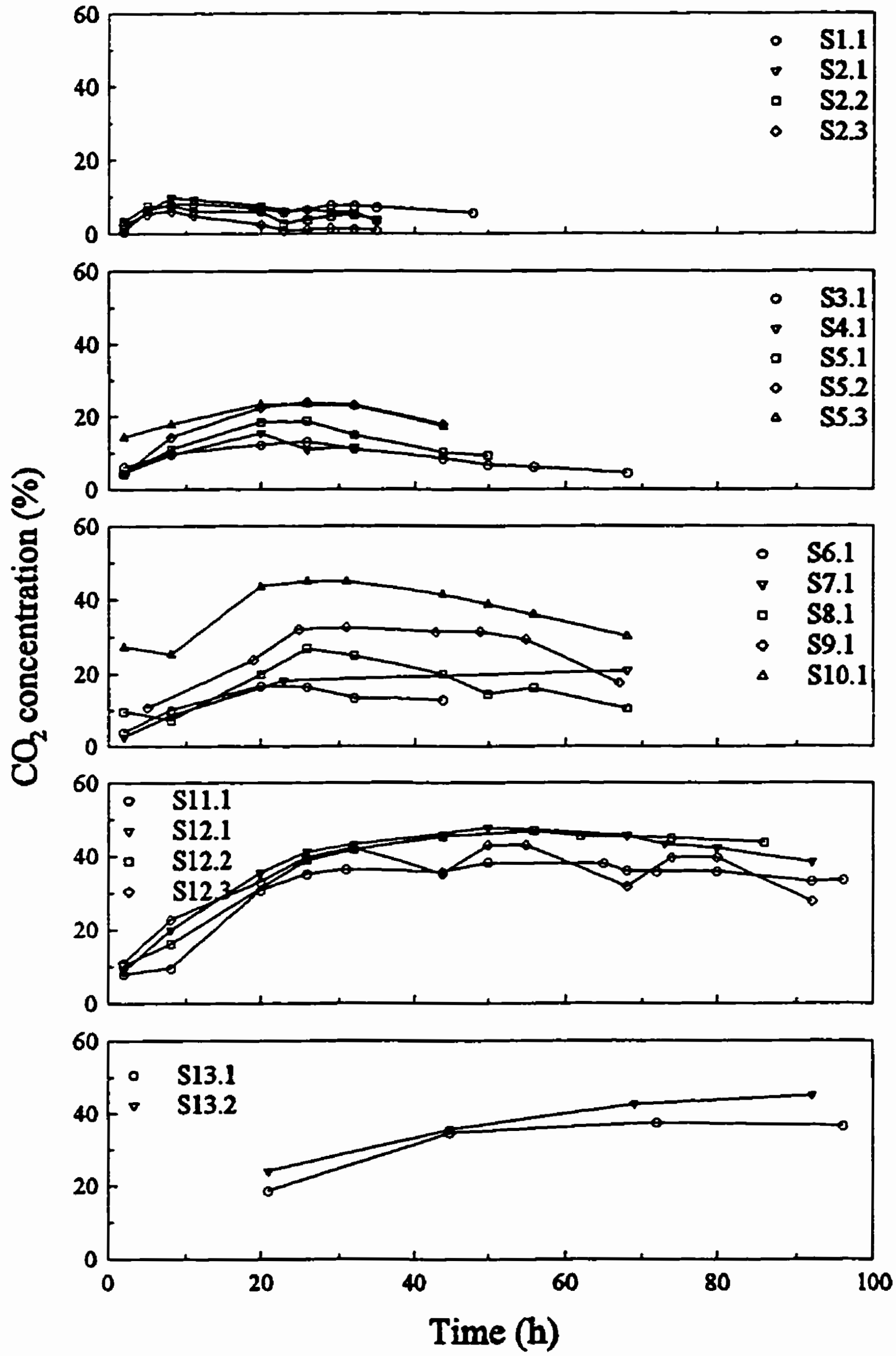


Fig. 4.13 Mean CO_2 concentration for the twenty experiments conducted in empty bins at various stages of sealing. The plots represent *No sealing*, *Method #1*, *Method #2*, *Method #3*, and *Method #4* from top to bottom, respectively.

When the bins were half-filled with wheat, only 97 kg of dry ice was added to the bin because of the reduced air volume. Of the 97 kg, 4 kg (calculated using 104 mg CO_2/kg wheat as an estimate for sorption) was added to compensate for sorption by the wheat. The observed CO_2 concentrations surpassed 40% for all four experiments (Fig. 4.14) similar to the results obtained in the empty bins sealed according to *Method #3*. Grain does not appear to negatively influence the CO_2 concentration, although compensation for CO_2 sorption must be made. These four experiments identified a couple of concerns for future experiments. First, emptying the grain from the bin pulled the sampling tubes down unless they were attached with duct tape to the copper wire along their entire length (leaving only the ends of the tubes open for sampling). A second concern was that small weed seeds and other foreign material were sucked into the sampling tubes during the process of collecting samples, plugging the tubes. This problem was solved by covering the ends of the sampling tubes with fine mesh.

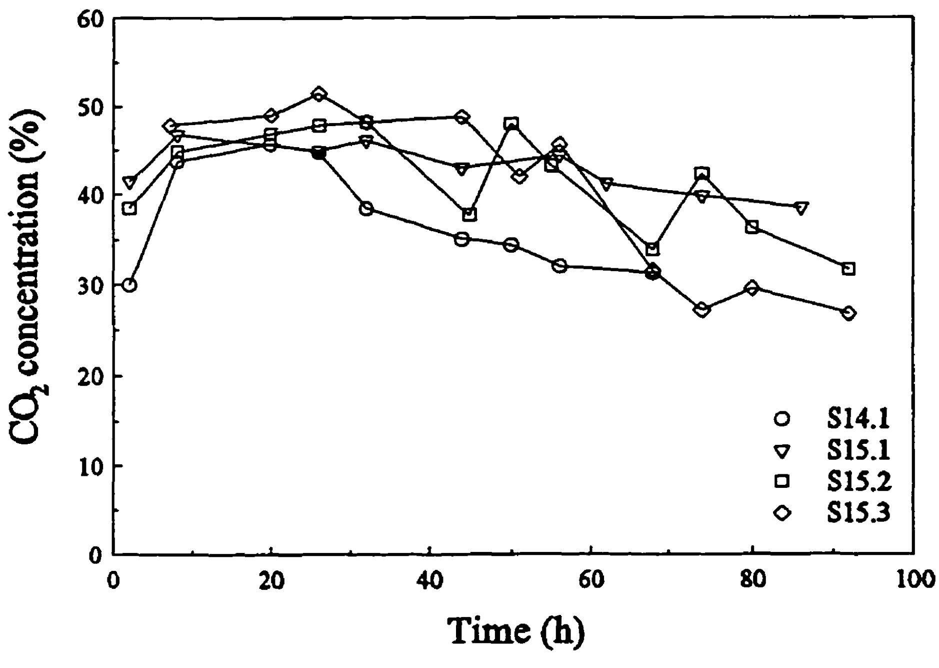


Fig. 4.14 Mean CO_2 concentration for the four experiments conducted in bins half-filled with wheat. Experiment S14.1 was sealed using *Method #2*; experiments S15.1, S15.2, and S15.3 were sealed using *Method #3*.

4.9 Detailed description of *Method #4*

A schematic diagram of the sealing method as applied to the opening in the bottom cone of the hopper bin is shown in Fig. 4.15. The sealing method had to be designed so that it did 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. 4.15). The 50 mm x 50 mm angle iron (B) provided sufficient horizontal clearance for the components of the roller mechanism. A second piece of angle iron (C) extended lower than the sliding-gate mechanism to provide vertical clearance. All four sides were constructed in the same way with the pieces of angle iron joined together using continuous welds to prevent leakage. A hole drilled through the angle iron allowed the crank used to open the unloading gate to be connected or disconnected. When disconnected, the hole was plugged with a #3 rubber stopper.

A flat piece of 18 gauge sheet metal (F) was used to cover the opening, with strips of closed cell neoprene/EPDM rubber (D) attached to both the bottom of the angle iron (C) and the top perimeter of the sheet metal (F), providing the seal. Hand-tightened C-clamps spaced approximately 150-200 mm apart were used to close the lid (Fig. 4.15). 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.

The bottom-cone opening was the most difficult opening to seal because of the gate mechanism. To seal the other four visible openings, angle iron was welded around the perimeter of each opening, creating flat surfaces. Sheet-metal lids were clamped down, with C-clamps providing the force to compress the strips of neoprene rubber.

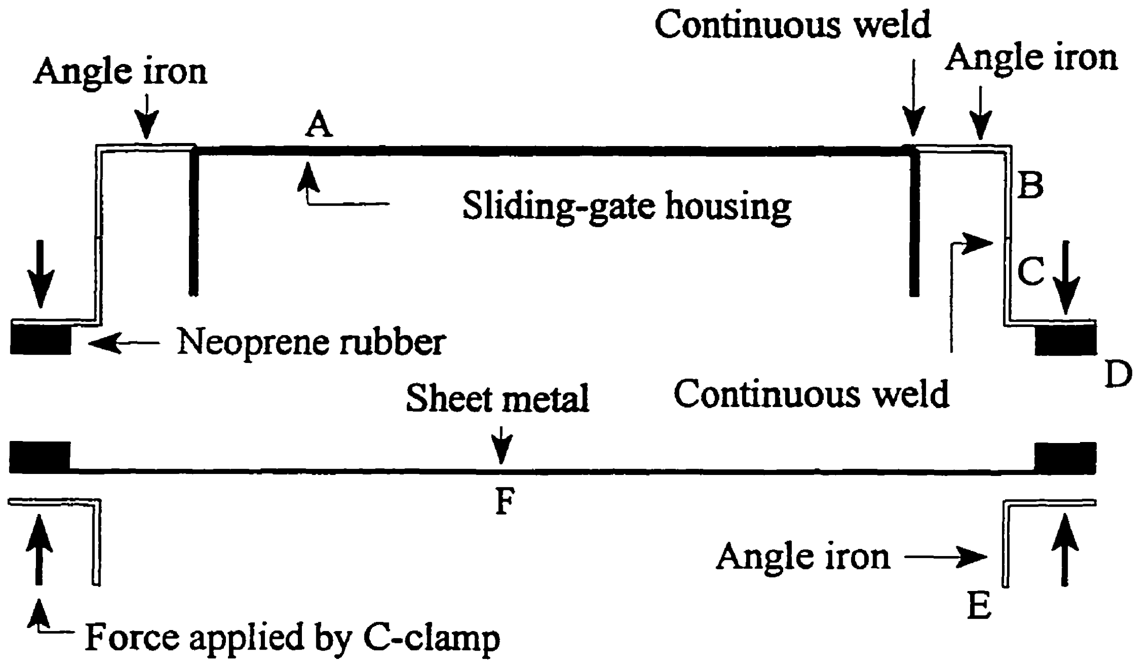


Fig. 4.15 Schematic of the sealing method used to seal the opening in the bottom cone of the hopper bin (*Methods #3* and *#4*).

4.10 Discussion of the sealing experiments

According to the evaluation criteria stated earlier, there were no successful sealing methods. I was unable to create and maintain a CO_2 concentration of 65% for 4 d, however, I do not consider this series of experiments to be a failure due to the significant improvements that were achieved. Radial and vertical uniformity of CO_2 were poor without sealing, but improved as better sealing methods were applied to the bin. Likewise, the mean CO_2 concentrations inside the bin rose from approximately 10% with no sealing to almost 50% with the later sealing attempts. These are significant improvements because the mass of dry ice added was constant for all experiments.

Further evidence that my sealing efforts were successful comes from a comparison with previous work by Alagusundaram et al. (1995). They calculated a retention efficiency (η_r) (%) as:

$$\eta_r = \frac{Cumulative\ ct\text{-}product * 100\%}{NDV\ of\ CO_2 * t_h * C_{th}} \tag{4.1}$$

where: t_h = duration of the experiment (h),

C_{th} = CO_2 concentration that would have been created by one domain volume of CO_2 gas, if all the introduced CO_2 gas stayed in the domain and none was sorbed by the grain (%), and

NDV of CO_2 = volume of CO_2 gas used divided by the domain volume.

The cumulative ct-product is the sum of ct-products calculated at each sampling time using:

$$ct\text{-}product = \frac{C_w^{ts+1} + C_w^{ts}}{2} * [(ts + 1) - (ts)] \tag{4.2}$$

where C_w^{ts+1} and C_w^{ts} are weighted-volume average CO_2 concentrations (%) at sampling times ts+1and ts (h).

In three experiments in empty bolted-steel bins, Alagusundaram et al. (1995) calculated retention efficiencies of 33.7, 39.8, and 43.0%. My analysis used the same equations, but I did not use weighted-volume average CO_2 concentrations. Rather, I calculated a cumulative ct-product for each sampling location in the bin and then found the mean cumulative ct-product. The retention efficiencies obtained for the experiments in empty bins ranged from a low of 7% with *No sealing* to a high of 79% with the bin sealed according to *Method #3* (Table 4.7). The volume of CO_2 gas used was calculated using the ideal gas law assuming standard pressure, an initial mass of 136 kg of dry ice pellets, and a temperature of 20°C. These assumptions have introduced some error into the retention efficiencies, but it is apparent that the sealed, welded-steel hopper bins retained CO_2 gas better than the bolted-steel bins used by Alagusundaram et al. (1995). Although my initial objectives were not achieved, I am satisfied with the final sealing method and the level of gas-tightness it provides.

As a consequence of the results obtained in this series of experiments, it is necessary to alter my objectives for fumigation with CO_2. Rather than trying to maintain a CO_2 concentration of 65% for the 4 d required to kill all life stages of *C. ferrugineus*, it may be more practical to aim for a longer exposure period at a lower CO_2 concentration. Shunmugam et al. (1993) concluded that 8 d at 30% CO_2 would kill all life stages of *C. ferrugineus*. Allowing 2 d for sublimation of the dry ice, an appropriate fumigation duration may be 10 d if CO_2 concentrations above 30% can be maintained.

Table 4.7 Mean cumulative ct-products and retention efficiencies (η_r) for experiments S1.1 to S13.2 calculated according to the procedure in Alagusundaram et al. (1995).

Experiment	Sealing Method	Mean Cumulative ct-product (%•h)	η_r (%)
S1.1	*No sealing*	365	15
S2.1	*No sealing*	306	17
S2.2	*No sealing*	206	12
S2.3	*No sealing*	118	7
S3.1	*Method #1*	541	16
S4.1	*Method #1*	981	17
S5.1	*Method #1*	659	26
S5.2	*Method #1*	871	39
S5.3	*Method #1*	915	41
S6.1	*Method #2*	591	27
S7.1	*Method #2*	1191	35
S8.1	*Method #2*	1141	33
S9.1	*Method #2*	1759	52
S10.1	*Method #2*	2519	74
S11.1	*Method #3*	3037	63
S12.1	*Method #3*	3617	78
S12.2	*Method #3*	3439	79
S12.3	*Method #3*	3227	69
S13.1	*Method #4*	2203	49
S13.2	*Method #4*	2412	57

To obtain CO_2 uniformity, it may be appropriate to use forced recirculation in all further experiments. Though my limited comparison suggests that forced recirculation does not improve uniformity in well-sealed bins, I am not confident in this conclusion. Other researchers (Banks et al. 1991; Peng and Chen 1993; Alagusundaram et al. 1995) have observed vertical CO_2 stratification inside large bins. It is possible that my bins were sealed better than those used in the previously mentioned research papers, and consequently, behave differently. Gas molecules should disperse uniformly throughout a well-sealed container, however, it is difficult to ignore the influence of gravity on the CO_2 molecules inside tall structures. It is reasonable to assume that gravity causes a force imbalance that inevitably causes vertical stratification. Greater vertical non-uniformity may have been observed in the bins without forced recirculation if the experimental duration was lengthened beyond 4 d. Based on this discussion, I decided to use forced recirculation with the next series of experiments.

Consideration should also be given to the practicality of the successful sealing method. Although considerable effort was required to reach the final design, the design itself is quite simple. Minimal labour is required to make the required modifications. Although not recommended, the modifications can be completed when the bin is full of grain. Additionally, the method has adequate flexibility that almost any make and model of welded-steel hopper bin could be sealed. It is hoped that bin manufacturers will incorporate these ideas into new bins and begin to sell sealable bins.

5. EXPERIMENTAL FUMIGATIONS IN FULL-SIZE BINS

5.1 Objectives for the experimental fumigations

The objective of this second series of experiments was to test the sealed, welded-steel hopper bins under actual conditions by conducting CO_2 fumigations. Specifically, I wanted to observe the CO_2 concentrations generated by a single application of dry ice over a 10-d period. Additional experiments were planned with an extra quantity of dry ice added to attempt 4-d fumigations. Caged adult *C. ferrugineus* were placed inside the bins for selected experiments to determine the mortality caused by the generated atmospheres. Discussion of the insect mortality is deferred to Chapter 6.

An equally important sub-objective was to identify an acceptable procedure for purging the bins. Because the bins were now well sealed, the addition of gaseous CO_2 into the bin had to be accompanied by a release of air from the bin.

5.2 Description of purging methods

Purging is crucial to the successful completion of a CO_2 fumigation. Before the start of a fumigation, the interstitial airspace is suitable for insect survival. During a fumigation, the interstitial airspace is toxic to the insect. Consequently, there must be a transition from the former to the latter environment. With most chemical fumigants, the transition is accomplished simply by adding a small quantity of the fumigant (parts-per-million) to the storage environment. These small quantities are unlikely to cause substantial pressure increases inside a perfectly sealed bin, even if no air is released from the bin. With CO_2 fumigations, however, large quantities of gaseous CO_2 must be added to the bin because CO_2 only becomes toxic to insects at the parts-per-hundred level. The addition of large quantities of CO_2 to a sealed bin would cause dangerous pressure increases if an equivalent quantity of air was not released from the bin. This exchange of air for CO_2,described as purging, is a necessary part of a CO_2 fumigation. In this context, "air" refers to molecules of N_2 and O_2.

Four different purging methods were tested during this research. Three factors were varied to create the four purging methods: 1) location of the dry ice during sublimation, 2) location of the CO_2 entry point, and 3) location of the purge valve.

For the first purging method (Fig. 5.1a) (experiment F1.1), the dry ice was augered into the bin using a grain auger and the pellets were spread over the top surface of the grain. Purging continued by leaving a purge valve, at the bottom of the bin, open. There was no entry point for the gaseous CO_2 because sublimation of the dry ice occurred inside the bin. For this method, it was assumed that the CO_2 would first distribute horizontally in the head space and then move downward through the grain bulk, forcing the air ahead of it out the purge valve at the bottom of the bin. The second purging method (experiment F2.1) was identical to the first, except for the location of the purge valve (Fig. 5.1b). Instead of allowing the gases to escape from the bottom of the bin, a valve at the top of the bin was left open to allow the escape of gases from the top of the bin. In this situation, I assumed that the CO_2 would first move down into the grain bulk rather than spreading horizontally. Once the CO_2 reached the bottom, it would move upward along the periphery of the bin, forcing air ahead of it out the purge valve at the top of the bin. For the third purging method (Fig. 5.1c) (experiment F3.1), dry ice was placed inside the holding box at ground level (Fig. 4.3). After sublimating, the gaseous CO_2 was ducted into the bottom of the bin and the air expelled through the purge valve at the top of the bin. It was assumed that the heavier CO_2 would fill the bottom portion of the bin and gradually work its way up, forcing the air out the top purge valve. Finally, for the fourth purging method (experiment F4.1), the sublimated CO_2 that originated in the holding box was ducted into the bin through an opening in the top of the bin (Fig. 5.1d). The excess gases were expelled from the purge valve at the bottom of the bin. I assumed that the CO_2 would behave as described above for the first method.

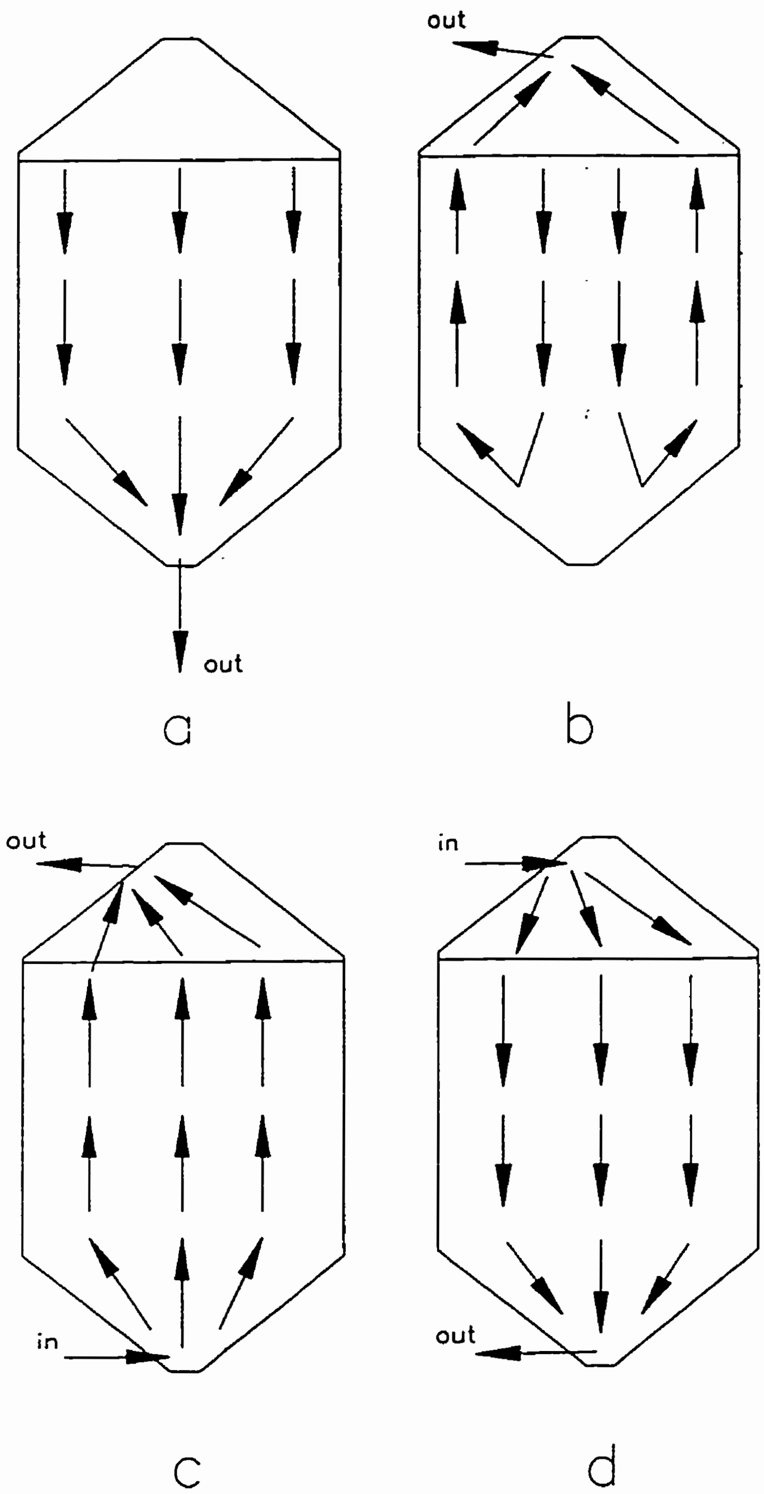


Fig. 5.1 The four purging methods tested in the full-size hopper bins. The arrows show the assumed direction of travel of the gases within the bin. For the first two methods (a & b), the dry ice pellets were augered into the bin; for the last two methods (c & d), gaseous CO_2 from a holding box was ducted into the bins.

5.3 Procedure for experimental fumigations

Chronologically, purging occurs before the CO_2 concentrations can be monitored. Consequently, the first four experiments (F1.1 to F4.1) were conducted with the purpose of selecting the best purging method (of those described in Section 5.2). After attempting each purging method once, the four methods were assessed and the best method was selected. Four additional 10-d fumigations were then conducted to assess the selected purging method further and to monitor the CO_2 concentrations (experiments F4.2 to F4.5). Following the completion of the 10-d fumigations, four experiments of 4-d exposure were conducted, also using the previously selected best purging method (experiments F4.6 to F4.9). The welded-steel hopper bins were always filled with 69 t of wheat to a capacity of approximately 75%. Between 82 and 88 kg of dry ice was added for the 10-d exposures, but 107 kg of dry ice was added for the 4-d exposures in an attempt to obtain higher peak CO_2 concentrations.

Immediately after addition of the dry ice, the purge data (i.e., the pressure inside the bin; and the temperature, flow rate, and CO_2 concentration of the gas leaving the purge valve) were collected for 2-3 h. After an additional 4-20 h, the purge valve was closed and the recirculation pump was started. The recirculation pump ran continuously throughout the 10-d (and 4-d) fumigations. Grain temperatures were recorded and gas samples were withdrawn and analyzed for the 11 sampling points along the centreline of the bin (Fig. 4.1) at daily intervals throughout the fumigations. In selected experiments, caged adult *C. ferrugineus* were placed inside the bins to determine whether lethal exposures were being achieved. Details of this aspect of the research are given in Chapter 6.

5.4 Experimental results

5.4.1 Purging results The purging data collected from the full-size hopper bins are included in Appendix D. The purge loss was calculated as the mass of CO_2 leaving the bin per unit time (g CO_2/min) based on the pressure inside the bin and the temperature, flow rate and CO_2 concentration of the gas leaving the purge valve. The purge loss is shown graphically for experiments F1.1 to F4.1 (Fig. 5.2), experiments F4.1 to F4.4 (Fig. 5.3), and experiments F4.6 to F4.9 (Fig. 5.4). Purge loss data were not collected during experiment F4.5.

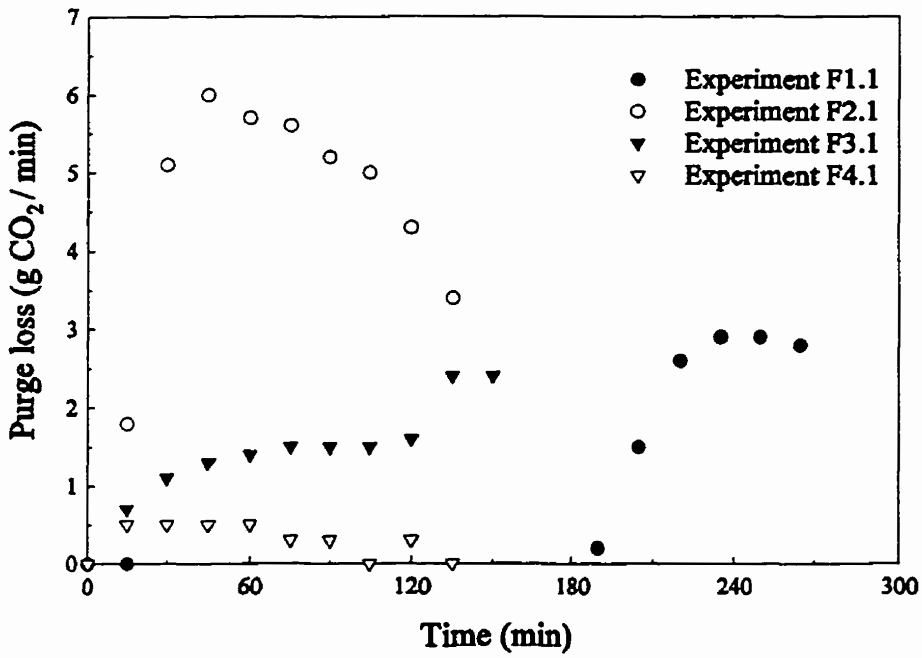


Fig. 5.2 Comparison of the observed purge loss from the four purging methods (experiments F1.1 to F4.1).

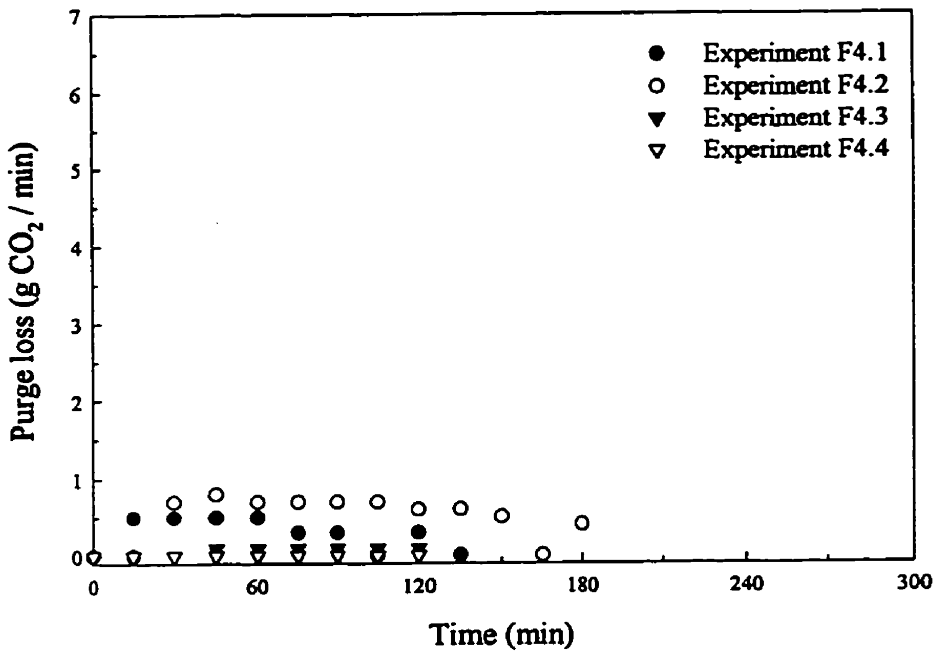


Fig. 5.3 Observed purge loss during 10-d experiments when the fourth purging method was used (experiments F4.1 to F4.4). Purge loss data were not collected during experiment F4.5.

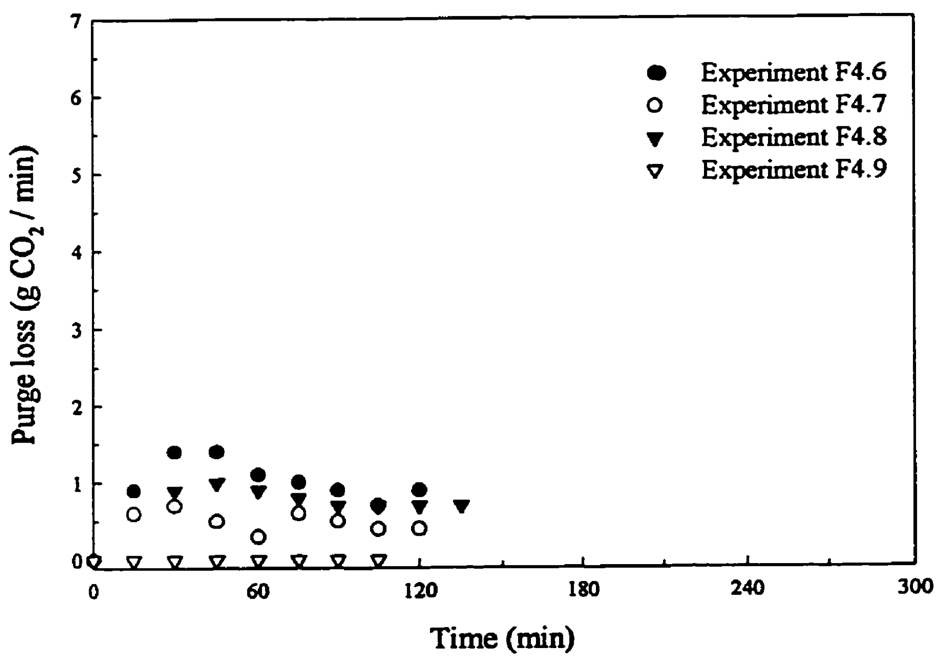


Fig. 5.4 Observed purge loss during the 4-d experiments when the fourth purging method was used (experiments F4.6 to F4.9).

5.4.2 Observed CO_2 concentrations Carbon dioxide concentrations and grain temperatures were measured and recorded at daily intervals for all 12 experiments (Appendix E). Data were collected at 11 sampling locations along the centreline of the bin (locations 0 to 10 in Fig. 4.1). From the CO_2 concentration data; mean, standard deviation (S.D.), and coefficient of variation (CV) values were calculated for each day's data (Table 5.1). Using the mean CO_2 values from Table 5.1, plots of the CO_2 concentrations over the duration of the experiments were generated (Figs. 5.5 to 5.7). Figure 5.5 shows the concentrations from the four experiments (F1.1 to F4.1) in which the four purging methods were tried. After selecting the best purging method, an additional four experiments of 10-d duration (i.e., a total of five experiments of 10-d duration; F4.1 to F4.5) were completed (Fig. 5.6). Finally, four experiments of 4-d duration (F4.6 to F4.9) were completed (Fig. 5.7).

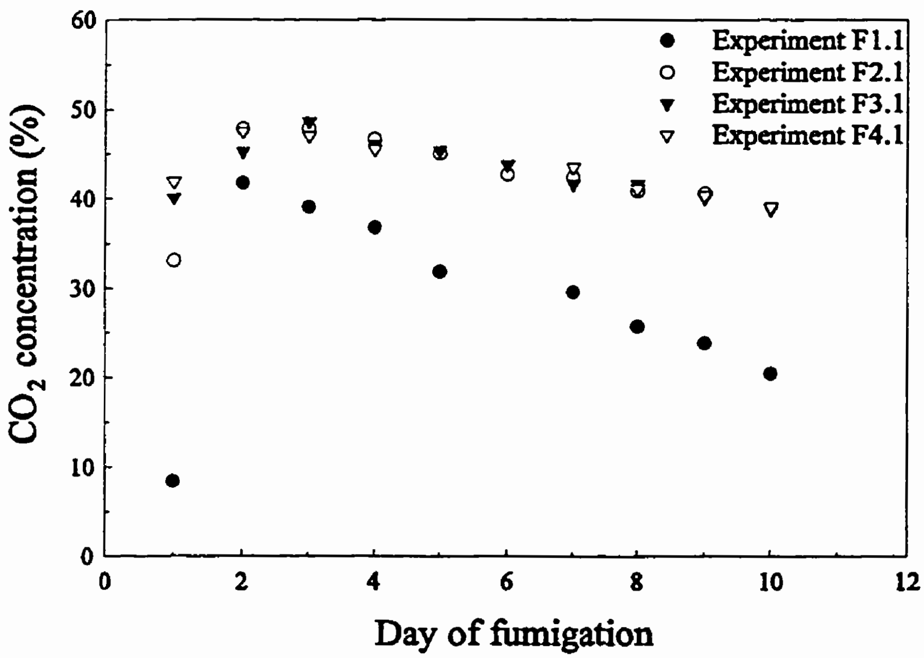


Fig. 5.5 Plots of the mean CO_2 concentration inside the experimental bins at daily intervals throughout the 10-d fumigations. Experiments F1.1 to F4.1 represent the four purging methods that were tried.

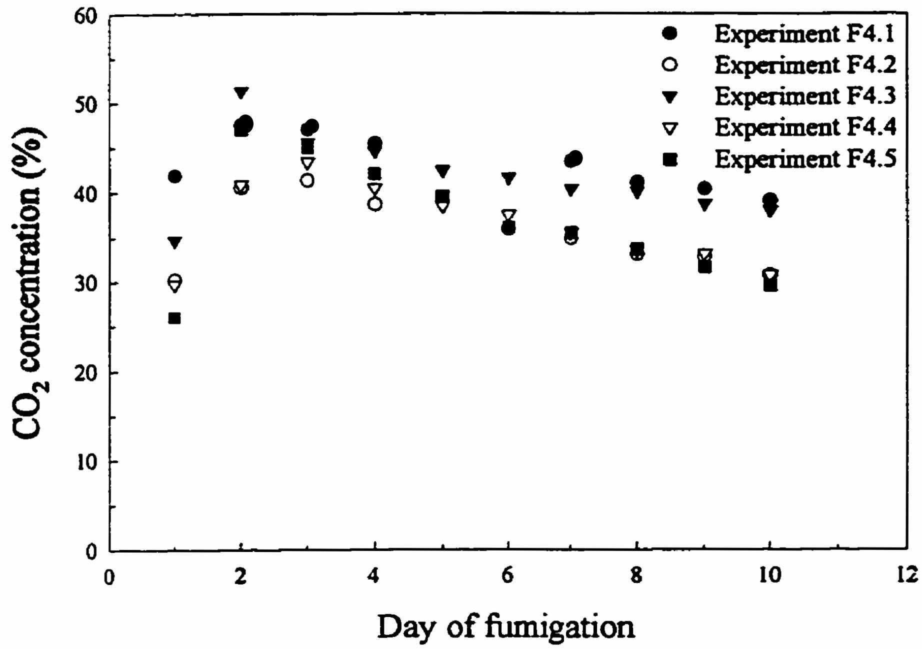


Fig. 5.6 Plots of the mean CO_2 concentrations inside the experimental bins at daily intervals throughout the 10-d fumigations. Experiments F4.1 to F4.5 were conducted using the fourth purging method.

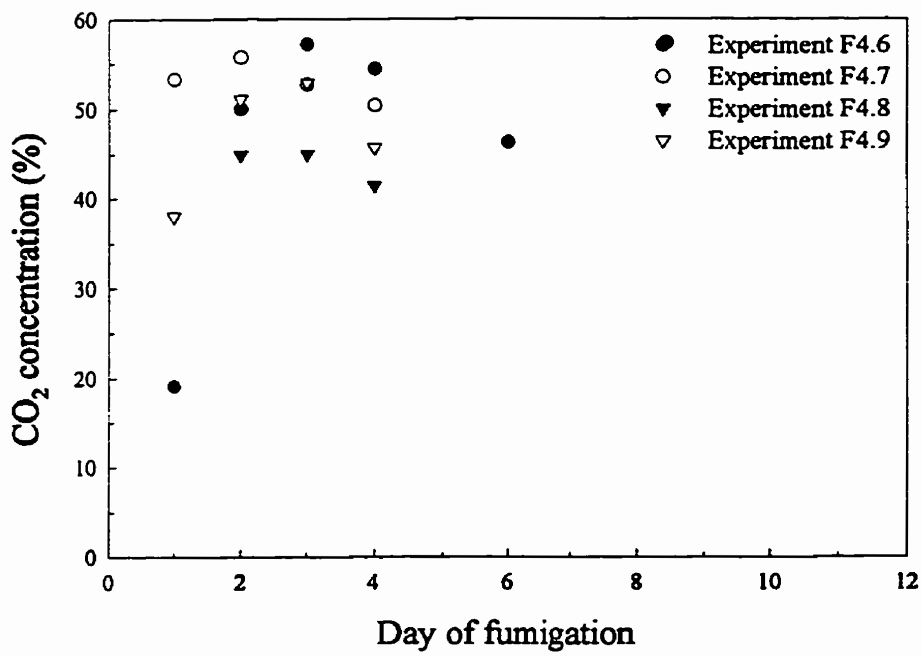


Fig. 5.7 Plots of the mean CO_2 concentrations inside the experimental bins at daily intervals throughout the 4-d fumigations. Experiments F4.6 to F4.9 were conducted using the fourth purging method.

Table 5.1 Mean, standard deviation, and coefficient of variation values for the 11 sampling points along the centreline of the experimental bins for each day of the experimental duration for all 12 of the experimental fumigations.

Experiment	CO_2 Concentration	Day of Experiment									
		1	2	3	4	5	6	7	8	9	10
F1.1	Mean (%)	8.5	41.8	39.1	36.8	31.9		29.6	25.8	23.9	20.5
	S.D.	9.10	1.22	1.83	0.80	1.43		1.12	0.88	0.83	0.62
	CV (%)	107	3	5	2	4		4	3	3	3
F2.1	Mean (%)	33.1	47.8	47.9	46.7	45.1	42.7	42.4	40.9	40.6	
	S.D.	15.95	2.02	1.07	0.74	1.23	1.29	0.88	0.81	0.67	
	CV (%)	48	4	2	2	3	3	2	2	2	
F3.1	Mean (%)	40.1	45.2	48.6	46.0	45.4	43.8	41.6	41.6	40.1	38.8
	S.D.	25.64	8.36	1.30	0.54	0.51	0.36	0.82	0.58	0.93	1.07
	CV (%)	64	18	3	1	1	1	2	1	2	3
F4.1	Mean (%)	41.9	47.5	47.0	45.5			43.5	41.1	40.4	39.1
	S.D.	2.71	2.07	2.92	2.11			0.74	1.49	1.39	2.46
	CV (%)	6	4	6	5			2	4	3	6
F4.2	Mean (%)	30.2	40.6	41.4	38.7		35.9	34.9	33.1	32.8	30.7
	S.D.	3.88	2.00	0.68	0.56		0.62	0.35	1.35	0.68	0.97
	CV (%)	13	5	2	1		2	1	4	2	3
F4.3	Mean (%)	34.7	51.3	45.6	44.6	42.5	41.6	40.4	40.1	38.7	38.0
	S.D.	3.66	5.55	1.51	1.47	2.43	2.05	1.51	1.46	1.67	2.27
	CV (%)	11	11	3	3	6	5	4	4	4	6

Experiment	CO_2 Concentration	Day of Experiment									
		1	2	3	4	5	6	7	8	9	10
F4.4	Mean (%)	29.7	40.9	43.4	40.5	38.5	37.5	35.5	33.5	33.1	30.7
	S.D.	7.19	1.61	0.57	0.86	1.12	0.83	0.43	0.53	0.43	0.80
	CV (%)	24	4	1	2	3	2	1	2	1	3
F4.5	Mean (%)	26.0	47.0	45.0	42.1	39.5	36.1	35.5	33.6	31.6	29.5
	S.D.	9.95	1.72	1.93	1.43	0.96	1.49	1.15	0.94	0.95	1.62
	CV (%)	38	4	4	3	2	4	3	3	3	5
F4.6	Mean (%)	19.1	50.0	57.2	54.4		46.3				
	S.D.	2.49	7.19	1.90	2.13		3.95				
	CV (%)	13	14	3	4		9				
F4.7	Mean (%)	53.3	55.7	52.7	50.4						
	S.D.	2.16	2.44	3.10	2.96						
	CV (%)	4	4	6	6						
F4.8	Mean (%)		44.9	45.0	41.4						
	S.D.		1.69	0.60	1.33						
	CV (%)		4	1	3						
F4.9	Mean (%)	38.0	51.1	52.9	45.7						
	S.D.	8.94	1.98	1.60	1.59						
	CV (%)	24	4	3	3						

5.5 Discussion of purging results

5.5.1 Selection of best purging method According to my previous definition, purging is complete once a lethal environment has been created inside the storage bin. This definition, however, lacks a measure of the efficiency by which the transition occurs. If only air is expelled when CO_2 is added, purging would be 100% efficient. When CO_2 is lost from the bin, the efficiency drops below 100%. In addition to creating a lethal environment, therefore, purging should also minimize CO_2 loss.

The best purging method could not be selected based on the creation of a lethal environment because the mean CO_2 concentrations were similar for three of the four experiments (Fig. 5.5). Only the first purging method could be rejected because the mean CO_2 concentration declined to ≈20% by the tenth day of experiment F1.1 (Fig. 5.5).

To select the best purging method, the purge losses were considered. Purge losses ranged from approximately 0.5 to 6.0 g CO_2/min (Fig. 5.2). The results from experiment F1.1 warrant special discussion. Within 15 min of sealing the bin following the introduction of the dry ice onto the grain surface (the 13-mm diameter purge valve at the bottom of the bin remained open), excessive pressure developed inside the bin. Fortunately, the water-filled pressure relief valve (Fig. 4.2) functioned as designed and no damage was done to the bin. With the water gone from the pressure relief valve, however, purge loss data could not be collected. After approximately 3 h, the pressure relief valve was refilled with water and data collection resumed. After the 3 h period, the purge loss still reached approximately 3 g CO_2/min. This incident suggested that, besides the environment created and the purge losses observed, the purging method must also be practical. The first method was considered impractical because of the high pressures created inside the bin.

The high pressure was probably caused by an increased rate of sublimation. To increase the rate of purging, the pellets were placed on the grain surface to use the heat within the grain bulk to increase the rate of sublimation. When liquid CO_2 is used for fumigation, vaporization occurs instantaneously and purging is completed in a short time. With dry ice, it was expected that purging would take a long time to complete because sublimation of the entire mass of dry ice did not occur instantaneously. With the purge valve left open for a long time, it was inevitable that some CO_2 would move through the grain bulk and out the purge valve before sublimation of all the dry ice was complete, thereby reducing the purging efficiency. It was assumed, therefore, that the addition of heat would increase the rate of sublimation and decrease the purge loss. Because the expense of adding supplemental heat was not considered feasible, it was hoped that the heat within the grain bulk would be adequate. The observed pressure increase when the water was forced from the pressure relief valve (experiment F1.1) indicated that the desired increase in sublimation rate was produced. The purge valve (13-mm diameter) was supposed to accommodate the pressure increase by allowing the escape of air, however, it did not allow enough air to escape. Future research might investigate whether a larger opening would decrease the pressure and enable pellets of dry ice to be augered onto the grain surface. This procedure, however, may cause localized moisture and spoilage problems (Mann et al. 1997).

The second purging method generated results similar to the first method. Rather than allowing the water to be forced from the pressure relief valve, a secondary purge valve (50-mm diameter) was opened a total of five times during the first 75 min of data collection to relieve the pressure. The pressure decreased when the effective purge opening increased. This supports my assumption that this method could potentially work if a larger purge valve was used. Despite this potential, I rejected the second purging method because the purge losses approached 6 g CO_2/min (Fig. 5.2).

For the third and fourth purging methods, the dry ice was placed inside the holding box rather than onto the grain surface. This procedural change yielded lower purge losses (Fig. 5.2). For the third method, the purge loss peaked at 2.5 g CO_2/min and the secondary purge valve was not needed to release pressure during the data collection period. A pressure increase was observed, however, when the purge valve was closed and the recirculation pump was started. The pump was stopped to allow purging to continue. The purge valve remained open for approximately 24 h, but purge loss data were collected for only the first 2.5 h.

In contrast to the first three methods, the fourth method displayed only a small pressure increase. Purge loss was calculated to be approximately 0.5 g CO_2/min (Fig. 5.2), but I am uncertain of the exact rates because the rate of flow through the purge valve was too small for the flowmeter being used (Cole Parmer FM044-40C with a minimum calibrated flow of 3.0 L/min). The purge valve remained open for approximately 24 h primarily as a precaution. The valve was then closed and the recirculation pump was started.

The third and fourth purging methods only differed in their gas inlet and outlet locations. For the third method, with the inlet at the bottom of the bin, the gaseous CO_2 entered a region of limited interstitial volume. Before reaching the head space above the grain bulk, the CO_2 had to force its way up through the grain bulk. For the fourth method, the gaseous CO_2 directly entered the head space. The pressure did not increase as quickly because the CO_2 molecules initially distributed throughout the head space, allowing more time for the air to move through the grain bulk and out the purge valve. Similarly, Chakrabarti et al. (1993) found that it was more effective to add CO_2 to the head space of the bin as opposed to the bottom.

To summarize, the fourth purging method worked because the rate of CO_2 entry into the bin was reduced by placing the dry ice pellets into the holding box and allowing sublimation to occur inside the box. Additionally, entry of the gaseous CO_2 into the head space provided a greater volume into which the gaseous CO_2 could distribute while air was being expelled through the bottom purge valve. The combination of these two factors contributed to offset the pressure increase observed with the other three purging methods.

5.5.2 Assessment of the best purging method The fourth method was selected as the best purging method based on only a single trial of each method. Additional trials are needed to confirm my decision. Purging data were collected during four of the five 10-d fumigations and all four of the 4-d fumigations (Appendix D). The observed purge losses are shown for the 10-d fumigations (Fig. 5.3) and for the 4-d fumigations (Fig. 5.4).

For the 10-d fumigations, the purge loss remained below 1 g CO_2/min for all four experiments (Fig. 5.3). Experiment F4.4 produced a zero purge loss (Fig. 5.3). Unfortunately, this observation is not accurate. Based on observation during purging, gases were escaping from the purge valve at a rate below the range detectable by the flowmeter (i.e., 3.0 L/min). The flow rate was recorded as zero (Appendix D) though detectable CO_2 concentrations were recorded leaving the bin. Experiment F4.4 had the lowest purge loss, but it was not zero. Experiments F4.4 and F4.5 were conducted late in the fall when low ambient temperatures resulted in low sublimation rates. The rate of CO_2 entry was reduced and subsequently, the purge loss was reduced. Because of the results obtained from experiment F4.4, purge data were not collected during experiment F4.5.

The purge loss usually increased for the 4-d fumigations compared with the 10-d fumigations probably because more dry ice was added to the holding box for the 4-d fumigations. It is likely that the amount of gaseous CO_2 produced in a given time by sublimation would be more when 107 kg of dry ice is used than when 83 kg of dry ice is used because of the greater surface area. Consequently, more gaseous CO_2 was ducted into the bin during the same period and, therefore, more CO_2 was lost through the purge valve. The purge losses for the 4-d fumigations, however, were less than 1.5 g CO_2/min (i.e., less than the purge losses from the other three purging methods).

Based on the purge data collected during these experiments, I remain confident with the selection of the fourth purging method. There were no problems with excessive pressure increases for any of the experiments and no high purge losses. It is apparent, however, that the purge loss is related to the sublimation rate of dry ice. In turn, the sublimation rate of dry ice probably depends on temperature and the quantity of dry ice initially present. These factors should be considered to ensure that these results are applicable to conditions other than my experimental conditions.

5.5.3 Purging efficiency One further means for evaluating these four purging methods is to consider the purging efficiency. Previously, three equations for calculating the purging efficiency were presented (Eqs. 2.10, 2.11, and 2.12). These equations were considered with respect to my experimental results.

The three equations give purging efficiency assuming: 1) no mixing (Eq. 2.10), 2) free mixing (Eq. 2.11), and 3) no mixing in the grain bulk and free mixing in the head space (Eq. 2.12). Because CO_2 concentrations were observed leaving the purge valve (Appendix D), Eq. 2.10 was rejected. Mixing was clearly occurring, but detecting where it was occurring was not possible. Equation 2.12 could not be used because it requires knowledge of where the mixing occurred. Therefore, Eq. 2.11 (specifically Eq. 2.11a) was used to calculate the purging efficiencies with the assumption of free mixing throughout the storage atmosphere.

Purging normally occurs when a large quantity of gaseous CO_2 forces air out of the storage environment. Purging is complete once the purge valve is closed. The purge valve is closed when the CO_2 concentration leaving the bin is equal to the desired concentration. Using liquid CO_2, this process is usually completed in a matter of hours. With dry ice, two or three days are required to complete sublimation, however, I left the purge valve open for the initial 6 - 24 h only. When the purge valve was closed, the CO_2 concentration leaving the bin was not equal to the desired concentration. Consequently, I used the mean peak CO_2 concentration in Eq. 2.11a rather than the CO_2 concentration at the time of closing the purge valve.

Another factor to be considered was sorption of CO_2 by the wheat kernels. Normally, purging takes place quickly and sorption is not a concern. In this situation, however, sorption could not be ignored. For the 10-d fumigations (experiments F1.1 to F4.5), the quantity of CO_2 sorbed by the grain (25.3 kg by 69 t of wheat) was predicted using a sorption value of 367 mg CO_2/kg wheat (Cofie-Agblor et al. 1997) based on an assumed temperature of 20°C and an assumed CO_2 concentration of ≈65%. Because the temperatures were not always 20°C (Appendix E), Eq. 2.2 was used to calculate a better estimate of the CO_2 sorbed for each experiment (Table 5.2). When calculating the purging efficiency using Eq. 2.11a, this improved estimate of sorption was used. For the 4-d fumigations (experiments F4.6 to F4.9), I initially calculated an amount of dry ice predicted to be sorbed (17.3 kg by 69 t of wheat) using a sorption value of 250 mg CO_2/kg wheat (Cofie-Agblor et al. 1997). A smaller value was used because the CO_2 concentrations had not reached 65% during the 10-d fumigations. The smaller sorption value corresponded to a CO_2 concentration of approximately 50%. Again, the temperatures varied so Eq. 2.1 (which corresponds to an initial CO_2 concentration of 48.3%) was used to calculate a better estimate of sorption (Table 5.2).

Based on the previously discussed considerations, the purging efficiencies were calculated using Eq. 2.11a (Table 5.3). Based solely on the purging efficiency, the third method would have been chosen, although the fourth method had the second highest efficiency. The purging efficiencies ranged from 69 to 92% for the five 10-d fumigations (Table 5.3). The range was likely due to mean peak CO_2 concentrations ranging from 41.4 to 51.3%. The reason why mean CO_2 concentrations varied by 10 percentage points is not known. The mean purging efficiency from the 10-d fumigations (i.e., 81.3%) appears greater than the mean purging efficiency from the 4-d fumigations (i.e., 70.3%), however, they are not statistically different (Student's t-test, α=0.05). The purging efficiencies observed in these experiments agree with those reported by Banks (1979).

Table 5.2 Quantity of CO_2 sorbed during each experiment calculated using Eq. 2.2 for experiments F1.1 to F4.5 and Eq. 2.1 for experiments F4.6 to F4.9.

Experiment	Mean Temperature (°C)	Sorption Rate (mg CO_2/kg wheat)	Mass Sorbed (kg)
F1.1	4	317	21.9
F2.1	9	305	21.0
F3.1	15	291	20.1
F4.1	17	286	19.7
F4.2	19	281	19.4
F4.3	20	279	19.3
F4.4	15	291	20.1
F4.5	12	298	20.5
F4.6	21	276	19.0
F4.7	21	276	19.0
F4.8	22	274	18.9
F4.9	16	288	19.9

Table 5.3 Purging efficiencies calculated using Eq. 2.11a for the experimental fumigations.

Experiment	Mean Peak CO_2 Concentration (%)	Day of Peak Concentration	Experimental Bin	Purging Efficiency, e_2 (%)
F1.1	41.8	2	A	79
F2.1	47.9	3	B	83
F3.1	48.6	3	A	88
F4.1	47.5	2	B	84
F4.2	41.4	3	A	69
F4.3	51.3	2	B	92
F4.4	43.4	3	A	75
F4.5	47.0	2	B	86
F4.6	57.2	3	A	79
F4.7	55.7	2	B	76
F4.8	45.0	3	A	55
F4.9	52.9	3	A	72

Initially, I thought that the purging efficiencies varied because the two sealed experimental bins did not display the same level of gas-tightness. Insufficient evidence exists, however, to correlate purging efficiency with the bin used. After further investigation, there is an interesting correlation between the day on which the mean peak CO_2 concentration was observed and the bin used. Ignoring experiments F1.1 and F2.1, mean peak CO_2 concentrations always occurred on the third day of the fumigation in bin A and on the second day in bin B. The pressure on the first day of the fumigation tended to be higher inside bin A than bin B (comparing experiments conducted not more than a couple of weeks apart having approximately equal ambient temperatures) (Appendix E). With increased pressure, the density of the gas increased yielding an increased sorption potential. Consequently, the amount of CO_2 sorbed during the first day of the fumigation may have been more than expected under conditions of atmospheric pressure. When the pressure decreased by the second or third day, some desorption may have occurred, increasing the concentration of CO_2 in the bin. These circumstances could have resulted in peak CO_2 concentrations on the third day of the fumigation.

5.6 Discussion of observed CO_2 concentrations

5.6.1 Ten-day fumigations Similar to the sealing experiments described previously (experiments S1.1 to S15.3), the observed CO_2 concentrations never reached expected levels (65%). For the 10-d fumigations, CO_2 concentrations peaked between 40 and 50%, although 83 kg of dry ice should have generated a concentration between 60 and 70% assuming compensation for sorption was adequate. It should be noted, however, that CO_2 concentrations remained above 30% in all cases except experiment F1.1 (Table 5.1). Lower concentrations were observed in experiment F1.1 because the water had been forced out of the pressure relief valve allowing the escape of gaseous CO_2 from the bin. With a larger volume of purge gas leaving the bin, lower CO_2 concentrations were expected.

With the exception of experiment F1.1, the experiments are repeatable (Figs. 5.5 and 5.6). The mean CO_2 concentrations are undistinguishable for experiments F2.1, F3.1, and F4.1 (Fig. 5.5). Experiments F4.1 to F4.5 showed more variation (Fig. 5.6), but all followed the same trend.

A measure of the variation within the bin is given by the coefficient of variation (CV). For the 10-d fumigations, CV values were always less than 10% from the third day to the tenth day (Table 5.1). These results are similar to those observed during the sealing experiments. Variation was large during the initial hours when sublimation was occurring and while the interstitial gases were being mixed. Once this transient phase was complete, however, the variation within the bin was small. The high degree of uniformity probably was due to forced recirculation which was used for all experiments.

5.6.2 Four-day fumigations The extra dry ice added for the 4-d fumigations yielded small improvements (Fig. 5.7), although variation between the experiments increased. The variation may have decreased if the experimental duration was extended. Variation within the bin was small as CV values were less than 10% in most cases after the first day (Table 5.1).

The experimental results support my earlier conclusion that the 4-d fumigations are not feasible. It is not known how much dry ice would be required to achieve a CO_2 concentration of 65%. Furthermore, because of the variation observed, predicting a successful fumigation accurately would be difficult, even if higher CO_2 concentrations could be generated. Finally, the fumigations would not be successful because sublimation of the dry ice occurs slowly and peak concentrations are not observed until the second or third day.

5.6.3 Retention of CO_2 The retention efficiency indicates the proportion of CO_2 retained in the bin to the volume of gaseous CO_2 initially added. Because it indicates the efficiency with which the fumigation is achieved, the retention efficiency was used to evaluate the fumigation procedures.

Retention efficiencies (η_r) were calculated for each of the 12 experiments using Eq. 4.1 (Table 5.4). The cumulative ct-product was calculated as described in Section 4.10 as opposed to how it was calculated by Alagusundaram et al. (1995). With an assumed porosity of 39% in the grain bulk (Muir and Sinha 1988) and the grain filled to within approximately 1.5 m of the top of the bin, the domain volume was calculated to be 44.7 m^3. The volume of gas added varied because the mass of dry ice was not constant for all experiments (Appendix E). Retention efficiencies ranged from 29 to 47% for the 10-d fumigations and from 19 to 32% for the 4-d fumigations (Table 5.4). Neglecting experiment F1.1 because of the excessive purge loss, the retention efficiencies ranged from 34 to 47% for the 10-d fumigations.

These retention efficiencies do not compare well with the values reported in Table 4.7 for the experiments in sealed bins (i.e., experiments S11.1 to S13.2), however, Eq. 4.1 does not account for sorption. The quantity of dry ice added in experiments F1.1 to F4.9 consisted of a quantity expected to be sorbed. After compensating for sorption, retention efficiencies ranged from 55 to 82% for the 10-d fumigations and 28 to 47% for the 4-d fumigations (Table 5.4). The values for the 10-d fumigations compare favourably with the values given in Table 4.7.

The mean retention efficiency for the 10-d fumigations of 65.9% is significantly (Student's t-test, α=0.05) greater than the value of 38.3% for the 4-d fumigations. Although some mean peak CO_2 concentrations above 50% were observed during the 4-d fumigations (Fig. 5.7), the efficiency decreased. It can be concluded, therefore, that adding extra dry ice, as was done for the 4-d fumigations, is not beneficial. All of my experimental evidence suggests that 10-d fumigations should be promoted rather than 4-d fumigations if dry ice is to be used as the source of CO_2.

Table 5.4 Values of retention efficiencies (η_r) calculated according to Eq. 4.1 (Alagusundaram et al. 1995) both without and with compensation for sorption for the fumigations of 10-d and 4-d duration.

Experiment	Mean Cumulative ct-product	Sorption	
		Not Considered	Considered
	(%•h)	η_r (%)	η_r (%)
F1.1	5941	29	55
F2.1	9299	39	67
F3.1	9883	47	82
F4.1	7219	34	58
F4.2	7274	34	59
F4.3	9282	44	75
F4.4	8352	39	69
F4.5	7631	36	63
F4.6	3525	25	37
F4.7	4485	32	47
F4.8	2656	19	28
F4.9	3955	28	42

5.7 Sublimation rate of dry ice

5.7.1 Importance of sublimation rate to CO_2 fumigation In my previous discussion, I have drawn some conclusions that were dependent upon knowledge of the sublimation rate of dry ice. Specifically, I assumed that sublimation rate varies with temperature, with the initial quantity of dry ice, and with forced recirculation. Although these assumptions are reasonable, they have not been confirmed. A limited study of the sublimation rate of dry ice was considered beneficial to the overall understanding of a CO_2 fumigation.

5.7.2 Apparatus for measuring sublimation rate The sublimation rate of dry ice was measured by placing a quantity of dry ice on an electronic balance and recording the change in mass with time. To automate data collection, the electronic balance was connected to a data acquisition system. The experiments were conducted inside an environment chamber so that the surrounding temperature could be controlled. The chamber was vented outside to allow the gaseous CO_2 to escape from the building.

5.7.3 Variables considered in sublimation Experiments were conducted to investigate the influence of temperature, initial mass of dry ice, and forced convection on the rate of sublimation. The influence of temperature was observed by placing 5 kg of dry ice inside a steel box (similar to the holding box used in previous experiments) and exposing the box to different temperatures. Three replicates were done at 0, 10, 20, and 30°C.

The influence of initial mass was investigated by collecting mass change data for three initial masses (2.5, 5, and 10 kg) inside the factory packaging (lined paper bags). Additionally, 17 and 83 kg of dry ice were placed inside a large steel drum. Unfortunately, no comparison of different masses was conducted inside the steel box, so I have included the results obtained from the factory packaging in their place.

Finally, tests were conducted with 83 kg of dry ice inside a large steel drum at temperatures of 0, 10, 20, and 30°C both with and without exposure to forced recirculation. The vacuum pump (as described previously in Section 4.4) continuously forced the movement of gases through the bulk of dry ice pellets.

5.7.4 Sublimation rate results Plots of the decaying mass of dry ice are shown for 0°C (Fig. 5.8), 10°C (Fig. 5.9), 20°C (Fig. 5.10), and 30°C (Fig. 5.11). The data were fitted to an exponential decay equation for each temperature using SigmaPlot (version 3.02 Jandel Corporation, San Rafael, CA).

Although the replicates were not conducted simultaneously, the data are consistent at all four temperatures with the consistency improving with increasing temperature.

As expected, the rate of sublimation increased as temperature increased (Fig. 5.12). The change was minimal, however, when the temperature increased from 20 to 30°C. This observation is significant for this research because it shows that artificially raising the temperature above 20°C to increase the rate of sublimation would not be beneficial.

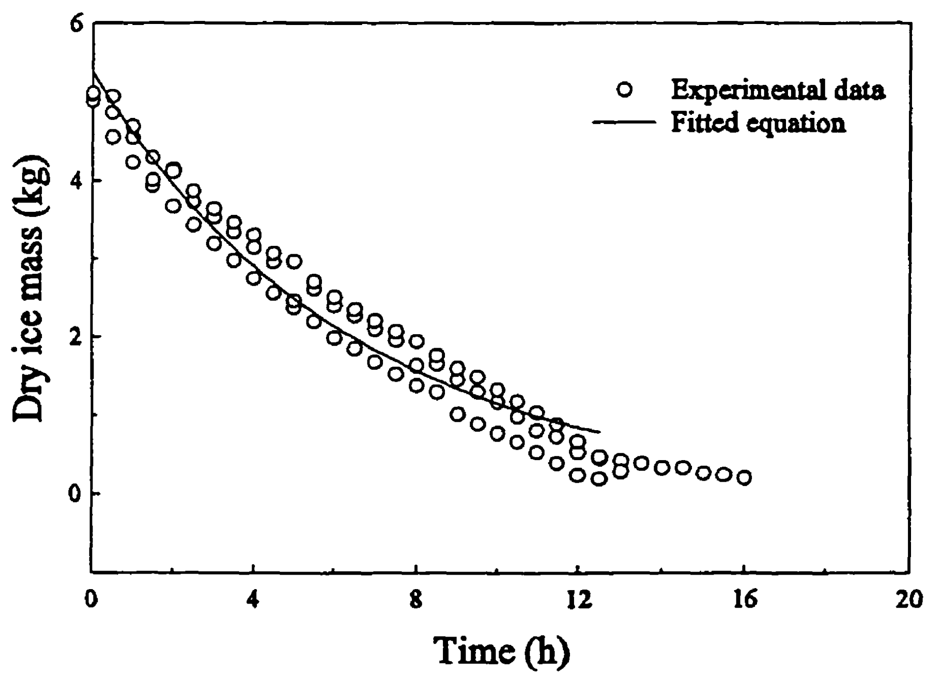


Fig. 5.8 Observed mass decay from an initial mass of 5 kg of dry ice pellets inside a steel box exposed to an outside temperature of 0°C.

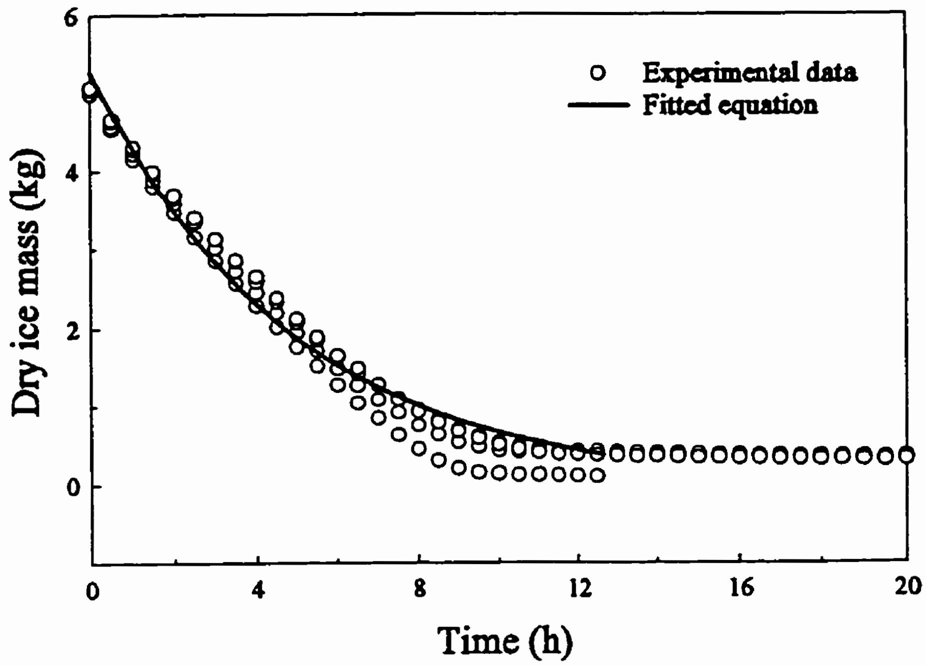


Fig. 5.9 Observed mass decay from an initial mass of 5 kg of dry ice pellets inside a steel box exposed to an outside temperature of 10°C.

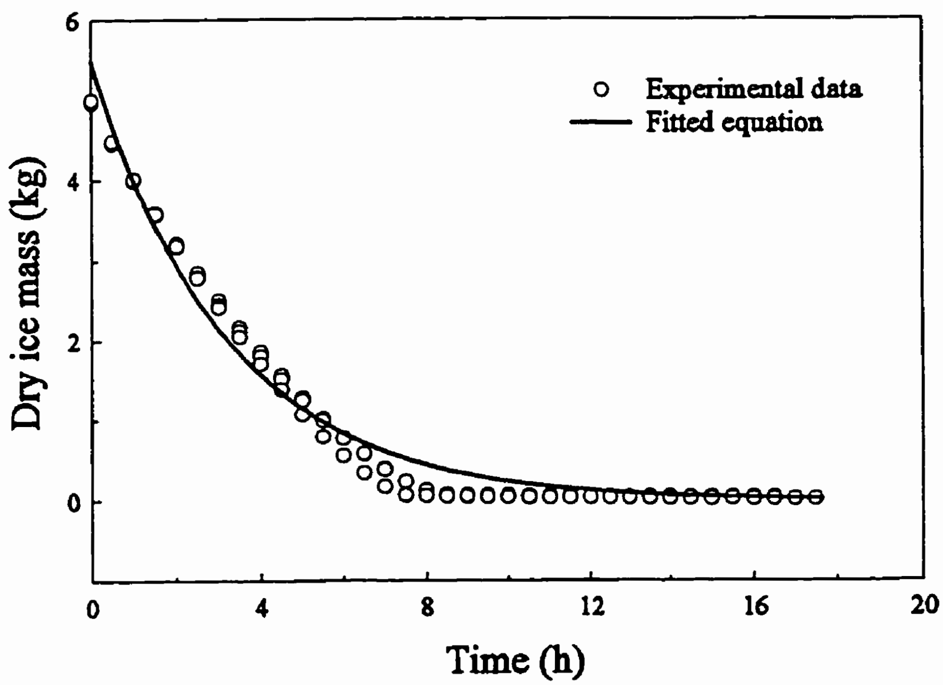


Fig. 5.10 Observed mass decay from an initial mass of 5 kg of dry ice pellets inside a steel box exposed to an outside temperature of 20°C.

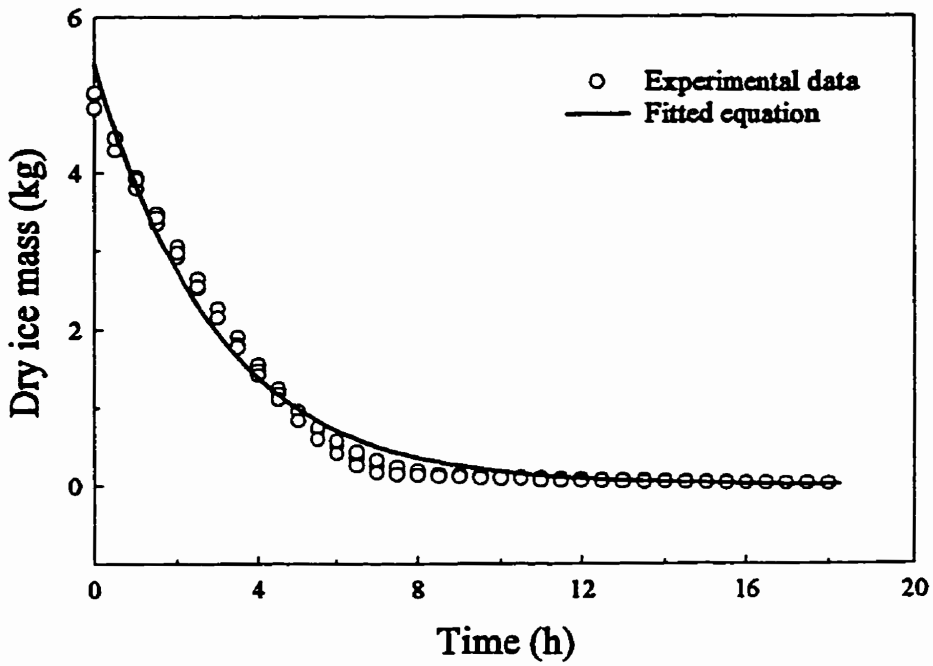


Fig. 5.11 Observed mass decay from an initial mass of 5 kg of dry ice pellets inside a steel box exposed to an outside temperature of 30°C.

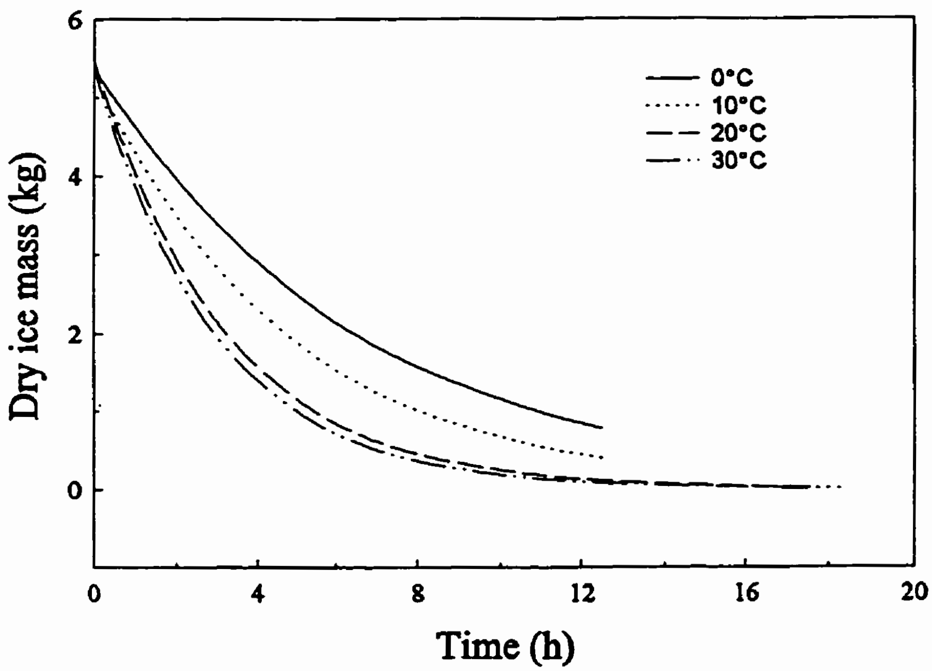


Fig. 5.12 Plots of the exponential decay equations fit to the experimental data using SigmaPlot. The exponential lines illustrate the influence of temperature on the sublimation rate of dry ice.

As expected, the rate of sublimation increased as the initial mass of dry ice increased (Figs. 5.13 and 5.14). The change in slope of the curves was not drastic when the initial mass of dry ice in the factory packaging increased from 2.5 to 10 kg (Fig. 5.13), but a large difference was observed between 17 and 83 kg in the large steel drum (Fig. 5.14). A reasonable explanation for this behaviour is that a greater mass of pellets provides a greater surface area resulting in a greater rate of sublimation. This fact has implications for this research because larger bins will require more dry ice, and consequently, a greater rate of sublimation is to be expected. Although the rate of sublimation may have negligible influence on the ultimate CO_2 concentrations, it can influence the purging process. To avoid excessive pressure increases in large bins, increasing the diameter of the purge valve may be necessary. This relationship requires further investigation.

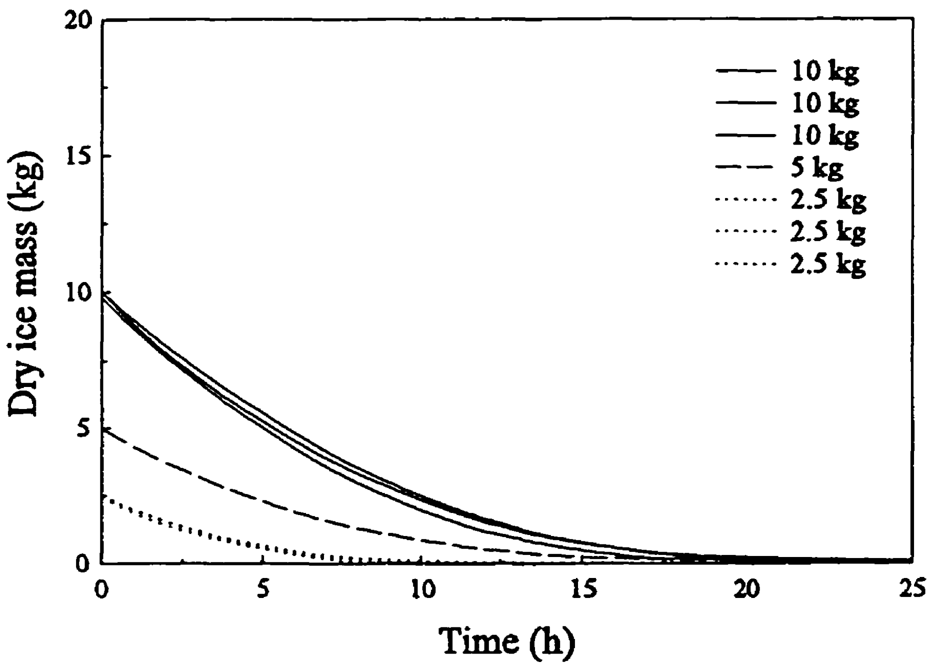


Fig. 5.13 Observed mass decay from initial masses of 2.5, 5, and 10 kg of dry ice pellets inside factory packaging exposed to an outside temperature of 30°C.

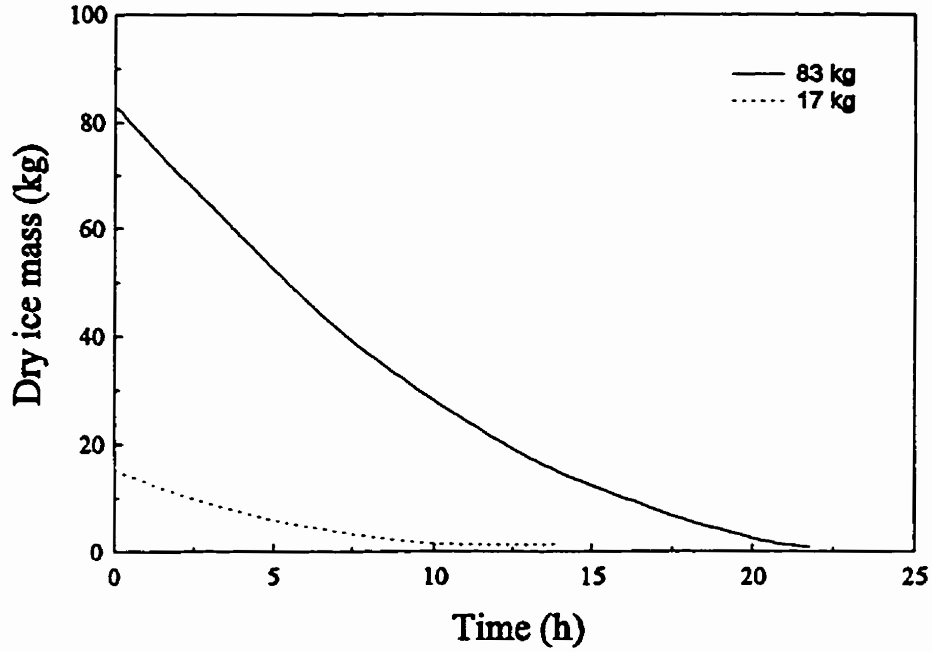


Fig. 5.14 Observed mass decay from initial masses of 17 and 83 kg of dry ice pellets inside a steel drum exposed to an outside temperature of 30°C.

The final variable considered was the influence of forced recirculation. The rate of sublimation of 83 kg of dry ice pellets both with and without forced recirculation is shown at 0°C (Fig. 5.15), at 10°C (Fig. 5.16), at 20°C (Fig. 5.17), and at 30°C (Fig. 5.18). The influence of forced recirculation was apparent at all temperatures, although the difference decreased with increasing temperature. This fact is significant for CO_2 fumigation because it suggests that forced recirculation increases the rate of sublimation at low temperatures, but may not be beneficial if the ambient temperature is 30°C. At 30°C, the energy input to run the recirculation pump may not be justified. However, because forced recirculation may also be beneficial for creating CO_2 uniformity within tall structures, the recirculation pump should probably be run even if the ambient temperature is 30°C.

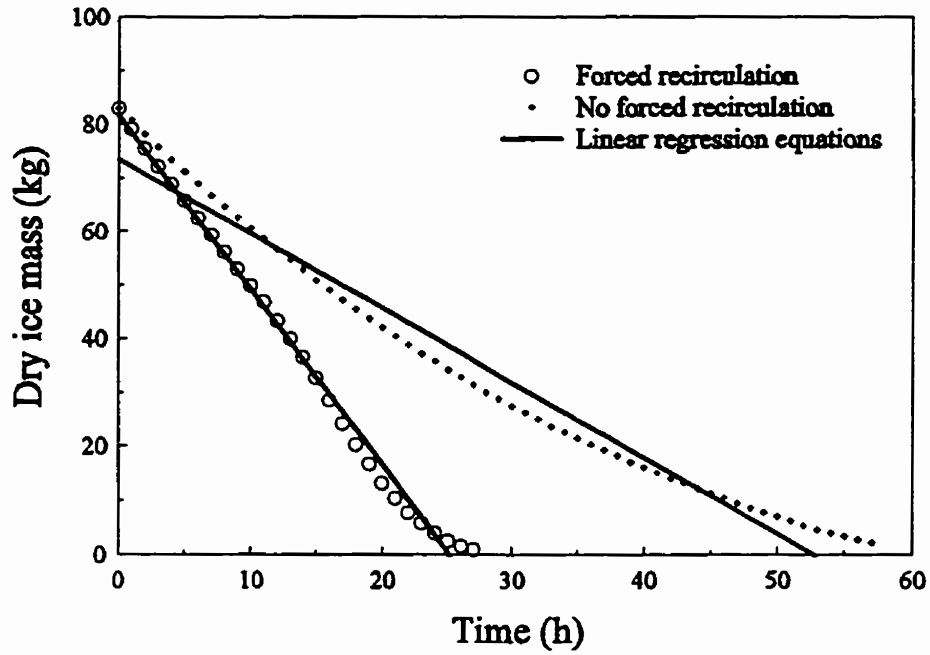


Fig. 5.15 Observed mass decay from initial masses of 83 kg of dry ice pellets inside a steel drum exposed to an outside temperature of 0°C both with and without forced recirculation.

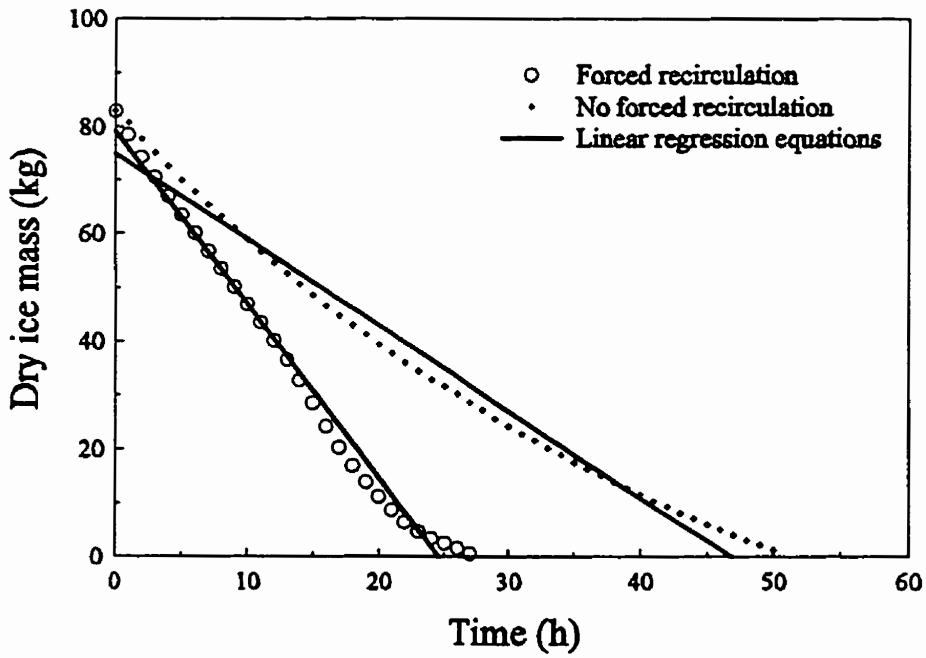


Fig. 5.16 Observed mass decay from initial masses of 83 kg of dry ice pellets inside a steel drum exposed to an outside temperature of 10°C both with and without forced recirculation.

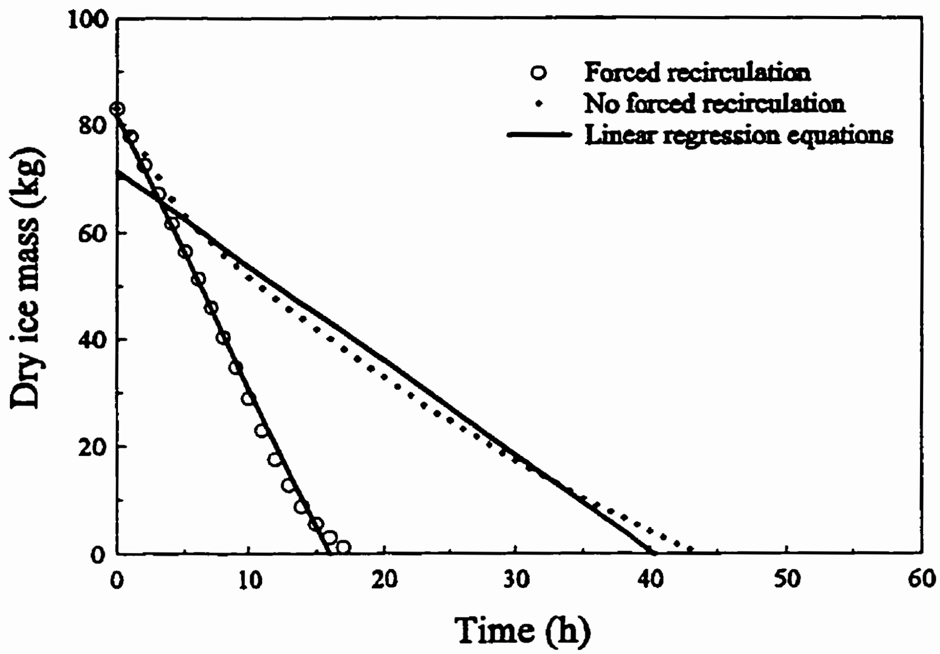


Fig. 5.17 Observed mass decay from initial masses of 83 kg of dry ice pellets inside a steel drum exposed to an outside temperature of 20°C both with and without forced recirculation.

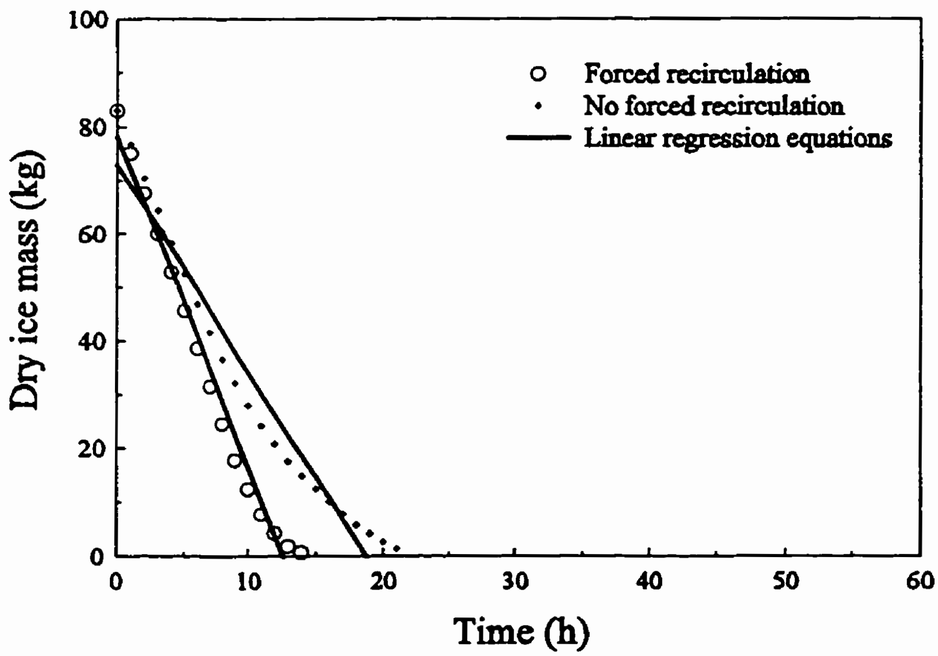


Fig. 5.18 Observed mass decay from initial masses of 83 kg of dry ice pellets inside a steel drum exposed to an outside temperature of 30°C both with and without forced recirculation.

The results presented in this section do not form a complete study of the rate of sublimation of dry ice. Consequently, I have not attempted to model or derive equations for the rate of sublimation. A more detailed study would have to be conducted before further analysis could be done. These limited results do, however, agree with some of my previous assumptions. The rate of sublimation increases with increasing temperature, with increased initial quantities of dry ice, and with forced recirculation.

6. INSECT MORTALITY

6.1 Requirements of a CO_2 fumigation

The purpose of a CO_2 fumigation is to kill the insects present in the stored grain. If the insects are not killed, the procedure must be considered a failure. Although much has been learned about CO_2 fumigations and many improvements made during this research, a necessary final test was to assess the mortality of insects exposed to increased CO_2 concentrations in full-size welded-steel hopper bins.

Because insect populations develop quickly under optimal conditions, complete control is desirable. The survival of a few insects could potentially cause reinfestation of the stored grain. In addition, though review of the literature concluded that resistance to CO_2 is unlikely to develop, the survival of insects from a CO_2 fumigation provides an opportunity for resistance to develop.

6.2 Design of insect cages

The effectiveness of a CO_2 fumigation should be tested against a naturally-occurring insect infestation, but quantifying the insect mortality with a high level of confidence is difficult because the exact number of insects present before and after fumigation is not known. Mortality can be accurately quantified only if a known number of insects are placed inside the bin. The insects must be confined so that they cannot escape into the grain bulk.

Probe traps prevent insect escape (Loschiavo 1974), therefore, they satisfy the primary requirement for insect cages. To assess insect mortality throughout the grain bulk, the cages needed to be placed into the bin as it was being filled and to be removed after emptying the bin. A probe trap constructed of copper (Loschiavo and Atkinson 1973) had adequate strength to withstand the forces caused by the moving grain during unloading, but the brass mesh in the upper portion of the trap was replaced with copper pipe (eight 3-mm diameter holes allowed the entry of fumigation gases). Insects were placed inside glass or plastic vials (Loschiavo and Atkinson 1973) in the bottom section of the cage. Escape was prevented by the funnel-shaped entrance to the vial. An eye-bolt was attached to the top of the cage so that the cage could be suspended inside the bin with steel wire.

6.3 Testing of gas entry into insect cages

The gas concentration inside the insect cage must be identical to the gas concentration within the grain bulk. Experiments were conducted to confirm that holes in the copper pipe allowed adequate movement of gases into the insect cage.

An insect cage was placed inside a pilot-scale bin (Fig. 6.1). Nylon sampling lines were placed at locations A to E, (location B was inside the insect cage). Type T copper-constantan thermocouples were placed at locations A, B, D, and E. Pellets of dry ice were placed in a plastic container suspended from the top of the pilot bin, above location A. The lid of the pilot bin was closed, but the seal was not airtight.

Six experiments were conducted, three with empty pilot bins and three with wheat-filled pilot bins. The mass of added dry ice was calculated to give CO_2 concentrations of 20, 50, and 80% for both the empty and wheat-filled bins. Temperatures were recorded and gas samples collected 1, 3, 5, and 7 h after addition of the dry ice (Tables 6.1 to 6.6). Small quantities of gas were removed (during purging and sample collection) to prevent the unnecessary movement of gases into the cage.

For the three experiments conducted in the empty pilot bin, the CO_2 concentration at location E was generally greater than the CO_2 concentration at location A (Tables 6.1, 6.2, and 6.3). A possible explanation is that vertical stratification was occurring inside the 1.68 m-tall pilot bin. A second explanation is that the lid of the pilot bin was not airtight resulting in some leakage of CO_2. Because location A was closest to the lid, CO_2 from this region would be the first to leak. Due to the variation, locations A and E were omitted from further analysis. From the mean and standard deviation (S.D.) values of locations B, C, and D; coefficient of variation (CV) values were calculated

(Table 6.7). With CV values less than 6%, I concluded that the CO_2 concentration inside the cage was the same as that outside the cage at the same elevation.

In the second set of experiments (Tables 6.4, 6.5, and 6.6), the presence of grain increased the variation between the top and bottom of the pilot bin at 1 and 3 h, but by 7 h the variation was much less. The CV values ranged from 39 to 50% at 1 h, but only 2 to 4% at 7 h (Table 6.7). These observations are reasonable because grain slows the movement of CO_2 molecules and, therefore, it takes longer for the CO_2 to disperse from the top to the bottom when grain is present.

Based on the results from these six experiments, I concluded that the insect cage design was adequate because the CO_2 concentration inside the cage was consistent with the CO_2 concentration outside the cage. This ensures that the caged insects will be exposed to the same environment as they would be exposed to in a naturally-infested bin.

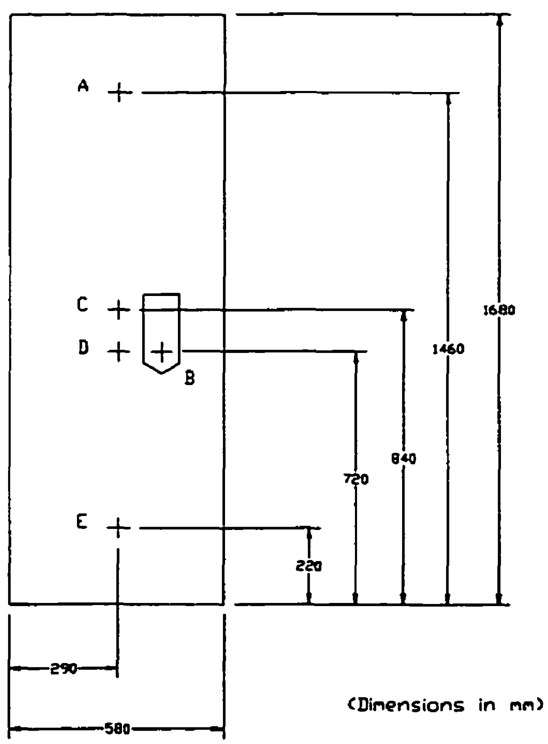


Fig. 6.1 The pilot bin used to test the uniformity of CO_2 inside the insect cage. Points A through E indicate the locations from which gas samples were collected.

Table 6.1 Observed CO_2 concentrations and temperatures for locations A to E inside an empty pilot bin. Assuming no leakage, 176 g of dry ice was predicted to create a CO_2 concentration of approximately 20%.

Sample Location	CO_2 Concentration (%)				Temperature (°C)			
	1 h	3 h	5 h	7 h	1 h	3 h	5 h	7 h
A	10.2	21.0	21.7	19.2	20.5	21.1	23.9	25.2
B	11.3	21.5	21.7	18.0	20.9	20.2	22.7	24.4
C	11.0	21.7	22.0	18.0				
D	12.0	22.6	20.5	18.4	20.2	20.4	23.0	24.4
E	12.1	22.2	21.4	19.2	20.0	20.2	22.3	23.6

Table 6.2 Observed CO_2 concentrations and temperatures for locations A to E inside an empty pilot bin. Assuming no leakage, 440 g of dry ice was predicted to create a CO_2 concentration of approximately 50%.

Sample Location	CO_2 Concentration (%)				Temperature (°C)			
	1 h	3 h	5 h	7 h	1 h	3 h	5 h	7 h
A	15.9	30.4	39.3	39.2	19.8	20.3	22.6	23.2
B	16.0	33.5	43.2	45.1	19.6	19.6	21.8	22.6
C	16.5	34.7	44.6	44.6				
D	16.7	33.7	40.0	44.0	19.5	19.7	22.0	22.6
E	17.5	35.5	44.4	44.9	19.4	19.6	21.8	22.0

Table 6.3 Observed CO_2 concentrations and temperatures for locations A to E inside an empty pilot bin. Assuming no leakage, 704 g of dry ice was predicted to create a CO_2 concentration of approximately 80%.

Sample Location	CO_2 Concentration (%)				Temperature (°C)			
	1 h	3 h	5 h	7 h	1 h	3 h	5 h	7 h
A	20.1	40.2	50.0	47.9	15.0	17.8	19.2	22.8
B	22.2	42.7	56.0	57.0	16.1	18.1	19.1	21.7
C	23.0	44.6	55.2	55.9				
D	22.7	44.7	55.3	52.0	16.2	18.2	18.9	22.1
E	23.3	44.6	56.0	56.9	16.4	18.1	18.9	21.9

Table 6.4 Observed CO_2 concentrations and temperatures for locations A to E inside a wheat-filled pilot bin. Assuming no leakage and with compensation for sorption, 88 g of dry ice was predicted to create a CO_2 concentration of approximately 20%.

Sample Location	CO_2 Concentration (%)				Temperature (°C)			
	1 h	3 h	5 h	7 h	1 h	3 h	5 h	7 h
A	35.3	22.7	17.1	13.6	19.9	18.5	19.4	20.1
B	4.9	18.7	19.5	19.3	20.9	21.0	21.0	21.0
C	3.1	16.3	19.6	17.9				
D	2.3	19.5	19.9	18.4	20.9	21.0	21.0	21.0
E	2.1	19.0	20.3	19.2	20.0	20.0	20.1	20.0

Table 6.5 Observed CO_2 concentrations and temperatures for locations A to E inside a wheat-filled pilot bin. Assuming no leakage and with compensation for sorption, 221 g of dry ice was predicted to create a CO_2 concentration of approximately 50%.

Sample Location	CO_2 Concentration (%)				Temperature (°C)			
	1 h	3 h	5 h	7 h	1 h	3 h	5 h	7 h
A	41.2	38.9	45.2	35.7	19.7	14.6	14.0	15.8
B	5.8	8.7	33.9	34.3	20.4	20.4	20.6	20.7
C	3.4	25.5	34.0	34.6				
D	2.5	27.0	33.6	33.6	20.4	20.5	20.7	20.7
E	2.5	23.6	28.0	29.6	21.9	21.8	21.8	21.7

Table 6.6 Observed CO_2 concentrations and temperatures for locations A to E inside a wheat-filled pilot bin. Assuming no leakage and with compensation for sorption, 358 g of dry ice was predicted to create a CO_2 concentration of approximately 80%.

Sample Location	CO_2 Concentration (%)				Temperature (°C)			
	1 h	3 h	5 h	7 h	1 h	3 h	5 h	7 h
A	47.5	45.6	50.7	48.2	20.3	15.0	13.1	13.2
B	12.3	36.5	42.2	45.4	23.8	23.8	23.7	23.5
C	10.4	32.3	41.1	45.4				
D	3.9	34.3	41.0	44.2	23.6	23.6	23.6	23.4
E	2.7	35.3	37.6	40.5	23.2	23.0	22.9	22.7

Table 6.7 Mean, standard deviation (S.D.), and coefficient of variation (CV) values for location B inside the insect cage and locations C and D outside the insect cage, both when the pilot bin was empty and when filled with wheat.

Sampling Time	Locations B,C&D	Calculated CO_2 Concentration (%)					
		Empty			Filled with Wheat		
		20	50	80	20	50	80
1 h	Mean (%)	11.4	16.4	22.6	3.4	3.9	8.9
	S.D.	0.51	0.36	0.40	1.33	1.71	4.40
	CV (%)	4	2	2	39	44	50
3 h	Mean (%)	21.9	34.0	44.0	18.2	20.4	34.4
	S.D.	0.59	0.64	1.13	1.67	10.16	2.10
	CV (%)	3	2	3	9	50	6
5 h	Mean (%)	21.4	42.6	55.5	19.7	33.8	41.4
	S.D.	0.79	2.36	0.44	0.21	0.21	0.67
	CV (%)	4	6	1	1	1	2
7 h	Mean (%)	18.1	44.6	55.0	18.5	34.2	45.0
	S.D.	0.23	0.55	2.63	0.71	0.51	0.69
	CV (%)	1	1	5	4	2	2

6.4 Mortality of caged insects not exposed to CO_2

Besides assurance that CO_2 could enter the insect cages, I also needed to ensure that the insects would not die simply from being caged because I wanted to conclude that the presence of CO_2 was the only factor contributing to the death of the insects. Ten insect cages, held at a temperature of 25°C, were used in this test. One hundred adult *C. ferrugineus* were placed inside each cage.

The first attempt failed because wheat germ was not placed inside the cages. This error resulted in high rates of insect mortality after 1 wk due to starvation. When the procedure was repeated, 1 g of wheat germ and 100 adult *C. ferrugineus* were placed inside each of the 10 cages. At the end of the first week, five of the cages were opened and the insects were examined. A mean mortality of 2.5% was observed from the five cages (Table 6.8). The insects likely died due to old age.

Insect species such as *C. ferrugineus* have a short lifespan (6 - 8 months on average). The insects used in this procedure were not selected based on age. It is likely that some insects were near the end of their natural lifespan and died of old age during the first week of captivity.

Results from the remaining five cages after 2 wk of captivity reinforced my assumption that the observed mortality was due to old age. The mean mortality increased to 5.4% (Table 6.8). As the insects were 1 wk older, it was expected that more of them would die. Because the observed mortality was low, I concluded that captivity inside the insect cages did not cause mortality.

6.5 Mortality of caged insects exposed to fumigation with CO_2

6.5.1 Placement of the cages The placement of cages within the bin is important because variations in the CO_2 concentration can lead to incomplete disinfestation of insects. Although I previously concluded that CO_2 uniformity was high in both the radial and vertical directions (Chapter 4), I needed to be certain that minor variations would not permit insect survival. An assessment of insect mortality from many locations in the grain bulk was required.

Insect cages were placed at four elevations within the grain bulk (Fig. 6.2) and at three radial locations for each elevation (Fig. 6.3), except the lowest elevation where only two radial locations were possible because of the shape of the bottom cone of the bin. For the top three elevations, cages were placed at the centre of the bin, within 200 mm of the bin wall along four perpendicular radii, and at the midpoint of the bin radius along each of the four perpendicular radii (a total of nine cages per elevation). Only five cages were placed at the lowest elevation with one at the centre of the bin and four near the bin wall. This distribution of cages gave a good physical representation of the grain bulk.

Table 6.8 Mortality of caged adult *C. ferrugineus* not exposed to CO_2.

	Cage Number	Initial Insects	Live (#)	Dead (#)	Mortality (%)
One Week of Captivity	1	100	97	3	3
	2	100	97	3	3
	3	100	100	0	0
	4	99	96	3	3.3
	5	100	97	3	3
Two Weeks of Captivity	6	103	97	6	5.8
	7	99	96	3	3.3
	8	100	93	7	7
	9	100	94	6	6
	10	100	95	5	5

Five experiments were conducted with caged insects present within the grain bulk. In three of the five experiments (F4.3, F4.8, and F4.9), cages were placed at all 32 of the locations described in the previous paragraph. For the remaining two experiments, only 16 cages were used. For experiment F4.4, cages were placed at locations 1, 2, 4, 8, 10, 11, 13, 15, 16, 18, 21, 23, 26, 28, 29, and 31. The following experiment, F4.5, had cages placed at locations 3, 5, 6, 7, 9, 12, 14, 17, 19, 20, 22, 24, 25, 27, 30, and 32.

Because of the resistance offered by the grain, pushing the insect cages into the grain to a depth of more than about 0.5 m was difficult. After filling the bin to a depth of approximately 1 m, cages 1 to 5 were placed at the appropriate locations. Steel wire was used to tie the insect cages to the access ladder on the inside wall of the bin so that the cages would remain inside the bin after unloading. This procedure was repeated until all four levels were completed.

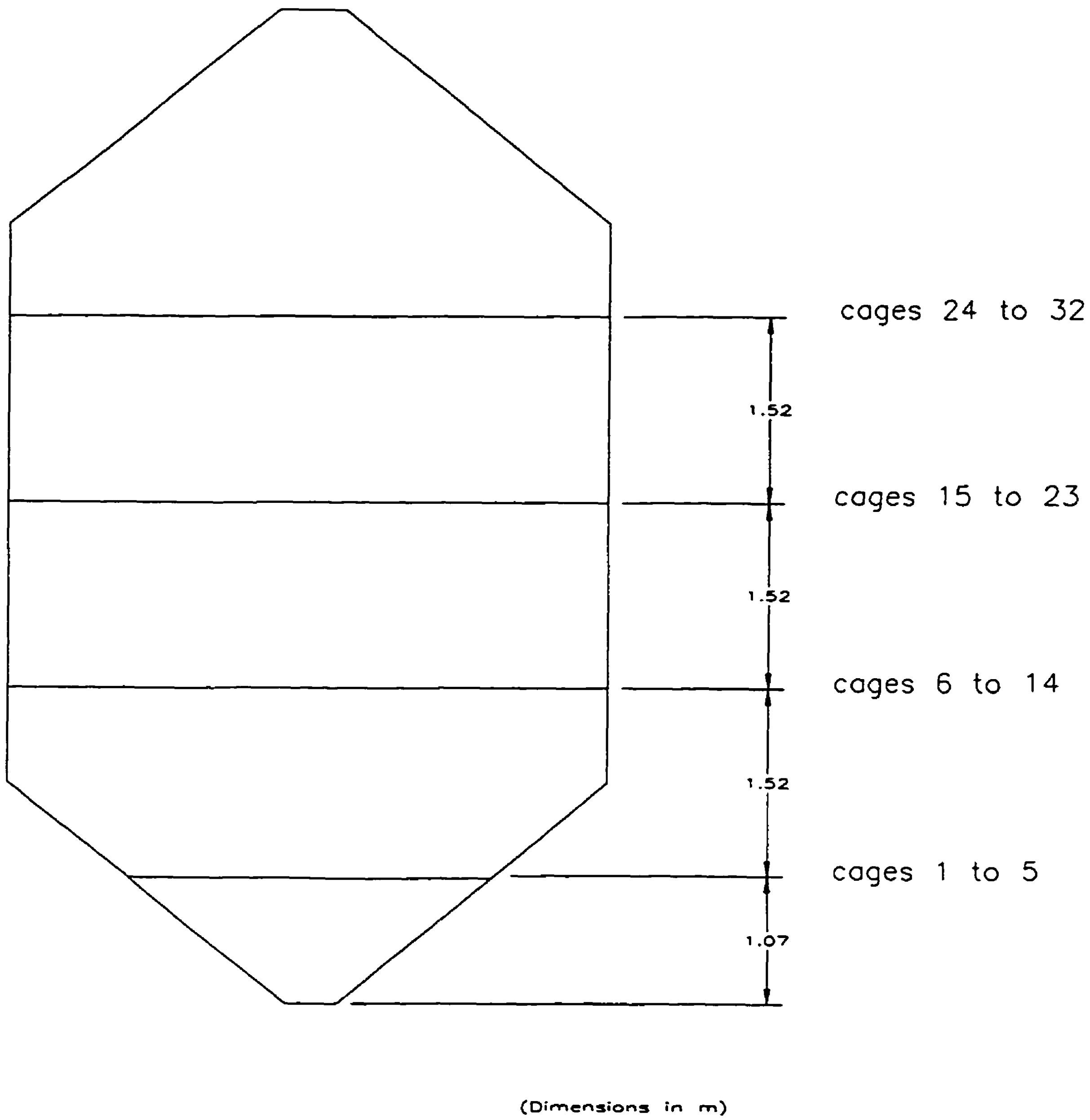


Fig. 6.2 Vertical distribution of the 32 insect cages located throughout the grain bulk in the full-size welded-steel hopper bin. (Refer to Fig. 6.3 for radial placement of cages).

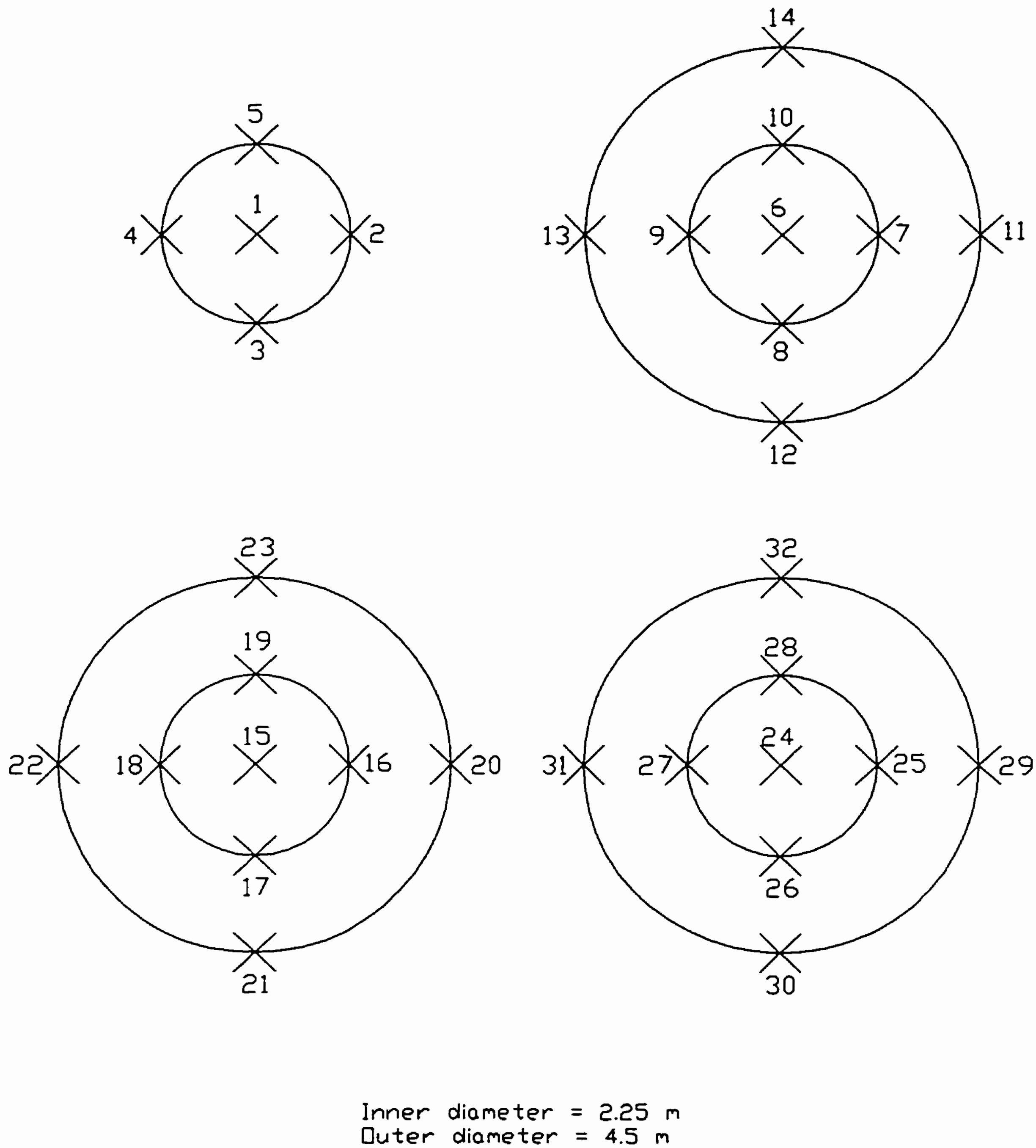


Fig. 6.3 Radial distribution of the 32 insect cages located throughout the grain bulk in the full-size welded-steel hopper bin. (Refer to Fig. 6.2 for vertical placement of cages).

6.5.2 Observed insect mortalities The overall objective of the experiments described in this chapter was to investigate the effectiveness of an actual CO_2 fumigation against the survival of adult *C. ferrugineus*. Banks et al. (1980) described several situations in which insects were present several months after fumigation with CO_2. It was not clear whether the presence of these insects was due to incomplete control during the fumigation or due to reinfestation of the imperfectly sealed storage structures. The possibility exists, however, that mortalities <100% enable infestations to reappear under optimal conditions. Consequently, 100% mortality must always be considered the goal. Two different fumigation treatments were tested during this research, 10-d and 4-d exposures to CO_2.

The observed insect mortalities for the five experiments are presented in Appendix F. Insect mortalities based on all sampling locations for each of the five experiments (Table 6.9) showed that the 10-d fumigation was more effective than the 4-d fumigation. Only two replicates of the 4-d fumigation were conducted because the observed mortalities (i.e., 95.3 and 79.8%) were considered too low to be acceptable. For the 10-d fumigations, the results were better. Complete mortality (i.e., 100%) was obtained in experiment F4.3 when the mean temperature within the grain bulk over the 10-d period was 20°C. Experiments F4.4 and F4.5 were conducted later in the fall when the mean temperatures within the grain bulk fell to 16 and 13°C, respectively. The observed mortalities for these two experiments were 99.8 and 99.7% (three and five insects, respectively, survived the fumigations).

There is some indication that insect survival may be correlated with location because all three surviving insects in experiment F4.4 and two of the five surviving insects in experiment F4.5 were in cages near the bin wall. Of the remaining three insects, two were at mid-radius and one at the centre. For these two experiments, more live insects were found near the bin wall than at the other locations. It is expected that the periphery of the grain bulk (i.e., near the bin wall) would have the greatest temperature fluctuations which may have helped insect survival near the wall.

Table 6.9 Observed insect mortalities for the 10-d and 4-d CO_2 fumigations in full-size welded-steel hopper bins.

Experiment	Length of Exposure (d)	Mean Temperature (°C)	Mean CO_2 Concentration (%)	Insect Mortality (%)
F4.3	10	20	41.8	100
F4.4	10	16	36.3	99.8
F4.5	10	13	36.6	99.7
F4.8	4	22	43.8	95.3
F4.9	4	18	46.9	79.8

A reasonable explanation for the decline in mortality from experiment F4.3 to F4.5 is the decline in the mean temperature. As the temperature drops, the rate of metabolism for insects slows, resulting in a reduced rate of respiration (Person and Sorenson 1970). With a reduced rate of respiration, less CO_2 will be inhaled and a lower rate of mortality is expected. A reasonable conclusion from these results is that the duration of a CO_2 fumigation should be lengthened beyond 10 d if the temperature within the grain bulk is below 20°C. I cannot conclude how many extra days will be required. It should be noted, however, that if the temperature within the grain bulk is below 20°C, it is unlikely that the insect population will increase because it is too cold. Kawamoto et al. (1989) simulated population dynamics of *C. ferrugineus* in stored wheat at various constant temperatures and RHs starting from an initial population density of one newly-emerged female and one male per kg of wheat. Population increase decreased significantly when temperatures decreased from 30 to 20°C. At 20°C and 70% RH, there was virtually no population increase for six months. At temperatures below 20°C, as in experiments F4.4 and F4.5, therefore, it is likely that population increase would not occur. Therefore, if the grain is to be sold before it warms again, extending the duration of a CO_2 fumigation beyond 10 d is probably unnecessary because a significant portion of the population would be killed and the survivors would probably be undetectable.

The poor results obtained from experiments F4.8 and F4.9 were unexpected based on experiments F4.6 and F4.7 where mean CO_2 concentrations were above 50% for 4 d (Table 5.1). By contrast, the CO_2 concentration peaked at 45.0% for experiment F4.8 and was above 50% for only 2 d during experiment F4.9. For all four experiments, the same mass of dry ice (i.e., 107 kg) was added. I cannot explain the difference between the first two and the last two replicates, although this drop in mean CO_2 concentration likely contributed to the lower insect mortalities.

The CO_2 concentrations were not consistent for the three 10-d fumigations either (experiments F4.3, F4.4, and F4.5 in Fig. 5.6). Despite differences in CO_2 concentrations, the insect mortalities remained nearly constant for the three experiments (Table 6.9). The greatest mortality, however, does correspond with the highest mean CO_2 concentration. The combination of reduced temperature and reduced mean CO_2 concentration is likely the cause of the decline in insect mortality observed in experiments F4.4 and F4.5.

Although both the 10-d and 4-d experiments displayed variation in mean CO_2 concentration and insect mortality, I am more confident in recommending a 10-d fumigation. If there was no variation in mean CO_2 concentration, the 4-d fumigation could probably be successful. Completion of a fumigation in 4 d is desirable for field applications. Unfortunately, I could not control the variation. The best way to overcome the effects of variation is to allow more time for the fumigation to be completed. I conclude, therefore, that 10-d fumigations are more likely to be successful in practice than 4-d fumigations.

6.6 Fumigation of an induced infestation

Despite the tests done to ensure that caged insects react the same as uncaged insects to CO_2 exposure, I could not conclude with certainty that test and actual conditions would be the same. One test was done with an uncaged insect infestation of grain to ensure that the fumigation procedure was effective under actual conditions.

A small welded-steel hopper bin (approximately 17.5 m^3 capacity) at the Agriculture and Agri-Food Canada Research Farm approximately 20 km south of Winnipeg, MB was used for this experiment (hereafter this bin will be referred to as bin C). The bin was retrofitted, as described previously in this thesis, to create a sealed bin. The sealing effort was successful based on the results of two pressure decay tests conducted after the bin had been filled with wheat in which the pressure decayed from 1.37 to 0.69 kPa in 32 min (1920 s) (Appendix L). With the bin sealed adequately, cultures of *C. ferrugineus* were emptied onto the top surface of the wheat inside the hopper bin. The insects were not counted, but it was estimated that approximately 30 x 10^3 adults were added to the hopper bin to create an initial adult insect density of approximately three insects per kg of wheat. When the insects were added, the temperature along the centreline of the grain bulk ranged from 18 to 26°C. Under these conditions, insect survival was not jeopardized.

After leaving the bin for about 3 wk, nine probe traps (White et al. 1990a) were pushed into the wheat to a depth of approximately 1 m to get a representative sample of the number of insects near the surface of the wheat. The probe traps remained in the wheat for 1 wk before being removed and before counting the captured insects. Trap counts ranged from 4 to 120 insects (Table 6.10) with the total made up of live and dead insects. In total, 343 insects were captured, of which 288 were living and 55 were dead. Death of the 55 insects was likely caused by a combination of overcrowding and lack of food inside the probe traps. The high trap counts confirmed that the wheat was infested with *C. ferrugineus*. All live insects were returned to the hopper bin.

The bin was sealed and a 10-d fumigation was started with the addition of 14 kg of dry ice. At daily intervals, for 10 d, grain temperatures were recorded and gas samples were collected and analyzed (experiment F4.10 in Appendix G). On the tenth day, the bin was opened and allowed to ventilate for 24 h before nine probe traps were again inserted. After 1 wk, the probe traps were removed and the captured insects were counted. Four of the nine probe traps contained no insects, live or dead (Table 6.10), but one probe trap had 16 insects, 15 of which were dead. A total of 4 live and 19 dead insects were counted.

The presence of insects in the probe traps at the end of the 10-d fumigation is cause for concern. The mean CO_2 concentration over the 10-d period was 43.9%, ranging from a high of 50.9% to a low of 38.7%. A mean temperature of 21°C was observed over the same period. Based on the results obtained for experiments F4.3 to F4.5 presented previously, I did not expect to find any insects after fumigation. Calculating the exact level of mortality is impossible because I do not know the exact numbers of insects present before and after the fumigation, however, numbers of captured insects after the fumigation compared to the numbers from before indicate about 94% mortality.

The dead insects found inside the probe traps are also difficult to explain. It is possible that they crawled into the probe traps and then died due to starvation. This is typically what happens in this kind of trap. It could also be that they managed to crawl into the probe traps, but died due to the residual CO_2 concentration. There is also one further possibility. Weed seeds and broken kernels were found inside probe traps upon removal from the grain bulk. These small particles must have fallen through the holes of the probe traps while they were being inserted or extracted from the grain bulk. If weed seeds and small particles could have fallen into the probe traps, then it is also possible that dead insects fell into the probe traps. I have no way of determining how the dead insects got inside the probe traps. Although the CO_2 fumigation did not eliminate the natural infestation of *C. ferrugineus*, it was effective at reducing the insect population considerably.

Table 6.10 Probe trap counts from before and after a 10-d CO_2 fumigation of an induced infestation in a welded-steel hopper bin.

Trap Number	Before Fumigation		After Fumigation	
	Live (#)	Dead (#)	Live (#)	Dead (#)
1	4	0	0	0
2	78	11	1	0
3	8	1	0	0
4	19	1	0	2
5	94	26	0	2
6	12	2	2	0
7	7	1	0	0
8	62	13	1	15
9	4	0	0	0
Totals	288	55	4	19

6.7 Equation for predicting the mortality of *C. ferrugineus*

6.7.1 Rationale for the equation In my literature review, I concluded that a simple concentration-time product could not predict insect mortality because many different ct-values were given for the same species of insect (these ct-values were all supposed to yield similar rates of mortality). Rameshbabu et al. (1991) tried to incorporate more factors than just CO_2 concentration and exposure time into a mortality equation for *C. ferrugineus*, but it can be shown that their equation does not fit the recommendations given by Annis (1987) or Shunmugam et al. (1993). To the best of my knowledge, no other equation for mortality of *C. ferrugineus* exists.

Predicting insect mortality under conditions of declining CO_2 concentrations is especially difficult. An equation to predict the mortality of *C. ferrugineus* would be useful because the rate of gas loss is likely to vary from bin to bin.

6.7.2 Development of the equation Without theory to predict insect mortality, an empirical equation is the best alternative. The literature was searched for cases of *C. ferrugineus* mortality under conditions of elevated CO_2 concentrations (Appendix H). Most of the data found were for mortality of *C. ferrugineus* exposed to a temperature of approximately 25°C with limited data for other temperatures. Using the data corresponding to a temperature of 25°C, the following empirical equation was obtained using SigmaPlot (Eq. 6.1):

$$E = 650 \times 10^3 \ C_c^{-2.1662} \tag{6.1}$$

where E is the exposure time (h) required to attain complete insect mortality at a given CO_2 concentration, C_c (%). The fit between the empirical equation and the compiled data for a temperature of 25°C was good ($R^2 = 0.96998$) (Fig. 6.4). The data for temperatures other than 25°C were also plotted (Fig. 6.4). As expected, the CO_2 concentration required to achieve complete mortality increased as the temperature decreased below 25°C and decreased as the temperature rose above 25°C.

With Eq. 6.1, it is assumed that both the temperature and CO_2 concentration remain constant throughout the fumigation period. I have previously shown that CO_2 concentrations do not remain constant throughout a fumigation.

When the CO_2 concentration varies, the fumigation period is divided into intervals. For each interval, Eq. 6.1 is used to calculate the lethal exposure time based on the CO_2 concentration observed during that interval. A ratio of the interval to the lethal exposure time is then calculated, and summed over all intervals to give a cumulative lethality index (CLI) (Eq. 6.2). Complete insect mortality should result when the cumulative lethality index equals one.

$$CLI = \sum_{i=\text{first interval}}^{\text{last interval}} \frac{t_i}{0.65x10^6 \ (C_c)_i^{-2.1662}} \tag{6.2}$$

where: t_i = interval length (h), and

$(C_c)_i$ = CO_2 concentration observed during interval i (%).

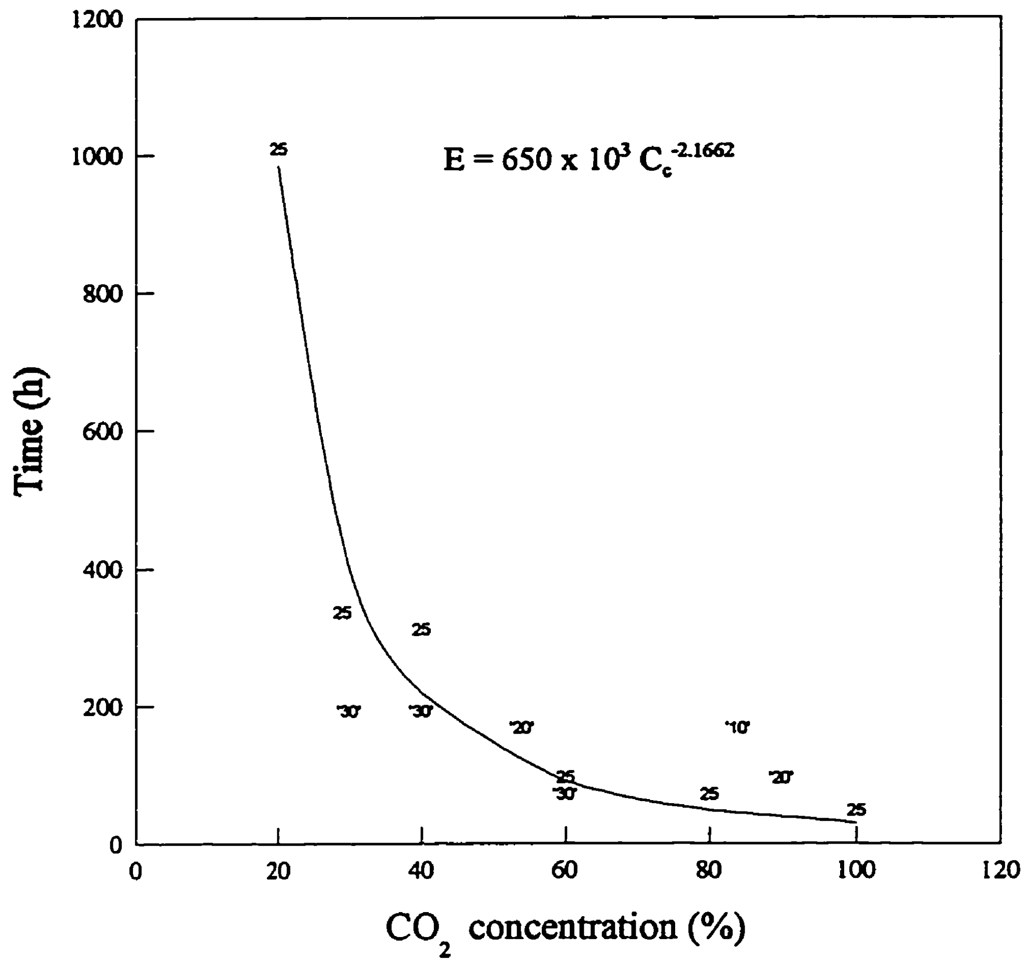


Fig. 6.4 The mortality data for adult *C. ferrugineus* exposed to elevated CO_2 concentrations at various temperatures (compiled from: Anonymous 1983; Rameshbabu et al. 1991; Shunmugam et al. 1993; White and Jayas 1991; White and Jayas 1993; White et al. 1988; White et al. 1990b). A relationship between CO_2 concentration and exposure time was obtained from the data corresponding to a temperature of 25°C.

An important benefit to be gained from the use of Eq. 6.2 is that insect mortality can be predicted when increasing, constant, or decreasing CO_2 concentrations occur in grain. A difficulty with the use of dry ice as the source of CO_2 is that the sublimation period can be lengthy when the ambient temperature is low. With Eq. 6.2, however, I can include the lethal effects that occur during the sublimation period.

6.7.3 Testing of the equation The cumulative lethality indexes were calculated for the six experiments in which insects were exposed to CO_2 (Fig. 6.5). Because gas samples were collected at daily intervals, I divided the fumigation period into 24-h intervals. I approximated the CO_2 concentration for each 24-h interval as the average of the current and previous day's values. For example, the CO_2 concentration for the first interval was the average of zero and the CO_2 concentration recorded on the first day. For the tenth interval, the CO_2 concentration was the average of days nine and ten. Based on these assumptions, the CLI values displayed in Fig. 6.5 were obtained.

There is agreement between Fig. 6.5 and Table 6.9. Of the five experiments, F4.3 is the only one where 100% mortality was observed (Table 6.9). Figure 6.5 shows experiment F4.3 having a cumulative lethality index greater than one, which suggests that 100% mortality should have been attained. The observed mortalities for experiments F4.4 and F4.5 were just less than 100% (Table 6.9). Figure 6.5 shows high cumulative lethality indexes for experiments F4.4 and F4.5, but less than one. The cumulative lethality indexes were much smaller for experiments F4.8 and F4.9 (Fig. 6.5) which corresponds to the lower observed mortalities (Table 6.9). Although I was not able to calculate the exact mortality for experiment F4.10, it was less than 100%. Based on my calculations, Fig. 6.5 suggests that 100% mortality should have been obtained.

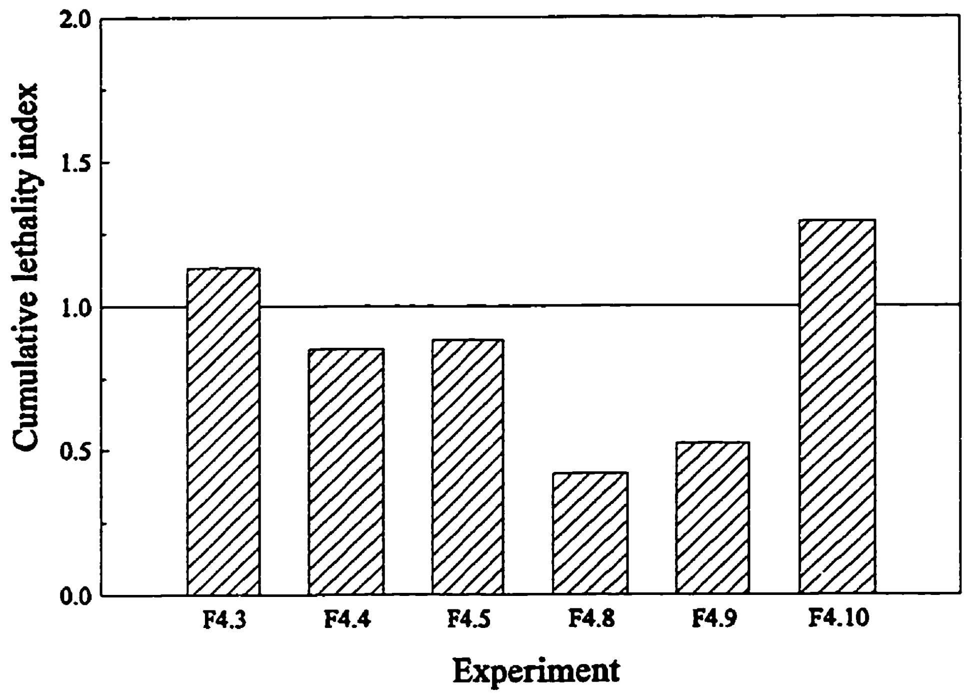


Fig. 6.5 Cumulative lethality indexes for the six experiments in which adult *C. ferrugineus* were exposed to CO_2.

Calculation of the cumulative lethality index using Eq. 6.2 provides a viable tool for predicting the effectiveness of a CO_2 fumigation. It should be noted, however, that Eq. 6.1 is based on data at 25°C. The relationship will change for other temperatures, but at present, there are insufficient mortality data for *C. ferrugineus* to generate equations for other temperatures. This may be a project for future research.

7. PREDICTING THE ADEQUACY OF A STORAGE STRUCTURE

7.1 Rationale

Fumigation with CO_2 was successful in the experimental bins, but the experimental bins do not represent all bins that are present in western Canada. In Chapter 4, it was shown that sealing is vital to the efficiency and, ultimately, to the success of a fumigation. Even if all bins were sealed according to the method that I developed, not all bins will be sealed to the same level of gas-tightness. A method is required that would allow a farmer to assess any bin.

7.2 Proposed relationship

7.2.1 Overview of relationship The pressure decay test (PDT) is commonly used to assess the gas-tightness of storage structures. The storage structure is pressurized to an initial value and then the pressure decays to some final value (typically equal to one-half of the initial value). The time required for the pressure to decay indicates the gas-tightness of the storage structure, but does not yield the actual rate of gas loss to be expected. Sharp (1982) related the pressure decay time to the pressure, but not to the leakage area. The gas loss rate, however, depends on the leakage area.

Pressure decay standards indicate the gas-tightness a bin should achieve. If the bin does not meet the pressure decay standard, the usual recommendation is to seal it better. This procedure is very inflexible. In cases where additional sealing may be cost-prohibitive, it would be beneficial if the farmer could predict the fumigation duration required to kill the insects based on the expected gas loss rate from the bin. I have previously shown (Chapter 6) that the required exposure can be calculated using Eq. 6.2 if the concentration decay profile (with time) is known. Predicting the required exposure for any bin should be possible if both the initial CO_2 concentration and the rate of gas loss are known.

I propose to relate both pressure decay time and gas loss rate to a common factor of leakage area. The farmer could then conduct a PDT. With the resulting pressure decay time, the leakage area could be calculated and, subsequently, substituted into the gas loss equation, yielding the expected gas loss rate. Knowing both the expected gas loss rate and the planned initial CO_2 concentration, a CO_2 concentration profile could be generated.

7.2.2 Derivation of pressure decay relationship For the first step of my proposed two-step process, a relationship between the pressure decay time and the leakage area is needed. I propose that the pressure decay time, t_p, can be found by taking a ratio of the volume of air leaving the bin to the average rate of volume flow leaving the bin:

$$t_p = \frac{V_L}{Q_L} \tag{7.1}$$

where: t_p = pressure decay time [time for the pressure to decay from an initial value to a value equal to one-half of the initial value] (s),

V_L = volume of air leaving the bin (m^3), and

Q_L = average volume flow rate leaving the bin (m^3/s).

The ideal gas law can be used to calculate the volume of air leaving the bin and the Bernoulli equation to calculate the average volume flow rate leaving the bin.

The number of moles of air in the bin at the initial decay test pressure is:

$$n_{P_d} = \frac{(P_d + P_{atm})\ V}{R\ T_K} \tag{7.2a}$$

where: n_{P_d} = number of moles at pressure P_d above atmospheric (mol),

P_d = initial decay test pressure (i.e., pressure above atmospheric) (kPa), and

P_{atm} = atmospheric pressure (kPa).

The number of moles of air in the bin when the pressure decays to $\frac{1}{2}P_d$ is:

$$n_{\frac{1}{2}P_d} = \frac{(\frac{P_d}{2} + P_{atm})\ V}{R\ T_K} \tag{7.2b}$$

where: $n_{\frac{1}{2}P_d}$ = number of moles at pressure $\frac{1}{2}P_d$ above atmospheric (mol).

Assuming the volume and temperature both remain constant, the number of moles of air expelled from the bin is equal to the difference:

$$\begin{aligned} n_{P_d} - n_{\frac{1}{2}P_d} &= \frac{(P_d + P_{atm})\ V}{R\ T_K} - \frac{(\frac{P_d}{2} + P_{atm})\ V}{R\ T_K} \\ &= \frac{P_d\ V}{2\ R\ T_K} \end{aligned} \tag{7.3}$$

The volume of air (m^3) to be expelled from the bin is:

$$V_L = \frac{P_d\ V\ M_{air}}{2\ R\ T_K\ \rho_{air}} \tag{7.4}$$

Equation 7.4 will serve as the numerator in Eq. 7.1. In the following pages, the relationship for the denominator will be developed. I assumed that the air leaves the bin through a circular hole.

The velocity head plus the pressure head is constant if points 1 and 2 are at the same height. Point 1 is located inside the bin directly in front of a hole through the bin wall. Point 2 is located within a hole through the bin wall.

$$\rho\ \frac{v_1^2}{2} + P_1 = \rho\ \frac{v_2^2}{2} + P_2 \tag{7.5}$$

where: ρ = density (kg/m^3),

v_1 = velocity of air inside the bin directly in front of a hole through the bin wall (m/s),

v_2 = velocity of air through a hole in the bin wall (m/s),

P_1 = pressure inside the bin (kPa), and

P_2 = pressure on the outside of the hole (kPa).

According to the law of conservation of mass, the volume flow rate through two sizes of ducts will remain constant assuming the density does not change:

$$v_1 A_1 = v_2 A_2 \tag{7.6}$$

where: A_1 = cross-sectional area of the bin (m^2), and

A_2 = cross-sectional area of the hole (m^2).

Because I was not interested in v_1 and A_1, they were eliminated from the equation by substituting Eq. 7.6 into Eq. 7.5:

$$\rho \left(\frac{A_2}{A_1}\right)^2 \frac{v_2^2}{2} + P_1 = \rho \frac{v_2^2}{2} + P_2$$

$$P_1 - P_2 = \rho \frac{v_2^2}{2} - \rho \left(\frac{A_2}{A_1}\right)^2 \frac{v_2^2}{2}$$

$$P_1 - P_2 = v_2^2 \frac{\rho}{2} \left[1 - \left(\frac{A_2}{A_1}\right)^2\right] \tag{7.7}$$

$$v_2^2 = \frac{2 (P_1 - P_2)/\rho}{\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]}$$

The ratio A_2/A_1 approaches zero because the cross-sectional area of the hole is small compared with the cross-sectional area of the bin. The pressure inside the bin (P_1) is equal to (P_{bin} +P_{atm}). Similarly, P_2 is equal to the atmospheric pressure, P_{atm}. Finally, because air is the gas under consideration, the density is equal to ρ_{air}. Substitution of these values and simplification yields:

$$v_2 = \left[\frac{2 P_{bin}}{\rho_{air}}\right]^{½} \tag{7.8}$$

To account for a small friction loss through an orifice, an experimental orifice coefficient, C_d, is introduced to yield the velocity through the orifice opening:

$$v_2 = C_d \left[\frac{2\ P_{bin}}{\rho_{air}} \right]^{½} \tag{7.9}$$

If the Reynolds number is above 20 000 and the diameter ratio is less than ≈ 0.5, the value of C_d is approximately constant and has a value of 0.61 (Geankoplis 1983). Another source describes an equation recommended for a concentric orifice with corner taps (Fox and McDonald 1985):

$$C_d = 0.5959 + 0.0312\ \beta^{2.1} - 0.184\ \beta^8 + \frac{91.71\ \beta^{2.5}}{{Re_{D_1}}^{0.75}} \tag{7.10}$$

where: β = ratio of the orifice opening to the pipe diameter.

With the assumption that $A_2/A_1 \rightarrow 0$, β = 0 and C_d = 0.5959.

Although equations for flow through an orifice may be used to describe the movement of air through circular holes, I am unsure how accurate these equations would be for non-circular holes (irregular holes are likely to be present in the full-size bins). Consequently, a typical value for C_d was used (C_d = 0.6) . There are too many unknowns to justify choosing another value of C_d.

The volume flow rate, Q, is equal to the velocity times the cross-sectional area of the hole:

$$Q = v_2\ a = C_d\ a \left[\frac{2\ P_{bin}}{\rho_{air}} \right]^{½} \tag{7.11}$$

where: a = cross-sectional area of the hole (m^2).

Substitution of Eqs. 7.4 and 7.11 into Eq. 7.1 yields:

$$t_p = \frac{\dfrac{P_d\ V\ M_{air}}{2\ R\ T_K\ \rho_{air}}}{C_d\ a \left[\dfrac{(2 \times 10^6)\ P_{bin}}{\rho_{air}} \right]^{½}} \tag{7.12}$$

A factor of 10^6 is required in the denominator to match units. The derived expression relates leakage area with pressure decay time.

The air density at any temperature was calculated using Eq. 7.13 obtained by fitting tabulated data (the pressure was assumed constant at 101.325 kPa) (Geankoplis 1983) using SigmaPlot:

$$\rho_{air} = \frac{0.3531 \times 10^6}{T_K} \tag{7.13}$$

where: ρ_{air} = air density (g/m^3).

7.2.3 Derivation of gas loss rate relationship Assuming that most of the gas loss from a bin during a fumigation occurs because of a concentration gradient rather than a pressure gradient, the dispersion of gases is appropriately described by the diffusion process. Diffusion is the mixing of one gas with another. There is, however, another process that more closely describes the loss of gaseous CO_2 from a sealed bin. If a bin is well sealed, it can be assumed that only small holes remain. Effusion is a process by which a gas escapes from a container through a small hole. Effusion, therefore, properly describes the process that is occurring.

The movement of gas molecules through openings takes place because of the random motion of the molecules. Because effusion is a random process, it is appropriately described using statistics. Rather than being able to predict with certainty the number of molecules left inside a volume after a given time, we can expect that there will be an average number of molecules left after a given time. Gillespie (1993) used the Markov process theory to calculate the number of molecules (i.e., mean and variance) left inside a given volume after a given time. The relationships presented by Gillespie are quite complex and preliminary investigation yielded poor agreement with my experimental results. A less complex relationship was presented by Bernardini (1989), who described the movement of gaseous molecules from one vessel to another through a hole of known area. The number of molecules passing through the hole in a short time is given by:

$$\Delta N = \frac{N}{V_c} a \, v_m \, \Delta t \qquad (7.14)$$

where: ΔN = number of molecules passing through the hole in a short time,

N = initial number of molecules inside the container,

V_c = volume of the container (m^3),

a = cross-sectional area of the hole (m^2),

v_m = velocity of the molecules (m/s), and

Δt = time interval (s).

The velocity of the CO_2 molecules through the hole was calculated using the principles of diffusion:

$$v_m = \frac{D \, \Delta C}{\rho_{CO_2} \, \Delta x} \qquad (7.15)$$

where: D = diffusion coefficient of CO_2 into air (m^2/s),

ΔC = concentration gradient across the opening (kg/m^3),

ρ_{CO_2} = density of CO_2 (kg/m^3), and

Δx = thickness of the boundary (m).

The diffusion coefficient varies with temperature. Holsen and Strunk (1964), tabulated in Geankoplis (1983), obtained diffusion coefficients of 14.2×10^{-6} m^2/s at 3°C and 17.7×10^{-6} m^2/s at 44°C. I used linear interpolation to obtain values for temperatures between 3 and 44°C.

The velocity varies with the concentration gradient (Eq. 7.15). As the gradient decreases due to leakage (it is assumed that the ambient CO_2 concentration will not increase), the velocity decreases yielding a lower gas loss rate. Consequently, I calculated the velocity and number of molecules passing through the hole iteratively using an interval of 3600 s.

The volume of the container, V_c, was approximated by the head space rather than the entire airspace volume because Eq. 7.14 assumes that the gaseous molecules are moving from one empty vessel to another. The presence of grain in the bin contradicts the stated assumption of an empty vessel, except in the head space.

Thus far, I have accounted for the CO_2 molecules escaping from the head space, but I have not considered the CO_2 molecules entering the head space from the layer of grain. The diffusion coefficient of CO_2 through wheat is 4.11×10^{-6} m^2/s (Singh et al. 1985), approximately one-third of the value for CO_2 through air. Because the CO_2 molecules take longer to travel through the grain bulk than through the head space, I have assumed that the number of CO_2 molecules entering the head space from the grain bulk will be equal to the ratio of the two diffusion coefficients (i.e., $D_{CO_2\ through\ grain} : D_{CO_2\ through\ air}$) times the number of CO_2 molecules escaping from the head space.

A QBASIC computer program was used to calculate the total mass of CO_2 lost from the bins (Appendix I). The mass of CO_2 (g) lost was calculated according to:

$$\Delta g = \frac{(\Sigma \Delta N)\ (M)}{6.022\ x\ 10^{23}} \tag{7.16}$$

The daily gas loss rate was calculated by dividing the total grams of CO_2 lost, Δg, by the number of days of the experiment.

7.3 Procedure for verifying relationships

7.3.1 Pilot bins To evaluate the derived relationships, experiments were conducted in pilot bins in which the leakage area was controlled. Oil drums were selected because they could be sealed well. One 95 L (25 gal) (drum A) and three 170 L (45 gal) drums were purchased. Two of the 170 L drums were welded together end-to-end, creating a 340 L drum (drum C) (i.e., the bottom of one drum and top of the other drum were removed). The calculated volumes of the drums were 0.118 m^3 (drum A), 0.212 m^3 (drum B), and 0.437 m^3 (drum C). Because the drums were partially filled with wheat (drum A was 88% filled, drum B was 87% filled, and drum C was 91% filled), airspace volumes were 0.055, 0.099, and 0.194 m^3, respectively.

Automobile tire valves were mounted onto the tops of the drums to allow the bins to be pressurized using an air compressor. Holes of known diameter were made in thin brass plates soldered to brass fittings that could be screwed into threaded openings in the tops of the drums (i.e., the holes were located in the membrane of the head space, therefore, all CO_2 molecules leaving the pilot bins had to pass through the head space). Several other fittings were made for attaching a plastic line to a cylinder of gaseous CO_2, a pressure measuring device, and a gas sampling tube. One semi-rigid nylon tube and one type T copper-constantan thermocouple were inserted into the grain approximately half way to the bottom of the drum. All three drums were instrumented identically.

To evaluate the relationship between pressure decay time and leakage area, the pilot bins were pressurized to 1.5 kPa with an air compressor. Pressures and temperatures were recorded at 1 s intervals for drums A and B and 5 s intervals for drum C until the pressure decayed by one-half. Pressure was measured using a digital micromanometer (Model MP6KSR, Neotronics of North America, Gainesville, GA). The micromanometer and thermocouple were connected to a data acquisition system. The PDTs were repeated five times for each of the five hole sizes (i.e., 0.6, 0.8, 1.1, 1.3, and 1.5 mm diameter) in each of the three pilot bins (drums A, B, and C).

The relationship between gas loss rate and leakage area was evaluated by purging the pilot bins with gaseous CO_2. Immediately after purging, the drums were sealed (except the holes of known diameter). At 30 min intervals for a duration of 4 h, a gas sample was collected and analyzed and the temperature inside the pilot bin was recorded. Approximately 24 h later, data were collected for an additional 2 h at 30 min intervals. Three replicates for each of the five hole sizes in each of the three pilot bins were conducted.

7.3.2 Full-size bins The experiments in the full-size bins were conducted in conjunction with the experimental fumigations described in Chapter 5. Pressure decay tests were conducted before the start of all experimental fumigations except those in which caged insects were present in the grain bulk. High pressures cause insect mortality (Caliboso et al. 1994; Nakakita and Kawashima 1994) and I did not want to introduce a variable that potentially could have influenced insect mortality, although the pressures I was generating were much less than those reported in the literature. An electric fan was used to pressurize the bins to 1.5 kPa above atmospheric pressure. The electric fan was connected to the holding box with valve 1 open, but valves 2, 3, and 4 closed (Fig. 4.3). The fan was shut off when the pressure equalled 1.5 kPa and valve 1 was immediately closed. Data were recorded manually (usually at 5 min intervals) until the internal pressure decayed below 0.75 kPa. Pressures were measured with an U-tube manometer. Three replicates were conducted in most cases.

Data for the rate of gas loss from the full-size bins have already been reported in this thesis (Chapter 5). The CO_2 concentrations measured at daily intervals throughout the experimental fumigations were used to obtain values for the rates of gas loss from the bins.

7.4 Experimental results in pilot bins

7.4.1 Pressure decay in pilot bins The pressure decay data from the replicates (Appendix J) were pooled and plotted for each pilot bin and each hole size (Figs. 7.1 to 7.5). Pressures below 0.6 kPa were omitted from analysis. Because the data followed linear trends over the range tested (Figs. 7.1 to 7.5), linear regression analyses were done for each group of data using SigmaPlot. The regression equations and R^2 values are summarized in Table 7.1. In all cases, R^2 values were high (> 0.98).

The experimental decay times (t_{exp}) calculated using the regression equations (Table 7.1) were compared with the decay times predicted by Eq. 7.12. Values of t_{exp} are presented for each combination of pilot bin and hole size (Table 7.2).

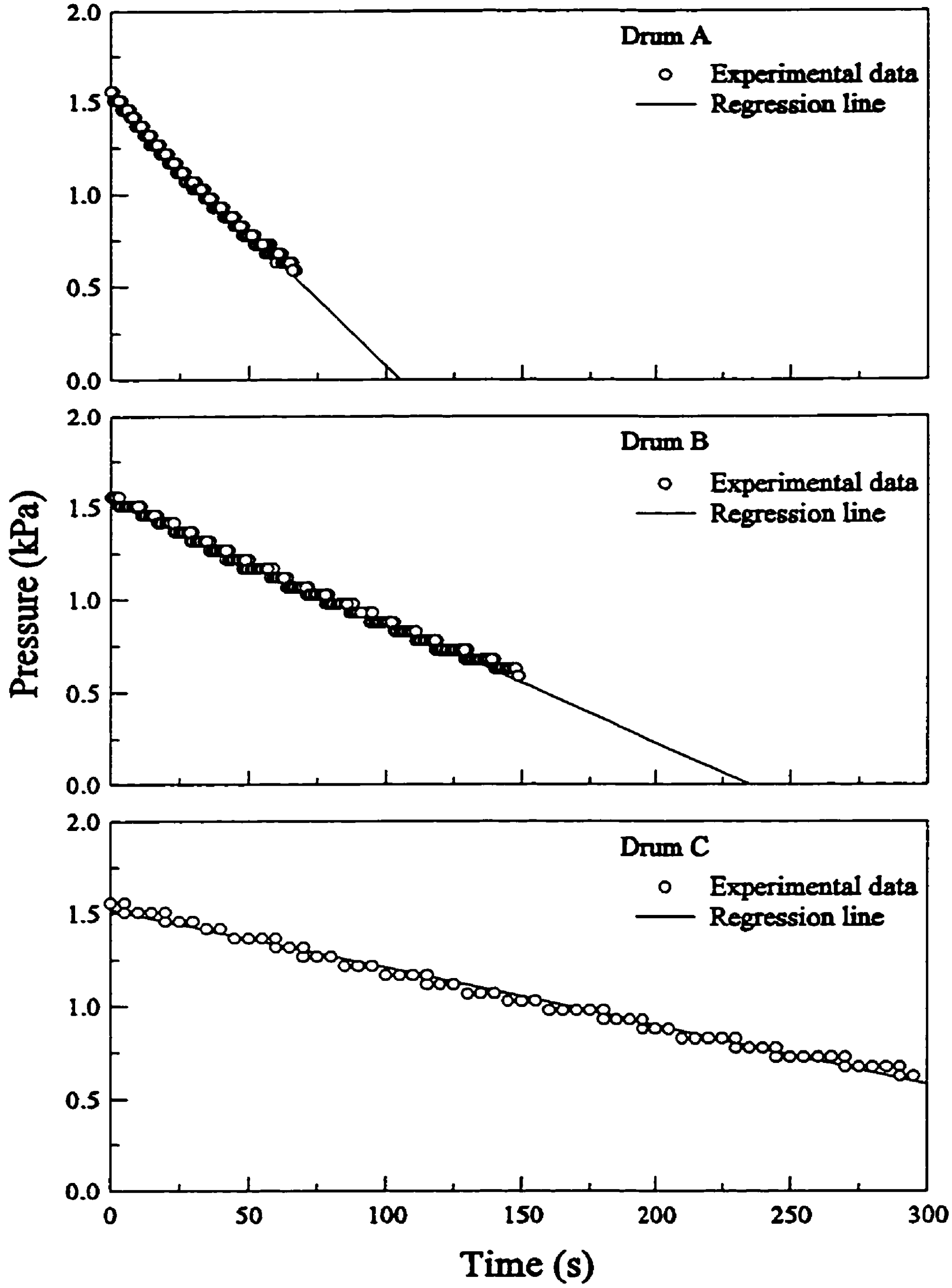


Fig. 7.1 Pressure decay data from wheat-filled pilot bins (drums A, B, and C) with a circular hole of 0.6-mm diameter.

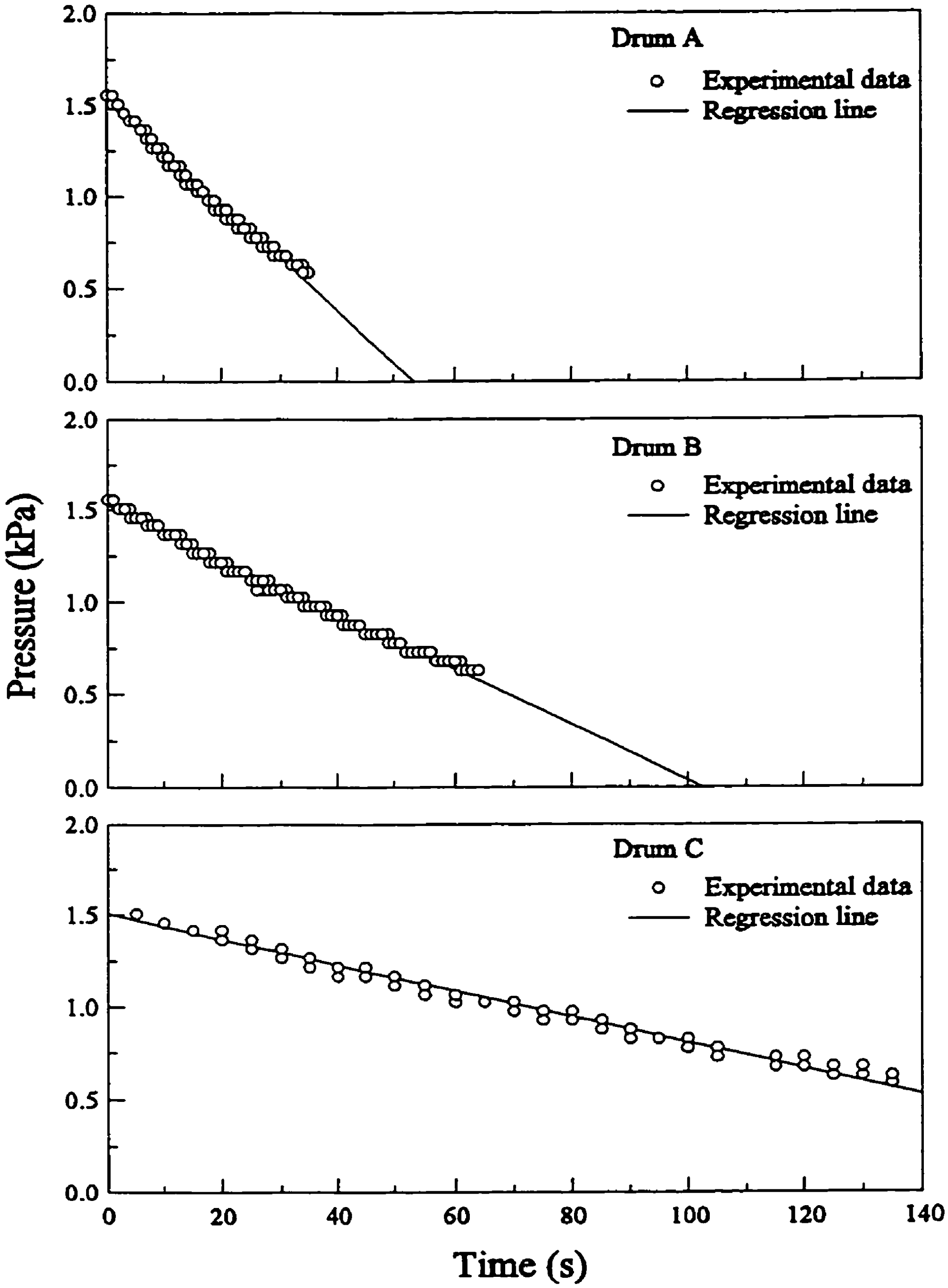


Fig. 7.2 Pressure decay data from wheat-filled pilot bins (drums A, B, and C) with a circular hole of 0.8-mm diameter.

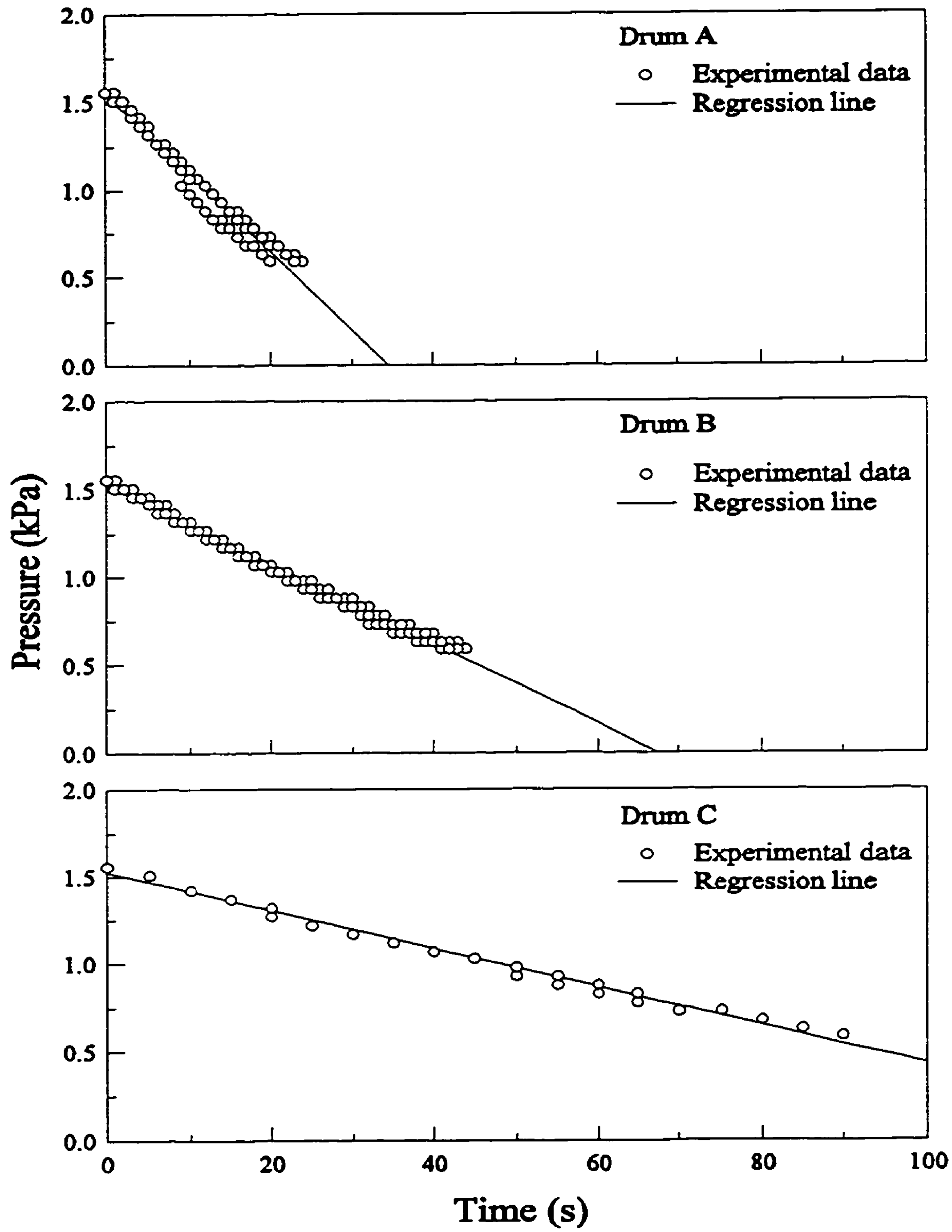


Fig. 7.3 Pressure decay data from wheat-filled pilot bins (drums A, B, and C) with a circular hole of 1.1-mm diameter.

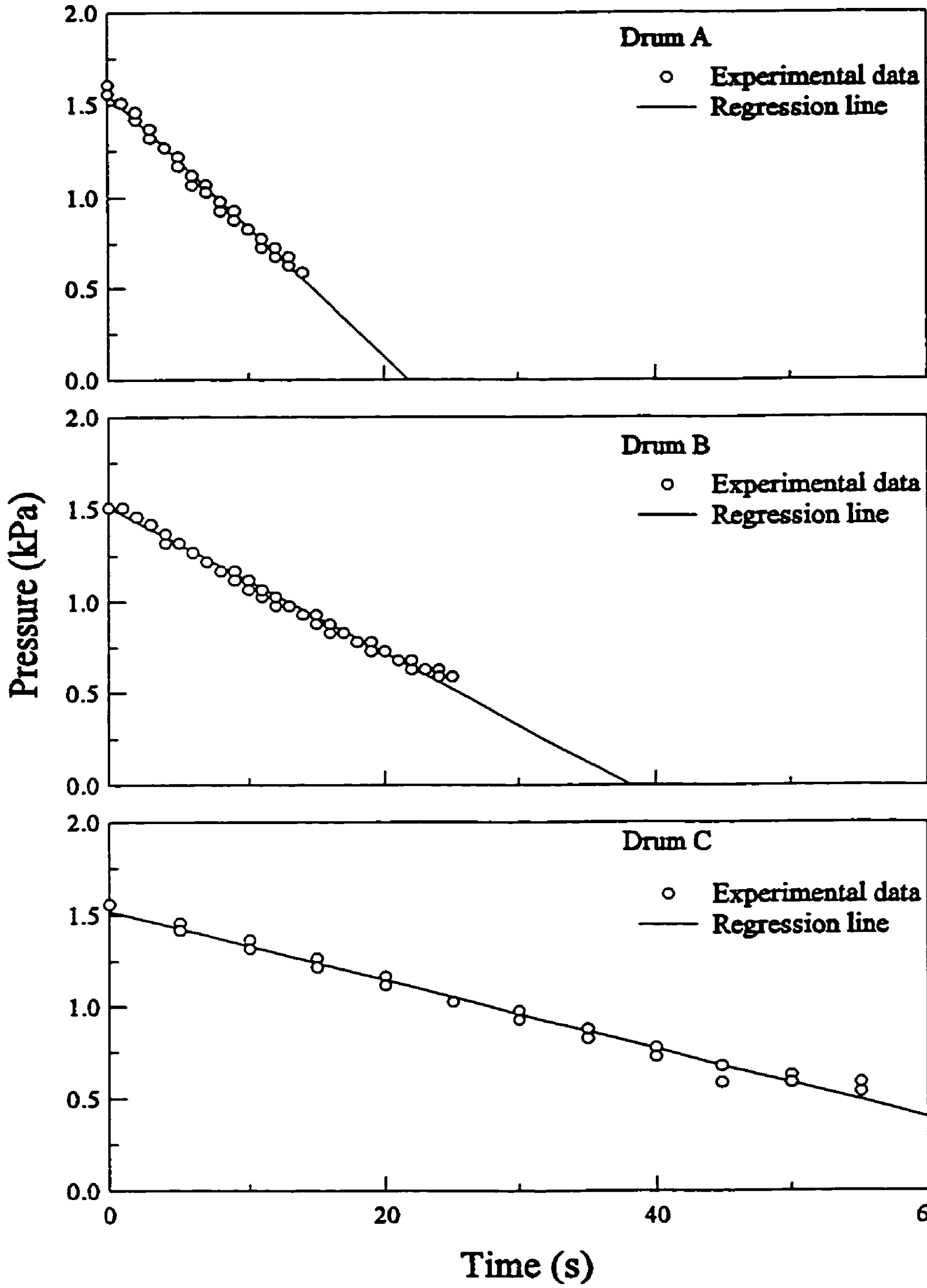


Fig. 7.4 Pressure decay data from wheat-filled pilot bins (drums A, B, and C) with a circular hole of 1.3-mm diameter.

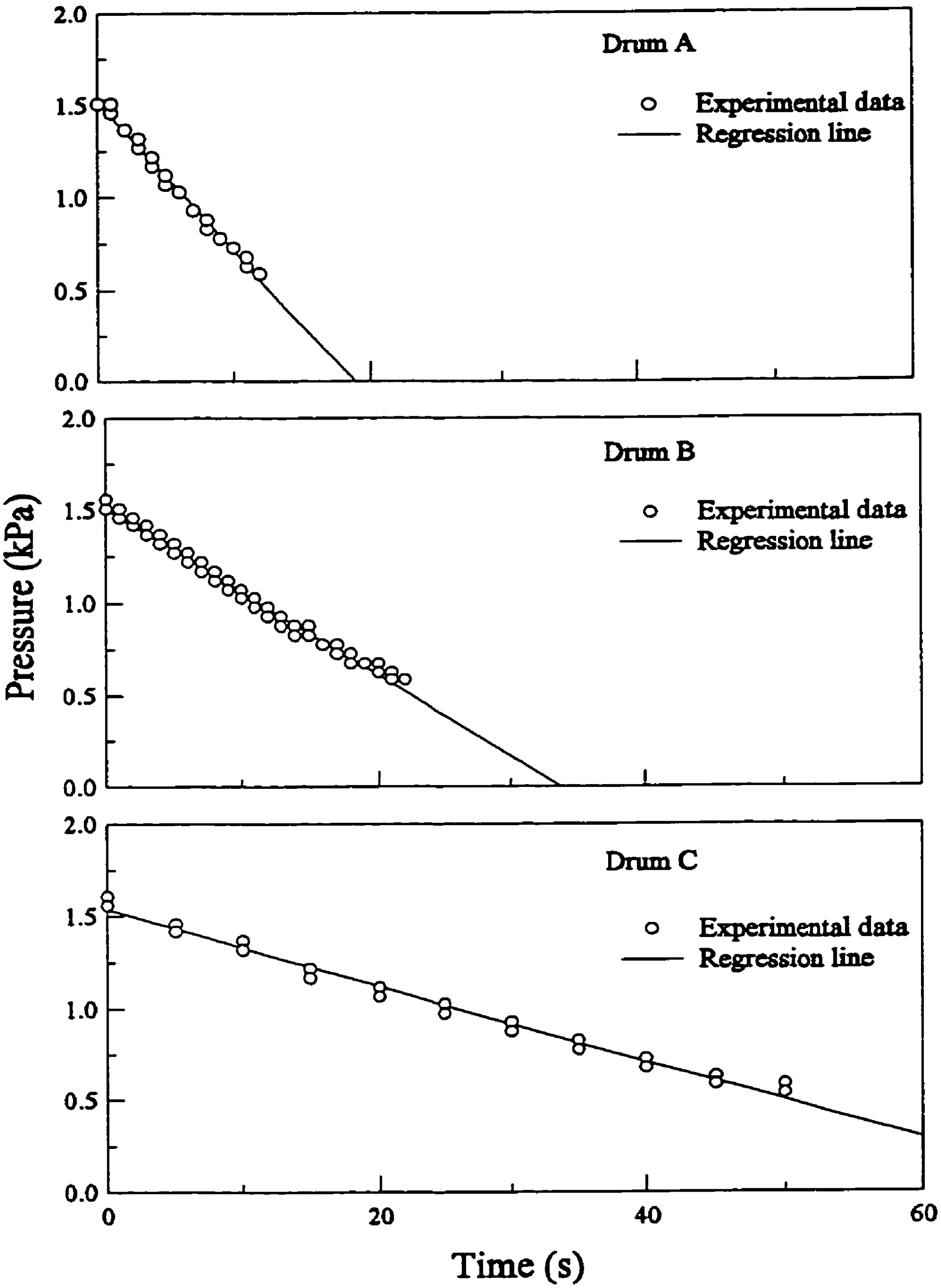


Fig. 7.5 Pressure decay data from wheat-filled pilot bins (drums A, B, and C) with a circular hole of 1.5-mm diameter.

Table 7.1 Regression equations and R^2 values for the pressure decay relationships in pilot bins with holes of a known diameter.

Pilot Bin	Hole Diameter	Regression Equation	R^2 Value
Drum A	0.6 mm	P = -0.0144t + 1.51	0.9903
	0.8 mm	P = -0.0285t + 1.53	0.9902
	1.1 mm	P = -0.0448t + 1.54	0.9656
	1.3 mm	P = -0.0715t + 1.56	0.9932
	1.5 mm	P = -0.0801t + 1.52	0.9946
Drum B	0.6 mm	P = -0.0065t + 1.53	0.9933
	0.8 mm	P = -0.0149t + 1.53	0.9927
	1.1 mm	P = -0.0227t + 1.53	0.9909
	1.3 mm	P = -0.0395t + 1.51	0.9923
	1.5 mm	P = -0.0447t + 1.51	0.9890
Drum C	0.6 mm	P = -0.0031t + 1.52	0.9913
	1.8 mm	P = -0.0070t + 1.51	0.9860
	1.1 mm	P = -0.0109t + 1.53	0.9913
	1.3 mm	P = -0.0187t + 1.52	0.9871
	1.5 mm	P = -0.0207t + 1.54	0.9893

Table 7.2 Observed and predicted pressure decay times for the pilot bins with holes of a known diameter.

Pilot Bin	Hole Diameter (mm)	Pressure Decay Time			
		Observed	Predicted*		
		t_{exp} (s)	$t_{P_{bin}}$ (s)	$t_{\frac{3}{4}P_{bin}}$ (s)	$t_{\frac{1}{2}P_{bin}}$ (s)
Drum A	0.6	53	54	62	76
	0.8	27	27	31	38
	1.1	18	15	18	22
	1.3	11	10	12	14
	1.5	10	8	9	11
Drum B	0.6	120	97	112	137
	0.8	52	48	55	68
	1.1	34	28	32	39
	1.3	19	18	21	26
	1.5	17	14	16	20
Drum C	0.6	247	190	219	268
	0.8	109	94	108	133
	1.1	72	54	63	77
	1.3	41	36	41	50
	1.5	38	28	32	39

* Decay times were predicted using P = 1.5 kPa (P_{bin}), 1.125 kPa ($\frac{3}{4}P_{bin}$), and 0.75 kPa ($\frac{1}{2}P_{bin}$).

For predicting t_P, temperatures inside the pilot bins were averaged for all replicates (Table 7.3). A problem was observed with the data acquisition system for the temperature data inside drum C. The explanation for this problem is not known, but I decided not to use the temperature data from drum C. Rather, I assumed a temperature of 11°C for all experiments inside drum C.

Table 7.3 Mean temperatures inside pilot bins during the pressure decay experiments.

	Hole Size				
Pilot Bin	0.6 mm	0.8 mm	1.1 mm	1.3 mm	1.5 mm
Drum A	11.6	11.4	11.7	11.7	10.6
Drum B	11.0	10.9	10.9	11.5	11.3
Drum C	11.0*	11.0*	11.0*	11.0*	11.0*

*Due to a problem with the data acquisition equipment, temperatures of 11.0°C were assumed inside drum C.

As mentioned earlier, an average volume flow rate leaving the bin was required. The volume flow rate is proportional to the pressure inside the bin, P_{bin}. If the pressure remained constant inside the bin, the volume flow rate would remain constant. During the PDTs, the internal pressure did not remain constant, and therefore, the volume flow rate leaving the bin was not constant either. As the pressure decreased, the volume flow rate also decreased. For an initial comparison between experimental and predicted pressure decay times, I calculated the pressure decay times assuming three initial bin pressures (P_{bin} = 1.5, ¾P_{bin} = 1.125, and ½P_{bin} = 0.75 kPa) (Table 7.2). The predicted and experimental values were graphed (Fig. 7.6).

For the smaller hole sizes, ¾P_{bin} (i.e., 1.125 kPa) gave the best match with the experimental data in most cases, but at larger hole sizes all three pressures gave similar results (Fig. 7.6). To quantify the fit between experimental and predicted pressure decay times, absolute differences were calculated between the experimental time and each of the other predicted times (Table 7.4). Summed absolute differences show that ¾P_{bin} yielded the best fit to the experimental data (Table 7.4).

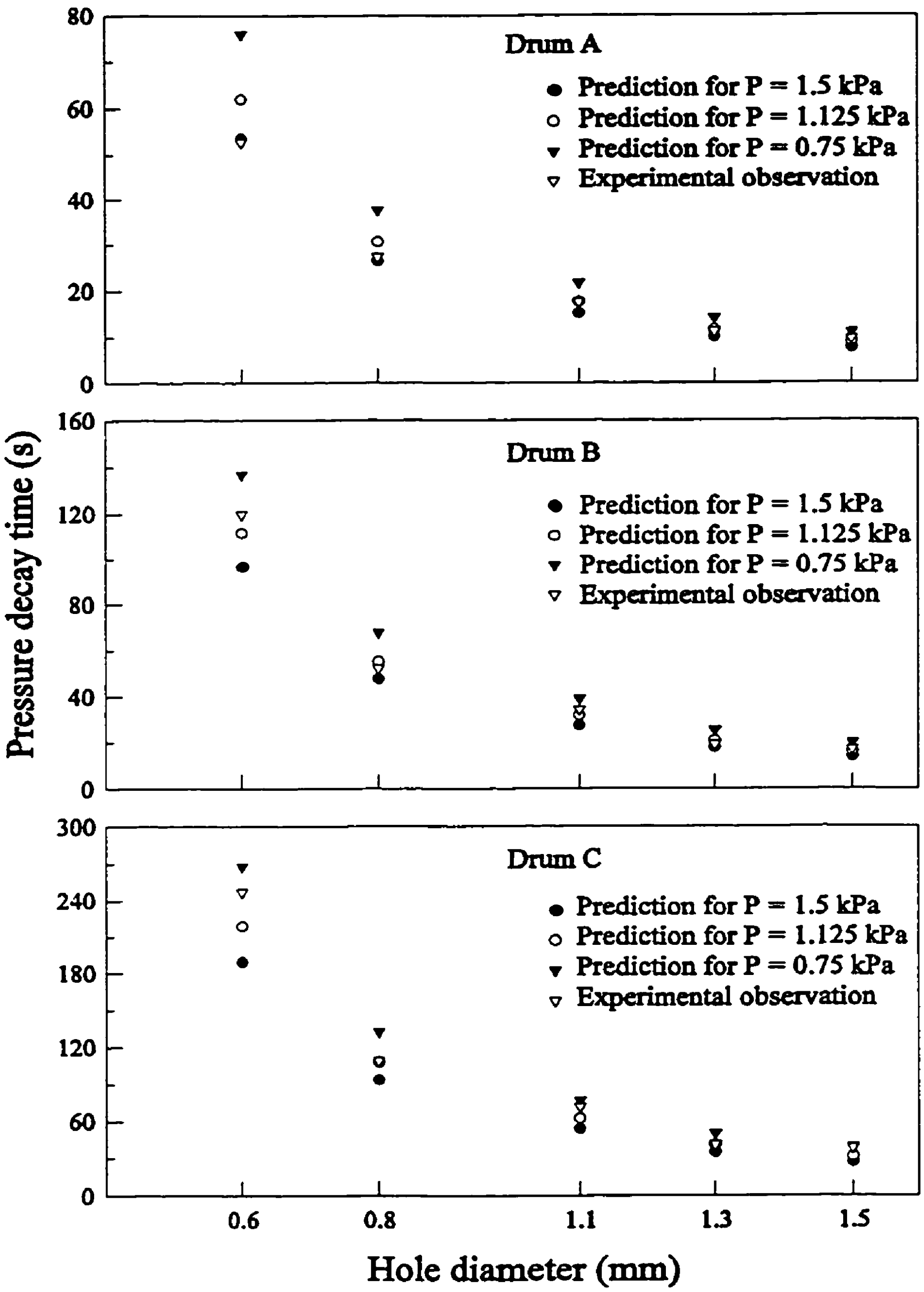


Fig. 7.6 Pressure decay times predicted based on three initial pressures (1.5, 1.125, and 0.75 kPa) and pressure decay times observed during the experiments for all three pilot bins (drums A, B, and C) and all five hole sizes (0.6, 0.8, 1.1, 1.3, and 1.5 mm).

Table 7.4 Absolute differences between experimental and predicted pressure decay times for the pilot bins with holes of a known diameter.

Pilot Bin	Hole Diameter (mm)	$\mid t_{Pbin} - t_{exp} \mid$ (s)	$\mid t_{¼Pbin} - t_{exp} \mid$ (s)	$\mid t_{½Pbin} - t_{exp} \mid$ (s)
Drum A	0.6	1	9	23
	0.8	1	3	10
	1.1	2	0	4
	1.3	1	0	3
	1.5	1	1	1
Drum B	0.6	23	8	17
	0.8	4	3	16
	1.1	7	3	5
	1.3	1	2	6
	1.5	3	1	3
Drum C	0.6	57	28	21
	0.8	15	1	24
	1.1	17	9	5
	1.3	6	0	9
	1.5	11	6	1
	Total	151	74	148

Based on the results obtained from these experiments, I am confident that Eq. 7.12 can be used to predict the pressure decay time. Equation 7.12 was rearranged to solve for leakage area:

$$a = \frac{\dfrac{P_d\, V\, M_{air}}{2\, R\, T_K\, \rho_{air}}}{C_d\, t_p \left[\dfrac{(2 \times 10^6)\, P_{bin}}{\rho_{air}}\right]^{½}} \tag{7.17}$$

In an actual situation, the farmer would measure pressure decay time and use Eq. 7.17 to calculate the leakage area.

7.4.2 Gas loss rate from pilot bins The results from the experiments to evaluate the gas loss rate equation are included in Appendix K. The mean of the last four concentration readings taken on the second day was lower than the mean of the last four concentration readings taken on the first day for most experiments (Student's t-test, α=0.05) (Table 7.5) suggesting that gas loss was occurring.

The experimental gas loss rate was calculated using a series of steps. First, the volume of gaseous CO_2 lost from the pilot bins was calculated based on the mean concentrations (described in the previous paragraph) and the total airspace volume within the pilot bins. Next, the CO_2 density was determined based on the average temperature within the pilot bins (from Table 7.3). The mass of CO_2 iost was equal to the product of the volume and density. Division by the interval between the two sampling times (Table 7.6) yielded the gas loss rate (Table 7.7).

The observed daily gas loss rates (Table 7.7) do not offer much useful information. Experimental replicates were not consistent (CV values ranged from 34 to 135%). The explanation for these inconsistent results is not known. Sorption may have been a factor. It had been planned that the experiments would occur in immediate succession. In this scenario, sorption would have been a factor for the first couple of experiments, but should have had little influence thereafter. The experiments were not all conducted in immediate succession, therefore, sorption may have been a factor in several experiments. A second explanation may be that one sampling location was not yielding an adequate representation of the CO_2 concentration inside the pilot bins.

The predicted gas loss rates ranged from 0.89 to 13.53 g/d (Table 7.8). The magnitude of the predicted rates of gas loss is similar to the magnitude of the observed rates of gas loss, but the randomness in observed results is a cause for concern. Variation between replicates was high (CV values ranged from 1 to 32%) (Table 7.8). In addition, the gas loss rate decreased as hole diameter increased from 1.3 to 1.5 mm for drum A (Table 7.8). The explanation for this inconsistent result is not known, but may be due to incorrectly estimated CO_2 concentrations (i.e., CO_2 concentrations based on only a single sampling location).

Table 7.5 Initial and final CO_2 concentrations inside the wheat-filled pilot bins with holes of a known diameter during the gas loss rate experiments.

		Replicate 1		Replicate 2		Replicate 3	
Pilot Bin	Hole Diameter (mm)	Initial CO_2 (%)	Final CO_2 (%)	Initial CO_2 (%)	Final CO_2 (%)	Initial CO_2 (%)	Final CO_2 (%)
Drum A	0.6	75.1	71.5*	56.7	54.1*	63.2	61.8
	0.8	51.1	47.7*	67.1	61.9*	71.6	69.2*
	1.1	81.8	73.1*	81.5	76.2*	67.2	66.6
	1.3	85.2	78.9*	83.3	81.0	83.6	78.8*
	1.5	62.3	55.7*	77.7	67.7*	77.4	73.9*
Drum B	0.6	66.3	62.4*	66.0	62.4*	72.3	70.4*
	0.8	72.1	69.2	56.9	56.3	62.9	62.9
	1.1	87.2	83.4*	87.4	84.5*	87.8	81.5*
	1.3	72.2	69.4*	77.1	72.8*	85.1	82.1*
	1.5	80.9	70.1*	83.9	79.4*	69.5	69.6
Drum C	0.6	63.1	62.4	67.4	65.2*	71.1	69.9*
	0.8	65.5	58.1*	61.2	57.8*	67.4	63.9*
	1.1	69.5	64.8*	71.0	66.8*	81.3	77.8*
	1.3	75.4	66.1*	80.1	76.6*	68.7	63.9*
	1.5	83.9	80.2*	84.1	82.2*	86.9	79.3*

* Asterisked final CO_2 concentrations are significantly different (Student's t-test, $\alpha=0.05$) from corresponding initial concentrations. The initial concentration is approximated by the mean of the last four readings taken on the first day of the experiment. The final concentration is approximated by the mean of the last four readings taken on the second day of the experiment.

Table 7.6 Concentration decay times for wheat-filled pilot bins with holes of a known diameter.

Pilot Bin	Hole Diameter (mm)	Concentration Decay Time (s)		
		Replicate 1	Replicate 2	Replicate 3
Drum A	0.6	66000	74700	77400
	0.8	77400	68700	71400
	1.1	83100	72300	58500
	1.3	71100	69300	75900
	1.5	78300	245700	64800
Drum B	0.6	82500	69300	74700
	0.8	66000	74700	77400
	1.1	71400	69300	75900
	1.3	78900	246000	64800
	1.5	83100	72300	58500
Drum C	0.6	77400	68700	71400
	0.8	82500	69300	74700
	1.1	78600	246300	64800
	1.3	83100	72300	58500
	1.5	71700	69300	75900

Table 7.7 Observed gas loss rates from wheat-filled pilot bins with holes of a known diameter.

Pilot Bin	Hole Diameter (mm)	Observed Gas Loss Rate (g/d)			Mean	S.D.	CV
		Replicate 1	Replicate 2	Replicate 3	(g/d)		(%)
Drum A	0.6	4.87	3.13	1.62	3.21	1.63	51
	0.8	4.05	6.94	3.08	4.69	2.01	43
	1.1	9.20	6.48	0.91	5.53	4.23	76
	1.3	7.71	2.89	5.50	5.37	2.41	45
	1.5	7.33	3.54	4.70	5.19	1.94	37
Drum B	0.6	7.68	8.44	4.13	6.75	2.30	34
	0.8	7.07	1.30	0.00	2.79	3.76	135
	1.1	8.33	6.55	12.99	9.29	3.33	36
	1.3	5.55	2.74	7.25	5.18	2.28	44
	1.5	20.34	9.90	-0.27	9.99	10.31	103
Drum C	0.6	2.93	10.25	5.38	6.19	3.73	60
	0.8	28.57	15.62	14.92	19.70	7.69	39
	1.1	18.34	5.23	16.57	13.38	7.11	53
	1.3	34.33	15.01	25.44	24.93	9.67	39
	1.5	15.74	8.36	30.55	18.22	11.30	62

Table 7.8 Predicted gas loss rates from the wheat-filled pilot bins of a known diameter.

Pilot Bin	Hole Diameter (mm)	Predicted Gas Loss Rate (g/d)			Mean (g/d)	S.D.	CV (%)
		Replicate 1	Replicate 2	Replicate 3			
Drum A	0.6	1.58	0.89	1.12	1.20	0.35	29
	0.8	1.41	2.46	2.67	2.18	0.68	31
	1.1	5.68	5.82	4.19	5.23	0.90	17
	1.3	8.68	8.57	8.45	8.57	0.12	1
	1.5	5.94	5.33	9.41	6.89	2.20	32
Drum B	0.6	1.21	1.25	1.46	1.31	0.13	10
	0.8	2.96	1.80	2.22	2.33	0.59	25
	1.1	7.03	7.28	7.30	7.20	0.15	2
	1.3	7.06	6.20	10.31	7.86	2.17	28
	1.5	11.08	12.11	8.82	10.67	1.68	16
Drum C	0.6	1.12	1.32	1.42	1.29	0.15	12
	0.8	2.37	2.16	2.53	2.35	0.19	8
	1.1	4.62	4.22	6.61	5.15	1.28	25
	1.3	8.15	9.27	7.06	8.16	1.11	14
	1.5	12.36	12.85	13.53	12.91	0.59	5

A second set of experiments was conducted to control some of the factors that I suspected were causing the variation in the wheat-filled bins. Dowlex 2027A polyethylene resin pellets were obtained from a local supplier. These polyethylene pellets have a size and shape similar to wheat kernels. Although no tests of bulk porosity were conducted, I assumed that their porosity was similar to that of wheat kernels. The purpose for using these pellets was to eliminate the probable influence of CO_2 sorption.

The experimental apparatus was also modified. Five oil drums were obtained (size equal to drum B) and were instrumented as described previously except that three sampling lines were inserted near the top, middle, and bottom of the drums. It was anticipated that three sampling points would yield a more accurate description of the CO_2 concentration inside the pilot bins. All five of the pilot bins were connected to a single cylinder of gaseous CO_2. The pilot bins were filled with polyethylene pellets to a depth of 0.63 m yielding a head space of 0.051 m^3 and a total airspace volume of 0.114 m^3 (assuming a porosity of 39%). Data were collected at 24-h intervals.

The observed CO_2 concentrations and temperatures are included in Appendix K. The experimental gas loss rates were calculated as described previously for the experiments with wheat-filled bins except that mean CO_2 concentrations were calculated based on the three sampling locations as opposed to samples from four sampling times. The daily gas loss rate was calculated using the mean CO_2 concentrations from the first and fourteenth days (in some situations the mean CO_2 concentration was higher on the second day than the first and this value was used as the initial value).

Five replicates were done for each of the seven hole sizes: 0, 0.6, 0.8, 1.1, 1.3, 1.5, and 12.7 mm diameter. Although some variation still existed, the experimental results (Table 7.9) were better than those from the wheat-filled pilot bins (Table 7.7). The observed gas loss increased with increasing hole size as expected, except for hole sizes of 1.3- and 1.5-mm diameter. The explanation for these unexpected results is not known.

Observed gas loss rates usually decreased from replicate 1 to 5 (Table 7.9). Although all five pilot bins were purged simultaneously from a single tank of gaseous CO_2, the CO_2 concentrations were not consistent (Table 7.9) because the quantity of gaseous CO_2 reaching each bin was not equal. These variations in initial CO_2 concentration influenced the observed gas loss rates because the number of molecules available to exit through the hole depends on the molecular density.

Gas loss was observed during the five replicates in pilot bins with no holes. Sample calculations showed that the CO_2 lost due to sampling did not account for the observed losses. One potential explanation is that small holes were present in the membranes of the pilot bins. A second explanation could be that a small amount of CO_2 was sorbed by or reacted with the polyethylene pellets. Although the correct explanation for this observation is not known, the gas loss was low enough to be negligible.

Table 7.9 Observed and predicted gas loss rates from the pellet-filled pilot bins with holes of a known diameter.

Hole Diameter (mm)	Replicate	Initial CO_2 Concentration (%)	Observed Gas Loss (g/d)	Mean*	S.D.*	Predicted Gas Loss (g/d)	Mean*	S.D.*	Ratio: Predicted/Observed
0	1	80.6	1.28			0.00			0.0
	2	81.6	0.87			0.00			0.0
	3	78.3	1.47	1.29	0.30	0.00	0.00	0.00	0.0
	4	71.5	1.66			0.00			0.0
	5	63.0	1.16			0.00			0.0
0.6	1	72.0	0.91			1.21			1.3
	2	73.0	3.76			1.24			0.3
	3	64.1	2.31	2.10	1.06	0.98	0.94	0.30	0.4
	4	54.0	1.66			0.71			0.4
	5	47.9	1.85			0.57			0.3
0.8	1	83.1	3.64			2.60			0.7
	2	83.3	3.36			2.61			0.8
	3	84.7	3.94	3.26	0.58	2.69	2.37	0.38	0.7
	4	74.2	2.51			2.16			0.9
	5	66.8	2.84			1.81			0.6
1.1	1	76.9	3.76			3.19			0.8
	2	74.5	3.71			3.04			0.8
	3	74.0	3.42	3.40	0.41	3.01	2.81	0.37	0.9
	4	64.4	2.74			2.42			0.9
	5	64.4	3.39			2.41			0.7
1.3	1	76.4	3.04			3.86			1.3
	2	75.2	2.85			3.77			1.3
	3	72.0	2.51	2.44	0.55	3.54	3.34	0.58	1.4
	4	64.8	2.11			3.04			1.4
	5	56.6	1.69			2.48			1.5
1.5	1	81.0	3.21			4.62			1.4
	2	78.1	2.79			4.40			1.6
	3	76.2	2.36	2.45	0.55	4.25	4.03	0.58	1.8
	4	68.5	1.93			3.67			1.9
	5	62.0	1.94			3.19			1.6
12.7	1	83.8	7.36			7.44			1.0
	2	84.7	7.80			7.52			1.0
	3	83.0	6.91	6.89	0.78	7.36	7.10	0.51	1.1
	4	77.6	5.74			6.89			1.2
	5	71.2	6.64			6.31			1.0

* The mean and S.D. values were calculated using the gas loss values from all five replicates.

As with the wheat-filled bins, the predicted gas loss rates were of the same magnitude as the observed gas loss rates (Table 7.9). As expected, the gas loss rate increased with increasing hole size. Ratios of the predicted to observed gas loss rates yielded values ranging from 0 to 1.6. The ratio of zero can be ignored because it corresponds to the case with no holes. Ratios of 1.4 and 1.6 were obtained for the hole sizes of 1.3 and 1.5 mm. According to the data (Table 7.9), the equations over-predicted the gas loss in these two cases, but I believe there is a problem with the experimental data. If these exceptions are ignored, the ratios of predicted to observed gas loss rates ranged from 0.4 to 1.0. Although the equations under-predicted the gas loss rates, they adequately modelled the actual experiments.

7.4.3 Equating pressure decay to gas loss rate in pilot bins Ideally, I wanted to compare the predicted gas loss rates to the observed gas loss rates. Because the observed gas loss rates from the wheat-filled bins were erratic, no meaningful comparison could be made. Although the observed gas loss rates from the pellet-filled bins were more consistent, no PDTs were conducted for these bins. Therefore, I compared the calculated leakage areas with the actual leakage areas using the data from the wheat-filled bins.

Using the pressure decay times calculated previously (Table 7.2), a value of 1.125 kPa for P_{bin}, the entire airspace volume, and the air density calculated using Eq. 7.13, the predicted leakage areas were calculated (Table 7.10). The actual leakage areas (Table 7.10) were calculated based on the nominal diameters of the drill bits used to make the holes in the brass plates.

Equation 7.17 adequately predicts the leakage area in the pilot bins (Table 7.10). The greatest error was 16.7%, but the error was <10% in 9 out of the 15 cases. Based on these results, I am confident that Eq. 7.17 can be used to predict the leakage area in imperfectly sealed bins with reasonable accuracy.

Table 7.10 Predicted and actual leakage areas for the wheat-filled pilot bins.

Pilot Bin	Hole Diameter (mm)	Predicted Leakage Area (mm^2)	Actual Leakage Area (mm^2)	Percent Error (%)
Drum A	0.6	0.300	0.257	16.7
	0.8	0.590	0.519	13.7
	1.1	0.884	0.899	1.6
	1.3	1.450	1.370	5.8
	1.5	1.600	1.770	9.6
Drum B	0.6	0.239	0.257	7.0
	0.8	0.552	0.519	6.4
	1.1	0.844	0.899	6.1
	1.3	1.510	1.370	10.2
	1.5	1.690	1.770	4.5
Drum C	0.6	0.227	0.257	11.7
	0.8	0.516	0.519	0.6
	1.1	0.781	0.899	13.1
	1.3	1.370	1.370	0.0
	1.5	1.480	1.770	16.4

7.5 Experimental results in full-size bins

7.5.1 Pressure decay in full-size bins The pressure decay data for the full-size hopper bins are included in Appendix L. The pressure was measured and recorded at 5 min intervals and when the pressure had decayed by one-half. The data were pooled and grouped according to the three experimental bins (bins A and B as described in Chapter 4 and bin C as described in Chapter 6). Regression analysis was used to find the relationship between pressure and time for each of the three bins (Figs. 7.7, 7.8, and 7.9). The calculated R^2 values were 0.8393 for bin A, 0.7035 for bin B, and 0.9679 for bin C. The pressure decayed more rapidly in bin B than bin A although the two bins were manufactured and sealed identically, confirming my earlier assumption that all sealed bins will not achieve the same level of gas-tightness.

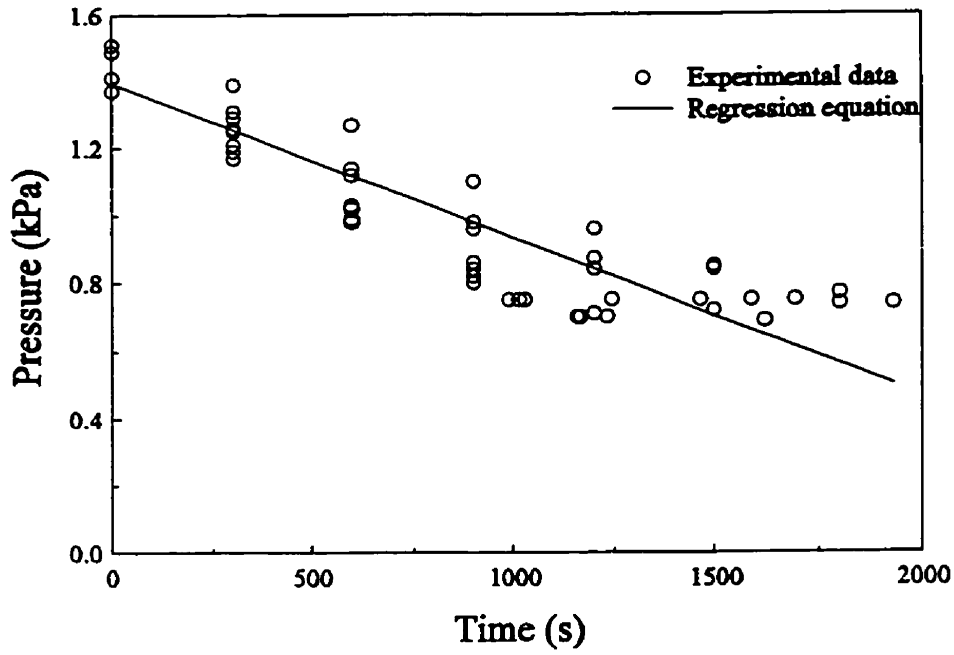


Fig. 7.7 The relationship between pressure and decay time for full-size bin A. The regression equation is ***Pressure = $-4.6x10^{-4}$ time + 1.394*** with an R^2 value of 0.8393.

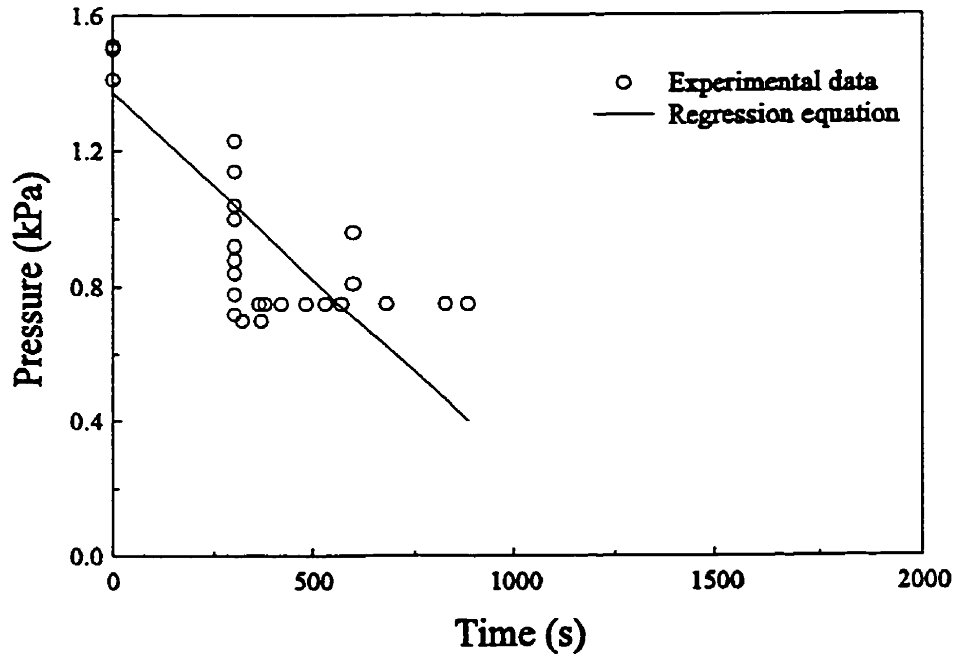


Fig. 7.8 The relationship between pressure and decay time for full-size bin B. The regression equation is ***Pressure = $-1.1x10^{-3}$ time + 1.373*** with an R^2 value of 0.7035.

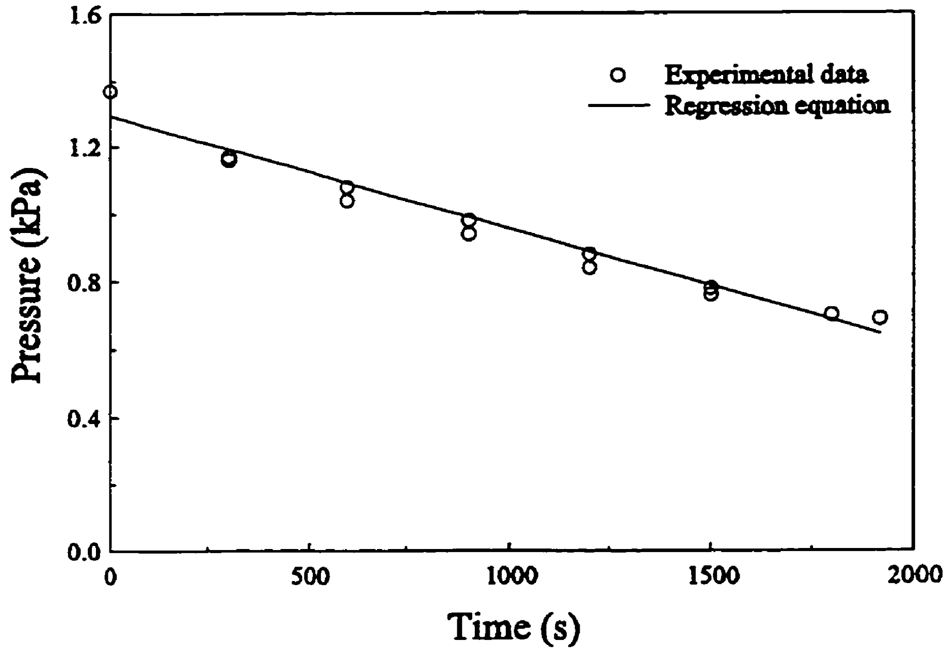


Fig. 7.9 The relationship between pressure and decay time for full-size bin C. The regression equation is ***Pressure = -3.39x10⁻⁴ time + 1.295*** with an R^2 value of 0.9679.

Average pressure decay times (Table 7.11) were calculated for the eight experiments for which PDTs were conducted. After substituting these average pressure decay times into Eq. 7.17, leakage areas ranging from 1 to 35 mm^2 were calculated (Table 7.11). The airspace was calculated to be 44.7 m^3 for bins A and B, and 6.8 m^3 for bin C. The average leakage area was 9.9 mm^2 for bin A, 26.0 mm^2 for bin B, and 1.0 mm^2 for bin C. Due to the longer pressure decay times (Appendix L), it was expected that bin A would have a smaller leakage area than bin B.

The predicted areas compare favourably with those stated in the literature. Banks et al. (1980) stated that imperfections in a 2000 t storage structure may total 1000 mm^2. The capacity of bin A (and bin B) is approximately 80 t. If the volume to leakage area ratio is constant, an 80-t storage structure would have leaks totalling 40 mm^2. Banks and Ripp (1984) gave another example of a $20x10^3$ t storage structure having leaks totalling 8000 mm^2. After scaling down, an 80-t storage structure would have leaks totalling 32 mm^2. These scaled-down values (40 and 32 mm^2) are similar to the values of 9.9 and 26.0 mm^2 calculated for bins A and B, respectively. It was expected that the leakage areas would be smaller than those reported in the literature because my pressure decay times were greater than 5 min (i.e., the Australian standard). An additional comparison can be made with the leakage area of 1260 mm^2 for the walls of an unsealed bolted-steel bin (Peck 1994). As expected, the leakage area for a sealed welded-steel bin is much less than for an unsealed bolted-steel bin.

Table 7.11 Average pressure decay times and predicted leakage areas for the experiments in full-size bins. Pressure decay tests were not conducted for all experiments.

Experiment	Bin	Average Pressure Decay Time (s)	Predicted Leakage Area (mm^2)
F1.1	A	1499	8.8
F2.1	B	702	18.5
F3.1	A	1764	7.3
F4.1	B	530	24.2
F4.2	A	1012	12.6
F4.6	A	1186	10.7
F4.7	B	359	35.5
F4.10	C	1920	1.0

7.5.2 Gas loss rate from full-size bins A measure of the gas loss was obtained by converting the mean CO_2 concentrations (Chapter 5) into masses of CO_2 and by fitting curves to the decaying mass profiles (Figs. 7.10 to 7.12). Due to the apparent linear nature of the mass decay profiles, linear regression analyses were done (Table 7.12). For the regression analyses, it was assumed that day 2 was the start of the mass decay profile (peak CO_2 concentrations were delayed due to sublimation). The regression results show that the mass of CO_2 decayed at rates ranging from 0.16 to 2.27 kg/d (Table 7.12). Experiment F4.6 displayed an increase in CO_2 mass with time. In this experiment, for some reason, sublimation took longer to complete and the CO_2 mass did not peak until the fourth day.

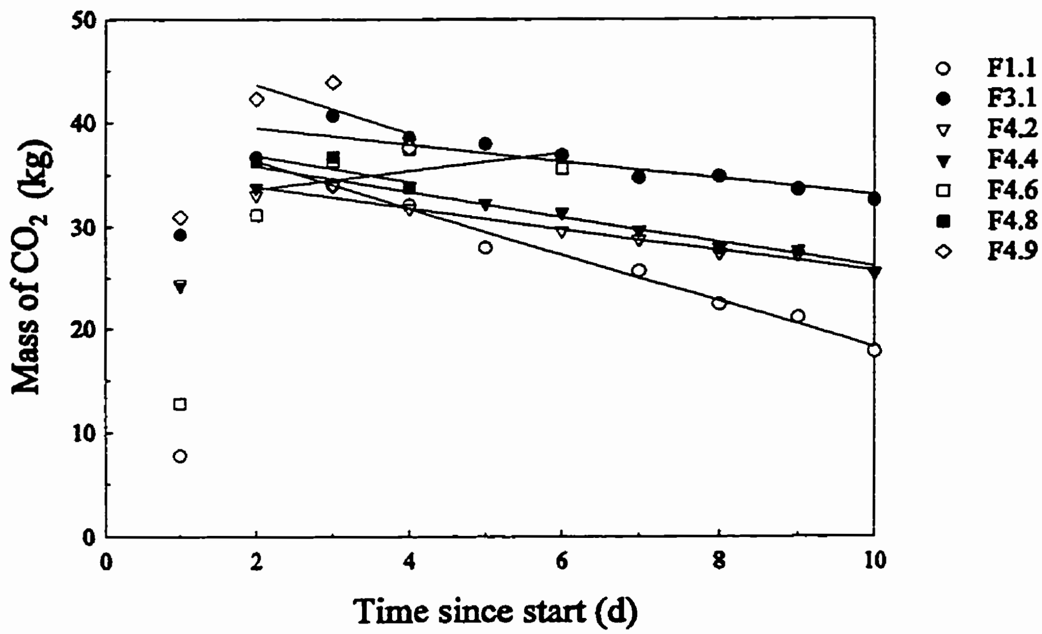


Fig. 7.10 Observed CO_2 mass decay inside full-size bin A. Lines are best fit lines for each test. Data for day 1 were not included in regression analysis because of on-going sublimation.

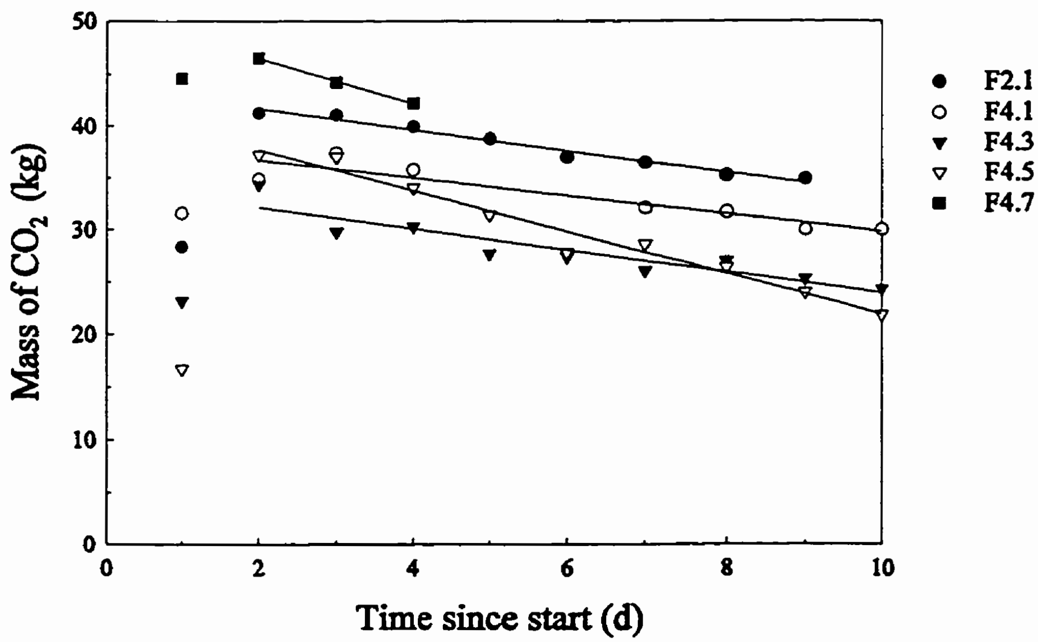


Fig. 7.11 Observed CO_2 mass decay inside full-size bin B. (Refer to Fig. 7.10 for further explanation.)

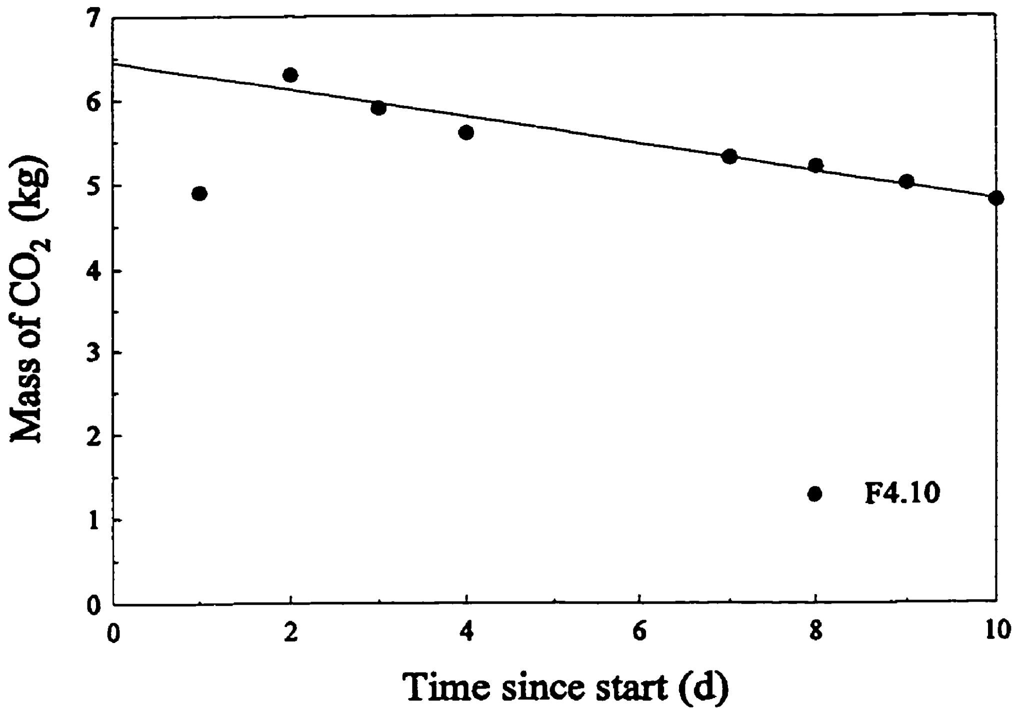


Fig. 7.12 Observed CO_2 mass decay inside full-size bin C. (Refer to Fig. 7.10 for further explanation.)

As was done for the pilot bins, the predicted gas loss rate was calculated using Eq. 7.16. Because forced recirculation was used in the full-size bins, it was expected that the CO_2 molecules in the full-size bins would be moving faster than the CO_2 molecules in the pilot bins. Consequently, calculating the velocity by diffusion was not appropriate for the full-size bins. It was assumed that the velocity of the CO_2 molecules could be estimated by the airflow rate through the recirculation pump [1.7 ft^3/min (802×10^{-6} m^3/s) measured using a rotameter (Brooks R-8M-25-2, Brooks Instrument Division, Hatfield, PA)]. The airflow rate divided by the cross-sectional area of the automotive heater hose yielded the velocity through the recirculation pump (2.82 m/s).

I assumed that gas loss occurred from the head space (i.e., 6.2 m^3 for bins A and B, 1.0 m^3 for bin C) of the bins. I also assumed that CO_2 molecules entered the head space from the grain bulk at a rate equivalent to one-third the rate at which they were leaving the head space through the hole.

This ratio is similar to that used for the pilot bins (i.e., the ratio of the diffusion coefficients). The initial CO_2 concentration was calculated as the mean concentration on the second day of the fumigation. The experimental duration was 9 d for experiments F1.1 to F4.5 & F4.10 and 3 d for experiments F4.6 to F4.9. The predicted leakage areas (Table 7.11) were used in calculations.

The total mass of CO_2 lost during each experiment was predicted using the modified computer program (Appendix I) and the assumptions described in the previous two paragraphs. The total mass lost was divided by the experimental duration (i.e., either 9 or 3 d) to yield the predicted gas loss rate (Table 7.13). Comparison of the observed and predicted gas loss rates shows the adequacy of the prediction equations and assumptions (Table 7.13). The observed gas loss rate was approximately three times greater than the predicted gas loss rate for experiment F1.1. This abnormality can be explained by the excessive pressure that forced the water out of the pressure relief valve and that allowed the escape of excessive amounts of CO_2. In the other cases, the agreement between observed and predicted gas loss rates was better with predicted loss rates typically less than observed loss rates for the 10-d experiments and greater than observed loss rates for the 4-d experiments.

Table 7.12 Regression equations and R^2 values for the mass decay relationships in full-size bins. Mass decay relationships were determined for only those experiments for which pressure decay tests were conducted.

Experiment	Bin	Regression Equation	R^2 Value
F1.1	A	mass = -2.27 d + 40.9	0.9881
F2.1	B	mass = -1.03 d + 43.8	0.9755
F3.1	A	mass = -0.81 d + 41.1	0.7302
F4.1	B	mass = -0.87 d + 38.5	0.8642
F4.2	A	mass = -1.03 d + 36.0	0.9635
F4.6*	A	mass = 0.87 d + 31.9	0.2953
F4.7	B	mass = -2.15 d + 50.8	0.9984
F4.10	C	mass = -0.16 d + 6.4	0.9533

* Sublimation was delayed and peak CO_2 concentration occurred on day 4.

Table 7.13 Observed and predicted gas loss rates for the full-size bins.

Experiment	Bin	Observed Loss Rate (kg/d)	Predicted Mass Loss (kg)	Predicted Loss Rate (kg/d)
F1.1	A	2.27	6.60	0.73
F2.1	B	1.03	8.35	0.93
F3.1	A	0.81	6.45	0.72
F4.1	B	0.87	8.14	0.90
F4.2	A	1.03	6.59	0.73
F4.6*	A	-0.87	4.88	1.63
F4.7	B	2.15	8.92	2.97
F4.10	C	0.16	1.06	0.12

* Sublimation was delayed and peak CO_2 concentration occurred on day 4.

7.6 Discussion of the proposed relationship

My proposed relationship (between pressure decay time and leakage area) predicted leakage areas in pilot bins with small errors. Also, the leakage areas predicted for the full-size bins compare favourably with published sources (Banks et al. 1980; Banks and Ripp 1984).

The proposed relationship between gas loss rate and leakage area could not be validated with wheat-filled pilot bins due to inconsistent results. The consistency of the results improved, however, when the pilot bins were filled with plastic pellets. The ratios of predicted to observed gas loss rates ranged from 0.4 to 1.0. In the full-size bins, predicted gas loss rates compared well with the observed gas loss rates.

Based on my experimental results, leakage areas in imperfectly sealed bins can be calculated from pressure decay times obtained from pressure decay tests. With the predicted leakage area and the planned initial CO_2 concentration, the CO_2 concentration profile can be projected over time and the required length of fumigation can be calculated. The proposed relationships, therefore, are important tools for successful fumigation of insects in stored grain using CO_2.

8. CONCLUSIONS

As stated in Chapter 3, the primary objective of this research was to achieve a lethal CO_2 environment in a full-size farm grain bin. Based on my research, the following can be concluded:

1. Full-size welded-steel hopper bins are suitable for fumigation with CO_2 because they have easily identifiable leakage areas that can be sealed effectively with minimal effort. Retention efficiencies improved from 7% before sealing to 79% after sealing, showing that a much greater proportion of the added CO_2 was being held inside the bin. The CO_2 environment within the bins was uniform with average CV values <10% in both the radial and vertical directions.

2. The air can be purged from full-size welded-steel hopper bins by ducting gaseous CO_2, produced by sublimation of dry ice, into the head space of the bin and by allowing "air" to exit through a purge valve at the bottom of the bin. Using this method, dangerous pressure increases were prevented and purge losses were reduced. Purging efficiencies ranged from 69 to 92% for the 10-d fumigations and from 55 to 79% for the 4-d fumigations.

   Lethal CO_2 environments were created during the 10-d experiments as CO_2 concentrations typically remained above 30% for the entire duration. The addition of extra dry ice increased the CO_2 concentrations marginally for the 4-d experiments, but not enough to create an environment lethal to *C. ferrugineus* for a 4-d exposure. Retention efficiencies were significantly lower for the 4-d experiments compared with the 10-d experiments, further confirming that 10-d fumigations are more practical.

3. Observed mortalities of caged adult *C. ferrugineus* were 100, 99.8, and 99.7% from three 10-d fumigations. Lower mortalities of 95.3 and 79.8% were observed from two 4-d fumigations. Fumigation of uncaged insects with a 10-d exposure sharply reduced the insect population,

although not all insects were killed. A relationship between "CO_2 concentration" and "exposure time to complete mortality" was developed based on previously published sources. When this equation was used in a cumulative manner by calculating the proportion of a lethal environment experienced to date at daily intervals, it predicted complete mortality in two cases and less than complete mortality in the remaining four cases. Because these results are similar to the observed mortalities, it can be concluded that this equation does a reasonable job of predicting the required exposure under conditions of changing CO_2 concentration. Based on this insect mortality data, I concluded that 10-d fumigations should be promoted over 4-d fumigations.

4. The gas loss rate from a bin can be related to pressure decay time through a common factor of leakage area. Leakage areas in pilot bins, predicted by pressure decay times, were predicted with <10% error in 9 out of 15 cases. Ratios of the predicted to observed gas loss rates in pilot bins varied from 0.3 to 1.9, showing the potential of the gas loss rate equation.

   Although actual leakage areas in the full-size bins were not known, predictions based on the pressure decay times were consistent with published values. Predicted gas loss rates from the full-size welded-steel hopper bins compared favourably with the observed rates of gas loss. Consequently, the proposed relationship between pressure decay time and gas loss rate can be used to predict the gas loss rate which, in turn, can be used to calculate the required length of exposure before starting the fumigation.

9. RECOMMENDATIONS FOR FUTURE RESEARCH

Although this research has been successful, I have identified several concerns that require further study:

1. My results showed that forced recirculation has no significant influence on radial and vertical uniformity despite literature sources stating that it should improve uniformity. My research was not planned to test the influence of forced recirculation. Consequently, I believe that further research should be conducted before concluding that forced recirculation has no significant influence on CO_2 uniformity.

2. Through this research, I have shown that the procedure for purging the air from the bin is an important aspect of a CO_2 fumigation that should not be overlooked. My results clearly showed that the fourth purging method was both practical and efficient, however, I did not consider the size of the exit valve opening as a variable. Controlled experiments varying the size of the exit valve opening may further decrease unnecessary purge losses.

3. Due to my decision to use dry ice as the source of CO_2, an understanding of the sublimation rate of dry ice is required. My limited study suggested that sublimation rate increases with increasing temperature, increasing initial mass of dry ice, and forced recirculation. A more detailed study of dry ice sublimation might result in effective methods to control the purging process.

4. An important result of this research is Eq. 6.2 which can be used to calculate the required exposure for adult *C. ferrugineus* under conditions of changing CO_2 concentration. Although this equation adequately described the insect mortality in my experiments, it requires further

validation. Mortality data for adult *C. ferrugineus* at temperatures other than 25°C would allow the development of additional equations.

5. In Chapter 7, I developed equations relating pressure decay time and gas loss rate to leakage area. Although agreement with the pilot bins was good and predictions for the full-size bins were reasonable, further validation is required to confirm some of the assumptions that I made.

6. Based on the gas-tightness obtained, assuming that the sealed bin should be a barrier against the entry of insects into the grain bulk seems reasonable. If the bin is cleaned thoroughly before filling in the fall, there should be no insects in the bin initially. Then, if the bin is sealed immediately after filling, insect infestations should be prevented. Experiments should be conducted to confirm this speculation because, if correct, sealing immediately after filling may prevent the need for any type of fumigation.

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Appendix A - Permeability of Recirculation Duct

Temperature and CO_2 concentration data collected to assess the permeability of the recirculation duct (heater hose and ABS pipe) to CO_2. Three replicates were conducted for each duct material. Data were collected at 15 min intervals for 4 h. Temperatures were measured using a type T copper-constantan thermocouple and were read using a digital temperature indicator. Gas samples were analyzed using a Matheson 8430 gas chromatograph.

Permeability of Heater Hose to Carbon Dioxide

	Replicate 1 Date: June 3, 1996		Replicate 2 Date: June 5, 1996		Replicate 3 Date: June 7, 1996	
Time (min)	CO_2 (%)	Temp. (°C)	CO_2 (%)	Temp. (°C)	CO_2 (%)	Temp. (°C)
0	40.0	9.3	60.2	16.0	60.8	15.4
15	53.3	9.7	50.3	16.2	54.2	17.3
30	51.1	10.0	48.0	16.6	50.1	18.3
45	46.9	10.2	47.8	16.7	46.3	19.2
60	45.0	10.5	44.1	16.9	46.3	19.7
75	43.5	11.0	42.8	17.0	42.6	20.4
90	43.5	11.2	40.6	17.0	40.9	20.6
105	41.5	11.6	40.9	17.0	41.0	21.0
120	40.7	12.0	39.2	16.9	38.8	21.1
135	40.0	12.4	37.5	16.9	37.6	21.3
150	39.3	12.7	36.4	17.0	37.2	21.5
165	36.1	12.9	36.6	17.0	36.3	21.6
180	35.8	13.0	35.0	17.1	33.2	21.9
195	34.3	13.2	33.6	17.2	32.9	22.1
210	32.8	13.5	34.1	17.3	33.4	22.2
225	31.9	13.6	31.6	17.3	31.6	22.4
240	33.0	13.8	29.5	17.3	30.4	22.3

Permeability of ABS Pipe to Carbon Dioxide

	Replicate 1 Date: June 13, 1996		Replicate 2 Date: June 14, 1996		Replicate 3 Date: June 21, 1996	
Time (min)	CO_2 (%)	Temp. (°C)	CO_2 (%)	Temp. (°C)	CO_2 (%)	Temp. (°C)
0	66.1	19.8	61.1	17.0	35.4	16.5
15	64.9	20.9	62.4	18.9	63.3	17.6
30	63.4	21.8	65.9	20.2	60.4	18.6
45	64.4	22.6	64.5	21.0	61.2	19.3
60	62.6	23.2	64.1	21.6	60.9	19.7
75	63.1	23.5	61.2	22.3	60.6	20.0
90	62.9	23.6	63.2	22.8	59.6	20.5
105	62.5	24.0	62.3	23.2	60.4	20.8
120	61.1	24.1	63.5	23.6	61.2	21.0
135	61.3	24.3	63.3	24.0	59.6	21.0
150	59.0	24.6	63.0	24.2	56.5	21.0
165	59.1	24.6	63.5	24.7	57.7	21.0
180	59.1	24.7	62.2	24.9	58.5	21.1
195	62.2	24.6	60.2	25.1	59.0	21.1
210	61.5	24.6	61.3	25.4	55.4	21.2
225	61.5	24.7	62.1	25.7	57.0	21.3
240	58.3	24.8	60.2	25.9	55.4	21.4

Appendix B - Summary of Sealing Techniques

A summary of the sealing techniques and recirculation details for experiments S1.1 through S15.3 conducted in two full-size welded-steel hopper bins located at the Glenlea Research Station during the summer and autumn of 1995. Sealing details are given for all five visible bin openings. Forced recirculation was used only where stated. Dry ice pellets were placed on the grain surface for experiments S14.1 through S15.3. For all other experiments, the dry ice was placed inside the steel holding box.

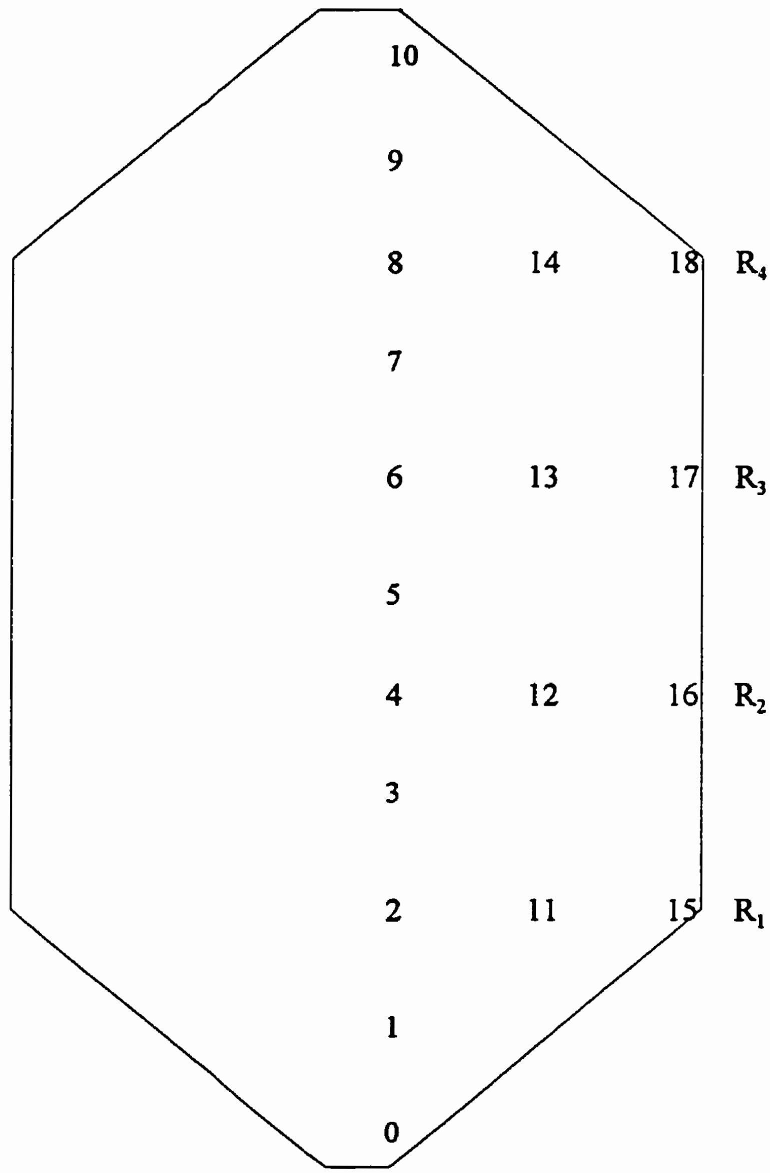
Experiment	Description of Sealing	Recirculation
S1.1	**Bottom-cone opening**: None **Top-cone opening:** None **Access manhole (roof):** None **Access manway (cone):** None **Aeration-duct opening**: None	top valve open
S2.1	**Bottom-cone opening**: None **Top-cone opening:** None **Access manhole (roof):** None **Access manway (cone):** None **Aeration-duct opening**: None	all valves open, (forced recirculation for initial 23 h)
S2.2	**Bottom-cone opening**: None **Top-cone opening:** None **Access manhole (roof):** None **Access manway (cone):** None **Aeration-duct opening**: None	all valves open
S2.3	**Bottom-cone opening**: None **Top-cone opening:** None **Access manhole (roof):** None **Access manway (cone):** None **Aeration-duct opening**: None	all valves open
S3.1	**Bottom-cone opening**: Inflated tire tube **Top-cone opening:** Vehicle weather stripping **Access manhole (roof):** Vehicle weather stripping **Access manway (cone):** Vehicle weather stripping **Aeration-duct opening**: Silicone caulking	all valves open
S4.1	**Bottom-cone opening**: Inflated tire tube **Top-cone opening:** Vehicle weather stripping **Access manhole (roof):** Vehicle weather stripping **Access manway (cone):** Vehicle weather stripping **Aeration-duct opening**: Silicone caulking	top valve open
S5.1	**Bottom-cone opening**: Inflated tire tube **Top-cone opening:** Vehicle weather stripping **Access manhole (roof):** Vehicle weather stripping **Access manway (cone):** Vehicle weather stripping **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation
S5.2	**Bottom-cone opening**: Inflated tire tube **Top-cone opening:** Vehicle weather stripping **Access manhole (roof):** Vehicle weather stripping **Access manway (cone):** Vehicle weather stripping **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation

Experiment	Description of Sealing	Recirculation
S5.3	**Bottom-cone opening**: Inflated tire tube **Top-cone opening:** Vehicle weather stripping **Access manhole (roof):** Vehicle weather stripping **Access manway (cone):** Vehicle weather stripping **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation
S6.1	**Bottom-cone opening**: Trough-shaped lid **Top-cone opening:** Vehicle weather stripping, clamped **Access manhole (roof):** Vehicle weather stripping, clamped **Access manway (cone):** Vehicle weather stripping, clamped **Aeration-duct opening**: Silicone caulking	top valve open
S7.1	**Bottom-cone opening**: Trough-shaped lid, corners fixed **Top-cone opening:** Vehicle weather stripping, clamped **Access manhole (roof):** Vehicle weather stripping, clamped **Access manway (cone):** Vehicle weather stripping, clamped **Aeration-duct opening**: Silicone caulking	top valve open
S8.1	**Bottom-cone opening**: Trough-shaped lid, corners fixed **Top-cone opening:** Vehicle weather stripping, clamped **Access manhole (roof):** Vehicle weather stripping, clamped **Access manway (cone):** Vehicle weather stripping, clamped **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation
S9.1	**Bottom-cone opening**: Trough-shaped lid, corners fixed **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Vehicle weather stripping, clamped **Access manway (cone):** Vehicle weather stripping, clamped **Aeration-duct opening**: Silicone caulking	top valve open
S10.1	**Bottom-cone opening**: Trough-shaped lid, corners fixed **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Vehicle weather stripping, clamped **Access manway (cone):** Vehicle weather stripping, clamped **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation
S11.1	**Bottom-cone opening**: Flat lid **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Neoprene rubber, clamped **Access manway (cone):** Neoprene rubber, clamped **Aeration-duct opening**: Silicone caulking	top valve open
S12.1	**Bottom-cone opening**: Flat lid **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Neoprene rubber, clamped **Access manway (cone):** Neoprene rubber, clamped **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation

Experiment	Description of Sealing	Recirculation
S12.2	**Bottom-cone opening**: Flat lid **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Neoprene rubber, clamped **Access manway (cone):** Neoprene rubber, clamped **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation
S12.3	**Bottom-cone opening**: Flat lid **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Neoprene rubber, clamped **Access manway (cone):** Neoprene rubber, clamped **Aeration-duct opening**: Silicone caulking	all valves open, forced recirculation
S13.1	**Bottom-cone opening**: Flat lid **Top-cone opening:** Flat lid **Access manhole (roof):** Flat lid **Access manway (cone):** Flat lid **Aeration-duct opening**: Flat lid	top valve open
S13.2	**Bottom-cone opening**: Flat lid **Top-cone opening:** Flat lid **Access manhole (roof):** Flat lid **Access manway (cone):** Flat lid **Aeration-duct opening**: Flat lid	all valves open, forced recirculation
S14.1	**Bottom-cone opening**: Trough-shaped lid, corners fixed **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Vehicle weather stripping, clamped **Access manway (cone):** Vehicle weather stripping, clamped **Aeration-duct opening**: Silicone caulking	all valves closed, dry ice pellets on grain
S15.1	**Bottom-cone opening**: Flat lid **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Neoprene rubber, clamped **Access manway (cone):** Neoprene rubber, clamped **Aeration-duct opening**: Silicone caulking	all valves closed, dry ice pellets on grain
S15.2	**Bottom-cone opening**: Flat lid **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Neoprene rubber, clamped **Access manway (cone):** Neoprene rubber, clamped **Aeration-duct opening**: Silicone caulking	all valves closed, dry ice pellets on grain
S15.3	**Bottom-cone opening**: Flat lid **Top-cone opening:** Isolated ventilation opening, clamped **Access manhole (roof):** Neoprene rubber, clamped **Access manway (cone):** Neoprene rubber, clamped **Aeration-duct opening**: Silicone caulking	all valves closed, dry ice pellets on grain

Appendix C - Data from Sealing Experiments

Carbon dioxide concentration data for experiments S1.1 through S15.3 conducted in two full-size welded-steel hopper bins located at the Glenlea Research Station during the summer and autumn of 1995. Mean, standard deviation (S.D.), and coefficient of variation (CV) values were calculated for each sampling time of each experiment along four radii (R_1, R_2, R_3, and R_4), the bin centreline, and for the entire bin. Some data points were excluded from analysis (experiments S14.1 through S15.3, indicated by *) due to sampling tubes becoming plugged with weed seeds and wheat kernels when grain was added to the bin. The sampling locations and bin radii are labelled in the following figure.



Centreline

Appendix C - Data from Sealing Experiments

	Bin Location	CO_2 Concentration (%)							
		S1.1 2h	S1.1 5h	S1.1 8h	S1.1 11h	S1.1 20h	S1.1 23 h	S1.1 26h	S1.1 29h
	0	0.0	3.5	7.9	8.8	7.7	6.4	6.5	7.9
	1	2.3	7.5	8.7	7.5	6.5	6.3	6.3	7.6
	2	1.7	7.1	8.8	8.5	6.2	6.3	6.9	8.1
	3	0.1	6.6	8.6	7.9	6.3	6.2	6.6	8.6
	4	0.2	8.1	8.7	8.3	7.1	5.8	6.8	8.0
	5	0.0	8.3	8.5	8.0	7.3	5.9	6.7	8.2
	6	0.0	7.2	9.1	8.5	7.3	5.9	6.9	8.9
	7	0.0	5.7	8.4	9.0	7.6	6.0	6.8	8.2
	8	0.0	4.4	7.6	8.4	8.1	6.0	6.6	7.6
	9	0.0	5.5	6.5	7.5	7.2	6.0	6.2	7.0
	10	0.0	4.4	3.8	5.7	2.3	1.5	5.5	4.1
	11	2.8	8.0	8.5	8.3	6.1	5.5	7.2	7.8
	12	1.5	8.1	8.4	8.7	6.3	5.9	7.1	7.5
	13	0.6	6.9	8.2	8.9	7.3	6.0	6.7	8.0
	14	0.1	3.0	8.6	8.0	7.0	6.0	7.0	8.3
	15	1.2	7.5	8.2	8.1	6.7	5.8	7.4	8.1
	16	0.8	7.5	8.6	8.0	6.5	5.7	7.7	8.8
	17	0.1	7.8	8.3	8.8	7.0	6.3	7.3	8.9
	18	0.0	5.6	8.4	8.8	6.2	6.1	6.5	8.3
R_1	Mean (%)	1.9	7.5	8.5	8.3	6.3	5.9	7.2	8.0
	S.D.	0.82	0.45	0.30	0.20	0.32	0.40	0.25	0.17
	CV (%)	43	6	4	2	5	7	4	2
R_2	Mean (%)	0.8	7.9	8.6	8.3	6.6	5.8	7.2	8.1
	S.D.	0.65	0.35	0.15	0.35	0.42	0.10	0.46	0.66
	CV (%)	78	4	2	4	6	2	6	8
R_3	Mean (%)	0.2	7.3	8.5	8.7	7.2	6.1	7.0	8.6
	S.D.	0.32	0.46	0.49	0.21	0.17	0.21	0.31	0.52
	CV (%)	138	6	6	2	2	3	4	6
R_4	Mean (%)	0.0	4.3	8.2	8.4	7.1	6.0	6.7	8.1
	S.D.	0.06	1.30	0.53	0.40	0.95	0.06	0.26	0.40
	CV (%)	173	30	6	5	13	1	4	5
Cent.	Mean (%)	0.4	6.2	7.9	8.0	6.7	5.7	6.5	7.7
	S.D.	0.81	1.62	1.53	0.90	1.57	1.39	0.41	1.28
	CV (%)	207	26	19	11	23	25	6	17
All	Mean (%)	0.6	6.5	8.1	8.2	6.7	5.8	6.8	7.9
	S.D.	0.88	1.65	1.18	0.75	1.20	1.06	0.49	1.04
	CV (%)	147	25	15	9	18	18	7	13

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S1.1 32h	S1.1 35h	S1.1 48h	S2.1 2h	S2.1 5h	S2.1 8h	S2.1 11h	S2.1 20h
	0	6.8	6.6	6.1	0.1	4.2	9.1	8.9	9.9
	1	8.4	7.4	3.4	3.0	9.5	10.2	8.9	7.2
	2	7.5	7.5	4.2	2.1	7.3	11.0	9.5	6.7
	3	7.6	7.3	6.0	1.2	7.8	10.2	10.2	7.9
	4	6.8	7.4	6.2	1.4	6.4	10.6	10.0	7.6
	5	7.1	7.2	6.2	0.9	6.2	10.7	9.6	8.2
	6	7.5	6.8	6.4	1.5	5.9	10.3	9.5	8.2
	7	7.7	8.4	6.7	0.3	5.7	10.4	9.3	7.7
	8	8.7	8.7	6.6	0.2	5.1	11.4	10.8	8.3
	9	7.6	8.0	6.3	0.1	5.1	9.7	10.8	8.6
	10	6.9	3.1	2.4	0.2	5.3	3.5	2.5	2.9
	11	8.0	6.5	2.6	4.5	9.7	10.0	9.1	5.3
	12	8.0	6.9	3.7	3.5	8.5	9.8	10.7	6.2
	13	8.1	6.6	5.7	1.9	6.0	9.4	9.7	6.8
	14	7.5	7.5	6.5	2.2	5.5	9.7	9.3	7.3
	15	7.5	7.3	5.1	3.1	8.0	11.0	8.7	7.0
	16	7.4	7.1	4.5	2.0	10.5	11.4	10.8	6.6
	17	7.8	7.4	5.7	2.6	7.2	10.1	9.2	6.7
	18	7.8	7.5	6.3	0.3	6.1	11.9	10.1	7.5
R_1	Mean (%)	7.7	7.1	4.0	3.2	8.3	10.7	9.1	6.3
	S.D.	0.29	0.53	1.27	1.21	1.23	0.58	0.40	0.91
	CV (%)	4	7	32	37	15	5	4	14
R_2	Mean (%)	7.4	7.1	4.8	2.3	8.5	10.6	10.5	6.8
	S.D.	0.60	0.25	1.28	1.08	2.05	0.80	0.44	0.72
	CV (%)	8	4	27	47	24	8	4	11
R_3	Mean (%)	7.8	6.9	5.9	2.0	6.4	9.9	9.5	7.2
	S.D.	0.30	0.42	0.40	0.56	0.72	0.47	0.25	0.84
	CV (%)	4	6	7	28	11	5	3	12
R_4	Mean (%)	8.0	7.9	6.5	0.9	5.6	11.0	10.1	7.7
	S.D.	0.62	0.69	0.15	1.13	0.50	1.15	0.75	0.53
	CV (%)	8	9	2	125	9	10	7	7
Cent.	Mean (%)	7.5	7.1	5.5	1.0	6.2	9.7	9.1	7.6
	S.D.	0.62	1.48	1.46	0.95	1.49	2.16	2.28	1.75
	CV (%)	8	21	27	95	24	22	25	23
All	Mean (%)	7.6	7.1	5.3	1.6	6.8	10.0	9.3	7.2
	S.D.	0.51	1.13	1.40	1.30	1.75	1.74	1.79	1.45
	CV (%)	7	16	26	80	26	17	19	20

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S2.1 23h	S2.1 26h	S2.1 29h	S2.1 32h	S2.1 35h	S2.2 2h	S2.2 5h	S2.2 8h
	0	6.8	7.6	13.9	18.8	8.8	16.7	19.6	14.4
	1	6.4	6.4	6.7	6.5	2.7	6.3	8.7	7.4
	2	6.5	6.9	6.3	4.6	2.6	3.5	7.4	8.3
	3	6.3	6.9	6.8	4.3	2.7	1.5	6.5	6.6
	4	6.3	7.1	6.9	4.7	3.0	1.7	5.8	6.6
	5	6.7	7.3	7.2	4.6	3.0	1.1	5.3	8.8
	6	6.6	6.9	6.4	4.4	2.9	0.9	6.2	6.7
	7	6.7	8.2	3.7	4.2	2.8	1.3	5.9	6.6
	8	6.6	7.1	2.4	3.5	2.4	1.0	5.2	6.0
	9	7.2	6.1	1.9	3.2	2.6	0.8	5.7	6.0
	10	1.8	1.8	1.3	3.5	2.5	0.8	5.2	4.7
	11	6.5	5.5	4.8	3.6	1.2	4.5	7.3	6.1
	12	6.8	6.1	4.7	4.1	2.2	1.9	6.6	5.6
	13	6.7	7.0	4.2	4.5	2.8	1.3	5.6	7.6
	14	6.8	6.4	1.9	3.7	2.4	0.9	5.5	5.8
	15	7.5	6.2	5.0	4.1	2.2	2.1	5.4	7.3
	16	7.3	6.8	4.6	3.5	2.8	1.2	5.7	6.3
	17	6.7	6.6	4.9	4.0	2.4	1.0	5.3	6.0
	18	6.5	6.1	3.6	4.2	2.4	0.9	4.8	6.4
R_1	Mean (%)	6.8	6.2	5.4	4.1	2.0	3.4	6.7	7.2
	S.D.	0.58	0.70	0.81	0.50	0.72	1.21	1.13	1.10
	CV (%)	8	11	15	12	36	36	17	15
R_2	Mean (%)	6.8	6.7	5.3	4.1	2.7	1.6	6.0	6.2
	S.D.	0.50	0.51	1.18	0.60	0.42	0.36	0.49	0.51
	CV (%)	7	8	22	15	16	23	8	8
R_3	Mean (%)	6.7	6.8	5.2	4.3	2.7	1.1	5.7	6.8
	S.D.	0.06	0.21	1.12	0.26	0.26	0.21	0.46	0.80
	CV (%)	1	3	22	6	10	20	8	12
R_4	Mean (%)	6.6	6.5	2.6	3.8	2.4	0.9	5.2	6.1
	S.D.	0.15	0.51	0.87	0.36	0.00	0.06	0.35	0.31
	CV (%)	2	8	33	9	0	6	7	5
Cent.	Mean (%)	6.2	6.6	5.8	5.7	3.3	3.2	7.4	7.5
	S.D.	1.47	1.68	3.50	4.44	1.84	4.76	4.18	2.56
	CV (%)	24	26	61	78	56	147	56	34
All	Mean (%)	6.5	6.5	5.1	4.9	2.9	2.6	6.7	7.0
	S.D.	1.17	1.29	2.80	3.43	1.49	3.71	3.26	2.03
	CV (%)	18	20	55	69	52	143	49	29

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S2.2 11h	S2.2 20h	S2.2 23h	S2.2 26h	S2.2 29h	S2.2 32h	S2.2 35h	S2.3 2h
	0	15.4	20.6	12.8	19.1	16.7	17.4	11.1	4.2
	1	7.2	12.5	3.9	7.2	7.8	6.2	3.3	4.0
	2	5.7	4.8	2.7	4.3	5.6	4.5	3.5	4.1
	3	5.2	3.5	3.4	2.5	5.0	4.3	3.5	4.5
	4	5.9	3.9	1.3	3.3	4.6	4.4	5.7	4.2
	5	5.7	4.1	0.9	1.3	2.2	4.5	3.5	2.0
	6	5.4	2.8	0.9	1.2	3.1	3.5	1.9	0.6
	7	5.5	4.3	1.2	1.2	1.9	4.8	2.1	1.3
	8	5.1	4.3	1.3	1.0	1.7	2.4	1.5	0.3
	9	4.6	2.9	0.9	0.6	1.2	1.8	1.7	0.5
	10	1.6	2.0	0.6	0.6	1.4	1.5	1.3	0.2
	11	5.3	2.9	2.1	4.4	5.5	2.0	2.9	3.9
	12	5.3	3.3	0.9	3.3	4.2	3.8	2.7	4.2
	13	5.6	4.3	1.0	1.4	1.9	2.8	2.0	1.3
	14	5.4	4.0	0.7	0.6	1.3	1.9	1.2	0.4
	15	5.3	3.3	2.3	4.4	4.7	3.2	2.7	0.3
	16	5.1	3.7	0.7	2.9	3.9	3.6	2.4	3.8
	17	5.5	4.1	0.5	0.8	2.7	3.4	1.6	0.8
	18	5.3	4.5	0.6	0.7	1.7	1.9	1.5	0.6
R_1	Mean (%)	5.4	3.7	2.4	4.4	5.3	3.2	3.0	2.8
	S.D.	0.23	1.00	0.31	0.06	0.49	1.25	0.42	2.14
	CV (%)	4	27	13	1	9	39	14	77
R_2	Mean (%)	5.4	3.6	1.0	3.2	4.2	3.9	3.6	4.1
	S.D.	0.42	0.31	0.31	0.23	0.35	0.42	1.82	0.23
	CV (%)	8	8	32	7	8	11	51	6
R_3	Mean (%)	5.5	3.7	0.8	1.1	2.6	3.2	1.8	0.9
	S.D.	0.10	0.81	0.26	0.31	0.61	0.38	0.21	0.36
	CV (%)	2	22	33	27	24	12	11	40
R_4	Mean (%)	5.3	4.3	0.9	0.8	1.6	2.1	1.4	0.4
	S.D.	0.15	0.25	0.38	0.21	0.23	0.29	0.17	0.15
	CV (%)	3	6	44	27	15	14	12	35
Cent.	Mean (%)	6.1	6.0	2.7	3.8	4.7	5.0	3.6	2.4
	S.D.	3.36	5.59	3.52	5.44	4.51	4.34	2.81	1.84
	CV (%)	55	94	130	141	97	86	79	78
All	Mean (%)	5.8	5.0	2.0	3.2	4.1	4.1	3.0	2.2
	S.D.	2.54	4.33	2.79	4.25	3.57	3.46	2.26	1.76
	CV (%)	44	86	137	133	88	84	76	81

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S2.3 5h	S2.3 8h	S2.3 11h	S2.3 20h	S2.3 23h	S2.3 26h	S2.3 29h	S2.3 32h
	0	7.9	7.0	4.8	0.8	0.5	4.2	3.0	1.5
	1	6.1	6.2	4.8	0.9	0.4	1.8	2.7	0.9
	2	6.2	5.8	6.1	0.8	0.5	1.2	2.3	0.8
	3	5.7	4.9	5.1	1.1	0.5	0.7	1.5	1.0
	4	6.0	5.6	5.5	1.0	0.6	0.7	1.2	1.0
	5	5.7	6.5	4.7	3.9	1.0	0.7	1.0	1.0
	6	5.7	6.6	4.5	3.9	1.0	0.7	0.9	3.4
	7	3.8	6.4	4.3	3.8	1.0	0.7	0.9	1.1
	8	4.0	6.5	4.4	4.2	1.2	0.7	0.8	0.9
	9	4.1	5.9	4.8	3.3	0.9	0.6	0.8	0.9
	10	1.8	5.3	3.5	2.6	0.9	0.6	0.8	0.9
	11	6.9	6.8	4.1	1.9	0.8	1.4	1.5	1.1
	12	6.0	6.6	4.8	3.1	0.8	0.9	0.7	1.0
	13	5.2	6.6	4.8	4.3	0.9	0.8	0.9	1.0
	14	5.0	7.1	4.9	4.5	1.0	0.8	0.9	0.8
	15	4.5	6.1	4.7	3.1	0.7	0.7	1.1	1.0
	16	5.2	6.2	4.6	3.4	0.7	0.8	0.9	0.9
	17	4.2	6.3	4.6	4.1	0.9	0.6	0.7	0.9
	18	3.9	6.1	5.0	3.5	0.9	0.5	0.7	0.8
R_1	Mean (%)	5.9	6.2	5.0	1.9	0.7	1.1	1.6	1.0
	S.D.	1.23	0.51	1.03	1.15	0.15	0.36	0.61	0.15
	CV (%)	21	8	21	60	23	33	37	16
R_2	Mean (%)	5.7	6.1	5.0	2.5	0.7	0.8	0.9	1.0
	S.D.	0.46	0.50	0.47	1.31	0.10	0.10	0.25	0.06
	CV (%)	8	8	10	52	14	13	27	6
R_3	Mean (%)	5.0	6.5	4.6	4.1	0.9	0.7	0.8	1.8
	S.D.	0.76	0.17	0.15	0.20	0.06	0.10	0.12	1.42
	CV (%)	15	3	3	5	6	14	14	80
R_4	Mean (%)	4.3	6.6	4.8	4.1	1.0	0.7	0.8	0.8
	S.D.	0.61	0.50	0.32	0.51	0.15	0.15	0.10	0.06
	CV (%)	14	8	7	13	15	23	13	7
Cent.	Mean (%)	5.2	6.1	4.8	2.4	0.8	1.1	1.4	1.2
	S.D.	1.63	0.63	0.67	1.47	0.28	1.07	0.83	0.75
	CV (%)	32	10	14	61	36	94	57	62
All	Mean (%)	5.2	6.2	4.7	2.9	0.8	1.0	1.2	1.1
	S.D.	1.36	0.56	0.53	1.33	0.22	0.84	0.69	0.58
	CV (%)	26	9	11	47	27	83	56	53

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S2.3 35h	S3.1 2h	S3.1 8h	S3.1 20h	S3.1 26h	S3.1 32h	S3.1 44h	S3.1 50h
	0	1.3	31.1	34.7	30.0	35.3	28.0	12.3	8.1
	1	0.7	18.1	23.1	17.5	21.4	15.6	9.4	7.0
	2	0.7	4.7	9.9	11.1	11.3	10.5	9.0	7.2
	3	0.7	4.0	7.7	9.6	8.9	8.6	7.9	6.3
	4	0.7	1.7	6.5	9.5	9.2	8.6	7.9	6.0
	5	0.8	2.9	5.4	9.4	10.1	8.1	7.9	6.6
	6	0.8	0.6	3.9	9.7	9.4	8.2	8.2	7.1
	7	0.8	1.5	4.2	9.8	9.6	7.8	8.1	7.2
	8	0.8	0.5	3.8	9.0	10.2	8.3	8.2	6.8
	9	0.5	0.4	3.8	9.3	9.2	7.9	6.6	6.0
	10	0.8	0.2	3.1	7.7	7.8	8.4	6.1	4.3
	11	0.8	3.1	8.6	11.6	9.2	8.9	7.5	7.2
	12	0.8	3.0	7.6	9.8	8.6	8.3	7.4	6.7
	13	0.8	1.7	8.0	9.0	8.7	7.6	8.4	7.0
	14	1.0	0.5	4.6	8.9	8.9	7.9	8.1	6.4
	15	0.7	2.9	6.9	9.4	8.8	8.1	7.4	6.9
	16	0.8	3.1	7.0	9.0	8.7	7.8	7.6	7.4
	17	0.8	1.2	5.5	8.4	9.8	8.2	8.9	8.4
	18	0.7	0.2	4.9	8.4	9.0	8.3	6.5	6.0
R_1	Mean (%)	0.7	3.6	8.5	10.7	9.8	9.2	8.0	7.1
	S.D.	0.06	0.99	1.50	1.15	1.34	1.22	0.90	0.17
	CV (%)	8	28	18	11	14	13	11	2
R_2	Mean (%)	0.8	2.6	7.0	9.4	8.8	8.2	7.6	6.7
	S.D.	0.06	0.78	0.55	0.40	0.32	0.40	0.25	0.70
	CV (%)	8	30	8	4	4	5	3	10
R_3	Mean (%)	0.8	1.2	5.8	9.0	9.3	8.0	8.5	7.5
	S.D.	0.00	0.55	2.07	0.65	0.56	0.35	0.36	0.78
	CV (%)	0	47	36	7	6	4	4	10
R_4	Mean (%)	0.8	0.4	4.4	8.8	9.4	8.2	7.6	6.4
	S.D.	0.15	0.17	0.57	0.32	0.72	0.23	0.95	0.40
	CV (%)	18	43	13	4	8	3	13	6
Cent.	Mean (%)	0.8	6.0	9.6	12.1	12.9	10.9	8.3	6.6
	S.D.	0.19	9.77	10.07	6.47	8.27	6.10	1.61	0.98
	CV (%)	25	164	104	54	64	56	19	15
All	Mean (%)	0.8	4.3	8.4	10.9	11.3	9.7	8.1	6.8
	S.D.	0.16	7.60	7.72	5.06	6.49	4.76	1.32	0.88
	CV (%)	20	177	92	46	58	49	16	13

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S3.1 56h	S3.1 68h	S4.1 2h	S4.1 8h	S4.1 20h	S4.1 26h	S4.1 32h	S4.1 116h
	0	5.6	4.0	5.2	12.6	16.1	11.7	10.3	2.5
	1	5.3	3.9	5.6	14.0	18.9	11.3	8.8	2.7
	2	5.9	4.5	5.3	14.1	18.0	11.9	15.3	2.1
	3	5.4	3.4	4.7	12.0	16.9	12.0	12.5	3.3
	4	5.9	4.1	4.8	13.0	16.2	12.3	10.7	3.5
	5	6.2	4.4	4.3	8.1	13.9	10.8	10.3	3.4
	6	6.2	5.8	4.6	6.7	14.0	10.4	10.7	4.2
	7	6.5	4.9	3.5	5.8	14.3	9.2	11.0	5.4
	8	6.6	4.6	3.6	5.2	13.9	9.1	10.5	6.0
	9	6.2	4.4	3.0	5.9	12.9	10.5	14.6	4.7
	10	6.1	3.8	3.6	5.3	12.9	10.1	10.4	6.1
	11	4.8	4.1	4.6	11.6	16.7	11.2	9.6	2.8
	12	5.7	4.6	3.2	9.2	14.9	13.3	11.0	2.7
	13	6.5	4.7	3.6	6.3	13.2	11.4	11.3	3.8
	14	5.9	5.1	3.6	5.5	13.8	11.4	10.3	6.4
	15	5.5	4.1	5.7	7.2	14.3	12.1	10.2	3.7
	16	5.4	4.8	6.3	6.0	14.0	12.8	10.2	1.9
	17	5.6	4.6	4.0	5.5	13.7	13.1	11.6	6.1
	18	5.7	4.2	3.7	5.6	13.3	14.0	14.0	6.4
R_1	Mean (%)	5.4	4.2	5.2	11.0	16.3	11.7	11.7	2.9
	S.D.	0.56	0.23	0.56	3.49	1.88	0.47	3.13	0.80
	CV (%)	10	5	11	32	11	4	27	28
R_2	Mean (%)	5.7	4.5	4.8	9.4	15.0	12.8	10.6	2.7
	S.D.	0.25	0.36	1.55	3.50	1.11	0.50	0.40	0.80
	CV (%)	4	8	33	37	7	4	4	30
R_3	Mean (%)	6.1	5.0	4.1	6.2	13.6	11.6	11.2	4.7
	S.D.	0.46	0.67	0.50	0.61	0.40	1.37	0.46	1.23
	CV (%)	8	13	12	10	3	12	4	26
R_4	Mean (%)	6.1	4.6	3.6	5.4	13.7	11.5	11.6	6.3
	S.D.	0.47	0.45	0.06	0.21	0.32	2.45	2.08	0.23
	CV (%)	8	10	2	4	2	21	18	4
Cent.	Mean (%)	6.0	4.3	4.4	9.3	15.3	10.8	11.4	4.0
	S.D.	0.42	0.64	0.85	3.77	2.06	1.10	1.97	1.40
	CV (%)	7	15	19	40	13	10	17	35
All	Mean (%)	5.8	4.4	4.4	8.4	14.8	11.5	11.2	4.1
	S.D.	0.47	0.53	0.94	3.32	1.77	1.31	1.71	1.55
	CV (%)	8	12	22	40	12	11	15	38

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S5.1 2h	S5.1 8h	S5.1 20h	S5.1 26h	S5.1 32h	S5.1 44h	S5.1 50h	S5.2 2h
	0	5.4	13.0	20.2	22.3	13.1	9.2	7.6	7.0
	1	6.8	16.0	18.3	17.2	13.8	8.3	8.7	8.3
	2	6.3	15.5	21.7	16.5	13.5	9.3	7.5	7.2
	3	5.5	13.5	17.6	21.8	15.5	9.5	8.1	7.4
	4	5.4	13.9	18.4	17.7	13.6	9.1	8.5	4.0
	5	3.3	9.9	19.7	18.6	16.0	9.4	10.4	4.1
	6	2.9	8.5	18.3	17.8	15.6	11.7	10.2	2.6
	7	4.1	7.7	17.5	19.6	16.2	8.6	9.5	2.7
	8	2.0	7.5	14.9	18.3	15.0	10.4	9.8	1.0
	9	1.6	7.4	18.0	16.9	15.6	17.1	9.7	0.7
	10	1.6	6.3	16.7	17.4	13.5	7.8	10.3	0.6
	11	3.5	10.9	19.4	17.8	14.5	8.7	9.3	6.6
	12	7.1	11.2	20.2	20.0	14.6	9.4	8.9	7.5
	13	3.5	8.1	18.8	16.4	14.4	10.2	9.0	6.9
	14	2.4	7.0	15.6	19.6	14.6	11.0	9.6	1.5
	15	8.3	9.3	20.5	17.8	13.9	9.9	8.7	7.6
	16	3.4	10.4	20.5	20.5	15.3	10.8	8.8	3.5
	17	3.8	8.4	20.3	19.5	14.7	10.9	8.6	1.6
	18	2.0	8.7	19.1	17.0	13.5	9.0	8.6	0.8
R_1	Mean (%)	6.0	11.9	20.5	17.4	14.0	9.3	8.5	7.1
	S.D.	2.41	3.22	1.15	0.75	0.50	0.60	0.92	0.50
	CV (%)	40	27	6	4	4	6	11	7
R_2	Mean (%)	5.3	11.8	19.7	19.4	14.5	9.8	8.7	5.0
	S.D.	1.85	1.83	1.14	1.49	0.85	0.91	0.21	2.18
	CV (%)	35	15	6	8	6	9	2	44
R_3	Mean (%)	3.4	8.3	19.1	17.9	14.9	10.9	9.3	3.7
	S.D.	0.46	0.21	1.04	1.55	0.62	0.75	0.83	2.82
	CV (%)	13	2	5	9	4	7	9	76
R_4	Mean (%)	2.1	7.7	16.5	18.3	14.4	10.1	9.3	1.1
	S.D.	0.23	0.87	2.25	1.30	0.78	1.03	0.64	0.36
	CV (%)	11	11	14	7	5	10	7	33
Cent.	Mean (%)	4.1	10.8	18.3	18.6	14.7	10.0	9.1	4.1
	S.D.	1.91	3.60	1.80	1.93	1.17	2.56	1.08	2.90
	CV (%)	47	33	10	10	8	26	12	70
All	Mean (%)	4.2	10.2	18.7	18.6	14.6	10.0	9.0	4.3
	S.D.	2.00	2.95	1.76	1.72	0.94	1.99	0.84	2.84
	CV (%)	48	29	9	9	6	20	9	66

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S5.2 8h	S5.2 20h	S5.2 26h	S5.2 32h	S5.2 44h	S5.3 2h	S5.3 8h	S5.3 20h
	0	19.4	22.6	23.1	21.4	21.6	12.3	20.3	20.8
	1	21.4	24.7	22.0	21.2	19.2	11.2	21.1	23.5
	2	18.5	22.8	25.0	27.3	19.5	12.9	21.9	24.4
	3	17.5	23.9	21.3	22.2	2.9	11.6	21.2	25.3
	4	17.6	22.0	24.4	22.8	18.5	11.8	20.8	24.8
	5	16.6	30.5	24.0	22.7	18.2	11.8	16.0	24.4
	6	9.8	21.0	24.4	23.6	18.4	18.5	15.5	22.9
	7	10.4	19.8	23.5	22.8	18.3	15.8	14.7	25.8
	8	7.8	19.5	22.2	23.5	20.0	22.0	13.8	20.0
	9	9.8	19.3	24.2	22.0	20.6	15.8	14.9	22.4
	10	6.3	18.7	26.4	22.0	17.6	12.0	14.4	21.2
	11	16.6	24.1	27.2	31.1	22.2	11.1	20.3	22.9
	12	11.6	25.8	26.2	27.0	18.4	14.7	19.6	24.1
	13	10.7	23.1	25.6	24.0	18.1	17.9	17.4	23.0
	14	7.7	19.5	22.7	24.0	27.3	17.3	16.4	23.0
	15	21.3	23.9	28.4	22.7	19.0	13.0	17.2	25.0
	16	16.2	23.1	23.6	22.8	10.2	15.2	14.7	24.4
	17	12.0	28.4	25.9	22.8	19.8	12.6	14.8	23.5
	18	23.4	24.3	22.2	23.1	13.7	12.1	13.5	22.7
R_1	Mean (%)	18.8	23.6	26.9	27.0	20.2	12.3	19.8	24.1
	S.D.	2.36	0.70	1.72	4.21	1.72	1.07	2.39	1.08
	CV (%)	13	3	6	16	9	9	12	4
R_2	Mean (%)	15.1	23.6	24.7	24.2	15.7	13.9	18.4	24.4
	S.D.	3.14	1.96	1.33	2.42	4.76	1.84	3.23	0.35
	CV (%)	21	8	5	10	30	13	18	1
R_3	Mean (%)	10.8	24.2	25.3	23.5	18.8	16.3	15.9	23.1
	S.D.	1.11	3.81	0.79	0.61	0.91	3.25	1.35	0.32
	CV (%)	10	16	3	3	5	20	8	1
R_4	Mean (%)	13.0	21.1	22.4	23.5	20.3	17.1	14.6	21.9
	S.D.	9.04	2.77	0.29	0.45	6.81	4.95	1.59	1.65
	CV (%)	70	13	1	2	33	29	11	8
Cent.	Mean (%)	14.1	22.3	23.7	22.9	17.7	14.2	17.7	23.2
	S.D.	5.31	3.37	1.47	1.66	5.05	3.49	3.29	1.93
	CV (%)	38	15	6	7	29	25	19	8
All	Mean (%)	14.5	23.0	24.3	23.6	18.1	14.2	17.3	23.4
	S.D.	5.23	3.10	1.92	2.40	4.97	3.02	2.91	1.54
	CV (%)	36	13	8	10	27	21	17	7

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S5.3 26h	S5.3 32h	S5.3 44h	S6.1 2h	S6.1 8h	S6.1 20h	S6.1 26h	S6.1 32h
	0	22.7	16.7	13.4	1.1	6.5	21.8	32.8	12.2
	1	24.4	21.3	14.5	5.5	15.5	16.3	14.0	11.7
	2	22.8	21.1	15.3	7.6	16.0	16.2	16.0	15.4
	3	26.0	23.7	15.7	6.4	9.0	19.3	16.9	13.8
	4	24.3	24.4	17.4	6.8	12.7	18.1	15.5	15.1
	5	21.9	25.2	19.0	5.5	9.4	17.3	17.2	16.8
	6	21.8	23.0	19.0	1.1	11.3	15.8	15.1	15.2
	7	24.0	24.6	19.8	0.5	8.0	18.9	15.4	15.0
	8	22.8	23.7	19.0	5.9	8.0	15.8	15.4	12.3
	9	23.1	22.8	17.9	0.9	6.7	14.5	15.9	13.3
	10	21.2	24.6	17.8	0.2	6.9	9.0	4.9	5.6
	11	23.4	23.9	16.7	6.8	19.5	14.5	20.0	12.9
	12	22.9	22.8	17.1	6.6	19.4	13.6	15.8	13.7
	13	22.9	24.1	17.6	4.1	16.6	13.8	14.9	15.0
	14	23.4	23.3	18.7	0.7	8.8	15.6	14.5	14.0
	15	22.0	23.0	16.4	6.6	16.9	14.2	16.0	13.2
	16	21.6	24.8	19.6	2.8	14.9	16.4	17.1	13.2
	17	24.6	22.8	19.4	6.1	8.7	17.2	14.4	12.2
	18	24.8	25.3	19.0	2.8	8.1	15.4	14.9	13.1
R_1	Mean (%)	22.7	22.7	16.1	7.0	17.5	15.0	17.3	13.8
	S.D.	0.70	1.43	0.74	0.53	1.82	1.08	2.31	1.37
	CV (%)	3	6	5	8	10	7	13	10
R_2	Mean (%)	22.9	24.0	18.0	5.4	15.7	16.0	16.1	14.0
	S.D.	1.35	1.06	1.37	2.25	3.42	2.27	0.85	0.98
	CV (%)	6	4	8	42	22	14	5	7
R_3	Mean (%)	23.1	23.3	18.7	3.8	12.2	15.6	14.8	14.1
	S.D.	1.41	0.70	0.95	2.52	4.03	1.71	0.36	1.68
	CV (%)	6	3	5	67	33	11	2	12
R_4	Mean (%)	23.7	24.1	18.9	3.1	8.3	15.6	14.9	13.1
	S.D.	1.03	1.06	0.17	2.62	0.44	0.20	0.45	0.85
	CV (%)	4	4	1	83	5	1	3	6
Cent.	Mean (%)	23.2	22.8	17.2	3.8	10.0	16.6	16.3	13.3
	S.D.	1.39	2.42	2.12	2.95	3.43	3.26	6.42	3.01
	CV (%)	6	11	12	78	34	20	39	23
All	Mean (%)	23.2	23.2	17.5	4.1	11.7	16.0	16.1	13.4
	S.D.	1.25	1.96	1.82	2.66	4.48	2.67	4.93	2.30
	CV (%)	5	8	10	65	38	17	31	17

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S6.1 44h	S7.1 2h	S7.1 8h	S7.1 23h	S7.1 68h	S8.1 2h	S8.1 8h	S8.1 20h
	0	12.0	0.9	5.5	13.8	15.6	15.6	7.9	16.1
	1	12.9	4.4	13.7	20.0	19.2	9.6	7.0	22.3
	2	12.3	5.0	13.8	22.5	21.6	9.5	8.5	21.0
	3	12.7	2.1	9.1	21.3	21.4	17.0	9.3	24.2
	4	13.7	3.3	8.6	18.9	22.6	9.8	11.1	26.8
	5	15.3	1.8	9.0	18.2	22.7	15.2	8.5	24.4
	6	11.6	3.1	8.0	17.9	20.4	8.6	6.6	20.2
	7	15.2	2.2	5.7	18.2	21.4	8.7	6.0	14.6
	8	15.4	1.5	6.1	16.9	26.1	5.1	4.5	14.7
	9	12.6	1.9	5.9	16.5	19.2	4.3	4.0	15.9
	10	5.8	1.0	5.5	15.1	17.8	2.6	4.6	17.6
	11	10.3	4.2	11.4	21.0	20.3	7.8	8.1	24.4
	12	11.0	5.7	15.3	20.2	20.9	10.9	7.9	23.8
	13	12.4	4.3	7.3	17.5	19.1	8.7	8.8	16.7
	14	12.0	1.4	32.5	16.8	13.5	4.5	7.1	25.0
	15	11.1	4.8	8.9	20.9	18.7	8.6	8.2	24.6
	16	13.2	2.5	13.6	20.9	19.1	10.5	9.4	22.3
	17	12.2	1.3	7.4	26.1	13.7	8.1	7.5	14.5
	18	14.8	2.3	9.2	20.7	19.3	5.1	6.3	18.3
R_1	Mean (%)	11.2	4.7	11.4	21.5	20.2	8.6	8.3	23.3
	S.D.	1.01	0.42	2.45	0.90	1.45	0.85	0.21	2.02
	CV (%)	9	9	22	4	7	10	3	9
R_2	Mean (%)	12.6	3.8	12.5	20.0	20.9	10.4	9.5	24.3
	S.D.	1.44	1.67	3.48	1.01	1.75	0.56	1.60	2.29
	CV (%)	11	43	28	5	8	5	17	9
R_3	Mean (%)	12.1	2.9	7.6	20.5	17.7	8.5	7.6	17.1
	S.D.	0.42	1.51	0.38	4.85	3.55	0.32	1.11	2.87
	CV (%)	3	52	5	24	20	4	14	17
R_4	Mean (%)	14.1	1.7	15.9	18.1	19.6	4.9	6.0	19.3
	S.D.	1.81	0.49	14.43	2.22	6.31	0.35	1.33	5.23
	CV (%)	13	28	91	12	32	7	22	27
Cent.	Mean (%)	12.7	2.5	8.3	18.1	20.7	9.6	7.1	19.8
	S.D.	2.66	1.33	3.06	2.56	2.78	4.70	2.22	4.29
	CV (%)	21	54	37	14	13	49	31	22
All	Mean (%)	12.4	2.8	10.3	19.1	19.6	9.0	7.4	20.4
	S.D.	2.19	1.49	6.19	2.85	3.05	3.87	1.81	4.16
	CV (%)	18	53	60	15	16	43	24	20

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO$_2$ Concentration (%)							
		S8.1 26h	S8.1 32h	S8.1 44h	S8.1 50h	S8.1 56h	S8.1 68h	S9.1 5.5h	S9.1 19h
	0	30.3	19.6	18.6	13.0	15.8	11.0	7.1	16.9
	1	32.7	24.8	22.5	17.2	15.5	12.1	15.2	25.5
	2	26.3	23.0	20.7	15.4	16.1	10.7	14.5	31.5
	3	29.5	26.4	21.3	15.8	17.2	10.4	12.7	27.7
	4	27.8	26.0	19.3	15.7	17.0	9.1	11.7	24.0
	5	26.3	26.4	20.1	15.5	17.0	10.2	9.6	27.3
	6	23.8	25.4	17.7	12.6	16.1	10.1	11.5	29.2
	7	26.0	26.5	18.9	12.5	18.7	11.5	6.5	20.8
	8	23.1	27.4	21.7	12.3	16.4	9.7	6.7	18.8
	9	24.6	24.8	19.9	14.2	14.1	9.7	13.8	19.2
	10	23.3	23.0	17.3	10.4	12.6	8.3	6.8	19.9
	11	24.7	23.0	21.7	15.3	14.0	13.0	15.2	29.0
	12	24.7	25.5	19.0	13.4	13.8	11.7	13.2	27.6
	13	22.7	23.2	17.9	13.0	15.3	12.6	11.6	24.9
	14	27.7	23.6	18.3	12.3	13.4	10.2	9.6	21.7
	15	28.1	24.8	20.1	17.4	14.3	14.9	14.1	27.9
	16	25.9	23.0	22.0	15.1	13.6	13.1	16.7	29.9
	17	27.8	24.0	18.8	14.0	12.8	14.9	16.0	31.5
	18	29.4	24.6	20.8	11.9	14.0	10.8	10.5	26.6
R_1	Mean (%)	26.4	23.6	20.8	16.0	14.8	12.9	14.6	29.5
	S.D.	1.70	1.04	0.81	1.18	1.14	2.10	0.56	1.84
	CV (%)	6	4	4	7	8	16	4	6
R_2	Mean (%)	26.1	24.8	20.1	14.7	14.8	11.3	13.9	27.2
	S.D.	1.56	1.61	1.65	1.19	1.91	2.03	2.57	2.97
	CV (%)	6	6	8	8	13	18	19	11
R_3	Mean (%)	24.8	24.2	18.1	13.2	14.7	12.5	13.0	28.5
	S.D.	2.68	1.11	0.59	0.72	1.72	2.40	2.57	3.35
	CV (%)	11	5	3	5	12	19	20	12
R_4	Mean (%)	26.7	25.2	20.3	12.2	14.6	10.2	8.9	22.4
	S.D.	3.26	1.97	1.76	0.23	1.59	0.55	1.99	3.94
	CV (%)	12	8	9	2	11	5	22	18
Cent.	Mean (%)	26.7	24.8	19.8	14.3	16.0	10.3	10.6	23.7
	S.D.	3.10	2.24	1.65	2.01	1.62	1.07	3.36	4.87
	CV (%)	12	9	8	14	10	10	32	21
All	Mean (%)	26.6	24.5	19.8	14.2	15.1	11.3	11.7	25.3
	S.D.	2.71	1.82	1.57	1.88	1.69	1.81	3.31	4.50
	CV (%)	10	7	8	13	11	16	28	18

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S9.1 25h	S9.1 31h	S9.1 43h	S9.1 49h	S9.1 55h	S9.1 67h	S10.1 2h	S10.1 8h
	0	28.0	29.2	29.9	27.4	26.3	14.7	28.5	24.0
	1	31.7	32.5	31.2	28.3	26.8	19.6	25.5	24.0
	2	34.4	34.8	31.1	29.6	28.0	18.9	27.4	24.5
	3	33.0	30.3	31.9	30.9	34.3	15.5	26.4	26.1
	4	33.2	31.0	31.6	37.1	33.9	16.8	28.6	25.2
	5	32.7	33.1	31.9	35.3	31.3	16.9	29.0	26.2
	6	30.6	32.3	31.1	31.9	28.9	18.6	29.1	26.2
	7	32.1	34.9	30.3	31.5	30.4	21.1	30.2	25.0
	8	31.5	32.8	30.9	32.4	33.7	19.6	29.6	25.2
	9	31.6	31.0	30.9	30.4	25.8	15.0	24.5	26.0
	10	32.4	33.3	32.2	29.1	21.2	14.7	21.2	23.5
	11	32.3	35.6	33.2	30.4	26.1	22.7	27.6	26.9
	12	30.0	34.6	28.8	34.6	27.2	20.3	27.9	25.4
	13	31.8	32.4	31.9	36.7	29.4	17.7	29.6	24.3
	14	30.9	29.6	31.7	31.0	30.0	12.8	26.9	27.1
	15	31.9	35.2	31.0	30.4	29.0	20.9	28.8	25.8
	16	30.2	31.2	31.2	36.0	27.9	17.8	29.3	26.2
	17	31.3	34.5	31.0	33.0	28.4	19.2	29.4	26.8
	18	27.6	35.6	30.8	31.4	29.5	20.4	28.8	27.0
R_1	Mean (%)	32.9	35.2	31.8	30.1	27.7	20.8	27.9	25.7
	S.D.	1.34	0.40	1.24	0.46	1.47	1.90	0.76	1.20
	CV (%)	4	1	4	2	5	9	3	5
R_2	Mean (%)	31.1	32.3	30.5	35.9	29.7	18.3	28.6	25.6
	S.D.	1.79	2.02	1.51	1.25	3.68	1.80	0.70	0.53
	CV (%)	6	6	5	3	12	10	2	2
R_3	Mean (%)	31.2	33.1	31.3	33.9	28.9	18.5	29.4	25.8
	S.D.	0.60	1.24	0.49	2.51	0.50	0.75	0.25	1.31
	CV (%)	2	4	2	7	2	4	1	5
R_4	Mean (%)	30.0	32.7	31.1	31.6	31.1	17.6	27.8	26.4
	S.D.	2.10	3.00	0.49	0.72	2.29	4.18	0.96	1.07
	CV (%)	7	9	2	2	7	24	3	4
Cent.	Mean (%)	31.9	32.3	31.2	31.3	29.1	17.4	27.1	25.1
	S.D.	1.65	1.79	0.70	2.90	4.07	2.27	2.58	0.98
	CV (%)	5	6	2	9	14	13	10	4
All	Mean (%)	31.4	32.8	31.2	32.0	28.8	18.1	27.7	25.5
	S.D.	1.66	2.05	0.93	2.81	3.16	2.64	2.14	1.10
	CV (%)	5	6	3	9	11	15	8	4

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S10.1 20h	S10.1 26h	S10.1 31h	S10.1 44h	S10.1 50h	S10.1 56h	S10.1 68h	S11.1 2h
	0	40.5	39.6	40.5	40.7	34.9	31.5	28.3	13.4
	1	43.6	43.7	42.3	39.1	36.5	34.2	29.9	10.3
	2	44.6	45.8	44.8	39.6	38.4	35.1	30.9	9.8
	3	44.2	45.2	45.2	39.8	39.3	36.2	30.2	10.0
	4	44.9	45.3	45.4	40.6	38.6	37.0	31.2	10.5
	5	45.6	46.0	46.4	41.6	39.0	38.1	32.5	9.5
	6	45.5	45.7	45.9	41.2	38.0	36.0	31.8	9.5
	7	41.9	45.9	45.9	43.0	40.7	37.7	32.1	4.8
	8	42.8	45.9	46.0	43.0	40.6	37.7	28.5	4.6
	9	43.2	46.2	46.6	43.8	39.1	34.4	25.4	1.8
	10	40.5	44.0	42.7	42.0	39.1	35.4	28.1	0.8
	11	44.5	46.0	44.0	40.4	37.8	35.6	31.2	4.1
	12	43.9	44.3	43.7	39.9	36.9	34.9	31.1	10.0
	13	45.0	45.3	44.6	39.9	38.6	36.4	31.5	8.3
	14	43.5	41.2	43.6	41.2	36.2	35.0	27.2	6.6
	15	44.6	44.3	45.1	40.5	37.2	36.6	31.3	9.4
	16	45.1	45.1	44.7	40.6	37.2	34.8	31.2	10.2
	17	44.2	45.8	44.1	40.1	38.4	35.9	30.8	9.2
	18	42.9	43.8	44.1	43.0	37.5	35.4	31.1	10.0
R_1	Mean (%)	44.6	45.4	44.6	40.2	37.8	35.8	31.1	7.8
	S.D.	0.06	0.93	0.57	0.49	0.60	0.76	0.21	3.18
	CV (%)	0	2	1	1	2	2	1	41
R_2	Mean (%)	44.6	44.9	44.6	40.4	37.6	35.6	31.2	10.2
	S.D.	0.64	0.53	0.85	0.40	0.91	1.24	0.06	0.25
	CV (%)	1	1	2	1	2	3	0	2
R_3	Mean (%)	44.9	45.6	44.9	40.4	38.3	36.1	31.4	9.0
	S.D.	0.66	0.26	0.93	0.70	0.31	0.26	0.51	0.62
	CV (%)	1	1	2	2	1	1	2	7
R_4	Mean (%)	43.1	43.6	44.6	42.4	38.1	36.0	28.9	7.1
	S.D.	0.38	2.35	1.27	1.04	2.26	1.46	1.99	2.73
	CV (%)	1	5	3	2	6	4	7	39
Cent.	Mean (%)	43.4	44.8	44.7	41.3	38.6	35.8	29.9	7.7
	S.D.	1.82	1.92	1.98	1.53	1.67	1.94	2.14	4.06
	CV (%)	4	4	4	4	4	5	7	53
All	Mean (%)	43.7	44.7	44.5	41.1	38.1	35.7	30.2	8.0
	S.D.	1.49	1.73	1.53	1.34	1.45	1.51	1.87	3.33
	CV (%)	3	4	3	3	4	4	6	41

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S11.1 8h	S11.1 20h	S11.1 26h	S11.1 31h	S11.1 44h	S11.1 50h	S11.1 56h	S11.1 68h
	0	14.9	34.6	37.8	38.4	38.8	37.6	36.7	35.1
	1	12.8	32.4	35.9	35.5	38.9	37.1	36.7	34.4
	2	9.8	31.8	35.3	36.2	38.3	37.1	37.1	34.8
	3	9.0	31.9	35.5	36.7	37.7	36.8	36.9	33.7
	4	9.4	32.8	36.7	38.2	39.5	39.0	38.7	36.5
	5	9.1	33.2	36.7	37.4	38.6	38.6	38.6	36.3
	6	9.4	31.6	36.8	38.1	38.6	39.7	39.1	37.2
	7	9.2	31.3	35.2	37.5	38.6	38.2	38.9	36.7
	8	8.8	30.9	35.9	37.5	20.9	36.7	37.3	36.7
	9	8.2	27.5	32.5	28.4	34.2	38.7	38.4	36.5
	10	3.3	19.1	26.8	33.9	27.1	39.1	38.3	36.4
	11	47.5	31.6	34.9	36.5	37.7	38.9	38.2	33.6
	12	8.8	32.1	34.5	36.4	37.2	37.1	36.7	34.7
	13	9.0	32.6	35.1	37.9	38.8	38.2	39.0	36.1
	14	8.4	23.9	29.8	34.9	35.9	34.7	35.9	33.9
	15	9.0	30.9	34.4	36.8	36.3	38.0	36.8	35.9
	16	8.8	32.7	33.8	37.8	39.3	37.5	38.4	34.7
	17	9.1	31.5	35.2	37.0	39.4	35.6	39.2	35.5
	18	9.1	32.7	34.3	37.4	38.8	38.5	38.4	36.1
R_1	Mean (%)	22.1	31.4	34.9	36.5	37.4	38.0	37.4	34.8
	S.D.	22.00	0.47	0.45	0.30	1.03	0.90	0.74	1.15
	CV (%)	100	2	1	1	3	2	2	3
R_2	Mean (%)	9.0	32.5	35.0	37.5	38.7	37.9	37.9	35.3
	S.D.	0.35	0.38	1.51	0.95	1.27	1.00	1.08	1.04
	CV (%)	4	1	4	3	3	3	3	3
R_3	Mean (%)	9.2	31.9	35.7	37.7	38.9	37.8	39.1	36.3
	S.D.	0.21	0.61	0.95	0.59	0.42	2.07	0.10	0.86
	CV (%)	2	2	3	2	1	5	0	2
R_4	Mean (%)	8.8	29.2	33.3	36.6	31.9	36.6	37.2	35.6
	S.D.	0.35	4.65	3.16	1.47	9.61	1.90	1.25	1.47
	CV (%)	4	16	9	4	30	5	3	4
Cent.	Mean (%)	9.4	30.6	35.0	36.2	35.6	38.1	37.9	35.8
	S.D.	2.85	4.21	3.04	2.90	6.04	1.04	0.94	1.14
	CV (%)	30	14	9	8	17	3	2	3
All	Mean (%)	11.2	30.8	34.6	36.4	36.6	37.7	37.9	35.5
	S.D.	9.04	3.64	2.57	2.27	4.74	1.26	1.03	1.12
	CV (%)	80	12	7	6	13	3	3	3

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S11.1 72.5h	S11.1 80h	S11.1 92h	S11.1 96h	S12.1 2h	S12.1 8h	S12.1 20h	S12.1 26h
	0	32.4	31.6	28.8	29.7	10.4	24.1	35.3	43.6
	1	35.7	34.6	32.4	32.6	9.2	23.9	37.1	41.1
	2	37.1	35.7	33.8	33.5	9.0	23.7	36.8	41.0
	3	36.8	36.0	33.4	33.4	8.8	23.3	36.3	40.1
	4	36.8	36.3	29.4	34.2	7.4	22.8	37.2	41.4
	5	36.8	36.2	33.2	33.5	9.2	19.7	36.9	41.4
	6	37.4	37.3	34.4	34.2	9.8	19.8	37.6	42.1
	7	37.8	37.0	34.5	34.3	8.2	16.3	35.8	42.0
	8	36.6	37.3	34.9	34.4	4.5	13.9	30.7	37.7
	9	36.3	36.9	34.6	34.5	5.3	15.3	34.3	40.3
	10	28.6	34.1	33.9	34.0	2.5	15.1	31.8	41.3
	11	35.5	36.1	33.8	33.3	8.3	21.2	38.0	41.8
	12	35.8	35.7	33.1	32.3	8.6	20.5	36.8	39.5
	13	37.3	36.8	34.2	33.9	9.3	18.8	29.0	40.0
	14	36.2	36.1	33.3	33.1	3.9	15.3	34.9	36.6
	15	35.0	35.3	33.7	33.1	8.0	21.0	37.7	42.2
	16	36.8	36.2	34.1	33.9	8.5	20.2	33.0	40.0
	17	36.4	36.7	33.8	33.6	6.0	18.8	35.2	40.6
	18	36.9	36.6	33.7	33.6	8.7	17.6	37.9	39.1
R_1	Mean (%)	35.9	35.7	33.8	33.3	8.4	22.0	37.5	41.7
	S.D.	1.10	0.40	0.06	0.20	0.51	1.50	0.62	0.61
	CV (%)	3	1	0	1	6	7	2	1
R_2	Mean (%)	36.5	36.1	32.2	33.5	8.2	21.1	35.7	40.3
	S.D.	0.58	0.32	2.48	1.02	0.67	1.42	2.32	0.98
	CV (%)	2	1	8	3	8	7	6	2
R_3	Mean (%)	37.0	36.9	34.1	33.9	8.4	19.1	33.9	40.9
	S.D.	0.55	0.32	0.31	0.30	2.06	0.58	4.44	1.08
	CV (%)	1	1	1	1	25	3	13	3
R_4	Mean (%)	36.6	36.7	34.0	33.7	5.7	15.6	34.5	37.8
	S.D.	0.35	0.60	0.83	0.66	2.62	1.87	3.62	1.25
	CV (%)	1	2	2	2	46	12	10	3
Cent.	Mean (%)	35.7	35.7	33.0	33.5	8.6	19.8	35.4	41.1
	S.D.	2.74	1.72	2.07	1.38	2.24	4.01	2.29	1.45
	CV (%)	8	5	6	4	26	20	6	4
All	Mean (%)	35.9	35.9	33.3	33.4	8.2	19.5	35.4	40.6
	S.D.	2.12	1.34	1.60	1.08	2.06	3.26	2.58	1.63
	CV (%)	6	4	5	3	25	17	7	4

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S12.1 32h	S12.1 44h	S12.1 50h	S12.1 56h	S12.1 68h	S12.1 73 h	S12.1 80h	S12.1 92h
	0	41.3	45.2	44.3	42.5	41.5	38.0	35.4	35.1
	1	41.6	47.3	45.4	45.4	43.1	42.7	40.4	36.5
	2	43.3	47.6	47.3	45.9	43.4	43.0	42.1	35.9
	3	43.1	46.7	46.2	46.8	42.8	43.3	42.4	37.1
	4	42.4	40.1	49.2	47.8	43.4	43.8	42.9	40.2
	5	43.7	47.4	49.5	48.4	43.2	44.6	43.5	36.1
	6	45.0	49.3	49.9	47.2	45.0	44.0	43.2	40.3
	7	45.1	49.2	49.8	49.3	68.5	44.7	43.8	40.3
	8	40.4	43.6	46.3	48.0	45.5	43.0	43.0	38.9
	9	43.8	40.2	47.6	48.9	42.4	44.6	42.9	40.3
	10	43.5	48.0	48.1	47.2	40.8	43.7	43.3	41.1
	11	42.1	27.6	46.7	46.3	41.8	44.0	42.9	38.0
	12	40.6	45.6	46.9	44.6	41.3	42.7	41.8	37.3
	13	44.5	48.6	46.6	48.5	44.9	43.7	43.4	40.3
	14	39.7	41.5	46.1	47.2	43.2	44.2	42.5	38.8
	15	42.8	46.5	47.3	43.9	41.6	43.1	40.8	36.7
	16	41.4	47.2	47.2	47.3	44.2	43.7	42.1	39.4
	17	43.7	48.4	48.3	47.7	44.8	44.5	43.4	40.3
	18	44.4	47.6	42.3	48.0	44.6	44.1	43.4	35.6
R_1	Mean (%)	42.7	40.6	47.1	45.4	42.3	43.4	41.9	36.9
	S.D.	0.60	11.24	0.35	1.29	0.99	0.55	1.06	1.06
	CV (%)	1	28	1	3	2	1	3	3
R_2	Mean (%)	41.5	44.3	47.8	46.6	43.0	43.4	42.3	39.0
	S.D.	0.90	3.72	1.25	1.72	1.50	0.61	0.57	1.50
	CV (%)	2	8	3	4	3	1	1	4
R_3	Mean (%)	44.4	48.8	48.3	47.8	44.9	44.1	43.3	40.3
	S.D.	0.66	0.47	1.65	0.66	0.10	0.40	0.12	0.00
	CV (%)	1	1	3	1	0	1	0	0
R_4	Mean (%)	41.5	44.2	44.9	47.7	44.4	43.8	43.0	37.8
	S.D.	2.54	3.10	2.25	0.46	1.16	0.67	0.45	1.88
	CV (%)	6	7	5	1	3	2	1	5
Cent.	Mean (%)	43.0	45.9	47.6	47.0	45.4	43.2	42.1	38.3
	S.D.	1.48	3.26	1.90	1.91	7.77	1.87	2.40	2.22
	CV (%)	3	7	4	4	17	4	6	6
All	Mean (%)	42.8	45.1	47.1	46.9	44.5	43.4	42.3	38.3
	S.D.	1.59	5.10	1.90	1.77	5.97	1.46	1.89	1.97
	CV (%)	4	11	4	4	13	3	4	5

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S12.2 2h	S12.2 8h	S12.2 26h	S12.2 32h	S12.2 44h	S12.2 56h	S12.2 62h	S12.2 74h
	0	7.9	22.1	39.6	41.2	40.1	46.7	44.8	48.2
	1	5.3	19.9	43.0	46.1	45.9	47.4	48.2	45.3
	2	5.6	23.3	43.1	47.0	51.1	51.1	49.8	48.2
	3	4.8	17.9	33.0	34.5	38.3	38.0	33.7	19.2
	4	4.7	18.0	41.9	33.6	37.6	36.8	34.1	44.8
	5	7.4	16.1	43.0	43.4	48.3	48.9	47.9	48.3
	6	6.7	20.0	40.1	47.3	49.3	51.2	49.3	48.7
	7	14.4	10.5	39.0	43.1	48.9	49.1	51.3	49.1
	8	16.2	8.9	37.2	43.8	48.4	50.1	50.1	49.1
	9	21.7	7.2	28.2	36.6	43.7	47.0	42.6	45.4
	10	17.9	12.5	38.9	40.9	45.7	47.7	47.3	46.8
	11	8.1	22.4	42.2	45.6	50.5	50.8	49.2	48.4
	12	7.1	22.7	40.3	45.0	49.0	47.1	47.4	47.0
	13	7.0	18.7	42.0	44.6	47.9	49.5	48.8	41.6
	14	6.3	22.9	43.6	46.8	49.7	51.2	50.4	43.2
	15	6.7	23.1	44.0	46.8	50.3	48.4	50.0	47.9
	16	6.5	23.7	43.4	46.7	49.8	49.8	49.0	48.8
	17	6.7	23.0	41.5	43.9	49.6	50.1	49.1	46.5
	18	14.8	12.4	37.1	37.5	48.8	49.2	50.6	47.5
R_1	Mean (%)	6.8	22.9	43.1	46.5	50.6	50.1	49.7	48.2
	S.D.	1.25	0.47	0.90	0.76	0.42	1.48	0.42	0.25
	CV (%)	18	2	2	2	1	3	1	1
R_2	Mean (%)	6.1	21.5	41.9	41.8	45.5	44.6	43.5	46.9
	S.D.	1.25	3.04	1.55	7.12	6.82	6.86	8.18	2.00
	CV (%)	20	14	4	17	15	15	19	4
R_3	Mean (%)	6.8	20.6	41.2	45.3	48.9	50.3	49.1	45.6
	S.D.	0.17	2.21	0.98	1.80	0.91	0.86	0.25	3.63
	CV (%)	3	11	2	4	2	2	1	8
R_4	Mean (%)	12.4	14.7	39.3	42.7	49.0	50.2	50.4	46.6
	S.D.	5.36	7.29	3.72	4.75	0.67	1.00	0.25	3.05
	CV (%)	43	49	9	11	1	2	0	7
Cent.	Mean (%)	10.2	16.0	38.8	41.6	45.2	46.7	45.4	44.8
	S.D.	6.12	5.47	4.63	4.82	4.69	4.87	6.18	8.65
	CV (%)	60	34	12	12	10	10	14	19
All	Mean (%)	9.3	18.2	40.1	42.9	47.0	47.9	47.0	45.5
	S.D.	5.04	5.39	4.01	4.35	4.14	3.98	5.06	6.69
	CV (%)	54	30	10	10	9	8	11	15

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S12.2 86h	S12.3 2h	S12.3 8h	S12.3 20h	S12.3 26h	S12.3 32h	S12.3 44h	S12.3 50h
	0	42.7	0.1	26.9	38.3	43.0	45.6	38.7	45.2
	1	43.4	13.3	26.9	37.3	40.5	43.2	36.1	43.4
	2	46.1	13.0	26.7	37.9	42.6	44.7	35.8	44.1
	3	44.1	12.9	27.3	37.4	41.4	42.2	35.4	44.2
	4	43.2	13.6	27.0	39.6	42.0	43.5	37.4	47.8
	5	39.7	13.5	26.0	40.1	40.7	44.6	37.1	44.4
	6	44.7	11.4	21.1	32.2	38.3	42.9	35.8	45.4
	7	42.5	12.0	21.4	31.7	37.8	39.9	35.1	41.4
	8	47.6	17.3	15.8	26.4	38.5	41.0	34.5	41.6
	9	40.5	4.3	16.8	19.3	36.8	38.2	29.3	40.0
	10	44.7	7.8	12.7	21.5	34.3	36.0	30.1	33.3
	11	45.5	12.5	25.7	37.4	41.3	40.6	29.3	43.8
	12	44.2	13.2	26.1	35.1	39.6	42.6	36.0	42.0
	13	44.7	14.0	26.8	39.5	41.2	39.2	37.1	46.1
	14	45.9	13.4	24.1	33.4	35.1	40.0	36.7	38.0
	15	46.5	13.4	26.6	10.1	39.5	44.0	35.7	43.5
	16	45.8	11.8	26.6	31.0	41.6	42.5	36.2	44.0
	17	45.3	12.8	21.8	37.0	42.1	42.5	37.4	44.2
	18	41.2	11.0	15.8	36.9	38.7	41.3	35.0	38.8
R_1	Mean (%)	46.0	13.0	26.3	28.5	41.1	43.1	33.6	43.8
	S.D.	0.50	0.45	0.55	15.91	1.56	2.19	3.72	0.30
	CV (%)	1	3	2	56	4	5	11	1
R_2	Mean (%)	44.4	12.9	26.6	35.2	41.1	42.9	36.5	44.6
	S.D.	1.31	0.95	0.45	4.30	1.29	0.55	0.76	2.95
	CV (%)	3	7	2	12	3	1	2	7
R_3	Mean (%)	44.9	12.7	23.2	36.2	40.5	41.5	36.8	45.2
	S.D.	0.35	1.30	3.11	3.71	1.99	2.03	0.85	0.96
	CV (%)	1	10	13	10	5	5	2	2
R_4	Mean (%)	44.2	13.9	18.6	32.2	37.4	40.8	35.4	39.5
	S.D.	3.21	3.18	4.79	5.35	2.02	0.68	1.15	1.89
	CV (%)	7	23	26	17	5	2	3	5
Cent.	Mean (%)	43.6	10.8	22.6	32.9	39.6	42.0	35.0	42.8
	S.D.	2.28	4.90	5.37	7.41	2.71	2.96	2.89	3.82
	CV (%)	5	45	24	23	7	7	8	9
All	Mean (%)	44.0	11.6	23.3	32.7	39.7	41.8	35.2	42.7
	S.D.	2.05	3.83	4.72	8.08	2.47	2.43	2.70	3.34
	CV (%)	5	33	20	25	6	6	8	8

Refer to page C1 for a visual representation of the bin locations.

	Bin Location	CO_2 Concentration (%)							
		S12.3 55h	S12.3 68h	S12.3 74h	S12.3 80h	S12.3 92h	S13.1 21h	S13.1 45h	S13.1 72h
	0	42.8	33.5	40.0	37.1	27.5	1.8*	N/A*	1.8*
	1	43.4	33.7	40.4	35.4	28.2	16.8	32.5	34.4
	2	43.7	29.2	40.6	37.6	28.7	18.6	35.7	38.8
	3	43.6	29.7	38.3	6.0*	27.5	18.9	36.1	37.8
	4	44.7	32.1	42.2	1.0*	30.7	18.8	36.5	38.9
	5	42.9	35.1	40.7	37.4	30.0	19.1	35.7	38.8
	6	45.9	34.3	39.2	44.0	29.9	18.7	35.5	38.8
	7	43.3	31.7	36.8	43.6	27.2	18.7	36.4	39.1
	8	42.4	32.5	39.5	42.3	27.5	18.5	35.9	39.3
	9	40.9	27.8	37.5	37.9	23.0	6.8*	19.4*	33.1
	10	37.5	28.2	40.9	41.5	22.5	N/A*	25.9	34.4
	11	44.7	32.8	38.5	44.1	28.8			
	12	42.2	32.0	40.8	42.1	26.5			
	13	45.2	28.7	39.2	41.4	29.2			
	14	40.1	31.2	37.9	43.7	27.4			
	15	38.9	32.2	37.9	42.4	29.8			
	16	43.5	32.1	39.3	42.1	31.2			
	17	44.7	32.7	39.5	43.9	28.9			
	18	44.7	32.7	41.7	42.4	28.4			
R_1	Mean (%)	42.4	31.4	39.0	41.4	29.1			
	S.D.	3.10	1.93	1.42	3.37	0.61			
	CV (%)	7	6	4	8	2			
R_2	Mean (%)	43.5	32.1	40.8	42.1	29.5			
	S.D.	1.25	0.06	1.45	0.00	2.58			
	CV (%)	3	0	4	0	9			
R_3	Mean (%)	45.3	31.9	39.3	43.1	29.3			
	S.D.	0.60	2.88	0.17	1.47	0.51			
	CV (%)	1	9	0	3	2			
R_4	Mean (%)	42.4	32.1	39.7	42.8	27.8			
	S.D.	2.30	0.81	1.91	0.78	0.55			
	CV (%)	5	3	5	2	2			
Cent.	Mean (%)	42.8	31.6	39.6	39.6	27.5	18.5	34.5	37.3
	S.D.	2.17	2.53	1.60	3.20	2.64	0.72	3.43	2.39
	CV (%)	5	8	4	8	10	4	10	6
All	Mean (%)	42.9	31.7	39.5	41.1	28.0			
	S.D.	2.20	2.07	1.46	2.85	2.25			
	CV (%)	5	7	4	7	8			

Refer to page C1 for a visual representation of the bin locations.
* Not included in analysis.

	Bin Location	CO_2 Concentration (%)							
		S13.1 96h	S13.2 21h	S13.2 45h	S13.2 69h	S13.2 92h	S14.1 2h	S14.1 8h	S14.1 20h
	0	1.1*	N/A*	N/A*	N/A*	N/A*	30.9	44.9	57.0
	1	33.1	25.8	36.9	42.6	40.3	47.5	61.8	58.0
	2	36.3	26.9	39.7	45.7	45.8	47.6	64.9	62.3
	3	37.4	27.5	41.5	45.3	44.1	37.7	61.1	59.7
	4	37.1	27.1	35.2	44.0	46.1	47.9	60.6	60.9
	5	36.5	22.4	35.8	42.0	46.7	46.9	65.5	57.6
	6	36.7	22.4	38.3	42.0	47.2	52.1	57.7	49.4
	7	37.1	26.5	35.4	44.7	46.7	12.2	32.3	37.3
	8	37.5	17.6	31.0	41.6	46.9	3.6	14.6	25.9
	9	34.5	16.5	28.1	38.3	42.4	2.0	8.7	18.4
	10	37.5	25.8	33.0	38.7	42.6	1.5	8.4	16.2
	11						46.8	59.8	56.2
	12						49.1	59.7	57.0
	13						48.9	56.7	49.2
	14						13.3	19.8	27.1
	15						35.1	51.2	58.0
	16						52.8	55.3	56.9
	17						56.0	57.4	50.4
	18						14.1	20.8	25.7
R_1	Mean (%)						43.2	58.6	58.8
	S.D.						7.00	6.92	3.13
	CV (%)						16	12	5
R_2	Mean (%)						49.9	58.5	58.3
	S.D.						2.55	2.84	2.28
	CV (%)						5	5	4
R_3	Mean (%)						52.3	57.3	49.7
	S.D.						3.56	0.51	0.64
	CV (%)						7	1	1
R_4	Mean (%)						10.3	18.4	26.2
	S.D.						5.84	3.33	0.76
	CV (%)						57	18	3
Cent.	Mean (%)	36.4	23.9	35.5	42.5	44.9	30.0	43.7	45.7
	S.D.	1.45	4.02	4.01	2.55	2.39	20.93	23.42	17.93
	CV (%)	4	17	11	6	5	70	54	39
All	Mean (%)						34.0	45.3	46.5
	S.D.						19.49	20.54	15.81
	CV (%)						57	45	34

Refer to page C1 for a visual representation of the bin locations.
* Not included in analysis.

	Bin Location	CO_2 Concentration (%)							
		S14.1 26h	S14.1 32h	S14.1 44h	S14.1 50h	S14.1 56h	S14.1 68h	S15.1 2h	S15.1 8h
	0	55.1	45.4	32.3	37.9	42.4	33.4	42.0	55.5
	1	58.4	46.0	48.2	48.1	33.4	36.3	42.2	62.9
	2	60.8	54.0	51.5	45.7	37.6	38.8	49.9	64.4
	3	59.7	43.8	30.9	28.2	7.0*	6.7*	63.6	62.8
	4	54.3	28.1*	5.5*	24.6*	1.4*	1.3*	68.5	61.6
	5	50.1	39.6	32.4	32.3	27.5	28.0	66.2	63.8
	6	41.3	38.1	32.8	31.3	29.7	28.7	67.9	67.1
	7	41.1	38.7	36.4	32.8	29.7	30.7	26.9	34.5
	8	31.0	30.1	33.3	30.9	30.5	28.9	11.9	17.0
	9	21.5	24.2	24.3	26.8	28.1	28.2	8.9	12.5
	10	18.2	25.5	29.0	30.2	28.8	28.6	8.6	11.4
	11	54.3	52.1	47.7	45.7	43.1	38.9	44.5	58.0
	12	48.8	45.7	33.1	31.7	34.6	33.8	58.0	63.7
	13	40.5	39.8	33.6	31.1	31.9	30.1	12.4	37.3
	14	27.2	29.8	27.8	30.1	30.8	28.7	51.4	57.0
	15	54.2	52.3	47.6	44.6	43.1	38.6	42.6	55.9
	16	50.0	46.7	41.5	37.8	35.8	34.7	19.2	57.4
	17	43.6	37.3	33.7	32.1	31.4	29.6	44.3	55.6
	18	27.9	29.9	28.7	28.1	27.1	27.8	16.2	24.4
R_1	Mean (%)	56.4	52.8	48.9	45.3	41.3	38.8	45.7	59.4
	S.D.	3.78	1.04	2.22	0.64	3.18	0.15	3.79	4.51
	CV (%)	7	2	5	1	8	0	8	8
R_2	Mean (%)	51.0	46.2	37.3	34.8	35.2	34.3	56.4	60.3
	S.D.	2.89	0.71	5.94	4.31	0.85	0.64	25.97	3.21
	CV (%)	6	2	16	12	2	2	46	5
R_3	Mean (%)	41.8	38.4	33.4	31.5	31.0	29.5	41.5	53.3
	S.D.	1.61	1.28	0.49	0.53	1.15	0.71	27.85	15.03
	CV (%)	4	3	1	2	4	2	67	28
R_4	Mean (%)	28.7	29.9	29.9	29.7	29.5	28.5	26.5	32.8
	S.D.	2.02	0.15	2.95	1.44	2.06	0.59	21.67	21.28
	CV (%)	7	1	10	5	7	2	82	65
Cent.	Mean (%)	44.7	38.5	35.1	34.4	32.0	31.3	41.5	46.7
	S.D.	15.34	9.53	8.42	7.23	5.00	3.97	24.15	23.03
	CV (%)	34	25	24	21	16	13	58	49
All	Mean (%)	44.1	39.9	35.8	34.7	33.3	32.0	39.2	48.5
	S.D.	13.30	9.16	7.99	6.83	5.40	4.11	21.22	19.18
	CV (%)	30	23	22	20	16	13	54	40

Refer to page C1 for a visual representation of the bin locations.
* Not included in analysis.

Appendix C - Data from Sealing Experiments

	Bin Location	CO_2 Concentration (%)							
		S15.1 26h	S15.1 32h	S15.1 44h	S15.1 56h	S15.1 62h	S15.1 74h	S15.1 86h	S15.2 2h
	0	56.1	57.9	53.7	50.7	47.9	44.0	40.3	44.5
	1	54.5	54.3	51.8	48.5	41.3	42.3	39.9	55.0
	2	59.6	56.0	37.4	50.3	38.6	40.3	39.9	55.1
	3	54.6	54.0	46.4	48.5	39.7	40.9	39.7	60.3
	4	53.9	49.4	47.5	46.3	4.7	42.7	42.3	60.2
	5	54.6	44.7	43.7	44.3	44.1	42.3	40.5	50.4
	6	44.1	42.9	42.9	43.3	44.5	44.7	41.3	35.4
	7	42.8	41.6	43.1	42.5	42.9	31.4	39.6	24.9
	8	28.5	37.3	38.7	41.5	39.2	38.5	34.9	14.8
	9	22.8	34.7	35.0	37.3	35.6	35.8	33.1	10.6
	10	22.9	34.2	33.3	35.6	34.7	35.0	33.2	12.4
	11	53.0	53.7	48.7	48.8	40.9	41.4	37.8	50.9
	12	49.5	38.4	48.4	45.9	34.6	40.0	40.1	55.1
	13	15.1*	8.8*	18.3*	12.3*	N/A*	N/A*	N/A*	41.4
	14	47.5	34.0	35.6	35.8	34.8	37.3	35.7	14.1
	15	54.1	50.3	46.5	46.6	41.3	39.9	37.5	51.2
	16	55.7	48.7	47.6	45.5	43.8	42.9	42.3	49.1
	17	46.7	43.8	43.4	44.4	43.3	42.3	41.4	52.8
	18	32.4	40.8	40.2	43.6	39.2	40.1	37.6	14.2
R_1	Mean (%)	55.6	53.3	44.2	48.6	40.3	40.5	38.4	52.4
	S.D.	3.54	2.87	5.99	1.86	1.46	0.78	1.31	2.34
	CV (%)	6	5	14	4	4	2	3	4
R_2	Mean (%)	52.5	46.0	47.5	46.3	40.2	40.9	40.0	54.8
	S.D.	3.19	6.16	0.49	0.40	5.59	1.62	1.27	5.56
	CV (%)	6	13	1	1	14	4	3	10
R_3	Mean (%)	45.4	43.4	43.2	43.9	43.9	43.5	41.4	43.2
	S.D.	1.84	0.64	0.35	0.78	0.85	1.70	0.07	8.84
	CV (%)	4	1	1	2	2	4	0	20
R_4	Mean (%)	36.1	37.4	38.2	40.3	37.7	38.6	36.1	14.4
	S.D.	10.04	3.40	2.35	4.04	2.54	1.40	1.39	0.38
	CV (%)	28	9	6	10	7	4	4	3
Cent.	Mean (%)	44.9	46.1	43.0	44.4	41.2	39.8	38.5	38.5
	S.D.	13.96	8.71	6.57	5.03	4.07	4.19	3.24	19.72
	CV (%)	31	19	15	11	10	11	8	51
All	Mean (%)	46.3	45.4	43.6	44.4	40.6	40.1	36.7	39.6
	S.D.	11.80	7.94	5.86	4.57	3.91	3.42	9.30	18.21
	CV (%)	25	17	13	10	10	9	25	46

Refer to page C1 for a visual representation of the bin locations.
* Not included in analysis.

	Bin Location	CO_2 Concentration (%)							
		S15.2 8h	S15.2 20h	S15.2 26h	S15.2 32h	S15.2 45h	S15.2 50h	S15.2 55h	S15.2 68h
	0	47.9	61.3	57.5	51.5	47.1	54.8	46.4	43.3
	1	64.7	64.4	60.1	47.8	38.4	49.7	32.3	35.5
	2	66.4	60.2	60.7	53.4	39.7	50.3	38.8	27.0
	3	55.0	11.5*	49.1	9.4*	8.3*	40.1*	26.3*	4.7*
	4	50.9	2.8*	45.7	1.7*	2.1*	36.7*	21.6*	0.9*
	5	66.0	57.6	53.2	43.3	35.5	48.0	44.9	31.4
	6	59.6	53.5	47.2	47.9	37.4	48.0	47.2	35.3
	7	38.7	48.9	51.2	47.7	39.6	47.8	46.0	35.8
	8	18.1	32.0	41.4	43.2	36.8	47.9	44.7	37.2
	9	13.5	24.2	32.0	40.8	33.0	41.0	44.4	30.5
	10	11.1	18.7	27.3	58.4	31.7	44.5	44.1	29.5
	11	59.1	60.8	61.0	54.8	49.9	48.8	48.8	37.8
	12	61.7	60.3	58.1	46.0	48.3	47.3	46.4	34.4
	13	57.6	54.9	51.6	47.2	41.4	47.0	46.6	33.9
	14	27.7	35.2	43.2	59.1	40.9	46.4	47.2	13.5
	15	56.0	58.4	60.9	59.8	24.8	48.9	47.6	30.9
	16	55.3	59.1	57.5	59.1	29.9	45.1	47.6	33.0
	17	58.4	56.4	47.2	47.4	37.3	45.9	47.8	34.8
	18	25.6	36.5	39.4	45.2	34.7	45.0	43.9	33.2
R_1	Mean (%)	60.5	59.8	60.9	56.0	38.1	49.3	45.1	31.9
	S.D.	5.34	1.25	0.15	3.36	12.62	0.84	5.46	5.47
	CV (%)	9	2	0	6	33	2	12	17
R_2	Mean (%)	56.0	59.7	53.8	52.6	39.1	46.2	47.0	33.7
	S.D.	5.43	0.85	6.99	9.26	13.01	1.56	0.85	0.99
	CV (%)	10	1	13	18	33	3	2	3
R_3	Mean (%)	58.5	54.9	48.7	47.5	38.7	47.0	47.2	34.7
	S.D.	1.01	1.45	2.54	0.36	2.34	1.05	0.60	0.71
	CV (%)	2	3	5	1	6	2	1	2
R_4	Mean (%)	23.8	34.6	41.3	49.2	37.5	46.4	45.3	28.0
	S.D.	5.05	2.32	1.90	8.66	3.15	1.45	1.72	12.69
	CV (%)	21	7	5	18	8	3	4	45
Cent.	Mean (%)	44.8	46.8	47.8	48.2	37.7	48.0	43.2	33.9
	S.D.	21.35	17.30	10.82	5.55	4.48	3.80	4.74	4.90
	CV (%)	48	37	23	12	12	8	11	14
All	Mean (%)	47.0	49.6	49.7	50.2	38.0	47.4	45.0	32.8
	S.D.	18.56	14.40	9.87	6.19	6.52	2.93	3.99	6.19
	CV (%)	39	29	20	12	17	6	9	19

Refer to page C1 for a visual representation of the bin locations.
* Not included in analysis.

	Bin Location	CO_2 Concentration (%)							
		S15.2 74h	S15.2 80h	S15.2 92h	S15.3 7h	S15.3 20h	S15.3 26h	S15.3 32h	S15.3 44h
	0	41.1	37.2	26.2	62.8	60.5	94.4	58.8	54.3
	1	42.0	37.0	29.9	66.9	64.3	65.1	62.7	57.0
	2	36.3	36.3	34.0	71.1	66.6	64.9	64.3	59.6
	3	30.9*	35.7	32.3	70.7	66.7	63.6	62.8	57.2
	4	32.2*	37.2	28.4	57.6	56.4	51.5	49.0	43.8
	5	44.5	37.4	34.6	67.8	59.5	48.4	45.8	47.3
	6	46.1	39.2	32.2	58.9	57.5	48.1	41.8	46.8
	7	43.0	36.4	33.4	34.8	44.7	45.4	44.3	45.2
	8	44.3	36.6	30.7	14.6	28.2	34.6	38.0	44.5
	9	40.6	32.9	31.1	12.4	17.6	26.2	34.1	39.8
	10	42.6	33.7	35.9	8.6	17.5	24.5	28.7	41.5
	11	46.0	33.7	36.6	56.4	59.3	57.6	58.3	55.5
	12	43.8	35.8	32.4	66.0	64.3	54.0	52.8	51.5
	13	45.7	38.7	30.3	64.1	59.8	44.3	43.2	41.2
	14	45.7	33.6	39.9	57.4	47.7	30.6	40.6	38.0
	15	43.2	36.0	35.6	61.1	52.7	55.8	53.3	41.0
	16	43.4	38.2	36.7	59.4	61.2	57.2	51.0	50.6
	17	43.8	39.3	38.4	55.6	57.4	54.1	46.5	47.2
	18	44.0	38.7	33.1	22.6	38.4	38.6	42.3	43.4
R_1	Mean (%)	41.8	35.3	35.4	62.9	59.5	59.4	58.6	52.0
	S.D.	4.99	1.42	1.31	7.51	6.95	4.82	5.51	9.77
	CV (%)	12	4	4	12	12	8	9	19
R_2	Mean (%)	43.6	37.1	32.5	61.0	60.6	54.2	50.9	48.6
	S.D.	0.28	1.21	4.15	4.42	3.98	2.86	1.90	4.21
	CV (%)	1	3	13	7	7	5	4	9
R_3	Mean (%)	45.2	39.1	33.6	59.5	58.2	48.8	43.8	45.1
	S.D.	1.23	0.32	4.24	4.29	1.36	4.94	2.41	3.35
	CV (%)	3	1	13	7	2	10	6	7
R_4	Mean (%)	44.7	36.3	34.6	31.5	38.1	34.6	40.3	42.0
	S.D.	0.91	2.56	4.77	22.76	9.75	4.00	2.17	3.48
	CV (%)	2	7	14	72	26	14	5	8
Cent.	Mean (%)	42.3	36.3	31.7	47.8	49.0	51.5	48.2	48.8
	S.D.	2.83	1.75	2.84	25.17	19.12	20.16	12.41	6.94
	CV (%)	7	5	9	53	39	39	26	14
All	Mean (%)	43.3	36.5	33.2	51.0	51.6	50.5	48.3	47.7
	S.D.	2.42	1.95	3.46	20.97	15.51	16.33	10.05	6.58
	CV (%)	6	5	10	41	30	32	21	14

Refer to page C1 for a visual representation of the bin locations.
* Not included in analysis.

	Bin Location	CO_2 Concentration (%)					
		S15.3 51h	S15.3 56h	S15.3 68h	S15.3 74h	S15.3 80h	S15.3 92h
	0	47.2	48.8	34.2	31.3	32.5	29.4
	1	52.2	52.0	36.5	32.0	31.0	27.2
	2	54.7	51.9	32.8	27.1	33.1	28.3
	3	49.5	49.8	34.1	28.0	28.4	28.4
	4	37.1	51.0	28.4	22.8	30.8	29.8
	5	40.5	46.2	34.8	31.1	26.7	22.4
	6	39.3	41.6	31.5	26.6	32.5	30.9
	7	37.8	42.4	30.4	26.9	28.4	26.1
	8	36.9	41.4	28.2	25.9	28.4	29.2
	9	34.5	38.4	27.4	23.6	30.5	21.4
	10	32.3	37.8	29.7	24.0	23.1	22.1
	11	47.4	48.7	36.5	31.4	26.0	26.1
	12	41.1	45.7	34.9	30.6	28.4	26.5
	13	41.0	42.2	26.9	23.3	29.1	28.9
	14	35.2	39.9	29.2	23.5	31.4	29.1
	15	34.2	39.2	26.2	24.1	28.6	26.2
	16	43.8	44.2	24.1	26.2	22.4	19.9
	17	40.7	44.9	30.3	30.9	31.4	18.4
	18	41.8	44.4	28.4	30.6	31.5	19.5
R_1	Mean (%)	45.4	46.6	31.8	27.5	29.2	26.9
	S.D.	10.39	6.61	5.22	3.67	3.59	1.24
	CV (%)	23	14	16	13	12	5
R_2	Mean (%)	40.7	47.0	29.1	26.5	27.2	25.4
	S.D.	3.37	3.57	5.44	3.91	4.33	5.04
	CV (%)	8	8	19	15	16	20
R_3	Mean (%)	40.3	42.9	29.6	26.9	31.0	26.1
	S.D.	0.91	1.76	2.39	3.81	1.73	6.71
	CV (%)	2	4	8	14	6	26
R_4	Mean (%)	38.0	41.9	28.6	26.7	30.4	25.9
	S.D.	3.43	2.29	0.53	3.61	1.76	5.57
	CV (%)	9	5	2	14	6	21
Cent.	Mean (%)	42.0	45.6	31.6	27.2	29.6	26.8
	S.D.	7.59	5.43	3.05	3.17	2.97	3.38
	CV (%)	18	12	10	12	10	13
All	Mean (%)	41.4	44.8	30.8	27.4	29.2	25.8
	S.D.	6.29	4.59	3.65	3.28	3.00	3.92
	CV (%)	15	10	12	12	10	15

Refer to page C1 for a visual representation of the bin locations.

Appendix D - Purging Data Collected from the Full-size Welded-steel Hopper Bins

The experimental data collected during purging of the welded-steel hopper bins with CO_2. A brief summary of the purging trials is given below.

Experiment F1.1: With the welded-steel hopper bin approximately 75% filled, 81.5 kg of dry ice was augered onto the grain surface. After closing the top, gases escaped through the bottom purge valve.

Experiment F2.1: With the welded-steel hopper bin approximately 75% filled, 88 kg of dry ice was augered onto the grain surface. After closing the top, gases escaped through the top purge valve.

Experiment F3.1: With the welded-steel hopper bin approximately 75% filled, 83 kg of dry ice was placed inside the steel holding box. Gases escaped through the top purge valve.

Experiments F4.1 through F4.4: With the welded-steel hopper bin approximately 75% filled, 83 kg of dry ice was placed inside the steel holding box. Gases escaped through the bottom purge valve.

Experiment F4.5: With the welded-steel hopper bin approximately 75% filled, 83 kg of dry ice was placed inside the steel holding box. Gases escaped through the bottom purge valve. PURGING DATA WERE NOT COLLECTED FOR THIS EXPERIMENT.

Experiments F4.6 through F4.9: With the welded-steel hopper bin approximately 75% filled, 107 kg of dry ice was placed inside the steel holding box. Gases escaped through the bottom purge valve.

Experiment	Time Since Start (min)	Temperature Leaving Bin (°C)	Gauge Pressure Inside Bin (kPa)	Flow Leaving Bin ($L \cdot min^{-1}$)	Concentration Leaving Bin (% CO_2)
F1.1	0	8.6	0.43	7.84	0.0
	15	7.1	*	17.32	0.5
	190	9.0	0.72	4.46	16.0
	205	8.6	1.10	6.77	33.9
	220	8.4	1.33	7.86	41.1
	235	7.7	1.39	7.86	43.3
	250	7.7	1.39	7.86	43.6
	265	8.0	1.45	7.86	43.0
F2.1	0	20.7	0.53	2.72	1.0
	15	19.7	1.57	18.32	23.3
	30	23.6	1.57	17.53	40.0
	45	22.9	1.57	17.53	43.2
	60	23.4	1.57	17.13	42.5
	75	24.1	1.57	18.32	40.7
	90	24.7	1.57	17.13	40.7
	105	24.3	1.57	15.95	41.3
	120	25.8	1.57	14.79	39.9
	135	26.3	1.57	13.64	37.2
F3.1	0	36.0	0.20	0.00	0.0
	15	36.6	0.80	4.46	8.7
	30	37.2	1.20	6.95	9.3
	45	36.4	1.47	8.40	8.8
	60	37.5	1.66	9.13	9.0
	75	37.4	1.78	9.50	9.2
	90	37.7	1.80	9.69	9.1
	105	37.7	1.78	9.50	8.9
	120	37.2	1.76	9.50	9.5
	135	38.0	1.94	9.69	14.2
	150	38.3	1.88	9.69	14.2
F4.1	0	13.7	0.20	0.00	2.3
	15	15.0	0.84	4.46	6.1
	30	14.6	0.80	4.11	6.2
	45	14.2	0.82	4.46	6.1
	60	14.5	0.81	4.29	5.9
	75	14.5	0.69	2.89	5.9
	90	14.9	0.69	2.72	5.6
	105	14.8	0.58	0.00	5.2
	120	14.8	0.63	2.38	5.8
	135	14.9	0.57	0.00	4.7

* Excessive pressure forced water out of pressure relief valve.

Experiment	Time Since Start (min)	Temperature Leaving Bin (°C)	Gauge Pressure Inside Bin (kPa)	Flow Leaving Bin ($L \cdot min^{-1}$)	Concentration Leaving Bin (% CO_2)
F4.2	0	14.4	0.04	0.00	0.0
	15	16.8	0.51	0.00	1.1
	30	17.8	0.84	4.46	8.4
	45	18.0	0.86	4.46	9.2
	60	17.7	0.86	4.29	8.8
	75	17.8	0.82	3.94	9.1
	90	17.8	0.83	3.94	9.2
	105	17.6	0.81	3.76	9.3
	120	17.7	0.80	3.59	8.8
	135	18.0	0.76	3.41	8.8
	150	18.1	0.70	3.07	9.1
	165	17.8	0.47	0.00	1.7
	180	17.4	0.63	2.20	8.8
F4.3	0	20.0	0.59	1.69	0.0
	15	20.5	0.96	5.17	0.0
	30	20.9	0.86	4.11	0.0
	45	20.7	0.84	4.11	1.6
	60	20.9	0.80	3.76	1.9
	75	20.8	0.67	2.38	2.1
	90	21.0	0.67	2.38	1.7
	105	21.0	0.72	2.72	1.7
	120	21.1	0.67	2.20	1.4
F4.4	0	15.6	0.07	0.00	0.0
	15	15.6	0.30	0.00	2.5
	30	15.6	0.41	0.00	2.6
	45	15.4	0.38	0.00	2.7
	60	15.5	0.33	0.00	2.7
	75	15.5	0.32	0.00	2.8
	90	15.6	0.30	0.00	2.8
	105	15.7	0.28	0.00	2.8
	120	15.5	0.26	0.00	2.8
F4.6	0	21.6	0.08	0.00	0.0
	15	22.4	0.82	4.11	12.1
	30	22.8	1.08	5.88	13.0
	45	23.1	1.08	5.88	13.0
	60	23.1	0.88	4.46	13.1
	75	23.1	0.88	4.29	12.5
	90	23.0	0.82	3.76	13.2
	105	23.1	0.74	2.89	13.3
	120	22.8	0.78	3.76	13.3

Experiment	Time Since Start (min)	Temperature Leaving Bin (°C)	Gauge Pressure Inside Bin (kPa)	Flow Leaving Bin ($L \cdot min^{-1}$)	Concentration Leaving Bin (% CO_2)
F4.7	0	20.5	0.02	0.00	0.9
	15	21.6	0.71	3.07	11.2
	30	21.7	0.72	3.24	12.0
	45	21.7	0.67	2.38	12.2
	60	21.8	0.61	1.35	11.6
	75	21.8	0.67	2.55	11.8
	90	21.8	0.65	2.20	12.3
	105	21.8	0.65	2.20	10.4
	120	21.8	0.65	1.86	12.1
F4.8	0	21.0	0.02	0.00	0.0
	15	21.2	0.37	0.00	9.2
	30	22.0	0.86	4.46	10.7
	45	22.6	0.96	5.17	10.8
	60	22.0	0.94	4.29	10.9
	75	21.7	0.92	4.11	10.0
	90	22.7	0.91	3.76	9.7
	105	22.4	0.88	3.76	10.0
	120	22.6	0.86	3.76	10.4
	135	23.8	0.85	3.59	10.6
F4.9	0	19.0	0.06	0.00	0.0
	15	19.0	0.44	0.00	0.0
	30	19.2	0.50	0.00	0.8
	45	19.3	0.52	0.00	0.0
	60	19.5	0.52	0.00	0.0
	75	19.6	0.52	0.00	0.0
	90	19.6	0.52	0.00	0.0
	105	19.5	0.32	0.00	0.0

Appendix E - Data from Experimental Fumigations in Full-size Welded-steel Hopper Bins

Carbon dioxide and temperature data collected during experimental fumigations in full-size hopper bins. A brief summary of the experimental details is given below. Data were collected along the centreline of the bin (locations 0 through 10 as illustrated in Figure 4.1) at daily intervals. Ambient temperature and gauge pressure inside the bin were also recorded at daily intervals. In all cases, the bins were filled to a capacity of approximately 75% with wheat. Approximately 83 kg of dry ice was added for the planned exposures of 10 d, but 107 kg of dry ice was added for the planned exposures of 4 d.

Experiment F1.1: Planned exposure of 10 d, commencing with the first purging method.

Experiment F2.1: Planned exposure of 10 d, commencing with the second purging method.

Experiment F3.1: Planned exposure of 10 d, commencing with the third purging method.

Experiments F4.1 through F4.5:
Planned exposures of 10 d, commencing with the fourth purging method.

Experiments F4.6 through F4.9:
Planned exposures of 4 d, commencing with the fourth purging method.

Experiment F1.1 Test Bin A Mass of Dry Ice Added: 81.5 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	May 15	May 16	May 17	May 18	May 19	May 20	May 21	May 22	May 23	May 24
Pressure (Pa)	59	20	0	20	39		10	39	10	10
Ambient Temperature	9.8°C	10.7°C	12.0°C	10.5°C	13.8°C		9.5°C	5.9°C	8.6°C	9.6°C
10	3.8% 9.5°C	39.6% 15.4°C	40.6% 13.4°C	37.0% 12.5°C	28.1% 17.8°C		31.6% 13.1°C	26.8% 8.9°C	23.2% 12.3°C	20.9% 12.7°C
9	2.2% -6.9°C	43.4% 7.3°C	42.3% 10.3°C	38.2% 9.8°C	32.0% 13.3°C		28.9% 9.9°C	25.5% 6.6°C	24.4% 8.0°C	20.8% 7.5°C
8	4.9% 2.0°C	43.3% 1.9°C	41.0% 0.7°C	37.1% 1.0°C	32.4% 0.2°C		30.5% -0.3°C	26.9% 0.7°C	23.7% 0.3°C	20.6% 0.7°C
7	5.1% 0.0°C	42.4% 0.0°C	38.2% -1.1°C	37.0% -0.2°C	32.2% -0.6°C		29.3% -0.9°C	25.9% 0.0°C	24.1% -0.5°C	19.9% -0.4°C
6	8.5% -1.0°C	42.4% -1.2°C	37.2% -2.2°C	36.3% -1.2°C	31.4% -1.6°C		31.0% -1.9°C	27.1% -0.9°C	23.6% -1.4°C	20.9% -1.3°C
5	34.8% -0.5°C	42.6% -0.6°C	39.7% -1.6°C	36.3% -0.7°C	31.5% -1.1°C		28.7% -1.4°C	25.0% -0.3°C	24.1% -0.8°C	21.2% -0.8°C
4	5.1% 0.8°C	41.5% 0.7°C	37.1% -0.4°C	35.5% 0.5°C	31.8% 0.2°C		30.1% -0.1°C	25.6% 0.8°C	24.3% 0.4°C	19.7% 0.3°C
3	4.7% 1.3°C	40.0% 1.3°C	38.2% 0.2°C	37.5% 1.4°C	33.9% 1.2°C		28.1% 1.2°C	25.1% 2.6°C	24.4% 2.5°C	19.8% 2.6°C
2	7.8% 4.8°C	41.7% 5.2°C	37.7% 5.1°C	37.4% 6.9°C	32.2% 8.0°C		29.7% 8.1°C	25.0% 9.1°C	25.4% 8.7°C	20.3% 8.4°C
1	4.8% 4.3°C	41.0% 5.0°C	40.5% 4.8°C	36.6% 6.9°C	32.8% 8.0°C		28.6% 8.1°C	24.5% 9.1°C	23.7% 8.9°C	20.0% 8.3°C
0	11.6% 10.1°C	41.9% 10.3°C	37.1% 13.0°C	35.7% 12.4°C	32.4% 13.6°C		28.7% 10.7°C	26.3% 8.9°C	22.1% 8.6°C	21.6% 8.8°C

Experiment F2.1 Test Bin B Mass of Dry Ice Added: 88 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	May 29	May 30	May 31	June 1	June 2	June 3	June 4	June 5	June 6	June 7
Pressure (Pa)	39	20	0	20	20	20	39	20	29	
Ambient Temperature	18.8°C	16.0°C	15.4°C	16.2°C	9.8°C	6.8°C	17.1°C	10.9°C	13.4°C	
10	8.2% 22.6°C	43.3% 18.2°C	46.0% 16.1°C	47.0% 17.8°C	44.9% 12.6°C	40.0% 7.7°C	41.8% 22.4°C	39.4% 10.8°C	39.0% 17.2°C	
9	10.0% 11.0°C	47.9% 14.1°C	48.2% 15.4°C	46.7% 15.9°C	45.4% 11.9°C	43.7% 8.0°C	42.9% 15.3°C	41.3% 11.5°C	41.0% 13.2°C	
8	14.2% 9.6°C	48.4% 10.0°C	48.8% 8.9°C	47.1% 7.9°C	45.9% 7.4°C	43.4% 7.6°C	43.3% 6.6°C	41.8% 7.5°C	41.1% 7.6°C	
7	30.3% 7.2°C	49.5% 7.5°C	47.4% 7.6°C	47.1% 7.8°C	45.2% 8.2°C	43.0% 8.6°C	42.8% 7.6°C	41.6% 8.2°C	40.5% 8.0°C	
6	53.9% 7.5°C	48.7% 7.6°C	47.1% 7.5°C	47.6% 7.4°C	45.2% 7.8°C	43.6% 8.2°C	42.8% 7.0°C	41.4% 7.6°C	40.6% 7.4°C	
5	45.8% 7.6°C	51.5% 7.9°C	48.8% 8.0°C	47.5% 7.9°C	46.1% 8.5°C	44.0% 8.8°C	43.5% 7.7°C	42.0% 8.2°C	41.4% 8.0°C	
4	34.2% 5.5°C	48.2% 5.6°C	47.7% 5.6°C	46.8% 5.5°C	44.8% 6.1°C	42.9% 6.5°C	42.6% 5.6°C	40.8% 6.1°C	41.0% 6.0°C	
3	37.9% 5.0°C	47.8% 5.1°C	48.3% 5.2°C	46.8% 5.1°C	45.7% 5.8°C	42.7% 6.1°C	42.2% 5.1°C	40.1% 5.4°C	40.7% 5.4°C	
2	37.1% 8.4°C	47.1% 8.7°C	49.9% 9.6°C	46.0% 8.7°C	47.0% 9.0°C	43.3% 8.5°C	42.8% 8.0°C	41.0% 8.4°C	41.0% 8.2°C	
1	42.0% 8.5°C	47.5% 8.5°C	47.5% 9.8°C	45.0% 8.8°C	42.4% 9.4°C	43.0% 8.7°C	41.9% 8.2°C	41.0% 8.2°C	40.9% 8.4°C	
0	50.8% 8.9°C	46.4% 9.5°C	47.0% 10.0°C	46.3% 10.1°C	43.7% 9.8°C	40.5% 10.1°C	40.3% 8.0°C	40.0% 9.2°C	39.9% 9.3°C	

Experiment F3.1 Test Bin A Mass of Dry Ice Added: 83 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	June 11	June 12	June 13	June 14	June 15	June 16	June 17	June 18	June 19	June 20
Pressure (Pa)	764	10	49	98	39	78	137	78	78	59
Ambient Temperature	26.0°C	19.5°C	22.1°C	25.4°C	20.6°C	17.0°C	22.6°C	20.2°C	18.3°C	17.5°C
10	19.8% 31.5°C	52.1% 20.4°C	50.1% 25.4°C	45.8% 32.8°C	46.0% 23.6°C	43.3% 22.4°C	42.2% 31.8°C	41.9% 25.0°C	40.8% 18.5°C	39.7% 19.0°C
9	21.4% 20.0°C	36.7% 20.6°C	48.8% 17.4°C	46.0% 19.5°C	45.7% 20.1°C	43.8% 18.4°C	42.9% 19.1°C	41.9% 19.2°C	39.0% 20.8°C	39.7% 15.7°C
8	13.6% 11.9°C	52.0% 11.4°C	49.9% 11.4°C	47.2% 12.3°C	45.6% 11.6°C	43.9% 12.3°C	42.1% 13.4°C	41.9% 12.9°C	39.1% 14.3°C	39.7% 13.5°C
7	30.0% 11.1°C	29.0% 10.6°C	46.5% 10.4°C	46.3% 11.1°C	44.0% 10.1°C	43.9% 10.4°C	41.2% 11.1°C	40.6% 10.3°C	38.9% 11.3°C	37.0% 10.3°C
6	19.2% 11.7°C	50.9% 11.0°C	50.3% 10.7°C	45.7% 11.3°C	45.4% 10.3°C	44.3% 10.4°C	40.6% 11.2°C	40.7% 10.2°C	41.3% 11.2°C	37.4% 10.2°C
5	28.4% 12.1°C	33.6% 11.3°C	48.0% 11.1°C	45.9% 11.7°C	45.4% 10.8°C	44.3% 10.8°C	40.7% 11.7°C	41.3% 10.8°C	41.4% 11.6°C	39.5% 10.7°C
4	30.8% 12.4°C	42.6% 11.6°C	47.3% 11.4°C	46.4% 11.9°C	45.6% 11.1°C	43.2% 11.0°C	40.5% 12.0°C	41.4% 11.1°C	40.3% 11.9°C	39.3% 11.0°C
3	63.3% 13.4°C	50.4% 12.5°C	47.3% 12.4°C	45.0% 12.9°C	45.1% 12.1°C	43.9% 11.9°C	41.3% 12.9°C	41.9% 11.9°C	39.6% 12.8°C	39.7% 11.9°C
2	47.2% 15.3°C	50.6% 15.2°C	49.0% 15.0°C	46.2% 15.6°C	45.5% 15.4°C	44.1% 14.8°C	42.3% 15.8°C	42.1% 15.2°C	40.9% 16.2°C	37.3% 14.6°C
1	83.3% 14.9°C	50.3% 14.7°C	49.4% 14.7°C	45.9% 15.2°C	45.3% 15.1°C	43.6% 14.4°C	42.0% 15.6°C	42.0% 15.1°C	40.0% 16.1°C	38.9% 14.6°C
0	83.6% 19.2°C	49.0% 15.7°C	47.5% 15.5°C	45.8% 16.2°C	45.5% 15.0°C	43.7% 16.2°C	42.3% 16.7°C	42.4% 15.4°C	39.5% 16.9°C	39.0% 15.2°C

Experiment F4.1 Test Bin B Mass of Dry Ice Added: 83 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	June 25	June 26	June 27	June 28	June 29	June 30	July 1	July 2	July 3	July 4
Pressure (Pa)	196	20	29	20			20	29	20	20
Ambient Temperature	16.6°C	20.6°C	30.2°C	N/A			25.0°C	28.5°C	28.8°C	19.3°C
10	41.2% 22.7°C	45.4% 24.9°C	39.2%	41.6%			42.4% 29.4°C	38.0% 35.9°C	36.8% 34.0°C	34.8% 23.3°C
9	42.7% 16.1°C	46.1% 19.2°C	49.5%	47.6%			45.0% 24.0°C	43.2% 24.9°C	41.7% 25.6°C	40.8% 18.6°C
8	43.0% 17.5°C	45.7% 17.2°C	47.9%	47.1%			44.0% 17.4°C	42.5% 16.5°C	41.4% 17.0°C	40.9% 15.5°C
7	39.1% 16.1°C	46.6% 15.9°C	47.0%	44.2%			43.0% 16.4°C	41.1% 15.4°C	40.8% 15.8°C	36.8% 14.2°C
6	12.4% 16.0°C	2.8% 15.6°C	2.8%	2.7%			3.1% 15.9°C	15.1% 14.8°C	3.0% 15.2°C	6.8% 13.7°C
5	36.1% 16.4°C	44.4% 16.1°C	45.9%	42.9%			43.2% 16.3°C	39.7% 15.1°C	40.2% 15.4°C	39.0% 14.1°C
4	41.4% 16.5°C	49.4% 16.2°C	48.9%	44.4%			43.2% 16.5°C	41.7% 15.3°C	39.8% 15.7°C	40.0% 14.4°C
3	42.7% 16.9°C	49.5% 16.6°C	48.3%	47.0%			42.8% 16.9°C	40.7% 15.6°C	41.1% 16.0°C	40.7% 14.8°C
2	42.3% 15.1°C	48.5% 15.3°C	48.4%	47.4%			44.0% 17.7°C	42.2% 16.5°C	40.1% 17.2°C	41.5% 15.9°C
1	45.1% 14.1°C	49.5% 15.0°C	47.5%	45.9%			43.8% 17.6°C	40.5% 16.6°C	41.0% 17.3°C	40.7% 15.9°C
0	45.2% 13.7°C	49.9% 14.0°C	47.5%	47.0%			43.4% 17.3°C	40.9% 16.4°C	40.9% 16.9°C	35.5% 14.8°C

Experiment F4.2 Test Bin A Mass of Dry Ice Added: 83 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	July 10	July 11	July 12	July 13	July 14	July 15	July 16	July 17	July 18	July 19
Pressure (Pa)	450	39	29	78		59	59	59	157	59
Ambient Temperature	21.8°C	20.9°C	16.7°C	23.4°C		20.2°C	20.8°C	23.0°C	19.9°C	16.0°C
10	36.4% 25.5°C	42.2% 24.3°C	41.4% 21.4°C	39.1% 23.1°C		35.7% 24.1°C	35.0% 24.5°C	31.3% 25.6°C	33.1% 26.9°C	31.0% 19.2°C
9	37.7% 18.4°C	37.3% 18.4°C	40.6% 18.9°C	39.3% 18.1°C		36.7% 17.0°C	34.7% 19.0°C	29.8% 19.3°C	32.1% 19.9°C	30.4% 18.1°C
8	31.8% 20.1°C	42.1% 19.6°C	41.6% 20.8°C	38.0% 18.7°C		35.5% 18.1°C	34.7% 19.0°C	33.9% 18.4°C	33.7% 17.6°C	31.6% 18.1°C
7	28.5% 19.6°C	42.0% 19.0°C	42.4% 20.2°C	38.6% 18.2°C		35.6% 17.5°C	35.0% 18.1°C	33.4% 18.5°C	32.1% 17.4°C	31.2% 17.7°C
6	29.9% 19.2°C	42.0% 18.5°C	41.7% 19.7°C	38.2% 17.7°C		35.5% 17.1°C	34.7% 17.8°C	33.8% 18.0°C	32.2% 16.9°C	31.2% 17.2°C
5	28.6% 19.3°C	39.9% 18.6°C	41.1% 19.8°C	38.5% 17.7°C		36.4% 17.1°C	35.4% 17.8°C	33.3% 17.8°C	32.9% 16.9°C	29.8% 17.2°C
4	24.7% 20.1°C	40.2% 19.2°C	40.2% 20.5°C	38.2% 18.3°C		35.6% 17.6°C	34.4% 18.1°C	33.7% 18.1°C	33.7% 17.5°C	29.8% 17.9°C
3	26.6% 20.5°C	41.1% 19.5°C	42.5% 20.7°C	38.6% 18.6°C		34.7% 18.0°C	34.7% 18.6°C	33.6% 18.4°C	33.9% 17.9°C	32.2% 18.1°C
2	28.2% 20.1°C	36.6% 19.1°C	41.3% 20.4°C	38.2% 18.4°C		36.3% 18.0°C	35.1% 18.7°C	34.3% 18.6°C	32.8% 18.3°C	30.8% 18.6°C
1	29.5% 19.6°C	41.0% 18.6°C	41.7% 19.7°C	39.8% 18.3°C		36.8% 17.5°C	35.6% 17.7°C	33.9% 18.3°C	32.6% 18.2°C	28.7% 18.3°C
0	30.7% 17.4°C	42.4% 18.6°C	41.3% 19.8°C	39.0% 17.8°C		35.7% 17.6°C	34.8% 18.7°C	33.6% 18.1°C	32.2% 17.6°C	30.8% 18.6°C

Experiment F4.3 Test Bin B Mass of Dry Ice Added: 83 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	July 23	July 24	July 25	July 26	July 27	July 28	July 29	July 30	July 31	Aug. 1
Pressure (Pa)	235	20	20	20	39	39	39	59	29	39
Ambient Temperature	16.9°C	18.7°C	19.7°C	19.2°C	20.4°C	17.6°C	20.0°C	23.2°C	21.6°C	24.2°C
10	31.1% 21.0°C	46.7% 26.0°C	42.5% 25.7°C	41.7% 24.2°C	36.7% 27.0°C	36.9% 26.4°C	37.7% 31.5°C	37.0% 31.2°C	34.7% 32.4°C	32.8% 34.6°C
9	38.4% 18.7°C	52.2% 23.4°C	47.9% 24.4°C	46.7% 22.6°C	44.5% 25.8°C	41.9% 23.6°C	40.2% 27.2°C	42.0% 28.2°C	39.3% 29.7°C	38.2% 31.8°C
8	35.4% 18.7°C	45.4% 19.2°C	45.6% 19.7°C	45.5% 18.6°C	44.1% 20.1°C	42.0% 20.4°C	40.2% 19.0°C	39.7% 19.2°C	39.6% 18.8°C	38.1% 20.3°C
7	32.6% 18.6°C	45.7% 19.2°C	45.4% 19.7°C	43.8% 18.6°C	42.5% 20.2°C	42.1% 20.6°C	40.2% 19.3°C	39.5% 19.6°C	38.7% 19.1°C	37.5% 20.8°C
6	1.4% 18.1°C	2.5% 18.8°C	3.2% 19.3°C	1.9% 18.2°C	1.4% 19.8°C	1.9% 20.2°C	1.6% 19.0°C	1.8% 19.2°C	1.7% 18.6°C	1.2% 20.6°C
5	29.9% 17.2°C	44.0% 18.2°C	39.6% 18.6°C	38.5% 17.9°C	35.2% 19.2°C	34.1% 19.6°C	26.5% 18.6°C	34.7% 18.8°C	33.7% 18.0°C	25.4% 20.0°C
4	30.2% 19.1°C	48.4% 20.1°C	45.3% 20.3°C	44.5% 19.7°C	42.9% 20.8°C	40.7% 21.1°C	39.5% 19.9°C	40.0% 20.0°C	39.1% 19.0°C	39.2% 21.0°C
3	17.9% 18.6°C	32.4% 19.9°C	12.8% 20.1°C	24.4% 19.7°C	12.9% 20.8°C	17.3% 21.2°C	19.5% 20.1°C	22.1% 20.3°C	11.9% 19.4°C	16.4% 21.4°C
2	35.4% 18.1°C	54.2% 19.8°C	46.0% 19.8°C	45.4% 19.8°C	42.9% 20.6°C	43.4% 21.0°C	42.5% 20.0°C	40.9% 20.1°C	39.9% 19.8°C	38.9% 21.3°C
1	40.0% 17.0°C	59.5% 19.2°C	46.5% 19.0°C	44.8% 19.3°C	43.2% 20.0°C	42.5% 20.4°C	42.2% 19.5°C	40.6% 19.7°C	39.1% 19.6°C	39.4% 21.0°C
0	17.5°C	57.9% 16.9°C	45.4% 18.7°C	44.1% 17.5°C	43.0% 19.4°C	43.0% 19.8°C	40.7% 18.7°C	40.7% 18.5°C	39.4% 18.8°C	40.1% 20.3°C

Experiment F4.4 Test Bin A Mass of Dry Ice Added: 83 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	Oct. 8	Oct. 9	Oct. 10	Oct. 11	Oct. 12	Oct. 13	Oct. 14	Oct. 15	Oct. 16	Oct. 17
Pressure (Pa)	88	10	20	39	59	78	78	69	69	39
Ambient Temperature	10.8°C	7.5°C	12.7°C	12.4°C	11.8°C	9.4°C	11.5°C	11.9°C	9.7°C	7.1°C
10	35.4% 10.5°C	43.4% 9.4°C	43.3% 13.7°C	41.3% 15.0°C	38.3% 14.8°C	38.7% 11.2°C	35.8% 11.4°C	34.1% 13.4°C	33.0% 12.5°C	31.0% 6.7°C
9	34.1% 10.2°C	42.6% 9.1°C	43.5% 13.4°C	41.4% 13.7°C	39.6% 12.7°C	38.0% 9.9°C	35.6% 10.9°C	34.1% 12.5°C	33.1% 11.4°C	29.6% 6.8°C
8	19.6% 15.9°C	42.8% 16.7°C	43.5% 15.7°C	41.0% 15.3°C	38.3% 14.9°C	38.0% 14.3°C	35.3% 15.0°C	32.7% 14.4°C	33.1% 14.0°C	30.4% 14.9°C
7	33.6% 16.8°C	41.1% 17.7°C	44.0% 16.8°C	40.1% 16.5°C	37.4% 16.4°C	37.6% 16.0°C	35.4% 16.9°C	33.2% 16.1°C	33.1% 15.9°C	29.4% 16.9°C
6	35.7% 16.8°C	41.6% 17.8°C	44.3% 16.9°C	42.0% 16.5°C	39.4% 16.6°C	37.5% 16.3°C	35.9% 17.2°C	33.1% 16.2°C	33.7% 16.1°C	31.3% 17.2°C
5	32.7% 16.5°C	39.8% 17.5°C	42.6% 16.5°C	40.3% 16.3°C	38.9% 16.2°C	36.8% 16.0°C	35.4% 16.9°C	33.0% 16.0°C	32.8% 15.8°C	30.0% 16.9°C
4	14.5% 16.0°C	39.1% 17.0°C	43.1% 15.9°C	40.3% 15.9°C	39.4% 15.8°C	37.8% 15.7°C	35.8% 16.4°C	34.3% 15.7°C	33.4% 15.3°C	31.7% 16.4°C
3	23.9% 15.2°C	39.5% 16.1°C	44.4% 15.7°C	40.5% 15.1°C	39.4% 15.0°C	38.3% 15.1°C	35.7% 15.7°C	33.9% 15.2°C	33.2% 14.6°C	30.2% 15.8°C
2	33.3% 15.8°C	38.5% 16.6°C	43.2% 15.5°C	40.4% 15.3°C	38.4% 15.1°C	37.5% 15.5°C	35.9% 15.8°C	33.7% 15.3°C	33.6% 14.7°C	31.3% 15.7°C
1	34.7% 15.9°C	40.9% 16.6°C	43.0% 15.2°C	39.9% 15.1°C	38.2% 14.7°C	36.6% 15.2°C	35.7% 15.4°C	33.6% 15.0°C	32.9% 14.2°C	31.6% 15.1°C
0	29.2% 15.3°C	40.3% 16.0°C	43.0% 14.6°C	38.8% 14.2°C	35.8% 14.2°C	35.8% 13.7°C	34.4% 14.9°C	33.1% 14.0°C	32.1% 14.0°C	30.7% 15.1°C

Experiment F4.5 Test Bin B Mass of Dry Ice Added: 83 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	Oct. 19	Oct. 20	Oct. 21	Oct. 22	Oct. 23	Oct. 24	Oct. 25	Oct. 26	Oct. 27	Oct. 28
Pressure (Pa)	59	20	20	20	20	20	20	20	20	10
Ambient Temperature	10.6°C	11.1°C	8.0°C	3.4°C	6.4°C	3.0°C	7.1°C	6.9°C	6.3°C	4.8°C
10	4.5%	25.4%	37.7%	27.8%	26.1%	25.0%	23.3%	22.9%	20.0%	6.3%
9	6.1% 10.9°C	46.7% 9.8°C	47.0% 8.2°C	44.2% 5.0°C	41.2% 6.5°C	37.4% 4.0°C	36.8% 6.7°C	33.8% 6.4°C	32.3% 6.4°C	30.2% 4.1°C
8	4.7%	35.8%	39.8%	33.8%	29.5%	22.9%	29.4%	27.7%	20.1%	12.9%
7	28.8%	47.7%	44.6%	42.1%	39.2%	35.6%	35.0%	32.8%	30.9%	29.2%
6	7.6%	34.6%	36.2%	32.4%	26.9%	20.9%	25.4%	17.6%	13.5%	15.6%
5	32.4% 13.5°C	45.8% 13.6°C	47.1% 13.6°C	42.9% 13.7°C	39.8% 13.4°C	34.7% 14.3°C	36.9% 14.4°C	34.8% 13.6°C	32.9% 13.3°C	30.1% 14.2°C
4	16.1% 13.2°C	46.9% 13.4°C	45.8% 13.3°C	42.0% 13.6°C	39.5% 13.3°C	37.3% 14.1°C	35.9% 14.2°C	34.3% 13.4°C	31.8% 13.2°C	31.1% 14.1°C
3	26.9% 12.6°C	46.9% 12.9°C	43.9% 12.8°C	42.4% 13.3°C	39.7% 12.9°C	37.1% 13.7°C	36.1% 13.8°C	34.0% 13.1°C	32.1% 12.8°C	30.0% 13.8°C
2	29.0% 13.6°C	44.0% 13.8°C	41.1% 13.4°C	39.1% 13.9°C	37.7% 13.5°C	33.4% 14.1°C	33.6% 14.1°C	31.8% 13.2°C	29.8% 12.9°C	25.7% 13.8°C
1	33.8% 13.6°C	49.9% 13.7°C	45.7% 13.2°C	42.2% 13.4°C	39.6% 13.1°C	35.7% 13.5°C	34.5% 13.6°C	34.0% 12.6°C	31.9% 12.1°C	29.7% 12.9°C
0	34.9% 12.5°C	48.1% 13.1°C	44.9% 13.0°C	41.6% 12.9°C	39.1% 12.2°C	37.4% 12.6°C	35.0% 11.9°C	33.6% 11.5°C	31.3% 11.1°C	29.9% 11.4°C

Experiment F4.6 Test Bin A Mass of Dry Ice Added: 107 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	Aug. 7	Aug. 8	Aug. 9	Aug. 10	Aug. 11	Aug. 12				
Pressure (Pa)	78	39	20	39						
Ambient Temperature	21.0°C	19.6°C	16.8°C	20.8°C						
10	20.1% 27.0°C	55.3% 25.8°C	56.7% 23.6°C	54.8% 22.2°C		49.3%				
9	19.1% 21.6°C	48.5% 21.2°C	57.7% 19.2°C	55.9% 18.6°C		48.9%				
8	17.7% 21.2°C	47.0% 22.2°C	59.0% 20.7°C	54.5% 20.4°C		49.0%				
7	13.7% 21.6°C	33.9% 22.4°C	53.3% 21.0°C	49.7% 20.6°C		43.6%				
6	11.1% 21.3°C	22.6% 22.2°C	41.5% 20.7°C	36.2% 20.4°C		38.0%				
5	7.8% 21.1°C	11.8% 22.0°C	13.8% 20.4°C	17.1% 20.2°C		6.8%				
4	11.6% 21.1°C	26.2% 22.1°C	4.1% 20.4°C	34.8% 19.9°C		37.8%				
3	21.3% 21.2°C	53.0% 22.2°C	59.2% 20.4°C	56.1% 20.2°C		49.2%				
2	20.0% 21.8°C	53.6% 22.6°C	58.0% 20.6°C	56.0% 20.4°C		48.7%				
1	19.7% 21.6°C	53.7% 22.5°C	57.8% 20.1°C	54.9% 19.8°C		42.0%				
0	21.4% 21.6°C	55.3% 22.4°C	56.1% 20.0°C	53.1% 19.2°C		39.5%				

Experiment F4.7 Test Bin B Mass of Dry Ice Added: 107 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	Aug. 14	Aug. 15	Aug. 16	Aug. 17						
Pressure (Pa)	78	29	29	39						
Ambient Temperature	18.7°C	21.7°C	22.0°C	17.6°C						
10	52.7% 23.9°C	56.3% 28.9°C	48.5% 28.5°C	48.4% 22.9°C						
9	57.7% 20.3°C	58.8% 19.9°C	56.0% 20.4°C	52.5% 21.3°C						
8	52.2%	53.6%	50.5%	46.3%						
7	55.3%	54.3%	53.6%	51.4%						
6	49.9%	50.3%	45.8%	44.0%						
5	52.0% 21.4°C	54.6% 21.3°C	53.7% 20.6°C	53.8% 21.4°C						
4	53.7% 21.4°C	55.9% 21.3°C	53.6% 20.7°C	51.4% 21.5°C						
3	50.6% 20.9°C	57.0% 20.7°C	54.7% 20.3°C	52.0% 21.1°C						
2	53.9% 21.5°C	58.4% 21.0°C	54.5% 20.8°C	51.3% 21.6°C						
1	53.8% 21.1°C	57.7% 20.6°C	53.9% 20.8°C	51.9% 21.3°C						
0	54.1% 21.3°C	55.9% 21.0°C	54.6% 20.1°C	51.9% 21.3°C						

Experiment F4.8 Test Bin A Mass of Dry Ice Added: 107 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	Aug. 24	Aug. 25	Aug. 26	Aug. 27						
Pressure (Pa)		20	117	98						
Ambient Temperature		19.2°C	18.5°C	18.1°C						
10		47.7% 24.0°C	45.7% 25.3°C	42.7% 20.7°C						
9		43.3% 23.7°C	44.2% 22.6°C	42.4% 19.3°C						
8		41.0% 21.5°C	45.8% 21.8°C	41.6% 21.4°C						
7		44.8% 21.6°C	44.6% 21.9°C	42.9% 21.6°C						
6		45.4% 20.9°C	45.4% 21.2°C	41.7% 21.1°C						
5		44.6% 22.2°C	45.5% 22.4°C	40.4% 22.3°C						
4		44.8% 22.5°C	44.5% 22.7°C	42.5% 22.6°C						
3		46.1% 22.3°C	45.0% 22.4°C	41.5% 22.6°C						
2		45.6% 22.5°C	45.7% 22.3°C	38.4% 22.6°C						
1		45.0% 22.3°C	44.5% 21.7°C	41.3% 22.2°C						
0		45.7% 22.2°C	44.5% 22.0°C	40.2% 21.6°C						

Experiment F4.9 Test Bin A Mass of Dry Ice Added: 107 kg Locations 0 through 10 correspond to those in Figure 4.1.

Date	Sept. 27	Sept. 28	Sept. 29	Sept. 30						
Pressure (Pa)	470	59	59	20						
Ambient Temperature	9.2°C	8.2°C	4.8°C	10.5°C						
10	42.7% 9.0°C	54.8% 9.7°C	55.4% 8.7°C	47.8% 15.4°C						
9	48.3% 9.1°C	52.4% 9.6°C	54.4% 7.8°C	46.0% 14.9°C						
8	42.2% 16.0°C	52.2% 16.0°C	54.0% 16.0°C	45.3% 15.8°C						
7	38.9% 18.7°C	49.8% 18.7°C	54.0% 18.8°C	43.4% 18.6°C						
6	43.4% 18.9°C	51.6% 19.1°C	53.5% 19.2°C	45.4% 19.2°C						
5	43.4% 18.7°C	52.1% 18.8°C	52.1% 18.8°C	42.9% 18.9°C						
4	17.0% 17.5°C	47.8% 17.8°C	52.7% 17.8°C	47.2% 18.0°C						
3	36.0% 17.7°C	50.4% 17.9°C	53.2% 17.8°C	47.7% 18.0°C						
2	26.1% 18.4°C	51.6% 18.7°C	50.5% 18.4°C	46.1% 18.6°C						
1	40.1% 18.5°C	50.7% 18.6C	50.7% 17.7°C	46.0% 18.0°C						
0	40.0% 18.0°C	48.3% 17.8°C	51.2% 17.6°C	44.8% 17.2°C						

Appendix F - Mortality of Caged Insects Exposed to Fumigation With CO_2

Caged adult *C. ferrugineus* were placed throughout the grain bulk in a total of five experiments. Experiments F4.3, F4.4, and F4.5 were 10-d fumigations while F4.8 and F4.9 were 4-d fumigations. Either 16 or 32 cages were placed throughout the grain bulk with 100 insects in each cage. Refer to Figs. 6.2 and 6.3 for location of the insect cages. Insects in control cages were not exposed to the fumigations.

Appendix F - Mortality of Caged Insects Exposed to Fumigation With CO_2

Experiment F4.3

Cage	Initial Insects	Dead (#)	Alive (#)	Mortality (%)
1	100	100	0	100
2	100	100	0	100
3	100	100	0	100
4	100	100	0	100
5	100	100	0	100
6	100	100	0	100
7	100	100	0	100
8	100	100	0	100
9	100	100	0	100
10	100	100	0	100
11	100	100	0	100
12	100	100	0	100
13	100	100	0	100
14	100	100	0	100
15	100	100	0	100
16	100	100	0	100
17	100	100	0	100
18	100	100	0	100
19	100	100	0	100
20	100	100	0	100
21	100	100	0	100
22	100	100	0	100
23	100	100	0	100
24	100	100	0	100
25	100	100	0	100
26	100	100	0	100
27	100	100	0	100
28	100	100	0	100
29	100	100	0	100
30	100	100	0	100
31	100	100	0	100
32	100	100	0	100
C#1*	100	16	84	16
C#2*	100	33	67	33

Experiment F4.4

Cage	Initial Insects	Dead (#)	Alive (#)	Mortality (%)
1	100	100	0	100
2	100	100	0	100
3•				
4	100	100	0	100
5•				
6•				
7•				
8	100	100	0	100
9•				
10	100	100	0	100
11	100	100	0	100
12•				
13	100	100	0	100
14•				
15	100	100	0	100
16	100	100	0	100
17•				
18	100	100	0	100
19•				
20•				
21	100	99	1	99
22•				
23	100	99	1	99
24•				
25•				
26	100	100	0	100
27•				
28	100	100	0	100
29	100	99	1	99
30•				
31	100	100	0	100
32•				
C#1*	100	6	94	6
C#2*	100	16	84	16

* Control cages not exposed to CO_2 fumigation.
• Insect cages were not placed at these locations.

Appendix F - Mortality of Caged Insects Exposed to Fumigation With CO_2

Experiment F4.5

Cage	Initial Insects	Dead (#)	Alive (#)	Mortality (%)
1[a]				
2[a]				
3	100	100	0	100
4[a]				
5	100	99	1	99
6	100	100	0	100
7	100	99	1	99
8[a]				
9	100	100	0	100
10[a]				
11[a]				
12	100	100	0	100
13[a]				
14	100	99	1	99
15[a]				
16[a]				
17	100	100	0	100
18[a]				
19	100	100	0	100
20	100	100	0	100
21[a]				
22	100	100	0	100
23[a]				
24	100	99	1	99
25	100	99	1	99
26[a]				
27	100	100	0	100
28[a]				
29[a]				
30	100	100	0	100
31[a]				
32	100	100	0	100
C#1*	100	15	85	15
C#2*	100	11	89	11
C#3*	100	11	89	11

Experiment F4.8

Cage	Initial Insects	Dead (#)	Alive (#)	Mortality (%)
1	100	100	0	100
2	100	98	2	98
3	100	99	1	99
4	100	98	2	98
5	100	99	1	99
6	97	94	3	97
7	100	95	5	95
8	100	100	0	100
9	100	99	1	99
10	100	98	2	98
11	100	96	4	96
12	100	96	4	96
13	100	93	7	93
14	100	97	3	97
15	100	97	3	97
16	100	90	10	90
17	100	94	6	94
18	100	87	13	87
19	100	94	6	94
20	100	97	3	97
21	100	98	2	98
22	100	97	3	97
23	100	91	9	91
24	100	93	7	93
25	100	100	0	100
26	100	92	8	92
27	100	91	9	91
28	100	95	5	95
29	100	88	12	88
30	100	97	3	97
31	100	81	19	81
32	100	94	6	94

* Control cages not exposed to CO_2 fumigation.
[a] Insect cages were not placed at these locations.

Appendix F - Mortality of Caged Insects Exposed to Fumigation With CO_2

Experiment F4.9

Cage	Initial Insects	Dead (#)	Alive (#)	Mortality (%)
1	100	79	21	79
2	100	90	10	90
3	100	87	13	87
4	100	83	17	83
5	100	71	29	71
6	100	91	9	91
7	100	80	20	80
8	100	63	37	63
9	100	70	30	70
10	100	88	12	88
11	100	61	39	61
12	100	54	46	54
13	100	77	23	77
14	100	68	32	68
15	100	77	23	77
16	100	83	17	83
17	100	88	12	88
18	100	84	16	84
19	100	82	18	82
20	100	86	14	86
21	100	81	19	81
22	100	83	17	83
23	100	91	9	91
24	100	92	8	92
25	100	94	6	94
26	100	90	10	90
27	100	77	23	77
28	100	80	20	80
29	100	87	13	87
30	100	70	30	70
31	100	72	28	72
32	100	74	26	74

Appendix G - Data from Fumigation of Uncaged Insects

Carbon dioxide and temperature data collected during an experimental fumigation of uncaged insects in a sealed welded-steel hopper bin (bin C) located at the Agriculture Canada Research Station at Glenlea, MB. Data were collected along the centreline of the bin (locations 0 through 3, with 0 closest to the bottom) at daily intervals. Ambient temperature and gauge pressure inside the bin were also recorded at daily intervals. The bin was filled to a capacity ɔf approximately 75% with wheat. The fumigation atmosphere was generated with 14 kg of dry ice.

Experiment F4.10 Test Bin C Mass of Dry Ice Added: 14 kg

Date	Aug. 20	Aug. 21	Aug. 22	Aug. 23	Aug. 24	Aug. 25	Aug. 26	Aug. 27	Aug. 28	Aug. 29
Pressure (Pa)	78	215	196	98			235	215	117	255
Ambient Temperature	19.3°C	21.7°C	20.4°C	28.8°C			20.2°C	24.0°C	24.8°C	21.3°C
3	21.2% 20.8°C	51.4% 20.2°C	48.6% 20.6°C	47.5% 20.4°C			43.7% 21.1°C	42.0% 20.8°C	39.5% 20.7°C	38.1% 20.2°C
2	49.4% 18.1°C	51.1% 18.6°C	45.9% 17.6°C	46.0% 18.7°C			42.9% 17.2°C	41.5% 17.8°C	41.7% 18.6°C	39.1% 18.2°C
1	35.0% 20.2°C	51.5% 19.6°C	49.2% 19.9°C	45.1% 20.5°C			41.3% 20.7°C	42.4% 20.5°C	40.4% 20.8°C	38.3% 20.4°C
0	53.0% 17.5°C	49.4% 23.2°C	46.6% 20.6°C	45.4% 30.8°C			42.3% 19.5°C	41.0% 23.4°C	40.9% 27.7°C	39.1% 21.4°C

Appendix H - Mortality of Adult *C. ferrugineus* due to CO_2 Exposure

Cases of adult *C. ferrugineus* mortality due to CO_2 found in the scientific literature. For each source, temperature, CO_2 concentration, and exposure time are listed. The data corresponding to a temperature of approximately 25°C were used to obtain an empirical equation relating CO_2 concentration (%) to the exposure time (h) required to attain complete insect mortality.

Source	Temperature (°C)	CO_2 Concentration (%)	Exposure time (h)
White et al. 1988	10	94.1 to 74.7	168
White and Jayas 1991	12 to 15	> 15	1008
White et al. 1988	20	> 54	168
Rameshbabu et al. 1991	20	90	96
White et al. 1990b	25±3	20	1008
White and Jayas 1993	25 to 20	29	336
Anonymous 1983	20 to 29	40	312
Anonymous 1983	20 to 29	60	96
Anonymous 1983	20 to 29	80	72
Anonymous 1983	20 to 29	100	48
Shunmugam et al. 1993	30	30	192
Shunmugam et al. 1993	30	40	192
Shunmugam et al. 1993	30	60	72

Appendix I - Computer Program used to Calculate CO_2 Loss

List of Program Variables

C = CO_2 concentration (%)

V = volume from which the CO_2 is leaking (m^3)

S = area of hole (m^2)

Et = experimental duration (s)

TC = temperature (°C)

TK = temperature (K)

P = pressure (kPa)

R = universal gas constant ($kPa \cdot dm^3 \cdot mol^{-1} \cdot K^{-1}$)

M = molecular mass of CO_2 (u)

agn = Avogadro's number

N = number of molecules of CO_2

D = diffusion coefficient of CO_2 through air ($m^2 \cdot s^{-1}$)

delX = thickness of brass film (m)

rho = density of CO_2 ($kg \cdot m^{-3}$)

NSTART = number of molecules of CO_2 at start

NLOST = number of molecules of CO_2 lost from bin

GLOST = mass of CO_2 lost from bin (g)

delC = concentration gradient across boundary

J = molecular flux ($kg \cdot s^{-1} \cdot m^{-2}$)

vel = velocity of CO_2 molecules ($m \cdot s^{-1}$)

delN = number of molecules of CO_2 going through the hole in time Et

addN = number of molecules of CO_2 entering the head space from the grain bulk

Calculating CO_2 Loss from Pilot Bins:

The following computer program was used to calculate the predicted CO_2 loss from the pilot bins. The program was written in the qbasic programming language. After input of the required data (i.e., initial CO_2 concentration, bin volume, hole area, duration of experiment, average temperature, and CO_2 density), the program computes: 1) the number of molecules of CO_2 leaving the head space of the bin through a hole of known area and 2) the number of molecules of CO_2 entering the head space from the grain bulk. For the pilot bins, the bin volume was approximated using only the head space. The number of molecules leaving the head space was calculated using the equation presented by Bernardini (1989) with the velocity of the molecules calculated using the diffusion rate of CO_2 through air. Because the velocity depends on the concentration gradient, it decreases as CO_2 molecules pass through the hole. The loss of CO_2 from the pilot bins was calculated iteratively with a new CO_2 concentration calculated for each time step. The number of molecules entering the head space from the grain bulk was calculated using a ratio of the diffusion coefficient of CO_2 through grain to that of CO_2 through air.

```
REM "Gas Loss from Pilot Bins"
REM "Written by D. Mann"
REM "December 1997"
CLS : PRINT : PRINT
INPUT ; "What is the initial CO2 concentration"; C: PRINT
INPUT ; "What is the volume of the bin"; V: PRINT
INPUT ; "What is the area of the hole"; S: PRINT
INPUT ; "What is the duration of the experiment (s)"; Et: PRINT
INPUT ; "What is the average temperature (C)"; TC: PRINT
INPUT ; "What is the density"; rho: PRINT
TK = 273.15 + TC
P = 101.33
R = 8.3144
M = 44.01
agn = 6.022E+23
REM "The initial number of molecules of CO2 inside the pilot bin is calculated."
N = ((P * C / 100 * V * 1000) / (R * TK)) * agn
REM "The diffusion coefficient of CO2 through air is calculated."
D = (8.54E-08 * (TC - 3)) + .0000142
delX = .00022
NSTART = N
NLOST = 0
GLOST = 0
FOR Y = 0 TO Et STEP 3600
   delC = .0196 * (C - .03)
   J = D * delC / delX
   vel = J / rho
   delN = (N * S * vel * 3600) / V
   addN = delN * 4.11E-06 / D
   N = N - delN + addN
   NLOST = NLOST + delN
   delN = 0
   addN = 0
   C = (((N * M) / (agn * 1000 * V)) / .0196) + .03
NEXT Y
REM "The total mass of CO2 lost is calculated."
GLOST = NLOST * M / agn
PRINT ; "The total grams of CO2 lost is"; GLOST
END
```

Calculating CO_2 Loss from Full-size Bins:

The following computer program was used to calculate the predicted CO_2 loss from the full-size bins. The program was written in the qbasic programming language. After input of the required data (i.e., initial CO_2 concentration, bin volume, hole area, duration of experiment, average temperature, and CO_2 density), the program computes: 1) the number of molecules of CO_2 leaving the head space of the bin through a hole of known area and 2) the number of molecules of CO_2 entering the head space from the grain bulk. For the full-size bins, the bin volume was approximated using an assumed head space (i.e., 6.2 m^3 for bins A & B; 1.0 m^3 for bin C). The number of molecules leaving the head space was calculated using the equation presented by Bernardini (1989) with the velocity of the molecules (i.e., 2.82 $m \bullet s^{-1}$) calculated based on the rate of gas movement through the recirculation pump. The number of molecules entering the head space from the grain bulk was calculated assuming that they would be entering the head space one-third as fast as they are leaving.

```
REM "Gas Loss from Full-size Bins"
REM "Written by D. Mann"
REM "January 1998"
CLS : PRINT : PRINT
INPUT ; "What is the initial CO2 concentration"; C: PRINT
INPUT ; "What is the volume of the bin"; V: PRINT
INPUT ; "What is the area of the hole"; S: PRINT
INPUT ; "What is the duration of the experiment (s)"; Et: PRINT
INPUT ; "What is the average temperature (C)"; TC: PRINT
INPUT ; "What is the density"; rho: PRINT
TK = 273.15 + TC
P = 101.33
R = 8.3144
M = 44.01
agn = 6.022E+23
REM "The initial number of molecules of CO2 inside the full-size bin is calculated."
N = ((P * C / 100 * V * 1000) / (R * TK)) * agn
vel = 2.82
NSTART = N
NLOST = 0
GLOST = 0
FOR Y = 0 TO Et STEP 3600
   delN = (N * S * vel * 3600) / V
   addN = delN / 3
   N = N - delN + addN
   NLOST = NLOST + delN
   delN = 0
   addN = 0
NEXT Y
REM "The total mass of CO2 lost is calculated."
GLOST = NLOST * M / agn
PRINT ; "The total grams of CO2 lost is"; GLOST
END
```

Appendix J - Pressure Decay Data for Pilot Bins

Experimental data for pressure decay time vs. leakage area collected using the three sizes of wheat-filled drums. The drums were pressurized with air to an initial pressure of 1.5 kPa and the decaying pressure was recorded by a digital micromanometer at specified intervals. The temperature inside the drum, T_d, and the ambient temperature, T_a, were measured using type T copper-constantan thermocouples.

For specific data, refer to the following pages:

Drum A, Hole size = 1.5 mm diameter: page J2
Drum B, Hole size = 1.5 mm diameter: page J3
Drum C, Hole size = 1.5 mm diameter: page J4
Drum A, Hole size = 1.3 mm diameter: page J5
Drum B, Hole size = 1.3 mm diameter: page J6
Drum C, Hole size = 1.3 mm diameter: page J7
Drum A, Hole size = 1.1 mm diameter: page J8
Drum B, Hole size = 1.1 mm diameter: pages J9-10
Drum C, Hole size = 1.1 mm diameter: page J11
Drum A, Hole size = 0.8 mm diameter: pages J12-13
Drum B, Hole size = 0.8 mm diameter: pages J14-16
Drum C, Hole size = 0.8 mm diameter: page J17
Drum A, Hole size = 0.6 mm diameter: pages J18-20
Drum B, Hole size = 0.6 mm diameter: pages J21-25
Drum C, Hole size = 0.6 mm diameter: pages J26-27

Drum A, Hole size = 1.5 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.51	11.0	13.6	1.51	11.2	13.5	1.51	11.9	14.0	1.51	11.1	12.9	1.51	10.2	14.2
00:01	1.46	12.3	13.5	1.46	5.9	13.4	1.46	8.3	14.0	1.46	9.5	13.2	1.51	8.1	14.2
00:02	1.37	11.5	14.2	1.37	12.2	13.5	1.37	9.2	13.0	1.37	9.5	12.4	1.37	12.2	13.4
00:03	1.27	10.6	13.5	1.27	7.9	14.2	1.27	11.2	14.0	1.27	12.4	13.8	1.32	10.4	14.1
00:04	1.17	12.7	13.8	1.17	11.6	14.0	1.22	8.8	14.0	1.22	10.6	12.8	1.22	10.4	13.0
00:05	1.12	8.0	13.9	1.07	10.9	14.2	1.12	11.3	14.1	1.12	13.5	12.9	1.12	11.9	14.5
00:06	1.03	11.0	13.9	1.03	14.1	14.2	1.03	12.6	13.3	1.03	8.7	13.3	1.03	10.2	13.8
00:07	0.93	12.7	13.7	0.93	10.3	13.9	0.93	11.3	13.9	0.93	8.7	14.6	0.93	9.7	14.4
00:08	0.88	11.9	14.0	0.83	11.8	13.2	0.88	11.0	13.9	0.88	11.3	12.4	0.88	12.0	13.1
00:09	0.78	8.7	13.8	0.78	9.1	13.3	0.78	12.9	13.6	0.78	11.4	13.0	0.78	8.8	14.1
00:10	0.73	12.4	14.0	0.73	11.0	14.4	0.73	12.5	14.1	0.73	7.2	13.9	0.73	12.2	13.6
00:11	0.63	11.4	13.7	0.63	12.2	12.7	0.63	9.5	14.3	0.63	10.2	13.8	0.68	9.6	14.2
00:12	0.59	6.1	13.9	0.59	8.6	14.2	0.59	12.0	13.5	0.59	7.9	12.0	0.59	10.9	14.0
00:13	0.54	9.1	14.0	0.54	10.2	13.9	0.54	9.7	14.4	0.54	13.1	14.1	0.54	10.3	14.3
00:14	0.44	11.3	13.1	0.44	10.5	14.2	0.44	10.6	13.9	0.44	6.8	13.5	0.49	11.9	13.3
00:15	0.44	10.6	12.2										0.44	11.3	14.1
00:16	0.39	13.2	14.2												
00:17	0.34	9.6	13.4												
00:18	0.29	11.7	14.6												
00:19	0.24	11.5	13.7												
00:20	0.24	9.6	13.8												
00:21	-1.03	11.0	14.2												

Drum B, Hole size = 1.5 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	7.4	15.0	1.51	13.6	14.9	1.51	10.1	14.5	1.51	13.3	15.4	1.51	7.8	14.7
00:01	1.51	11.7	15.2	1.51	10.3	13.8	1.46	11.6	13.3	1.51	11.4	14.1	1.51	11.4	15.4
00:02	1.46	10.8	14.4	1.46	12.5	14.7	1.42	13.0	14.9	1.42	12.0	14.3	1.46	12.5	15.3
00:03	1.42	13.6	15.2	1.42	10.6	13.5	1.37	9.8	13.9	1.37	10.9	14.3	1.37	12.0	14.8
00:04	1.37	10.5	14.5	1.37	12.0	14.9	1.32	13.4	14.5	1.32	11.4	14.7	1.32	11.7	15.6
00:05	1.32	12.2	14.9	1.32	13.2	14.7	1.27	9.6	14.4	1.27	12.5	14.2	1.27	11.3	15.3
00:06	1.27	9.7	14.6	1.27	12.0	14.7	1.22	12.5	14.7	1.22	13.7	14.9	1.22	9.2	15.0
00:07	1.22	12.3	14.4	1.17	11.5	14.5	1.17	10.9	14.8	1.17	5.4	14.3	1.17	13.0	15.0
00:08	1.17	6.3	14.7	1.17	13.3	14.4	1.12	10.0	14.0	1.12	9.0	14.5	1.12	9.8	15.7
00:09	1.12	14.1	13.9	1.07	9.0	14.3	1.07	10.2	14.4	1.07	13.3	14.4	1.07	12.4	14.4
00:10	1.07	8.6	14.9	1.07	12.4	14.7	1.03	10.6	14.8	1.03	7.9	14.5	1.03	10.4	14.4
00:11	1.03	12.3	14.5	0.98	13.1	15.0	0.98	13.2	14.5	0.98	9.5	15.3	0.98	12.5	15.2
00:12	0.98	13.0	14.0	0.98	13.2	15.3	0.93	10.0	14.9	0.93	11.6	15.0	0.93	8.1	15.0
00:13	0.93	12.3	14.9	0.93	9.3	14.7	0.88	11.2	14.3	0.88	13.2	15.3	0.88	13.6	15.2
00:14	0.88	11.3	15.0	0.88	13.2	14.7	0.83	9.6	14.9	0.83	13.0	14.8	0.83	12.5	14.8
00:15	0.88	11.2	14.5	0.83	11.1	15.1	0.83	10.5	13.7	0.83	12.7	15.2	0.83	10.6	13.7
00:16	0.78	8.8	14.9	0.78	7.2	14.5	0.78	11.9	14.9	0.78	13.7	13.7	0.78	11.4	15.5
00:17	0.78	12.8	13.5	0.73	11.4	14.7	0.73	8.6	14.3	0.73	11.6	14.8	0.73	13.6	14.9
00:18	0.73	14.4	14.0	0.73	11.6	14.4	0.68	11.8	14.7	0.68	8.3	15.2	0.68	11.3	14.5
00:19	0.68	12.5	14.1	0.68	12.2	14.5	0.68	12.3	14.8	0.68	13.0	14.2	0.68	14.5	14.5
00:20	0.68	8.0	14.7	0.63	12.6	14.9	0.63	12.2	14.9	0.63	12.2	14.2	0.63	9.4	14.4
00:21	0.63	11.3	14.5	0.63	6.5	14.2	0.59	10.9	14.9	0.59	7.0	14.8	0.59	13.0	14.8
00:22	0.59	11.7	14.7	0.59	13.3	13.8	0.54	14.2	14.4	0.54	11.1	14.5	0.59	7.3	15.0
00:23	0.54	8.5	14.5	0.54	12.4	14.9	0.54	12.5	15.3	0.54	11.4	15.4	0.54	12.9	14.7
00:24				0.54	10.7	13.3				0.49	10.7	13.9	0.49	9.4	14.7
00:25				0.49	7.0	14.7				0.49	11.5	14.9	0.49	12.5	15.2
00:26										0.44	11.7	14.9	0.44	10.4	14.6
00:27										0.39	13.1	15.2	0.39	13.2	15.2
00:28										0.39	9.8	13.7	0.39	11.2	15.3

Drum C, Hole size = 1.5 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.61	6.3	21.7	1.56	12.2	23.4	1.56	-10.1	22.5	1.61	-5.1	14.0	1.56	-5.8	21.1
00:05	1.46	8.1	22.5	1.46	-1.7	23.1	1.46	7.4	23.5	1.46	-4.3	13.4	1.42	7.6	22.0
00:10	1.37	-2.0	22.0	1.32	3.1	22.8	1.32	-6.2	23.6	1.32	11.6	17.0	1.32	2.5	21.5
00:15	1.22	-1.7	21.0	1.22	1.6	22.6	1.22	-3.8	22.7	1.22	0.5	18.4	1.17	-1.8	20.5
00:20	1.12	-4.5	22.3	1.07	-3.9	22.9	0.00	-1.6	22.9	1.07	1.8	16.8	1.07	-5.2	21.7
00:25	1.03	-4.9	22.2	0.98	0.5	22.7	1.03	-1.0	21.4	0.98	5.4	20.8	0.98	12.1	21.6
00:30	0.93	1.1	22.6	0.88	3.1	23.1	0.88	5.4	21.3	0.88	5.8	20.8	0.88	-0.8	21.4
00:35	0.83	-2.6	22.5	0.78	11.6	22.9	0.83	-42.6	41.9	0.78	14.1	20.8	0.78	3.8	21.6
00:40	0.73	7.4	21.6	0.73	4.3	22.0	0.73	2.6	31.4	0.68	0.2	21.0	0.68	-6.3	21.9
00:45	0.63	-0.6	22.0	0.63	-3.4	23.1	0.63	-2.1	28.7	0.63	3.2	16.0	0.59	233.9	22.1
00:50	0.59	-9.9	22.4	0.54	1.3	23.2	0.54	4.8	28.9	0.54	1.7	21.8	0.54	233.9	22.1
00:55	0.49	4.2	22.5	0.49	-0.3	22.6	0.49	-6.7	29.8	0.49	3.6	21.8			
01:00	0.44	2.5	22.5	0.44	-8.9	22.9	0.44	-13.7	29.7	0.39	-5.4	21.8			
01:05	0.39	4.7	21.8	0.39	9.2	23.3				0.34	3.6	22.0			

Drum A, Hole size = 1.3 mm diameter

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
(min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.61	10.0	14.2	1.56	12.6	14.5	1.56	13.6	14.3	1.56	13.0	13.6	1.56	11.2	13.7
00:01	1.51	13.4	14.4	1.51	9.6	13.9	1.51	12.8	13.7	1.51	12.3	14.0	1.51	11.3	14.5
00:02	1.46	9.3	13.8	1.42	12.7	13.4	1.42	9.8	14.2	1.42	12.4	14.3	1.46	11.4	12.9
00:03	1.37	11.6	13.3	1.32	12.8	14.8	1.32	9.8	14.2	1.32	13.4	14.5	1.37	9.2	15.0
00:04	1.27	9.0	13.4	1.27	7.8	13.6	1.27	12.8	14.1	1.27	11.4	13.9	1.27	12.8	13.6
00:05	1.22	12.2	13.7	1.17	13.2	14.1	1.17	11.8	14.2	1.17	13.4	15.1	1.17	7.1	14.8
00:06	1.12	10.3	13.4	1.12	11.7	14.2	1.12	13.2	14.5	1.07	12.6	14.2	1.12	11.9	14.0
00:07	1.07	11.2	14.3	1.03	13.2	14.4	1.03	10.4	13.7	1.03	8.4	14.5	1.03	9.9	14.1
00:08	0.98	11.6	14.4	0.98	10.9	12.2	0.98	14.0	14.5	0.93	12.2	14.2	0.98	12.8	13.6
00:09	0.93	11.7	13.8	0.88	12.3	14.1	0.88	12.4	14.5	0.88	12.9	13.0	0.88	13.2	14.7
00:10	0.83	11.7	14.4	0.83	9.9	14.8	0.83	13.3	13.9	0.83	9.9	13.5	0.83	12.4	14.1
00:11	0.78	12.3	13.8	0.78	13.6	14.2	0.78	12.5	13.8	0.73	6.0	14.8	0.78	8.8	14.3
00:12	0.73	11.2	14.4	0.68	10.7	12.9	0.68	13.2	13.8	0.68	12.6	13.7	0.73	12.8	14.1
00:13	0.68	12.9	14.3	0.63	12.5	14.2	0.63	12.6	14.4	0.63	12.3	14.3	0.68	13.9	14.2
00:14	0.59	12.7	14.3	0.59	13.9	13.8	0.59	8.6	14.5	0.59	12.4	13.4	0.59	10.9	14.6
00:15	0.54	9.6	14.3	0.54	11.6	12.8	0.54	13.2	14.1	0.54	12.3	14.5	0.54	11.8	14.3
00:16	0.49	7.6	14.4	0.49	9.8	13.9	0.49	11.7	14.1	0.49	12.1	13.6	0.49	11.0	14.2
00:17	0.44	12.8	14.3	0.44	13.9	13.1	0.44	12.5	14.5	0.44	14.3	14.1	0.44	8.2	14.8
00:18				0.39	9.6	14.7	0.39	12.1	13.8	0.39	8.8	14.0			
00:19							0.34	10.6	14.2	0.34	11.6	14.3			
00:20							0.34	8.4	13.9						
00:21							0.29	13.0	14.5						
00:22							0.24	13.6	13.8						

Drum B, Hole size = 1.3 mm diameter

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
(min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.51	12.4	15.1	1.51	8.8	14.7	1.51	11.8	15.3	1.51	12.8	14.6	1.51	12.9	14.8
00:01	1.51	8.3	15.0	1.51	10.3	14.1	1.51	12.1	15.2	1.51	8.4	13.3	1.51	12.8	14.5
00:02	1.46	11.2	15.1	1.46	11.2	15.1	1.46	11.1	14.5	1.46	13.6	15.7	1.46	8.4	15.3
00:03	1.42	5.6	14.4	1.42	12.3	15.1	1.42	12.0	15.1	1.42	9.5	15.3	1.42	12.7	14.8
00:04	1.32	10.4	14.4	1.37	12.3	15.4	1.37	10.4	15.0	1.37	12.2	14.3	1.37	13.1	15.6
00:05	1.32	9.8	15.3	1.32	12.8	15.1	1.32	13.2	15.0	1.32	10.5	15.3	1.32	7.1	15.5
00:06	1.27	13.2	15.0	1.27	12.9	15.0	1.27	13.1	14.5	1.27	13.5	14.3	1.27	12.2	15.4
00:07	1.22	12.5	13.0	1.22	12.1	14.2	1.22	11.7	15.0	1.22	11.1	14.6	1.22	12.9	14.5
00:08	1.17	12.3	14.4	1.17	12.9	15.0	1.17	9.3	14.7	1.17	13.1	15.1	1.17	12.4	15.4
00:09	1.12	11.8	14.7	1.12	10.6	15.1	1.17	12.1	14.8	1.12	11.3	15.0	1.12	10.6	14.8
00:10	1.07	13.0	14.7	1.07	13.0	14.2	1.07	10.2	14.8	1.12	12.3	15.5	1.12	12.7	15.3
00:11	1.03	8.7	14.6	1.07	12.5	14.8	1.07	12.9	14.8	1.07	10.8	15.5	1.07	12.9	15.1
00:12	0.98	12.6	15.1	1.03	10.7	14.7	1.03	10.5	13.5	1.03	13.1	15.3	1.03	11.5	15.1
00:13	0.98	11.3	15.0	0.98	11.4	14.6	0.98	12.8	15.0	0.98	8.1	14.1	0.98	10.2	15.0
00:14	0.93	12.8	15.2	0.93	12.4	15.3	0.93	12.9	14.2	0.93	11.2	15.1	0.93	12.4	15.5
00:15	0.88	12.8	15.2	0.88	10.9	13.6	0.93	11.2	13.5	0.93	11.7	15.0	0.93	8.2	15.3
00:16	0.83	12.5	14.7	0.88	10.5	15.0	0.88	12.5	14.5	0.88	14.2	15.3	0.88	12.6	15.2
00:17	0.83	13.0	15.0	0.83	12.7	14.8	0.83	14.0	14.6	0.83	14.4	15.5	0.83	9.5	15.6
00:18	0.78	9.3	14.4	0.78	13.4	15.0	0.78	9.2	14.1	0.78	9.6	14.5	0.78	11.5	14.9
00:19	0.73	15.2	14.5	0.78	7.7	14.4	0.73	12.9	14.7	0.73	9.6	15.0	0.73	10.4	14.8
00:20	0.73	13.6	15.1	0.73	13.5	15.5	0.73	10.4	13.9	0.73	12.4	15.4	0.73	12.2	14.5
00:21	0.68	10.4	14.5	0.68	10.3	14.8	0.68	13.1	15.9	0.68	10.4	14.8	0.68	8.0	13.5
00:22	0.63	11.0	14.5	0.68	11.9	15.1	0.68	7.9	14.2	0.68	13.3	15.0	0.68	12.8	15.6
00:23	0.63	12.3	15.6	0.63	11.8	15.1	0.63	12.4	14.2				0.63	11.9	15.3
00:24	0.59	12.6	15.6	0.63	9.8	14.8	0.59	12.9	15.0				0.59	11.7	14.8
00:25				0.59	9.1	14.8							0.59	8.9	13.7
00:26				0.59	12.4	15.3									
00:27				0.54	11.0	15.1									

Drum C, Hole size = 1.3 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	10.9	21.3	1.56	10.4	21.6	1.56	9.0	22.1	1.56	7.6	21.7	1.56	-4.0	22.0
00:05	1.46	-10.1	21.7	1.42	11.2	22.0	1.46	-2.7	21.1	1.46	7.4	22.4	1.42	-0.7	22.1
00:10	1.37	8.0	21.4	1.32	0.1	22.0	1.32	10.0	21.7	1.32	5.5	21.8	1.32	-2.1	22.2
00:15	1.27	4.0	21.7	1.22	-2.2	22.2	1.22	-0.7	21.8	1.22	-2.6	22.3	1.22	13.7	21.9
00:20	1.17	6.3	21.7	1.12	6.8	22.1	1.12	-2.7	21.8	1.12	3.0	22.6	1.12	-1.5	21.6
00:25	1.03	-0.4	22.1	1.03	-14.6	21.4	1.03	0.7	21.9	1.03	-15.1	21.8	1.03	-7.3	22.7
00:30	0.98	2.9	21.4	0.93	3.9	21.9	0.93	9.2	21.8	0.93	-2.3	21.8	0.93	-0.5	22.2
00:35	0.88	-1.1	21.6	0.83	3.2	22.1	0.83	4.7	21.9	0.83	6.6	21.5	0.83	0.1	22.1
00:40	0.78	0.7	21.4	0.73	6.8	22.0	0.78	-2.1	22.4	0.73	5.5	21.7	0.73	0.3	22.4
00:45	-0.59	-4.4	21.4	0.68	9.1	22.0	0.68	0.4	21.9	0.68	2.7	21.6	0.68	-2.6	22.6
00:50	0.63	6.1	22.0	0.63	8.4	21.2	0.63	14.9	22.3	0.59	14.0	22.3			
00:55	0.59	-3.7	21.6	0.54	7.1	22.1	0.59	0.8	22.0						
01:00	0.49	2.1	21.6	0.49	-2.7	22.0	0.49	-2.1	22.0						
01:05	0.44	7.0	22.0												

Drum A, Hole size = 1.1 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	13.4	13.8	1.56	8.9	13.0	1.56	9.4	14.9	1.56	12.5	14.0	1.56	13.5	14.3
00:01	1.56	13.0	14.6	1.51	13.3	14.5	1.51	10.0	14.2	1.51	11.4	14.6	1.51	12.7	12.7
00:02	1.51	13.2	13.8	1.51	12.7	14.6	1.51	13.0	14.0	1.51	10.2	13.3	1.51	12.8	14.4
00:03	1.46	11.6	12.1	1.46	9.6	14.6	1.46	11.9	15.2	1.42	13.6	14.3	1.46	12.8	12.4
00:04	1.42	13.2	14.1	1.37	13.8	12.9	1.37	12.9	13.8	1.37	11.1	14.6	1.37	13.4	14.5
00:05	1.37	9.8	14.3	1.32	10.2	14.4	1.32	13.0	14.6	1.32	12.5	13.7	1.32	11.9	14.2
00:06	1.27	10.3	14.4	1.27	12.6	14.1	1.27	13.3	13.8	1.27	9.2	14.1	1.27	13.0	14.6
00:07	1.27	12.9	13.7	1.22	11.9	13.9	1.22	13.0	14.7	1.22	12.3	14.0	1.22	12.9	14.1
00:08	1.22	12.8	14.5	1.17	12.2	14.1	1.17	11.1	13.0	1.17	10.0	14.2	1.17	12.7	13.6
00:09	1.17	7.2	14.6	-1.90	11.9	14.6	1.12	9.2	14.6	1.12	12.6	14.6	1.12	12.1	12.7
00:10	1.12	11.7	14.6	-0.34	13.3	15.0	1.07	11.8	13.8	1.07	12.9	13.8	1.07	13.3	14.4
00:11	1.07	12.8	13.5	-0.10	10.0	14.1	1.07	8.9	14.1	1.07	11.4	14.1	3.76	11.7	13.1
00:12	1.03	11.0	14.5	1.03	13.4	14.5	1.03	12.7	13.8	1.03	11.1	14.0	-0.68	12.4	14.2
00:13	0.98	12.8	13.5	0.98	10.1	14.3	0.98	12.0	14.9	0.98	13.8	14.6	-0.10	12.1	12.4
00:14	0.93	11.5	14.6	0.93	13.6	14.7	0.93	12.7	14.4	0.93	13.0	14.7	0.93	12.2	14.7
00:15	0.88	11.8	14.8	0.88	8.5	14.0	0.88	13.7	14.7	0.88	12.9	14.4	0.88	8.3	13.9
00:16	0.88	11.9	14.6	0.83	12.7	14.4	0.83	13.6	14.6	0.83	11.0	13.6	0.83	11.1	14.9
00:17	0.83	11.1	12.6	0.83	9.7	13.9	0.78	11.7	14.4	0.78	11.3	14.1	0.78	11.2	13.4
00:18	0.78	12.4	14.6	0.78	12.6	13.9	0.78	13.0	13.8	0.78	11.0	14.4	0.78	13.5	14.6
00:19	0.73	9.5	13.8	0.73	12.3	14.4	0.73	11.5	13.4	0.73	12.7	14.0	0.73	10.2	14.5
00:20	0.73	12.2	15.0	0.68	12.1	14.3	0.68	9.3	14.0	0.68	9.3	13.6	0.68	12.2	14.1
00:21	0.68	13.4	13.4	0.68	12.6	14.9	0.68	10.0	14.8	0.68	11.9	14.8	0.68	9.9	14.2
00:22	0.63	13.3	14.2	0.63	7.5	13.5	0.63	9.5	14.2	0.63	8.8	14.3	0.63	13.0	14.4
00:23	0.63	10.2	14.4	0.59	13.3	14.6	0.59	9.8	14.8	0.59	12.0	13.7	0.59	7.4	13.7
00:24	0.59	14.9	14.2	0.59	12.3	14.6				0.59	11.8	13.0	0.59	14.0	14.2
00:25	0.54	11.6	14.5	0.54	13.7	14.8				0.54	13.2	14.9	0.54	11.2	14.0
00:26	0.54	12.1	14.0	0.49	12.9	14.7							0.49	12.3	15.0
00:27	0.49	13.5	15.0	0.49	13.5	14.5									

Drum B, Hole size = 1.1 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	12.4	14.3	1.56	12.1	14.3	1.56	9.7	13.8	1.56	12.2	15.7	1.56	3.0	14.6
00:01	1.56	8.2	16.0	1.51	13.0	15.2	1.51	10.0	15.3	1.56	12.4	15.2	1.51	13.2	14.1
00:02	1.51	9.1	14.0	1.51	11.5	15.0	1.51	12.0	15.6	1.51	10.4	15.2	1.51	12.4	15.1
00:03	1.51	12.6	15.5	1.46	13.1	14.5	1.46	6.7	14.2	1.51	10.9	15.3	1.46	9.0	14.9
00:04	1.46	7.7	15.6	1.46	12.4	15.4	1.46	12.7	15.1	1.46	12.5	15.2	1.46	8.0	15.1
00:05	1.46	12.3	15.3	1.42	6.7	14.9	1.42	12.4	15.5	1.46	10.8	14.9	1.42	10.2	15.9
00:06	1.42	10.1	14.5	1.42	12.1	15.0	1.42	12.9	15.6	1.42	10.1	15.4	1.37	13.8	14.4
00:07	1.42	10.6	15.0	1.37	9.9	14.6	1.37	9.9	15.1	1.37	10.7	14.5	1.37	10.6	14.9
00:08	1.37	9.2	14.9	1.37	12.0	15.4	1.37	13.1	15.6	1.37	11.8	15.7	1.32	12.7	15.4
00:09	1.32	13.5	14.6	1.32	8.5	15.2	1.32	10.9	15.4	1.32	12.1	14.8	1.32	11.6	15.6
00:10	1.32	11.5	15.4	1.27	11.6	15.0	1.32	12.6	15.3	1.32	10.3	15.4	1.27	13.6	14.7
00:11	1.27	12.3	15.3	1.27	11.6	15.2	1.27	12.5	14.8	1.27	12.4	16.1	1.27	12.1	15.5
00:12	1.27	11.0	14.6	1.22	13.7	15.2	1.27	12.4	15.6	1.27	11.3	15.5	1.22	12.5	14.7
00:13	1.22	12.2	15.2	1.22	10.0	14.3	1.22	12.1	15.2	1.22	13.2	15.4	1.22	5.7	14.6
00:14	0.00	12.0	15.0	1.17	12.3	15.5	1.17	9.8	15.1	1.22	12.0	15.7	1.17	9.1	15.7
00:15	1.17	13.1	14.9	1.17	10.2	15.3	1.17	8.7	14.1	1.17	9.2	14.7	1.17	12.3	13.9
00:16	1.17	10.4	14.4	1.12	12.5	15.2	1.17	9.7	15.3	1.17	10.0	15.3	1.12	10.1	15.5
00:17	1.12	11.9	15.2	1.12	10.1	14.4	1.12	14.0	14.8	1.12	9.7	15.2	1.12	11.3	14.6
00:18	1.12	10.7	14.9	1.07	13.2	15.5	1.12	11.9	15.3	1.12	10.2	15.9	1.07	12.9	15.2
00:19	1.07	11.1	14.3	1.07	6.7	15.0	1.07	4.0	14.9	1.07	10.6	14.7	1.07	11.3	15.5
00:20	1.07	9.2	15.0	1.07	8.2	15.4	1.07	7.5	14.7	1.07	10.3	14.7	1.03	7.3	15.2
00:21	1.03	11.9	15.6	1.03	9.6	14.6	1.03	13.7	15.7	1.03	12.7	15.7	1.03	11.8	14.6
00:22	1.03	12.2	15.0	1.03	12.4	15.2	1.03	9.1	15.3	1.03	5.5	15.6	0.98	12.5	15.1
00:23	0.98	12.3	14.6	0.98	10.6	14.9	0.98	9.8	14.1	0.98	10.9	15.2	0.98	9.2	15.6
00:24	0.98	10.8	15.8	0.98	12.7	14.9	0.98	12.7	15.4	0.98	12.7	15.5	0.93	12.5	14.7
00:25	0.98	11.6	15.1	0.93	8.2	15.0	0.93	9.4	14.9	0.98	12.5	16.0	0.93	13.2	15.4
00:26	0.93	9.7	15.1	0.93	11.1	15.8	0.93	9.2	15.1	0.93	11.4	15.9	0.88	10.0	15.6
00:27	0.93	10.8	14.8	0.88	13.5	15.3	0.93	12.2	14.7	0.93	13.2	14.9	0.88	6.5	14.9
00:28	0.88	11.6	15.0	0.88	13.7	15.5	0.88	12.2	15.3	0.88	11.4	15.4	0.88	7.6	14.9

Drum B, Hole size = 1.1 mm diameter (continued)															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:29	0.88	10.4	15.4	0.88	12.2	15.2	0.88	10.9	14.6	0.88	11.6	14.1	0.83	10.0	15.3
00:30	0.83	11.3	15.1	0.83	12.0	15.3	0.83	10.3	15.3	0.88	10.7	15.4	0.83	8.8	15.9
00:31	0.83	11.6	15.1	0.83	8.3	14.8	0.83	10.5	15.3	0.83	12.4	15.8	0.78	9.5	14.5
00:32	0.83	10.1	14.6	0.78	12.4	14.9	0.83	10.0	15.6	-1.42	10.5	15.6	0.78	12.7	15.1
00:33	0.78	9.5	14.9	0.78	10.5	15.1	0.78	13.7	14.8	-0.20	9.6	14.9	0.73	12.2	15.9
00:34	0.78	12.7	15.9	0.73	9.0	15.4	0.78	11.8	15.3	-0.05	11.4	15.7	0.73	10.8	15.4
00:35	0.73	8.5	14.4	0.73	8.2	15.1	0.73	12.1	15.2	0.73	10.9	14.0	0.73	9.3	15.4
00:36	0.73	11.6	15.4	0.73	11.8	15.4	0.73	12.7	15.2	0.73	10.0	15.3	0.73	9.0	16.1
00:37	0.73	11.6	15.4	0.73	11.2	15.1	0.73	11.0	14.5	0.73	11.6	14.3	0.68	11.4	15.4
00:38	0.68	12.9	14.0	0.68	7.7	14.1	0.68	12.0	15.4	0.68	13.6	15.6	0.68	10.5	15.2
00:39	0.68	10.6	15.6	0.68	11.3	15.6	0.68	11.7	15.4	0.68	2.7	14.3	0.68	13.3	14.9
00:40	0.68	12.9	15.1	0.63	10.3	14.5	0.68	9.8	15.5	0.68	8.7	15.4	0.63	12.8	14.9
00:41	0.63	10.2	15.4	0.63	13.4	15.6	0.63	11.1	15.1	0.63	10.5	14.9	0.63	10.9	16.1
00:42	0.63	11.1	15.3	0.63	8.5	15.3	0.63	12.7	15.2	0.63	11.8	15.5	0.59	12.2	13.4
00:43	0.63	12.8	14.9	0.59	11.8	14.7	0.59	9.4	14.9	0.63	11.3	16.0	0.59	11.4	15.2
00:44	0.59	10.5	14.4	0.59	10.6	15.2	0.59	12.0	15.3	0.59	12.2	15.2	0.59	10.9	15.4
00:45													0.54	5.0	15.2

Drum C, Hole size = 1.1 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	4.9	22.8	1.56	-4.4	22.4	1.56	-3.2	22.7						
00:05	1.51	9.8	21.9	1.51	11.6	21.8	1.51	9.0	22.0						
00:10	1.42	11.3	22.3	1.42	-8.5	22.4	1.42	9.8	21.9						
00:15	1.37	4.7	22.5	1.37	2.2	21.9	1.37	-4.9	22.6						
00:20	1.32	5.1	22.7	1.27	12.0	22.3	1.32	6.7	21.6						
00:25	1.22	-7.1	22.1	1.22	-0.9	21.9	1.22	6.9	21.5						
00:30	1.17	-3.4	22.3	1.17	0.1	22.9	1.17	0.0	22.1						
00:35	1.12	3.0	22.7	1.12	2.7	22.7	1.12	9.8	22.8						
00:40	1.07	-2.8	22.4	1.07	1.8	22.4	1.07	-1.4	22.5						
00:45	1.03	2.7	22.8	1.03	4.0	22.2	1.03	5.4	22.0						
00:50	0.98	4.8	22.4	0.93	8.2	22.8	0.98	5.9	22.6						
00:55	-0.10	9.8	22.1	0.88	3.2	22.8	0.93	6.2	21.6						
01:00	0.88	3.2	22.4	0.83	3.7	22.7	0.88	-9.7	22.7						
01:05	0.78	9.0	22.5	0.78	10.9	22.4	0.83	-1.3	22.2						
01:10	0.73	3.7	21.7	0.73	-3.4	22.2	0.73	3.7	22.4						
01:15	0.73	-12.2	22.2	0.73	-0.8	22.4	0.73	-1.8	22.5						
01:20	0.68	-2.2	21.6	0.68	9.3	21.9	0.68	-0.3	21.5						
01:25	0.63	11.1	22.7				0.63	0.3	21.9						
01:30							0.59	3.8	22.3						

Drum A, Hole size = 0.8 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	8.8	13.3	1.56	11.6	13.8	1.56	11.8	13.8	1.56	12.7	14.1	1.56	12.2	14.3
00:01	1.56	11.1	14.5	1.51	12.7	14.0	1.56	10.7	14.5	1.51	11.9	14.7	1.56	10.3	14.7
00:02	1.51	13.5	14.4	1.51	10.2	13.3	1.51	11.7	13.4	1.51	9.6	14.0	24.56	11.5	14.3
00:03	26.27	13.9	14.3	1.46	11.4	14.7	1.46	12.4	14.4	1.46	12.5	14.5	-0.93	12.5	14.8
00:04	-0.78	9.0	14.0	1.42	12.3	13.0	1.42	12.0	13.7	1.42	6.5	14.3	-0.20	12.5	14.1
00:05	-0.05	12.7	15.1	1.42	14.4	13.5	1.42	12.3	13.8	1.42	12.5	14.5	0.68	11.2	14.3
00:06	1.37	4.7	13.6	1.37	12.4	13.8	1.37	12.5	14.0	1.37	10.7	14.4	1.37	11.2	14.2
00:07	1.37	13.1	14.6	1.32	8.3	14.4	1.32	9.6	14.5	1.32	13.0	14.4	1.32	12.2	14.8
00:08	1.32	12.4	14.5	1.27	13.3	14.3	1.27	11.9	13.6	1.27	10.5	14.6	1.32	13.2	14.1
00:09	1.27	12.2	14.0	1.27	10.1	14.9	1.27	11.7	14.4	1.27	10.5	14.7	1.27	13.0	14.1
00:10	1.27	8.6	14.1	1.22	12.9	13.0	1.22	12.7	13.7	1.22	9.1	14.1	1.22	9.5	13.4
00:11	1.22	10.1	15.1	1.17	10.4	14.0	1.17	9.5	13.9	1.17	8.8	14.5	1.22	10.7	15.2
00:12	1.17	13.9	13.6	1.17	11.1	14.3	1.17	12.9	14.4	1.17	13.6	14.4	1.17	11.1	13.9
00:13	1.17	12.7	14.5	1.12	9.8	13.0	1.12	7.1	13.5	1.12	8.5	14.2	1.12	12.6	15.0
00:14	1.12	8.5	13.8	1.07	12.4	14.1	1.07	11.9	14.3	1.07	11.1	14.5	1.12	11.6	15.2
00:15	1.07	13.4	14.7	1.07	10.5	14.8	1.07	12.4	14.4	1.07	13.0	14.5	1.07	11.8	13.5
00:16	1.07	12.5	14.4	1.03	8.3	14.0	1.03	11.4	14.3	1.03	11.6	15.0	1.07	12.6	14.3
00:17	1.03	12.2	15.0	1.03	14.8	13.7	1.03	12.1	13.4	1.03	10.4	14.9	1.03	10.8	14.8
00:18	0.98	10.3	14.5	-1.37	14.2	14.1	0.98	12.9	14.4	0.98	11.5	13.7	0.98	8.4	13.4
00:19	0.98	11.6	14.5	-0.24	9.1	13.8	0.93	10.3	13.4	0.98	11.4	14.9	0.98	12.6	14.7
00:20	0.93	14.6	14.5	-0.10	11.0	14.5	0.93	8.5	13.8	0.93	14.3	14.1	0.93	12.7	14.1
00:21	0.93	10.7	14.0	0.93	12.7	12.3	0.88	11.8	13.6	0.88	8.9	13.7	0.93	14.2	14.5
00:22	0.88	12.2	14.3	0.88	11.1	14.5	0.88	12.4	14.4	0.88	13.6	14.7	0.88	11.0	14.2
00:23	0.88	12.4	15.0	0.83	13.0	13.9	0.83	13.2	14.3	0.83	10.9	14.2	0.88	11.7	14.2
00:24	0.83	12.4	14.1	0.83	7.0	14.4	0.83	12.8	14.1	0.83	11.1	13.2	0.83	12.5	13.9
00:25	0.83	10.9	14.1	0.78	10.8	13.9	0.78	12.2	14.1	0.78	13.0	14.2	0.78	8.8	14.5
00:26	0.78	13.3	14.6	0.78	8.6	13.9	0.78	12.5	14.7	0.78	13.6	15.0	0.78	10.9	14.4
00:27	0.78	11.4	14.5	0.73	13.1	13.9	0.73	11.1	13.1	0.73	10.4	14.1	0.73	12.5	14.4
00:28	0.73	11.3	13.6	0.73	9.2	15.1	0.73	12.3	14.4	0.73	14.4	14.5	0.73	10.0	14.7

Drum A, Hole size = 0.8 mm diameter (continued)															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:29	0.73	13.9	14.6	0.68	12.9	14.1	0.68	9.8	14.4	0.68	9.5	13.7	0.73	13.0	14.1
00:30	0.68	13.8	15.4	0.68	10.1	13.4	0.68	9.3	13.8	0.68	12.5	14.5	0.68	9.5	15.0
00:31	0.68	10.6	14.7	0.68	12.7	14.7	0.68	12.8	12.9	0.68	8.6	14.1	0.68	13.3	14.5
00:32	0.63	12.9	13.9	0.63	6.4	14.2	0.63	12.6	14.4	0.63	12.2	14.7	0.63	11.4	14.7
00:33	0.63	10.3	15.0	0.63	11.6	14.4	0.63	11.6	13.7	0.63	11.1	14.7	0.63	11.6	14.1
00:34	0.63	12.7	14.1	0.59	7.8	14.5	0.59	13.9	14.3	0.59	11.8	14.7	0.59	9.5	14.5
00:35	0.59	11.4	14.3	0.59	11.6	14.5	0.59	13.3	14.4	0.59	11.7	13.8	0.59	11.2	14.7
00:36	0.59	13.3	14.7	0.54	10.3	13.6	0.54	10.5	14.2	0.54	12.5	14.5	0.59	12.5	14.0
00:37	0.54	10.9	14.6	0.54	11.1	14.1							0.54	12.1	14.5
00:38	0.54	14.1	14.4												
00:39	0.49	12.7	14.8												
00:40	0.49	10.3	15.0												
00:41	0.49	10.7	14.7												
00:42	0.44	12.0	13.9												
00:43	0.44	10.0	15.0												

Drum B, Hole size = 0.8 mm diameter

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
	Pressure	T_d	T_a	Pressure	T_d	T_a	Pressure	T_d	T_a	Pressure	T_d	T_a	Pressure	T_d	T_a
(min:s)	(kPa)	(°C)	(°C)	(kPa)	(°C)	(°C)	(kPa)	(°C)	(°C)	(kPa)	(°C)	(°C)	(kPa)	(°C)	(°C)
00:00	1.56	9.6	14.4	1.56	12.1	15.7	1.56	8.4	15.8	1.56	8.6	15.3	1.56	13.6	15.5
00:01	1.56	13.1	15.7	1.56	9.1	15.4	1.56	11.0	15.4	1.56	12.1	15.3	1.56	11.7	15.5
00:02	1.51	10.0	15.2	1.51	9.1	14.4	1.51	12.6	15.6	1.51	12.6	15.5	1.51	12.7	15.5
00:03	1.51	12.5	15.3	1.51	12.5	15.5	1.51	11.8	15.5	1.51	9.3	15.6	1.51	11.7	15.6
00:04	1.51	12.0	15.5	1.51	13.8	15.7	1.51	9.5	15.2	1.51	12.0	15.5	1.46	13.7	15.6
00:05	1.46	10.3	14.9	1.46	12.5	15.3	1.46	10.4	15.9	1.46	11.7	15.3	1.46	11.5	15.2
00:06	1.46	7.8	15.5	1.46	9.6	15.0	1.46	9.4	14.4	1.46	13.0	16.1	1.46	11.7	16.2
00:07	1.42	13.2	15.1	1.42	10.4	15.5	1.46	12.2	15.5	1.42	8.6	15.6	1.42	9.3	14.6
00:08	1.42	10.9	15.4	1.42	7.3	14.6	1.42	8.6	15.2	1.42	11.9	15.1	1.42	11.3	15.6
00:09	1.42	9.5	15.4	1.42	12.1	15.5	1.42	12.8	15.5	1.42	12.3	15.8	1.42	8.4	15.2
00:10	1.37	11.4	15.1	1.37	8.5	14.4	1.37	8.8	15.0	1.37	11.8	15.5	1.37	12.9	15.6
00:11	1.37	11.5	15.4	1.37	8.9	15.5	1.37	11.7	15.8	1.37	7.6	14.8	1.37	11.4	15.5
00:12	1.37	8.3	15.2	1.37	11.6	14.7	1.37	9.8	15.5	1.37	12.4	15.1	1.37	13.3	15.9
00:13	1.32	10.3	14.4	1.37	12.5	16.0	1.32	9.7	16.1	1.32	11.2	15.7	1.32	8.9	15.0
00:14	1.32	9.3	14.5	1.32	9.5	15.4	1.32	11.4	15.7	1.32	12.0	15.6	1.32	13.9	16.1
00:15	1.27	8.0	14.6	1.32	12.5	15.5	1.32	12.7	15.2	1.32	10.4	15.7	1.27	11.7	15.3
00:16	1.27	7.3	15.4	1.27	12.5	14.3	1.27	13.0	15.9	1.27	12.9	15.3	1.27	11.9	15.7
00:17	1.27	11.3	15.5	1.27	11.1	15.4	1.27	12.8	15.8	1.27	10.9	16.1	1.27	8.1	15.1
00:18	1.22	11.5	15.7	1.27	11.7	14.3	1.27	10.6	14.9	1.27	10.3	14.8	1.22	8.4	16.1
00:19	1.22	12.0	13.8	1.22	7.8	15.8	1.22	12.0	15.8	1.22	13.1	15.7	1.22	11.2	16.4
00:20	1.22	12.5	15.1	1.22	11.7	15.3	1.22	12.1	15.2	1.22	11.4	15.7	1.22	12.3	15.7
00:21	1.17	12.8	15.4	1.22	9.1	15.5	1.22	10.6	14.2	1.22	10.4	15.7	1.17	8.2	15.1
00:22	1.17	5.5	14.9	1.17	12.3	15.5	1.17	10.3	15.2	1.17	10.3	15.3	1.17	11.5	15.5
00:23	1.17	12.8	15.3	1.17	11.0	15.5	1.17	12.0	15.2	1.17	11.9	15.7	1.17	13.0	15.8
00:24	1.17	10.9	15.8	1.17	8.9	14.4	1.17	7.4	15.3	1.17	6.9	15.2	1.17	10.2	15.8
00:25	1.12	12.0	15.3	1.12	8.4	15.3	1.12	11.7	14.6	1.12	11.8	15.8	1.12	9.7	15.3
00:26	1.12	10.0	14.9	1.12	12.3	15.5	1.07	11.4	13.7	1.12	10.4	15.2	1.12	13.6	14.6
00:27	1.07	12.4	15.1	1.12	6.4	14.8	1.12	10.6	15.3	1.12	13.1	15.5	1.12	9.8	15.8
00:28	1.07	9.9	14.9	1.12	11.9	15.2	1.07	7.1	15.7	1.07	8.7	15.7	1.07	10.8	15.3

Drum B, Hole size = 0.8 mm diameter (continued)

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
(min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:29	1.07	11.3	15.2	1.07	10.6	15.5	1.07	9.8	15.5	1.07	10.1	14.6	1.07	11.9	15.7
00:30	1.07	10.1	15.2	1.07	9.8	15.5	1.07	9.8	15.3	1.07	12.9	14.8	1.07	12.5	16.1
00:31	1.03	11.6	15.2	1.07	11.5	15.2	1.03	11.0	15.4	1.03	12.5	15.6	1.03	11.3	15.7
00:32	1.03	11.3	15.2	1.03	11.7	15.4	1.03	10.5	15.3	1.03	9.3	15.5	1.03	10.3	15.7
00:33	1.03	10.5	15.2	1.03	9.1	15.4	1.03	10.0	15.0	1.03	13.0	14.8	1.03	11.7	15.6
00:34	0.98	10.8	15.4	1.03	12.6	15.5	1.03	9.1	15.4	1.03	9.9	15.7	0.98	7.8	16.1
00:35	0.98	10.6	15.9	0.98	10.9	15.2	0.98	11.7	15.7	0.98	11.7	15.1	0.98	9.6	15.5
00:36	0.98	11.7	15.4	0.98	10.3	15.9	0.98	12.9	15.5	0.98	11.4	15.3	0.98	12.5	15.5
00:37	0.98	12.0	15.8	0.98	11.9	15.7	0.98	12.6	15.5	0.98	13.0	15.6	0.98	9.8	16.2
00:38	0.93	11.4	15.7	0.93	11.2	15.4	0.98	10.2	15.9	0.98	6.9	15.5	0.93	9.6	15.1
00:39	0.93	4.5	15.4	0.93	10.8	15.1	0.93	12.1	14.8	0.93	7.7	15.3	0.93	10.7	15.7
00:40	0.93	9.3	15.3	0.93	11.4	15.5	0.93	10.8	14.8	0.93	6.8	15.6	0.93	11.7	15.8
00:41	0.88	11.9	14.8	0.93	8.6	15.2	0.93	12.8	14.5	0.93	12.5	15.3	0.88	10.2	16.1
00:42	0.88	10.5	15.2	0.88	12.3	15.4	0.88	6.7	15.2	0.88	11.5	16.1	0.88	11.8	15.4
00:43	0.88	11.0	14.6	0.88	9.4	15.3	0.88	12.4	14.6	0.88	9.3	14.7	0.88	11.2	15.9
00:44	0.88	13.0	15.2	0.88	9.5	15.2	0.88	11.7	15.4	0.88	11.7	15.2	0.88	8.8	15.3
00:45	0.83	14.0	15.2	0.83	12.7	15.4	0.83	12.0	15.7	0.83	12.8	15.5	0.83	12.3	16.1
00:46	0.83	9.0	15.8	0.83	12.3	15.5	0.83	8.9	14.7	0.83	10.6	15.7	0.83	9.2	14.5
00:47	0.83	11.4	15.2	0.83	10.6	14.9	0.83	12.3	15.5	0.83	10.1	15.5	0.83	11.6	16.0
00:48	0.83	11.2	15.4	0.83	11.7	15.5	0.83	11.3	15.8	0.83	12.8	15.8	0.83	11.3	15.8
00:49	0.78	11.7	15.0	0.78	12.2	15.3	0.83	10.5	15.7	0.78	12.5	15.7	0.78	10.7	15.9
00:50	0.78	9.0	15.0	0.78	5.1	15.4	0.78	10.7	15.6	0.78	12.6	15.8	0.78	12.2	15.3
00:51	0.78	12.5	14.7	0.78	11.6	15.3	0.78	11.7	14.6	0.78	12.1	14.7	0.78	13.5	16.1
00:52	0.73	10.9	15.5	0.73	12.0	15.8	0.73	7.6	14.4	0.73	11.9	15.8	0.73	8.0	15.8
00:53	0.73	9.6	14.7	0.73	7.9	14.1	0.73	7.8	15.5	0.73	9.3	15.5	0.73	11.2	15.5
00:54	0.73	8.9	15.7	0.73	11.4	15.7	0.73	10.8	15.1	0.73	12.4	15.6	0.73	9.6	15.5
00:55	0.73	12.0	14.7	0.73	14.2	15.8	0.73	14.4	14.6	0.73	11.3	15.3	0.73	11.2	15.6
00:56	0.73	9.8	15.5	0.73	7.4	15.3	0.73	9.4	15.5	0.73	11.9	15.7	0.73	10.2	15.6

Drum B, Hole size = 0.8 mm diameter (continued)

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
(min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:57	0.68	11.7	14.6	0.68	11.4	14.4	0.68	10.9	14.9	0.68	8.7	15.1	0.68	13.5	15.2
00:58	0.68	12.0	15.4	0.68	11.2	15.8	0.68	11.2	15.9	0.68	11.3	14.5	0.68	9.1	15.8
00:59	0.68	12.5	15.7	0.68	13.0	15.6	0.68	12.8	14.7	0.68	12.5	15.0	0.68	12.9	16.0
01:00	0.68	11.5	15.3	0.68	12.0	15.5	0.68	12.9	15.9	0.68	9.4	15.6	0.68	11.7	15.9
01:01	0.63	11.7	14.9	0.68	11.0	15.9				0.68	12.4	15.7	0.63	12.6	14.6
01:02	0.63	12.5	15.7	0.63	10.9	15.5				0.63	11.5	14.7	0.63	11.1	15.9
01:03													0.63	10.7	14.8
01:04													0.63	8.1	15.1

Drum C, Hole size = 0.8 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	3.5	22.1	1.56	-3.6	22.5	1.56	4.2	22.1						
00:05	1.51	-3.9	21.8	1.51	5.3	22.6	1.51	-10.8	22.7						
00:10	1.46	3.0	22.8	1.46	6.4	22.7	1.46	-3.6	22.7						
00:15	1.42	-2.0	22.7	1.42	6.1	22.6	1.42	3.7	22.9						
00:20	1.37	10.5	22.9	1.42	1.2	22.4	1.37	12.4	23.0						
00:25	1.32	-2.9	22.0	1.37	-3.8	22.3	1.37	11.0	22.7						
00:30	1.27	7.6	22.7	1.32	2.1	22.6	1.32	1.9	22.9						
00:35	1.22	11.8	22.1	1.27	0.6	22.1	1.27	10.4	22.7						
00:40	1.17	13.8	22.7	1.22	-9.2	22.9	1.22	2.0	22.7						
00:45	1.17	11.3	22.2	1.22	2.5	22.2	1.17	-3.6	22.6						
00:50	1.12	-0.2	22.5	1.17	8.6	22.9	1.17	-0.6	22.7						
00:55	1.07	0.5	22.5	1.12	-2.0	22.9	1.12	-1.9	22.5						
01:00	1.03	-7.0	22.5	1.07	5.2	23.1	1.07	5.4	22.4						
01:05	1.03	0.3	22.6	1.03	-1.0	22.3	1.03	11.8	22.3						
01:10	0.98	-2.2	22.6	1.03	5.8	22.6	0.98	0.3	22.9						
01:15	0.93	2.5	22.7	0.98	8.1	22.8	0.98	1.4	22.1						
01:20	0.93	-7.8	22.9	0.98	-5.9	22.6	0.00	-8.5	22.7						
01:25	0.88	1.0	22.3	0.93	2.1	22.4	0.93	7.8	23.2						
01:30	0.83	2.3	22.6	0.88	8.0	22.2	0.88	5.4	22.7						
01:35	0.83	-3.0	21.9	0.83	12.0	22.7	0.83	1.3	22.5						
01:40	0.78	1.1	22.3	0.83	11.8	22.7	0.83	-6.6	23.0						
01:45	0.73	-5.5	22.1	0.78	-3.1	23.1	0.78	11.0	22.3						
01:50	0.00	-5.5	22.7	0.73	4.6	22.9	0.73	0.4	22.6						
01:55	0.68	0.4	22.7	0.73	7.5	22.5	0.73	1.1	22.6						
02:00	0.68	8.1	22.9	0.68	12.9	22.2	0.68	-1.1	22.6						
02:05	0.63	6.5	22.6	0.68	-3.3	22.6	0.68	3.9	22.4						
02:10	0.63	-11.6	22.7	0.63	12.8	22.6									
02:15	0.59	6.6	22.2												

Drum A, Hole size = 0.6 mm diameter

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
(min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	11.2	14.7	1.56	9.8	14.4	1.56	10.7	14.9	1.56	13.3	14.5	1.56	12.7	14.6
00:01	1.56	10.8	14.6	1.56	10.7	14.0	1.51	11.1	13.2	1.51	12.1	14.5	1.51	12.9	14.6
00:02	1.51	12.6	14.6	1.51	12.9	14.3	1.51	11.6	14.6	1.51	11.8	14.2	1.51	11.0	14.7
00:03	1.51	12.4	13.9	1.51	11.8	14.1	1.51	12.6	14.3	1.51	11.6	14.0	1.51	10.0	14.3
00:04	1.51	12.3	13.7	1.51	9.7	14.5	1.46	11.6	14.3	1.46	10.3	14.0	1.46	12.2	15.1
00:05	1.46	10.4	13.9	1.46	12.0	14.7	1.46	10.4	14.8	1.46	13.6	15.3	1.46	8.3	14.4
00:06	1.46	9.3	14.2	1.46	13.9	13.7	1.46	13.7	14.8	1.46	10.3	14.4	1.46	12.7	14.9
00:07	1.46	11.9	13.2	1.46	10.3	14.6	1.42	9.4	14.6	1.42	13.1	14.6	1.42	12.0	14.0
00:08	1.42	13.2	14.4	1.42	11.8	14.3	1.42	13.7	14.3	1.42	8.8	13.6	1.42	13.5	15.1
00:09	1.42	11.0	13.4	1.42	13.5	13.9	1.42	11.6	14.9	1.37	12.2	14.4	1.37	12.2	15.1
00:10	1.37	12.1	14.7	1.37	14.2	13.9	-4.93	12.7	12.4	1.37	11.3	14.2	1.37	12.5	14.8
00:11	1.37	12.9	14.0	1.37	10.6	14.8	-0.39	11.3	14.5	1.37	12.1	14.8	1.37	12.2	14.9
00:12	1.37	9.6	14.5	1.37	13.7	14.6	-0.15	13.9	14.3	1.32	8.2	14.3	1.32	13.2	14.7
00:13	1.32	11.5	14.2	1.32	12.2	14.9	1.32	9.5	14.6	1.32	11.6	14.9	1.32	10.4	14.1
00:14	1.32	12.6	14.5	1.32	5.7	14.7	1.32	12.9	13.8	1.27	6.4	14.4	1.32	10.2	15.1
00:15	1.32	9.3	14.5	1.32	12.4	14.6	1.27	12.1	14.2	1.27	13.5	13.0	1.27	12.5	15.3
00:16	1.27	11.7	15.1	1.27	11.5	14.4	1.27	13.7	14.4	1.27	14.0	14.8	1.27	11.5	14.8
00:17	1.27	13.0	14.1	1.27	8.7	14.9	1.27	9.6	14.5	1.27	13.1	14.1	1.27	10.2	14.3
00:18	1.27	7.1	14.3	1.27	8.0	14.3	1.22	8.9	12.8	1.22	8.4	14.4	1.22	13.5	14.9
00:19	1.22	9.6	14.0	1.22	12.3	14.7	1.22	12.7	14.6	1.22	12.2	14.5	1.22	11.0	14.8
00:20	1.22	10.1	14.1	1.22	9.9	13.8	1.22	14.2	14.0	1.22	11.6	14.3	1.22	12.1	14.3
00:21	1.22	13.1	15.0	1.22	10.3	14.7	1.17	11.6	14.2	1.17	13.5	14.2	1.17	10.0	13.8
00:22	1.17	10.9	15.0	1.17	11.3	14.6	1.17	9.0	14.9	1.17	8.8	14.6	1.17	13.2	14.6
00:23	1.17	10.2	13.9	1.17	11.0	14.8	1.17	12.8	14.8	1.17	12.1	14.6	1.17	11.1	14.3
00:24	1.17	13.1	14.3	1.17	10.1	14.6	1.12	11.6	14.2	1.12	10.2	15.0	1.12	8.7	14.7
00:25	1.12	12.8	14.0	1.12	11.5	15.0	1.12	9.1	14.8	1.12	12.6	14.4	1.12	11.6	14.8
00:26	1.12	8.8	14.2	1.12	8.6	14.9	1.12	10.2	13.4	1.12	9.0	14.2	1.12	13.3	13.2
00:27	1.12	10.3	14.4	1.12	12.7	14.8	1.07	12.6	14.8	1.07	11.5	15.2	1.07	11.6	14.8
00:28	1.07	11.4	15.1	1.07	10.2	14.7	1.07	9.3	15.3	1.07	13.2	14.6	1.07	10.0	14.2

Drum A, Hole size = 0.6 mm diameter (continued)															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:29	1.07	10.2	14.4	1.07	12.3	14.5	1.07	13.2	13.4	1.07	13.9	14.4	1.07	13.7	14.6
00:30	1.07	12.9	14.7	1.07	9.5	15.0	1.07	11.9	14.4	1.03	11.9	14.5	1.07	13.8	14.5
00:31	1.03	10.9	13.7	1.07	9.8	13.1	1.03	12.6	13.9	1.03	13.5	14.4	1.03	12.5	14.9
00:32	1.03	10.5	14.4	1.03	12.0	14.5	1.03	11.8	14.3	1.03	13.6	14.9	1.03	9.5	14.4
00:33	1.03	10.5	14.2	1.03	13.5	14.8	1.03	7.7	14.3	1.03	11.3	14.7	1.03	14.6	14.3
00:34	0.98	12.9	14.1	1.03	12.2	14.8	0.98	14.5	14.9	0.98	11.8	14.6	0.98	11.6	15.1
00:35	0.98	10.4	14.7	0.98	12.0	14.2	0.98	12.2	14.0	0.98	12.6	14.9	0.98	11.0	14.4
00:36	0.98	12.1	14.7	0.98	12.7	14.9	0.98	13.1	14.8	0.98	13.3	15.2	0.98	12.7	14.7
00:37	0.98	10.2	14.1	0.98	11.4	14.6	0.98	11.8	14.2	0.93	8.5	14.6	0.93	13.2	14.8
00:38	0.93	13.0	14.4	0.93	13.0	14.4	0.93	11.7	14.8	0.93	11.8	15.1	0.93	10.6	14.3
00:39	0.93	12.2	14.9	-8.54	9.9	14.6	0.93	9.7	14.2	0.93	10.5	14.9	0.93	12.0	14.7
00:40	0.93	11.4	14.7	-0.54	12.6	13.8	0.93	12.9	14.8	0.93	10.0	15.2	0.93	9.5	14.3
00:41	0.93	11.9	13.7	-0.10	12.8	14.5	0.88	11.3	15.0	0.88	13.6	14.0	0.88	12.0	14.7
00:42	0.88	12.7	14.4	0.88	12.7	14.5	0.88	12.3	14.4	0.88	13.7	14.2	0.88	12.5	15.2
00:43	0.88	6.9	13.7	0.88	11.0	14.9	0.88	12.6	14.2	0.88	9.0	14.7	0.88	10.0	13.1
00:44	0.88	14.1	13.6	0.88	11.8	14.2	0.88	12.8	14.2	0.88	13.0	14.4	0.88	12.6	15.3
00:45	0.83	10.9	13.4	0.88	8.9	14.2	0.83	10.1	14.3	0.83	11.1	14.7	0.83	10.0	14.2
00:46	0.83	11.8	13.9	0.83	10.4	14.3	0.83	12.7	14.0	0.83	13.5	14.8	0.83	12.0	15.2
00:47	0.83	11.2	14.6	0.83	11.3	14.1	0.83	11.1	14.4	0.83	13.2	14.7	0.83	13.1	14.3
00:48	0.83	13.0	13.4	0.83	8.1	14.2	0.83	7.7	14.4	0.78	11.4	14.1	0.78	13.6	15.0
00:49	0.78	14.7	13.1	0.78	11.0	15.0	0.78	9.0	14.9	0.78	12.0	14.3	0.78	12.1	14.1
00:50	0.78	13.4	14.6	0.78	12.3	14.4	0.78	10.4	14.2	0.78	13.8	14.6	0.78	12.4	15.0
00:51	0.78	10.9	13.9	0.78	11.2	15.1	0.78	11.6	14.6	0.78	10.8	14.7	0.78	9.0	13.7
00:52	0.78	13.1	14.6	0.78	9.9	12.4	0.78	8.6	14.3	0.73	13.2	14.4	0.73	11.8	14.9
00:53	0.73	12.5	14.7	0.73	13.3	14.4	0.73	11.1	14.4	0.73	13.0	14.7	0.73	12.2	14.2
00:54	0.73	13.3	14.5	0.73	8.9	13.9	0.73	11.6	14.5	0.73	13.0	15.1	0.73	13.5	14.9
00:55	0.73	10.9	14.8	0.73	12.6	14.6	0.73	12.2	14.7	0.73	13.2	15.1	0.73	7.7	14.7
00:56	0.73	11.0	13.9	0.73	14.9	14.8	0.73	4.9	14.4	0.73	10.3	13.1	0.68	10.0	14.3
00:57	0.73	11.3	14.5	0.73	11.1	13.7	0.68	11.0	14.9	0.68	13.6	15.1	0.68	14.4	15.2

Drum A, Hole size = 0.6 mm diameter (continued)															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:58	0.73	11.4	14.4	0.68	12.2	14.9	0.68	13.3	15.1	0.68	11.6	13.8	0.68	12.5	14.2
00:59	0.68	13.4	13.1	0.68	13.3	14.9	0.68	13.1	14.9	0.68	10.3	14.7	0.68	11.9	14.4
01:00	0.68	12.0	13.5	0.68	13.2	15.2	0.68	13.1	14.4	0.63	8.8	14.6	0.68	10.6	14.8
01:01	0.68	12.0	14.5	0.68	10.6	14.4	0.68	10.5	13.9	0.68	12.4	14.8	0.68	12.9	14.9
01:02	0.68	12.6	14.7	0.68	12.3	14.2	0.63	13.3	14.9	0.63	10.8	14.7	0.63	13.0	14.8
01:03	0.63	12.9	14.5	0.63	7.9	14.8	0.63	12.1	13.9	0.63	13.1	14.9	0.63	13.2	14.7
01:04	0.63	12.0	15.2	0.63	12.2	14.4	0.63	10.4	15.7	0.63	11.2	14.1	0.63	10.5	14.3
01:05	0.63	9.8	14.8	0.63	12.4	14.2	0.63	10.1	14.2	0.63	13.0	14.7	0.63	11.8	14.2
01:06	0.63	14.4	13.7	0.63	12.6	14.7	0.59	12.9	15.1	0.59	9.4	14.6	0.59	6.9	14.8
01:07	0.59	14.1	15.3	0.59	10.1	14.5	0.59	11.0	13.9	0.59	13.0	14.7	0.59	12.9	14.8
01:08				0.59	12.0	14.7				0.59	11.1	14.7	0.59	10.2	14.4
01:09				0.59	11.3	14.6				0.59	13.1	14.6	0.59	13.0	14.6
01:10				0.59	11.2	14.8				0.59	6.5	14.4			
01:11										0.54	13.2	14.8			
01:12										0.54	11.6	14.4			
01:13										0.54	13.5	14.4			

Drum B, Hole size = 0.6 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	11.8	15.9	1.56	8.8	15.4	1.56	12.0	15.2	1.56	12.2	15.0			
00:01	1.56	14.3	15.4	1.56	9.3	13.5	1.56	7.5	16.0	1.56	11.1	15.5			
00:02	1.56	12.6	15.9	1.56	12.6	15.6	1.56	11.8	15.2	1.56	11.4	13.4			
00:03	-1.56	11.8	15.8	1.51	10.4	15.8	1.51	12.2	15.9	1.56	9.6	16.2			
00:04	-0.24	9.1	15.9	1.51	10.3	14.8	1.51	9.8	15.1	1.51	7.0	16.3			
00:05	-0.10	9.7	15.9	1.51	11.6	15.8	1.51	10.7	15.2	1.51	10.5	15.4			
00:06	1.51	12.3	16.0	1.51	9.8	14.2	1.51	10.9	15.5	1.51	11.0	15.5			
00:07	1.51	10.6	15.9	1.51	8.2	15.7	1.51	13.0	15.9	1.51	11.7	15.2			
00:08	1.51	10.8	15.5	1.51	10.2	15.2	1.51	9.8	15.6	1.51	8.5	15.5			
00:09	1.51	10.2	15.0	1.51	12.5	15.7	1.51	14.6	15.2	1.51	10.2	15.5			
00:10	1.51	11.0	15.6	1.51	10.9	14.3	1.51	10.0	15.4	1.51	8.6	16.0			
00:11	1.51	12.7	15.3	1.46	10.2	15.6	1.46	9.8	15.8	1.46	10.1	15.6			
00:12	1.46	11.5	15.6	1.46	7.8	16.0	1.46	9.2	15.5	1.46	12.0	15.0			
00:13	1.46	10.5	14.4	1.46	9.3	15.8	1.46	14.4	15.9	1.46	12.7	15.0			
00:14	1.46	11.1	15.8	1.46	11.1	14.1	1.46	13.5	15.4	1.46	10.6	15.0			
00:15	1.46	9.8	15.6	1.46	13.7	15.1	1.46	12.7	15.5	1.46	13.2	15.9			
00:16	1.46	10.9	15.9	1.46	11.4	15.9	1.46	10.5	15.2	1.46	9.8	15.9			
00:17	1.46	7.4	15.3	1.42	11.9	16.0	1.42	12.8	15.6	1.42	11.9	15.8			
00:18	1.42	12.6	15.9	-1.76	12.4	14.9	1.42	10.7	15.6	1.42	10.1	16.3			
00:19	1.42	12.9	16.0	-0.29	10.9	15.7	1.42	11.9	15.1	1.42	11.4	15.7			
00:20	1.42	10.8	15.5	-0.10	12.8	15.4	1.42	12.9	15.6	1.42	12.5	14.3			
00:21	1.42	10.9	15.7	1.42	10.3	15.4	1.42	12.7	15.7	1.42	9.7	15.9			
00:22	1.42	12.3	15.6	1.42	13.0	15.2	1.42	9.2	15.4	1.42	10.1	15.2			
00:23	1.42	11.0	15.9	1.37	11.9	15.3	1.37	11.6	15.7	1.42	12.7	15.5			
00:24	1.37	11.0	14.9	1.37	8.0	15.7	1.37	10.4	15.7	1.37	9.5	15.6			
00:25	1.37	12.3	14.3	1.37	10.5	15.1	1.37	11.3	15.7	1.37	12.2	15.7			
00:26	1.37	13.1	15.9	1.37	11.8	15.2	1.37	10.9	14.9	1.37	11.2	15.8			
00:27	1.37	11.5	15.9	1.37	8.9	15.2	1.37	12.5	15.5	1.37	12.2	15.7			
00:28	1.37	11.8	15.2	1.37	11.0	15.3	1.37	13.2	15.7	1.37	10.4	15.7			

Drum B, Hole size = 0.6 mm diameter (continued)															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:29	1.37	12.4	15.5	1.37	9.9	14.9	1.32	11.9	14.6	1.37	10.6	15.0			
00:30	1.37	13.2	15.7	1.32	11.8	15.2	1.32	10.5	15.9	1.32	11.7	14.4			
00:31	1.32	8.8	15.9	1.32	10.4	15.8	1.32	13.7	15.9	1.32	12.1	16.0			
00:32	1.32	12.0	15.3	1.32	8.9	14.7	1.32	11.7	16.1	1.32	9.6	15.7			
00:33	1.32	9.5	16.0	1.32	12.4	15.3	1.32	11.8	14.6	1.32	12.7	15.7			
00:34	1.32	9.9	15.4	1.32	9.5	14.5	1.32	13.0	14.5	1.32	12.2	16.5			
00:35	1.32	11.8	15.8	1.32	13.2	15.6	1.32	11.4	15.3	1.32	12.9	15.0			
00:36	1.32	11.0	15.0	1.27	10.9	15.3	1.27	10.1	15.4	1.27	9.4	15.9			
00:37	1.27	11.5	15.9	1.27	10.8	15.6	1.27	12.9	15.7	1.27	12.2	16.1			
00:38	1.27	12.6	15.1	1.27	12.1	15.4	1.27	12.2	15.7	1.27	11.3	15.7			
00:39	1.27	12.9	15.6	1.27	11.6	15.1	1.27	8.5	15.5	1.27	9.1	15.2			
00:40	1.27	12.4	15.6	1.27	11.5	14.5	1.27	9.6	15.7	1.27	12.2	15.9			
00:41	1.27	12.1	15.6	1.27	11.0	14.8	1.27	11.8	14.6	1.27	11.7	15.5			
00:42	1.27	7.0	15.8	1.27	11.6	15.6	1.22	7.6	15.9	1.27	11.1	16.1			
00:43	1.27	13.4	16.0	1.22	8.7	14.5	1.22	11.7	15.2	1.22	10.0	15.6			
00:44	1.22	8.4	16.2	1.22	12.1	15.8	1.22	11.9	15.5	1.22	12.9	15.2			
00:45	1.22	12.6	15.8	1.22	11.4	14.9	1.22	14.1	12.8	1.22	11.9	14.8			
00:46	1.22	8.1	15.3	1.22	9.5	15.8	1.22	11.9	15.8	1.22	12.6	16.8			
00:47	1.22	12.7	15.2	1.22	8.5	14.9	1.22	9.7	15.0	1.22	10.9	16.0			
00:48	1.22	9.2	15.8	1.22	10.3	15.3	1.17	9.3	16.2	1.22	10.3	15.0			
00:49	1.22	12.0	15.8	1.17	10.2	15.2	1.17	13.3	15.5	1.22	8.3	14.3			
00:50	1.22	9.0	15.4	1.17	12.7	14.1	1.17	12.3	16.3	1.17	10.6	15.9			
00:51	1.17	12.0	15.8	1.17	10.5	14.7	1.17	11.1	15.2	1.17	11.2	15.4			
00:52	1.17	11.5	15.9	1.17	14.2	16.2	1.17	11.8	15.6	1.17	11.8	15.5			
00:53	1.17	9.0	15.0	1.17	8.9	15.3	1.17	11.4	16.1	1.17	12.8	15.6			
00:54	1.17	11.7	15.4	1.17	12.2	15.7	1.17	13.6	16.2	1.17	12.0	15.9			
00:55	1.17	11.6	15.4	1.17	11.4	15.4	1.17	12.8	15.1	1.17	9.7	14.0			
00:56	1.17	10.4	15.8	1.17	11.6	15.8	-2.78	8.1	16.0	1.17	13.3	15.5			
00:57	1.17	13.2	15.4	1.17	12.2	16.0	-0.39	9.9	15.7	1.17	7.0	15.7			

Drum B, Hole size = 0.6 mm diameter (continued)

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
(min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:58	1.17	8.8	15.9	1.12	13.8	15.7	-0.15	11.9	15.5	1.12	8.2	15.2			
00:59	1.12	12.4	15.7	1.12	6.7	15.3	1.17	12.1	14.9	1.12	7.8	14.9			
01:00	1.12	11.1	15.9	1.12	12.6	15.4	1.12	9.3	14.3	1.12	12.2	15.0			
01:01	1.12	10.0	15.3	1.12	10.9	15.8	1.12	9.9	15.6	1.12	12.3	15.8			
01:02	1.12	12.9	15.1	1.12	13.6	15.3	1.12	10.0	14.9	1.12	10.8	14.1			
01:03	1.12	9.0	15.4	1.12	12.0	14.5	1.12	11.6	14.4	1.12	10.3	15.6			
01:04	1.12	12.5	16.0	1.07	12.6	15.6	1.07	12.2	15.5	1.07	13.6	16.5			
01:05	1.07	10.6	15.5	1.07	10.7	15.6	1.07	8.7	15.5	1.07	10.7	15.8			
01:06	1.07	12.5	15.8	1.07	13.1	14.9	1.07	12.9	13.8	1.07	11.8	15.5			
01:07	1.07	11.1	16.0	1.07	12.5	16.0	1.07	9.8	16.1	1.07	10.7	15.6			
01:08	1.07	12.4	15.3	1.07	11.8	15.7	1.07	10.1	15.4	1.07	9.6	15.0			
01:09	1.07	10.7	15.1	1.07	6.5	14.9	1.07	11.9	15.7	1.07	10.9	16.0			
01:10	1.07	12.5	15.8	1.07	11.4	15.6	1.07	12.0	15.7	1.07	11.9	16.5			
01:11	1.07	10.3	15.2	1.07	13.3	15.5	1.03	8.3	14.6	1.07	7.2	14.7			
01:12	1.07	12.6	15.8	1.03	6.5	15.1	1.03	11.3	15.2	1.03	12.0	15.3			
01:13	1.03	11.5	15.8	1.03	11.3	15.4	1.03	8.1	15.6	1.03	6.8	15.5			
01:14	1.03	14.2	15.6	1.03	7.0	14.9	1.03	12.0	15.2	1.03	11.1	15.7			
01:15	1.03	11.5	15.4	1.03	11.1	15.2	1.03	9.2	15.0	1.03	10.9	16.0			
01:16	1.03	12.0	15.6	1.03	9.8	15.6	1.03	12.7	15.6	1.03	12.9	15.2			
01:17	1.03	9.9	15.6	1.03	13.8	15.7	1.03	7.8	15.1	1.03	10.7	16.2			
01:18	1.03	11.5	15.4	1.03	10.3	15.9	0.98	13.3	15.1	1.03	10.3	16.5			
01:19	1.03	8.5	15.2	0.98	8.5	16.2	0.98	5.0	15.5	0.98	11.2	15.2			
01:20	0.98	11.9	15.6	0.98	10.7	15.0	0.98	11.9	15.7	0.98	12.8	15.7			
01:21	0.98	8.1	16.0	0.98	10.7	15.9	0.98	8.5	16.3	0.98	11.5	16.1			
01:22	0.98	10.7	15.1	0.98	10.0	14.7	0.98	10.8	15.6	0.98	11.8	15.7			
01:23	0.98	12.9	15.8	0.98	10.4	15.4	0.98	10.5	15.1	0.98	8.8	15.4			
01:24	0.98	12.1	15.4	0.98	8.8	15.4	0.98	12.0	15.5	0.98	12.5	15.6			
01:25	0.98	10.0	15.0	0.98	11.0	14.8	0.98	11.9	16.1	0.98	10.7	16.0			
01:26	0.98	11.3	15.6	0.98	11.6	15.7	0.98	12.5	14.5	0.98	13.3	15.5			

Drum B, Hole size = 0.6 mm diameter (continued)

Time	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
(min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
01:27	0.98	12.2	15.2	0.93	11.0	15.1	0.93	12.6	15.6	0.93	9.4	15.8			
01:28	0.93	13.6	16.0	0.98	5.9	14.1	0.93	9.2	15.9	0.93	10.2	15.6			
01:29	0.93	13.5	15.3	0.93	12.6	15.8	0.93	8.3	15.7	0.93	10.1	15.6			
01:30	0.93	10.0	15.2	0.93	9.3	14.1	0.93	12.3	15.2	0.93	12.5	15.8			
01:31	0.93	10.7	15.8	0.93	11.3	14.8	0.93	10.7	15.6	0.93	10.5	15.4			
01:32	0.93	9.5	15.6	0.93	9.4	15.6	0.93	9.0	15.2	-8.25	8.5	14.9			
01:33	0.93	10.4	15.8	0.93	10.9	15.0	0.93	10.6	15.2	-0.49	8.2	15.9			
01:34	0.93	11.1	15.6	0.88	11.4	15.2	0.88	12.2	15.5	-0.15	11.9	16.0			
01:35	0.93	13.3	15.3	0.88	11.7	15.6	0.88	9.6	16.3	0.93	12.5	15.7			
01:36	0.88	9.4	14.5	0.88	13.0	15.9	0.88	9.1	14.7	0.88	9.6	14.9			
01:37	0.88	12.1	15.1	0.88	7.2	14.7	0.88	9.6	15.1	0.88	11.1	16.4			
01:38	0.88	12.6	14.5	0.88	10.5	15.9	0.88	9.5	14.4	0.88	12.3	15.4			
01:39	0.88	12.1	15.9	0.88	8.7	14.3	0.88	12.0	16.0	0.88	10.5	15.4			
01:40	0.88	9.4	15.7	0.88	12.7	16.4	0.88	11.6	15.5	0.88	8.5	15.7			
01:41	0.88	10.0	15.1	0.88	11.2	15.6	0.88	11.4	15.7	0.88	12.1	15.7			
01:42	0.88	10.3	16.0	0.88	12.4	15.9	0.88	9.7	15.0	0.88	7.3	15.1			
01:43	0.88	11.0	16.0	0.88	9.5	15.8	0.83	10.3	15.9	0.83	8.5	15.8			
01:44	0.83	9.3	14.3	0.83	11.9	16.0	0.83	11.1	15.2	0.83	7.3	15.3			
01:45	0.83	13.0	15.7	0.83	5.4	14.3	0.83	10.7	15.7	0.83	11.9	16.2			
01:46	0.83	12.7	15.8	0.83	11.8	15.6	0.83	13.5	14.9	0.83	10.9	15.2			
01:47	0.83	11.8	14.7	0.83	8.0	15.9	0.83	11.7	15.2	0.83	13.2	16.1			
01:48	0.83	8.5	15.2	0.83	10.8	15.6	0.83	12.0	15.4	0.83	10.9	15.4			
01:49	0.83	12.7	14.7	0.83	8.2	15.3	0.83	10.5	16.0	0.83	11.2	15.4			
01:50	0.83	12.9	14.8	0.83	12.1	14.9	0.83	11.0	14.6	0.83	8.6	15.1			
01:51	0.83	11.0	15.6	0.83	9.3	15.2	0.78	12.4	15.7	0.83	12.0	15.8			
01:52	0.78	5.2	15.4	0.78	12.2	15.6	0.78	12.7	15.4	0.78	11.5	14.9			
01:53	0.78	13.7	13.8	0.78	10.8	15.6	0.78	11.6	14.6	0.78	11.7	15.4			
01:54	-7.42	9.7	16.3	0.78	13.3	15.6	0.78	11.8	15.4	0.78	9.7	15.6			
01:55	-0.54	11.6	15.2	0.78	12.9	15.8	0.78	12.0	16.0	0.78	10.8	15.0			

Drum B, Hole size = 0.6 mm diameter (continued)															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
01:56	-0.10	11.0	15.8	0.78	9.1	15.2	0.78	10.3	15.0	0.78	6.0	14.9			
01:57	0.78	10.9	15.3	0.78	9.2	15.6	0.78	10.8	16.0	0.78	11.2	15.8			
01:58	0.78	10.4	16.0	0.78	11.8	15.2	0.73	10.7	14.7	0.78	11.7	15.2			
01:59	0.78	12.7	14.0	0.73	11.1	15.4	0.73	13.0	15.7	0.73	11.1	15.7			
02:00	0.73	10.9	14.8	0.73	9.7	16.0	0.73	12.5	15.9	0.73	12.7	15.6			
02:01	0.73	11.1	15.8	0.73	11.5	14.5	0.73	8.6	15.5	0.73	13.9	15.2			
02:02	0.73	13.6	15.8	0.73	11.6	15.8	0.73	9.8	15.5	0.73	9.4	16.0			
02:03	0.73	9.3	15.2	0.73	13.0	15.5	0.73	10.9	15.5	0.73	10.1	15.5			
02:04	0.73	12.6	15.9	0.73	10.7	15.7	0.73	8.3	15.6	0.73	9.1	14.5			
02:05	0.73	10.0	15.8	0.73	11.5	14.7	0.73	7.3	15.5	0.73	12.7	15.4			
02:06	0.73	12.2	14.7	0.73	13.0	15.3	0.73	10.7	16.5	0.73	11.9	15.5			
02:07	0.73	13.7	15.1	0.73	12.1	15.4	0.73	12.2	15.7	0.73	13.2	16.0			
02:08	0.73	11.0	15.1	0.73	6.9	16.4	0.73	10.5	15.6	0.73	9.1	14.1			
02:09	0.73	9.3	15.4	23.63	12.0	15.4	0.68	11.8	15.5	0.73	11.7	15.2			
02:10	0.73	13.0	15.9	-0.78	7.0	15.4	0.68	7.6	14.7	0.68	10.3	15.0			
02:11	0.68	12.9	15.7	-0.15	11.1	15.6	0.68	11.6	15.2	0.68	11.0	15.9			
02:12	0.68	11.4	16.0	0.68	7.7	14.7	0.68	11.1	15.5	0.68	13.2	16.1			
02:13	0.68	10.3	15.2	0.68	12.1	15.7	0.68	12.5	15.7	0.68	10.2	15.6			
02:14	0.68	12.2	15.3	0.68	7.3	16.1	0.68	12.6	15.3	0.68	12.3	14.9			
02:15	0.68	10.2	16.4	0.68	11.0	14.9	0.68	13.2	15.6	0.68	11.2	15.8			
02:16	0.68	8.9	15.9	0.68	13.0	15.1	0.68	12.8	15.7	0.68	9.6	15.0			
02:17	0.68	8.3	15.8	0.68	12.9	15.4	0.68	13.2	16.1	0.68	10.1	14.6			
02:18	0.68	12.4	15.7	0.68	11.2	15.9	0.68	8.3	15.4	0.68	10.4	14.8			
02:19	0.68	11.3	15.6	0.68	11.4	15.4				0.68	13.0	15.7			
02:20	0.68	11.1	15.1							0.63	9.5	15.3			
02:21	0.63	7.2	15.6							0.63	10.1	16.0			
02:22	0.63	12.5	15.2							0.63	13.5	15.2			
02:23	0.63	11.6	15.6							0.63	11.7	16.1			
02:24	0.63	10.4	15.7							0.63	12.3	14.4			

Drum C, Hole size = 0.6 mm diameter															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
00:00	1.56	5.6	22.9	1.56	-2.7	22.8	1.56	10.0	22.7						
00:05	1.56	-7.7	22.3	1.51	4.5	22.9	1.17	5.2	23.0						
00:10	1.51	5.2	22.7	1.51	-2.7	23.0	1.51	3.7	23.0						
00:15	1.51	-0.3	22.9	1.51	11.2	22.6	1.51	8.4	23.2						
00:20	1.46	11.8	23.0	1.46	0.4	22.9	1.51	7.7	23.2						
00:25	1.46	9.7	22.9	1.46	7.2	22.7	1.46	-0.9	23.4						
00:30	1.46	0.6	22.9	1.46	-0.3	22.6	1.46	5.0	23.0						
00:35	1.42	8.6	22.5	1.42	0.4	22.6	1.42	-3.5	23.3						
00:40	1.42	-6.7	22.7	1.42	6.4	22.7	1.42	2.0	23.0						
00:45	1.37	13.7	22.5	1.37	6.5	23.3	1.37	-10.7	23.0						
00:50	1.37	-3.1	22.9	1.37	-6.1	23.1	1.37	4.2	22.7						
00:55	1.37	0.4	22.9	1.37	1.4	22.6	1.37	0.9	23.4						
01:00	1.32	4.7	22.7	1.32	2.8	22.5	1.37	9.4	23.4						
01:05	1.32	8.9	22.9	1.32	7.1	23.0	1.32	15.2	23.0						
01:10	1.27	6.6	22.9	1.27	1.3	22.3	1.32	16.4	23.0						
01:15	1.27	10.9	22.7	1.27	5.0	22.9	1.27	-1.0	23.2						
01:20	1.27	0.8	22.9	23.44	-2.3	22.4	1.27	2.8	23.1						
01:25	1.22	8.3	22.7	1.22	5.0	23.0	1.22	3.5	23.2						
01:30	1.22	5.6	22.3	1.22	5.2	23.0	1.22	14.6	23.2						
01:35	1.22	0.9	22.4	1.22	3.3	22.7	1.22	5.3	23.0						
01:40	0.00	0.6	22.9	1.17	2.6	22.8	1.17	8.4	23.4						
01:45	1.17	13.9	22.6	1.17	12.1	23.2	4.49	7.8	23.2						
01:50	1.17	8.6	22.6	1.17	-2.1	22.9	1.17	14.8	23.0						
01:55	1.12	7.5	22.7	1.17	9.7	22.9	1.17	-0.1	22.7						
02:00	1.12	6.2	22.4	1.12	-1.8	22.2	1.12	5.9	23.4						
02:05	1.12	-8.4	23.0	1.12	1.5	22.9	1.12	6.2	23.2						
02:10	1.07	4.9	22.9	1.07	2.0	23.0	1.07	-6.1	23.2						
02:15	1.07	-3.0	22.7	1.07	0.6	22.9	1.07	-0.3	23.0						
02:20	1.07	8.9	22.7	1.07	-2.1	22.7	1.07	-4.4	23.1						

Drum C, Hole size = 0.6 mm diameter (continued)															
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Replicate 5		
Time (min:s)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)	Pressure (kPa)	T_d (°C)	T_a (°C)
02:25	1.03	8.4	23.4	1.03	-1.4	22.8	1.03	-1.1	23.1						
02:30	1.03	4.7	23.0	1.03	6.4	23.0	1.03	-3.3	23.0						
02:35	1.03	8.3	22.1	1.03	-1.5	22.9	1.03	-5.8	22.7						
02:40	0.98	5.0	23.3	0.98	6.4	22.7	0.98	1.8	22.6						
02:45	0.98	-6.8	22.9	0.98	13.4	23.4	0.98	0.5	23.0						
02:50	0.98	4.0	22.9	0.98	5.2	23.0	0.98	0.9	22.8						
02:55	0.98	1.8	22.6	0.98	-5.7	23.0	0.98	-6.0	22.6						
03:00	0.98	5.4	23.0	0.93	7.5	23.3	0.93	-0.1	23.0						
03:05	0.93	3.4	22.4	0.93	7.1	22.8	0.93	2.0	23.1						
03:10	0.93	-3.6	23.2	0.93	12.2	22.1	0.93	11.1	22.5						
03:15	0.88	11.8	22.6	0.93	0.4	22.8	0.93	2.5	22.8						
03:20	0.88	7.4	22.5	0.88	7.7	22.7	0.88	-6.7	23.3						
03:25	0.88	11.3	22.4	0.88	0.2	22.9	0.88	12.4	23.6						
03:30	10.50	8.3	23.0	0.83	-2.9	22.6	0.83	0.3	23.0						
03:35	0.83	8.4	23.2	0.83	8.1	22.8	0.83	1.9	23.0						
03:40	0.83	2.7	22.7	0.83	3.4	22.8	0.83	0.3	23.0						
03:45	0.83	-2.0	22.5	0.83	8.5	23.2	0.83	3.7	23.0						
03:50	0.83	-0.1	22.3	0.78	1.0	22.8	0.83	0.0	23.0						
03:55	0.78	-9.4	23.0	0.78	6.4	22.8	0.78	0.7	22.7						
04:00	0.78	-9.5	22.3	0.78	0.4	22.9	0.78	1.5	22.8						
04:05	0.78	4.7	22.9	0.73	-2.3	23.3	0.78	0.8	23.0						
04:10	0.73	-3.4	22.7	0.73	12.2	22.8	0.73	3.2	23.1						
04:15	0.73	-5.3	22.7	0.73	-5.6	22.7	0.73	0.7	23.1						
04:20	0.73	10.9	22.6	0.73	4.7	23.1	0.73	1.4	22.7						
04:25	0.73	8.0	23.2	0.73	5.4	22.9	0.73	-13.0	22.7						
04:30	0.73	-5.6	23.3	0.68	-3.5	23.2	0.73	-2.1	22.0						
04:35	0.68	4.2	22.7				0.68	-2.5	22.6						
04:40	0.68	-5.2	23.0				0.68	0.5	22.8						
04:45	0.68	-9.8	22.5				0.68	1.6	22.8						

Appendix K - Gas Loss Rate Data for Pilot Bins

Experimental data from the leakage area vs. gas loss rate experiments.

Pages K2 - 9: Experiments were conducted in three sizes of wheat-filled pilot bins (drums A, B, & C). Gas concentration and bulk temperature data were collected at one location inside each pilot bin approximately one-third from the bottom. Three replicates of each hole size in each bin size were conducted.

Pages K10 - 16: Additional experiments were conducted in five pilot bins equivalent in size to drum B. The wheat was replaced with Dowlex 2027A Polyethylene resin pellets which were approximately equal to the size of wheat kernels. Temperature and gas samples were collected from three locations within each pilot bin and data were collected for a period of 14 d. Experiments were done for each of the previous five hole sizes, plus one series of experiments with no holes and one series of experiments with holes equal to 12.7 mm in diameter.

Drum A, Hole size = 1.5 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Aug. 8, 1996)			(Date: Aug. 9, 1996)			(Date: Aug. 12, 1996)		
09:35	19.0	84.2	11:45	21.3	89.8	12:00	21.4	88.2
10:05	20.6	73.5	12:15	21.0	79.6	12:30	21.4	80.0
10:35	21.2	64.4	12:45	21.0	76.4	13:00	21.5	77.4
11:05	21.4	63.5	13:15	21.2	77.0	13:30	21.6	75.2
11:35	21.6	63.5	13:45	21.4	75.1	14:00	21.6	77.0
12:05	21.8	59.1	14:15	21.6	79.4	14:30	21.7	76.5
12:35	21.9	65.5	14:45	21.6	78.0	15:00	21.7	78.5
13:05	22.0	61.9	15:15	21.6	75.7	15:30	22.0	77.1
13:35	22.1	62.7				16:00	22.1	77.3
(Date: Aug. 9, 1996)			(Date: Aug. 12, 1996)			(Date: Aug. 13, 1996)		
09:20	18.6	46.7	09:30	18.7	60.6	08:00	19.4	70.9
09:50	20.4	55.5	10:00	20.5	67.1	08:30	21.0	74.6
10:20	21.0	54.2	10:30	21.0	67.9	09:00	21.7	73.6
10:50	21.3	56.5	11:00	21.3	68.1	09:30	22.2	73.7
11:20	21.5	56.6	11:30	21.6	67.8	10:00	22.3	73.5

Drum B, Hole size = 1.5 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Sept. 7, 1996)			(Date: Sept. 14, 1996)			(Date: Sept. 25, 1996)		
10:55	17.2	86.9	11:55	13.3	88.0	16:15	14.8	89.3
11:25	18.6	83.1	12:25	15.7	83.7	16:45	16.3	71.2
11:55	19.3	80.5	12:55	16.8	83.8	17:15	17.0	64.4
12:25	20.0	82.8	13:25	17.3	82.7	17:45	17.3	67.3
12:55	20.4	79.5	13:55	17.7	83.6	18:15	17.4	62.1
13:25	20.6	81.8	14:25	18.0	84.2	18:45	17.6	70.0
13:55	20.9	80.7	14:55	18.2	83.4	19:15	17.5	70.1
14:25	21.0	81.1	15:25	18.6	84.2	19:45	17.6	69.1
14:55	21.3	80.0	15:55	18.7	83.7	20:15	17.6	68.9
(Date: Sept. 8, 1996)			(Date: Sept. 15, 1996)			(Date: Sept. 26, 1996)		
12:00	18.4	68.4	10:00	14.8	77.6	10:40	13.1	67.8
12:30	19.8	70.5	10:30	16.6	80.2	11:10	15.0	69.3
13:00	20.9	71.3	11:00	17.3	79.7	11:40	16.0	69.7
13:30	21.1	67.9	11:30	17.7	78.2	12:10	16.3	68.9
14:00	21.3	70.6	12:00	18.0	79.6	12:30	16.4	70.6

Drum C, Hole size = 1.5 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Aug. 13, 1996)			(Date: Aug. 14, 1996)			(Date: Aug. 15, 1996)		
12:50	23.4	87.1	12:30	23.4	90.1	11:25	22.6	88.0
13:20	23.6	87.6	13:00	23.0	85.9	11:55	22.8	89.8
13:50	24.1	86.5	13:30	23.4	84.5	12:25	23.0	89.8
14:20	24.5	86.3	14:00	23.9	86.8	12:55	23.6	88.2
14:50	24.7	85.7	14:30	24.3	84.4	13:25	24.3	84.7
15:20	25.0	84.3	15:00	24.6	83.7	13:55	24.5	87.0
15:50	25.1	81.7	15:30	24.8	83.9	14:25	24.9	87.1
16:20	25.3	83.7	16:00	25.0	84.4	14:55	25.2	87.0
						15:25	25.6	86.4
(Date: Aug. 14, 1996)			(Date: Aug. 15, 1996)			(Date: Aug. 16, 1996)		
10:15	19.5	75.1	09:15	19.2	73.8	10:30	20.7	74.8
10:45	21.4	81.3	09:45	21.0	81.5	11:00	22.5	79.5
11:15	22.4	78.7	10:15	21.7	81.0	11:30	23.6	78.5
11:45	22.8	79.8	10:45	22.6	82.8	12:00	24.0	82.1
12:15	23.1	80.8	11:15	22.7	83.3	12:30	24.5	76.9

Drum A, Hole size = 1.3 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Aug. 13, 1996)			(Date: Aug. 14, 1996)			(Date: Aug. 15, 1996)		
13:00	23.3	89.3	12:30	21.7	83.5	11:25	21.7	91.5
13:30	22.3	86.7	13:00	21.6	82.4	11:55	21.6	85.0
14:00	22.4	85.5	13:30	21.6	84.8	12:25	21.6	85.2
14:30	22.4	87.2	14:00	22.0	83.3	12:55	21.7	84.5
15:00	22.6	86.5	14:30	22.2	84.2	13:25	22.1	83.7
15:30	22.8	85.8	15:00	22.3	82.1	13:55	22.2	84.9
16:00	22.9	84.8	15:30	22.5	82.2	14:25	22.4	84.2
16:30	23.0	83.5	16:00	22.4	84.7	14:55	22.5	82.1
						15:25	22.6	83.3
(Date: Aug. 14, 1996)			(Date: Aug. 15, 1996)			(Date: Aug. 16, 1996)		
10:15	19.0	80.1	09:15	19.1	79.2	10:30	19.8	78.6
10:45	20.9	80.3	09:45	20.8	78.9	11:00	21.6	76.7
11:15	21.6	76.2	10:15	21.3	82.2	11:30	22.5	81.3
11:45	21.7	79.1	10:45	21.7	82.3	12:00	22.8	77.4
12:15	21.8	79.8	11:15	21.7	80.4	12:30	22.9	79.8

Drum B, Hole size = 1.3 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Aug. 8, 1996)			(Date: Aug. 9, 1996)			(Date: Aug. 12, 1996)		
09:30	17.5	74.8	11:40	21.0	88.3	12:00	21.0	88.5
10:00	19.4	79.7	12:10	21.0	78.6	12:30	21.0	88.2
10:30	20.4	68.0	12:40	21.1	78.4	13:00	21.2	85.9
11:00	20.8	71.8	13:10	21.4	76.6	13:30	21.5	85.5
11:30	21.0	74.8	13:40	21.6	75.0	14:00	21.6	85.4
12:00	21.3	72.3	14:10	21.8	78.0	14:30	21.9	83.7
12:30	21.5	73.7	14:40	21.8	77.9	15:00	22.1	86.0
13:00	21.6	69.6	15:10	22.0	77.4	15:30	22.4	85.4
13:30	21.8	73.2				16:00	22.6	85.4
(Date: Aug. 9, 1996)			(Date: Aug. 12, 1996)			(Date: Aug. 13, 1996)		
09:25	18.2	55.7	09:30	17.8	66.9	08:00	18.9	77.5
09:55	19.8	68.9	10:00	19.6	72.5	08:30	20.6	81.3
10:25	20.7	69.5	10:30	20.6	74.2	09:00	21.2	81.7
10:55	21.0	69.6	11:00	21.0	72.4	09:30	21.6	83.6
11:25	21.2	69.7	11:30	21.3	73.0	10:00	21.8	81.7

Drum C, Hole size = 1.3 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Sept. 7, 1996)			(Date: Sept. 14, 1996)			(Date: Sept. 25, 1996)		
11:25	19.4	80.1	12:25	17.4	81.5	16:45	17.4	69.3
11:55	20.4	74.8	12:55	18.4	78.5	17:15	18.1	68.1
12:25	21.2	77.0	13:25	19.2	78.6	17:45	18.6	66.5
12:55	21.6	73.0	13:55	19.5	80.5	18:15	18.8	64.4
13:25	22.0	74.7	14:25	19.8	80.1	18:45	19.0	68.8
13:55	22.4	75.7	14:55	20.2	80.1	19:15	19.0	68.5
14:25	22.8	76.5	15:25	20.5	79.8	19:45	19.0	68.8
14:55	23.1	74.6	15:55	20.8	80.2	20:15	19.0	68.8
(Date: Sept. 8, 1996)			(Date: Sept. 15, 1996)			(Date: Sept. 26, 1996)		
12:00	19.3	67.9	10:00	15.9	73.2	10:40	13.9	64.8
12:30	20.9	63.6	10:30	17.5	76.1	11:10	15.9	65.1
13:00	22.0	67.2	11:00	18.5	77.4	11:40	16.9	63.5
13:30	22.6	66.5	11:30	19.0	75.1	12:10	17.1	62.3
14:00	22.8	66.9	12:00	19.5	77.7	12:30	17.3	64.8

Drum A, Hole size = 1.1 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Sept. 7, 1996)			(Date: Sept. 14, 1996)			(Date: Sept. 25, 1996)		
10:55	18.1	81.0	11:55	14.3	86.4	16:15	14.6	82.5
11:25	19.2	81.5	12:25	16.5	83.2	16:45	16.0	58.3
11:55	19.7	84.7	12:55	17.3	82.4	17:15	16.5	71.5
12:25	20.3	83.0	13:25	17.8	82.2	17:45	16.9	70.1
12:55	20.5	80.9	13:55	18.0	82.0	18:15	17.0	64.4
13:25	20.6	81.5	14:25	18.1	82.2	18:45	17.1	67.0
13:55	20.8	81.6	14:55	18.2	81.7	19:15	17.0	64.2
14:25	20.9	82.2	15:25	18.4	81.1	19:45	17.2	68.5
14:55	21.0	81.9	15:55	18.5	81.0	20:15	17.1	68.9
(Date: Sept. 8, 1996)			(Date: Sept. 15, 1996)			(Date: Sept. 26, 1996)		
12:00	18.6	74.6	10:00	15.7	78.8	10:40	13.7	67.8
12:30	19.9	73.7	10:30	17.2	76.1	11:20	15.6	65.3
13:00	20.9	72.6	11:00	18.0	76.4	11:40	16.5	67.6
13:30	21.0	73.1	11:30	18.3	75.2	12:10	16.8	66.4
14:00	21.0	72.8	12:00	18.4	77.0	12:30	16.8	67.1

Drum B, Hole size = 1.1 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Aug. 13, 1996)			(Date: Aug. 14, 1996)			(Date: Aug. 15, 1996)		
12:55	21.7	90.8	12:30	21.5	83.9	11:25	21.0	91.7
13:25	22.2	88.3	13:00	21.5	86.0	11:55	21.3	86.7
13:55	22.6	87.6	13:30	21.7	83.0	12:25	21.5	89.1
14:25	22.8	88.3	14:00	22.2	87.6	12:55	21.8	87.3
14:55	23.0	87.4	14:30	22.5	86.1	13:25	22.4	84.5
15:25	23.4	85.8	15:00	22.7	87.8	13:55	22.6	88.4
15:55	23.5	88.3	15:30	22.9	87.6	14:25	22.9	87.0
16:25	23.6	87.2	16:00	23.0	87.9	14:55	23.1	87.3
						15:25	23.3	88.4
(Date: Aug. 14, 1996)			(Date: Aug. 15, 1996)			(Date: Aug. 16, 1996)		
10:15	18.5	83.8	09:15	18.3	79.8	10:30	19.6	77.8
10:45	20.4	84.8	09:45	20.1	85.5	11:00	21.3	74.3
11:15	21.4	80.3	10:15	20.8	82.6	11:30	22.4	82.3
11:45	21.4	82.8	10:45	21.3	86.8	12:00	22.8	85.1
12:15	21.6	85.6	11:15	21.3	83.2	12:30	23.0	84.2

Drum C, Hole size = 1.1 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Aug. 8, 1996)			(Date: Aug. 9, 1996)			(Date: Aug. 12, 1996)		
09:40	19.2	40.0	11:35	21.9	80.1	12:00	22.9	81.2
10:10	20.6	80.6	12:05	22.2	82.8	12:30	22.6	90.0
10:40	21.5	67.3	12:35	22.4	73.9	13:00	22.8	85.4
11:10	21.9	68.6	13:05	22.8	71.4	13:30	23.2	81.0
11:40	22.5	70.9	13:35	23.2	71.2	14:00	23.4	81.6
12:10	22.9	70.4	14:05	23.4	71.5	14:30	23.7	81.7
12:40	23.2	68.2	14:35	23.5	71.4	15:00	24.0	80.0
13:10	23.4	70.8	15:05	23.6	70.0	15:30	24.3	81.6
13:40	23.6	68.5				16:00	24.5	81.9
(Date: Aug. 9, 1996)			(Date: Aug. 12, 1996)			(Date: Aug. 13, 1996)		
09:30	19.0	43.8	09:30	18.7	51.0	08:00	19.5	70.6
10:00	20.8	62.9	10:00	20.6	67.4	08:30	21.0	77.1
10:30	21.5	64.8	10:30	21.5	65.5	09:00	22.0	76.9
11:00	21.9	65.9	11:00	22.1	67.4	09:30	22.6	77.8
11:30	22.0	65.7	11:30	22.7	67.0	10:00	22.9	79.3

Drum A, Hole size = 0.8 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Nov. 1, 1996)			(Date: Nov. 4, 1996)			(Date: Nov. 5, 1996)		
10:50	3.3	86.4	12:50	4.6	81.3	12:00	7.9	82.9
11:20	5.1	56.1	13:20	6.4	71.3	12:30	7.6	75.1
11:50	5.8	54.1	13:50	7.0	69.3	13:00	7.6	72.7
12:20	6.1	53.1	14:20	7.4	68.6	13:30	7.7	71.8
12:50	6.3	52.8	14:50	7.6	65.1	14:00	7.7	72.6
13:20	6.1	51.0	15:20	7.7	67.3	14:30	7.8	72.1
13:50	6.3	50.9	15:50	7.6	67.2	15:00	7.9	71.1
14:20	6.3	51.1	16:20	7.8	67.3	15:30	7.9	70.7
14:50	6.4	51.2	16:50	7.9	66.6	16:00	8.0	72.6
(Date: Nov. 2, 1996)			(Date: Nov. 5, 1996)			(Date: Nov. 6, 1996)		
10:20	1.7	46.3	09:55	4.2	62.3	09:50	4.8	65.5
10:50	3.9	47.7	10:25	6.4	63.2	10:20	6.8	70.0
11:20	4.8	47.2	10:55	7.0	62.5	10:50	7.5	69.1
11:50	5.1	48.3	11:25	7.3	62.4	11:20	7.9	69.1
12:20	5.3	47.7	11:55	7.6	59.3	11:50	8.0	68.6

Drum B, Hole size = 0.8 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Sept. 30, 1996)			(Date: Oct. 19, 1996)			(Date: Oct. 21, 1996)		
14:50	12.3	89.3	11:15	8.7	66.1	10:50	10.6	87.7
15:20	13.9	76.4	11:45	10.8	54.7	11:20	12.2	64.5
15:50	14.6	73.8	12:15	11.7	59.5	11:50	13.1	65.4
16:20	14.9	50.5	12:45	12.3	59.5	12:20	13.6	65.3
16:50	15.0	64.0	13:15	12.7	59.0	12:50	13.9	64.8
17:20	15.1	68.0	13:45	13.0	56.9	13:20	14.0	63.7
17:50	15.2	72.5	14:15	13.3	59.2	13:50	14.0	63.6
18:20	15.3	74.0	14:45	13.5	55.1	14:20	14.0	62.8
18:50	15.3	73.9	15:15	13.6	56.2	14:50	14.0	61.5
(Date: Oct. 1, 1996)			(Date: Oct. 20, 1996)			(Date: Oct. 22, 1996)		
11:10	11.2	68.2	10:00	10.2	53.0	10:20	9.4	62.5
11:40	13.1	69.5	10:30	11.8	54.9	10:50	11.2	63.6
12:10	14.0	69.1	11:00	13.0	56.5	11:20	12.2	62.4
12:40	14.4	69.2	11:30	13.4	56.1	11:50	12.5	62.8
13:10	14.5	69.1	12:00	13.6	57.5	12:20	12.8	62.7

Drum C, Hole size = 0.8 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Oct. 26, 1996)			(Date: Oct. 27, 1996)			(Date: Oct. 28, 1996)		
09:45	8.6	88.6	13:25	9.7	83.1	12:15	11.6	86.3
10:15	10.4	70.3	13:55	11.2	76.5	12:45	11.7	80.7
10:45	11.4	66.3	14:25	11.9	63.3	13:15	11.9	69.0
11:15	11.9	66.4	14:55	12.4	61.9	13:45	12.2	66.6
11:45	12.3	66.9	15:25	12.5	61.3	14:15	12.5	67.4
12:15	12.5	65.0	15:55	12.8	61.2	14:45	12.6	67.5
12:45	12.8	65.9	16:25	12.8	59.2	15:15	12.8	67.3
13:15	13.0	65.5	16:55	13.0	63.1	15:45	12.9	67.5
13:45	13.0	65.5				16:15	13.0	67.3
(Date: Oct. 27, 1996)			(Date: Oct. 28, 1996)			(Date: Oct. 29, 1996)		
10:40	8.6	58.2	10:10	8.0	40.2	11:00	8.9	52.8
11:10	10.9	58.0	10:40	9.7	58.1	11:30	10.9	64.3
11:40	11.6	59.1	11:10	10.9	57.0	12:00	11.7	64.3
12:10	11.7	58.5	11:40	11.2	57.2	12:30	12.3	63.7
12:40	11.8	56.9	12:10	11.4	58.7	13:00	12.4	63.4

Drum A, Hole size = 0.6 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Sept. 30, 1996)			(Date: Oct. 19, 1996)			(Date: Oct. 21, 1996)		
14:50	12.4	88.8	11:15	9.1	80.6	10:50	10.7	79.6
15:20	13.8	78.6	11:45	10.9	55.3	11:20	12.5	65.5
15:50	14.5	77.1	12:15	11.8	59.4	11:50	13.4	64.6
16:20	14.7	53.1	12:45	12.4	58.7	12:20	13.7	65.7
16:50	14.8	74.1	13:15	12.6	58.2	12:50	14.0	65.3
17:20	15.0	76.4	13:45	12.9	57.1	13:20	14.0	64.4
17:50	15.1	75.0	14:15	13.0	56.7	13:50	14.0	62.5
18:20	15.1	74.6	14:45	13.2	56.3	14:20	14.0	63.4
18:50	15.1	74.5	15:15	13.3	56.5	14:50	14.0	62.6
(Date: Oct. 1, 1996)			(Date: Oct. 20, 1996)			(Date: Oct. 22, 1996)		
11:10	11.6	65.7	10:00	10.4	49.1	10:20	10.2	61.1
11:40	13.6	70.7	10:30	12.0	54.5	10:50	12.0	61.6
12:10	14.5	71.5	11:00	13.1	54.0	11:20	12.8	62.1
12:40	14.8	71.8	11:30	13.4	53.7	11:50	13.1	62.7
13:10	14.9	71.8	12:00	13.6	54.0	12:20	13.4	60.8

Drum B, Hole size = 0.6 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Oct. 26, 1996)			(Date: Oct. 27, 1996)			(Date: Oct. 28, 1996)		
09:45	8.5	83.8	13:25	9.3	83.3	12:15	10.6	85.2
10:15	10.2	72.4	13:55	10.7	70.3	12:45	10.9	76.5
10:45	11.1	66.9	14:25	11.1	67.1	13:15	11.0	72.7
11:15	11.4	66.4	14:55	11.5	64.5	13:45	11.0	74.1
11:45	11.7	66.5	15:25	11.6	65.7	14:15	11.3	73.2
12:15	11.8	66.1	15:55	11.8	65.4	14:45	11.4	72.4
12:45	12.1	66.5	16:25	11.8	65.1	15:15	11.6	72.0
13:15	12.3	66.2	16:55	12.2	67.9	15:45	11.6	71.5
13:45	12.4	66.4				16:15	11.8	73.2
(Date: Oct. 27, 1996)			(Date: Oct. 28, 1996)			(Date: Oct. 29, 1996)		
10:40	7.9	62.8	10:10	7.3	49.2	11:00	8.4	65.2
11:10	10.2	62.9	10:40	9.0	63.3	11:30	10.5	70.7
11:40	11.0	62.0	11:10	10.2	62.2	12:00	11.2	70.5
12:10	11.0	62.0	11:40	10.6	63.6	12:30	11.6	70.4
12:40	11.1	62.7	12:10	10.7	60.3	13:00	11.6	69.8

Drum C, Hole size = 0.6 mm diameter

Replicate 1			Replicate 2			Replicate 3		
Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)	Time	Temp. (°C)	CO_2 (%)
(Date: Nov. 1, 1996)			(Date: Nov. 4, 1996)			(Date: Nov. 5, 1996)		
10:50	3.5	36.7	12:50	5.4	86.5	12:00	8.0	30.5
11:20	5.6	74.4	13:20	7.1	27.4	12:30	8.2	53.5
11:50	6.3	63.6	13:50	8.0	68.4	13:00	8.3	71.7
12:20	6.9	62.5	14:20	8.5	65.7	13:30	8.6	72.0
12:50	7.0	62.6	14:50	8.6	66.7	14:00	8.7	71.1
13:20	7.0	63.1	15:20	9.0	67.1	14:30	9.0	70.5
13:50	7.3	63.6	15:50	8.9	67.4	15:00	9.0	70.6
14:20	7.4	63.4	14:20	9.0	68.2	15:30	9.0	71.2
14:50	7.6	62.1	16:50	9.2	67.0	16:00	9.1	71.9
(Date: Nov. 2, 1996)			(Date: Nov. 5, 1996)			(Date: Nov. 6, 1996)		
10:20	2.3	60.6	09:55	4.6	54.5	09:50	5.0	62.2
10:50	4.4	61.8	10:25	6.8	64.9	10:20	7.0	69.9
11:20	5.6	63.0	10:55	7.5	66.5	10:50	7.9	69.7
11:50	5.9	63.0	11:25	7.9	66.2	11:20	8.3	69.7
12:20	6.2	62.9	11:55	8.2	63.1	11:50	8.5	70.2

Day	Replicate 1 - No hole Top	Mid	Bot	Replicate 2 - No hole Top	Mid	Bot	Replicate 3 - No hole Top	Mid	Bot	Replicate 4 - No hole Top	Mid	Bot	Replicate 5 - No hole Top	Mid	Bot
	CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)		
1	78.9	81.9	80.8	79.2	80.4	80.9	79.1	77.1	73.6	71.7	70.9	68.6	63.0	61.8	63.4
2	81.0	80.2	80.7	81.0	83.3	80.6	76.8	78.8	79.2	72.2	71.6	70.7	63.8	64.9	60.0
3	79.2	79.4	79.6	79.1	78.8	79.1	77.6	76.9	74.1	68.1	67.3	66.8	62.8	62.4	63.7
4	76.8	75.3	78.4	81.1	77.6	79.9	73.3	77.0	75.7	70.4	65.5	61.8	62.8	62.6	63.6
5	79.1	76.7	77.7	76.1	78.8	76.0	76.3	72.7	69.6	70.0	67.3	67.5	59.9	58.7	57.4
6	77.0	76.8	75.9	80.7	79.2	77.0	72.9	75.8	71.6	69.3	67.4	68.1	58.7	58.3	54.8
7	75.6	78.8	76.4	78.8	77.1	76.7	74.4	73.3	70.9	68.5	66.4	63.6	60.1	59.2	58.5
8	76.6	74.0	73.9	73.9	74.9	73.2	74.1	70.0	67.6	63.3	65.2	63.9	56.5	55.9	53.3
9	80.4	77.3	76.0	79.2	74.5	68.8	71.7	72.8	63.6	60.0	60.1	57.4	54.4	58.9	54.4
10	78.0	75.1	75.2	77.8	73.8	73.9	69.7	70.3	70.5	64.3	65.5	58.7	57.9	59.1	54.2
11															
12	77.5	75.4	73.2	72.5	70.9	70.7	71.2	72.5	69.3	65.1	66.0	60.6	53.4	56.7	57.1
13	73.4	72.7	73.2	74.9	76.0	70.4	68.7	69.8	67.0	64.3	63.6	58.4	55.9	55.1	55.1
14	72.7	73.4	70.3	73.9	78.9	74.6	67.8	67.5	70.1	63.7	58.2	59.5	54.3	55.2	56.3
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)		
1	18.3	18.2	18.1	18.2	18.0	17.9	18.1	17.8	17.7	18.0	17.8	17.7	18.3	18.1	18.1
2	19.3	19.1	18.9	19.2	18.9	18.8	19.0	18.5	18.4	19.1	18.8	18.6	19.2	19.0	18.9
3	19.4	19.5	19.6	19.4	19.4	19.3	19.2	19.2	19.0	19.3	19.3	19.0	19.4	19.4	19.4
4	19.6	19.3	19.2	19.3	19.0	18.8	19.2	18.9	18.8	19.1	18.8	18.7	19.3	19.2	19.0
5	19.7	19.6	19.4	19.5	19.2	19.1	19.6	19.2	19.1	19.4	19.0	19.0	19.7	19.3	19.2
6	19.6	20.0	20.1	19.4	19.7	19.6	19.4	19.7	19.6	19.3	19.5	19.1	19.5	19.9	19.8
7	21.1	21.2	21.1	21.0	20.9	20.7	20.9	20.8	20.4	20.7	20.7	20.3	20.9	21.1	20.8
8	19.2	20.6	20.5	19.1	19.7	19.6	19.1	20.2	20.3	18.8	19.3	18.8	19.1	20.2	20.0
9	19.7	20.8	20.6	19.6	19.8	19.9	19.5	20.4	20.4	19.4	19.7	19.3	19.5	20.4	20.3
10	20.1	21.0	20.9	19.8	20.3	20.2	20.0	20.6	20.7	19.9	20.1	19.6	20.0	20.8	20.6
11															
12	23.2	22.0	21.7	23.1	22.2	21.9	23.1	21.9	21.4	23.2	22.4	22.3	23.2	22.1	21.7
13	21.4	21.6	21.8	21.4	21.6	21.6	21.5	21.4	21.8	21.6	21.3	21.7	21.2	21.4	21.7
14	20.9	21.4	21.4	20.9	21.1	21.1	21.0	21.4	21.3	20.9	21.1	20.9	20.9	21.3	21.2

Day	Replicate 1 - 0.6 mm dia			Replicate 2 - 0.6 mm dia			Replicate 3 - 0.6 mm dia			Replicate 4 - 0.6 mm dia			Replicate 5 - 0.6 mm dia		
	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot
	CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)		
1	63.4	72.3	68.8	72.5	73.4	71.0	64.2	63.8	64.3	53.8	53.4	54.8	48.2	50.3	42.2
2	69.5	71.8	74.8	72.3	73.3	73.4	66.2	63.0	62.3	52.2	53.2	54.9	50.7	46.1	46.9
3	70.2	71.7	71.9	70.8	68.6	70.0	65.3	65.1	62.6	51.0	52.5	53.7	47.4	47.7	46.0
4	67.7	67.6	69.0	66.5	68.6	68.4	62.0	62.4	65.7	53.0	51.7	51.7	48.1	47.0	45.2
5	66.8	70.0	67.7	66.6	69.5	66.7	62.3	62.2	63.1	53.0	49.8	51.9	45.2	44.7	45.0
6	67.5	69.0	68.8	64.8	62.2	63.0	60.2	59.4	58.8	51.3	50.8	50.1	43.1	42.5	43.0
7	66.0	68.7	68.7	64.2	63.1	62.4	58.0	57.4	57.1	50.9	49.8	49.5	41.9	42.5	41.8
8	68.7	67.6	69.1	60.0	61.1	61.4	56.5	56.6	57.6	49.7	49.1	49.6	41.2	39.9	39.1
9	65.7	63.5	65.9	57.6	58.4	57.4	54.1	54.0	54.2	46.8	47.2	45.6	40.9	38.6	39.0
10	67.4	68.0	66.7	63.3	57.6	57.9	55.5	53.3	53.2	46.3	47.6	46.1	40.5	40.0	38.8
11	67.3	67.3	66.8	55.0	54.8	55.6	52.5	51.6	52.3	46.1	43.5	44.9	40.2	38.9	40.4
12	63.3	66.4	64.9	55.4	53.5	54.1	48.8	51.0	51.3	45.3	40.5	42.7	35.6	37.4	38.4
13	67.5	67.6	68.2	48.4	46.9	53.1	44.5	45.0	45.7	44.5	41.4	44.4	36.0	36.3	34.0
14	66.7	65.8	65.3	49.0	52.5	43.9	47.4	48.5	50.5	44.2	41.9	42.8	36.0	36.3	34.4
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)		
1	23.2	23.2	23.0	23.0	22.9	22.6	22.9	22.7	22.3	22.8	22.6	22.1	23.1	22.7	22.3
2	22.5	22.7	22.5	22.3	22.3	22.2	22.2	22.2	21.9	22.1	21.6	22.3	22.3	22.1	21.9
3	20.2	21.3	21.2	20.0	20.2	20.2	19.9	20.8	20.8	19.7	19.8	19.2	19.9	20.7	20.6
4	21.8	21.6	21.6	21.7	21.5	21.3	21.4	21.2	20.9	21.6	21.3	21.0	21.8	21.6	21.3
5	22.0	22.3	22.2	21.9	22.0	21.8	21.8	21.9	21.6	21.7	21.7	21.1	22.0	22.2	21.9
6	20.2	21.3	21.3	20.1	20.7	20.4	19.9	20.9	20.8	19.8	20.1	19.4	20.2	20.9	20.8
7	19.2	19.9	19.8	19.0	19.1	19.1	18.9	19.4	19.5	18.8	18.7	18.4	19.0	19.5	19.4
8	19.2	19.3	19.2	19.0	18.9	18.8	18.8	18.9	18.8	18.8	18.6	18.4	19.0	19.1	19.1
9	17.6	18.2	18.2	17.3	17.4	17.4	17.1	17.6	17.9	17.1	17.1	16.7	17.4	17.9	17.9
10	18.5	18.6	18.6	18.3	18.3	18.3	18.2	18.2	18.2	18.2	18.1	17.9	18.3	18.5	18.5
11	19.0	19.2	19.2	18.9	18.8	18.8	18.7	18.7	18.7	18.7	18.6	18.3	18.9	19.1	18.9
12	18.8	19.0	19.0	18.6	18.6	18.5	18.7	18.7	18.6	18.5	18.4	18.1	18.8	18.7	18.7
13	18.7	18.6	18.3	18.4	18.1	18.1	18.3	18.3	17.9	18.4	18.0	17.9	18.6	18.3	18.2
14	17.8	17.9	17.9	17.6	17.5	17.5	17.5	17.5	17.5	17.5	17.2	17.0	17.7	17.7	17.8

Day	Replicate 1 - 0.8 mm dia Top	Mid	Bot	Replicate 2 - 0.8 mm dia Top	Mid	Bot	Replicate 3 - 0.8 mm dia Top	Mid	Bot	Replicate 4 - 0.8 mm dia Top	Mid	Bot	Replicate 5 - 0.8 mm dia Top	Mid	Bot
	CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)		
1	80.4	85.1	83.7	80.6	83.4	85.8	82.4	85.1	86.7	70.1	72.8	79.7	60.4	64.7	75.2
2	70.2	75.4	72.7	72.7	79.5	73.3	72.6	75.7	71.9	67.3	71.1	68.2	61.7	65.4	60.7
3	74.9	77.5	77.7	76.1	78.3	76.3	73.3	71.1	73.6	68.8	69.6	65.5	61.8	61.9	57.9
4	75.3	75.9	77.2	74.6	76.9	74.1	71.9	71.7	74.5	67.6	68.4	63.7	59.9	58.8	58.1
5	74.5	75.7	76.5	73.5	74.1	72.4	71.0	67.5	71.9	66.5	66.2	66.2	59.1	59.3	57.0
6	73.3	73.9	75.4	73.6	70.4	70.4	66.6	69.7	69.9	64.1	64.7	68.0	56.1	54.4	58.9
7															
8	68.6	68.7	69.8	69.7	70.0	70.0	65.7	66.9	67.0	64.0	63.0	64.7	55.9	55.2	55.2
9	68.1	68.3	69.5	63.8	68.9	64.1	63.7	64.3	64.3	61.2	62.9	62.4	54.3	55.1	53.9
10	65.2	65.0	69.4	65.8	64.6	66.9	59.2	60.2	65.4	61.9	63.9	62.3	53.8	52.4	51.8
11	64.7	65.6	66.2	66.0	64.0	64.7	63.3	63.8	63.8	62.1	61.3	62.2	53.6	53.8	51.0
12	63.2	64.7	61.3	65.1	59.1	64.2	62.0	63.4	61.2	58.2	58.9	60.5	52.6	50.6	48.9
13	61.8	62.9	58.3	63.7	59.1	62.9	59.5	62.1	60.9	57.7	57.7	59.3	51.1	49.9	47.5
14	59.7	60.7	56.6	60.6	60.3	62.2	57.6	57.4	60.4	57.3	56.7	58.6	50.6	47.3	46.2
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)		
1	22.2	21.8	21.8	22.1	21.6	21.6	22.4	22.2	22.0	22.2	21.9	21.9	22.2	22.1	21.8
2	22.8	23.4	23.2	22.8	23.1	23.0	22.9	23.1	23.0	22.8	23.1	22.6	22.7	23.3	23.1
3	23.3	23.7	23.6	23.3	23.4	23.2	23.3	23.7	23.4	23.2	23.3	22.9	23.4	23.5	23.3
4	23.4	24.0	24.0	23.4	23.9	23.5	23.4	23.9	23.8	23.3	23.6	23.2	23.3	24.0	23.7
5	22.5	23.5	23.6	22.4	22.8	22.7	22.5	23.6	23.6	22.3	22.7	22.1	22.4	23.4	23.1
6	22.0	22.1	22.0	22.0	21.7	21.6	22.1	22.1	22.1	22.0	21.6	21.5	22.1	22.0	21.7
7															
8	19.2	20.7	20.7	19.1	19.9	19.8	19.2	20.6	20.8	19.0	19.7	19.4	19.2	20.3	20.3
9	20.3	20.9	20.9	20.2	20.5	20.4	20.3	20.8	20.8	20.1	20.3	20.1	20.3	20.5	20.6
10	19.0	20.1	20.1	18.9	19.3	19.4	19.0	20.0	20.1	18.8	19.1	19.0	19.8	19.8	19.1
11	20.4	20.7	20.7	20.4	20.5	20.4	20.4	20.6	20.6	20.4	20.4	20.3	20.4	20.6	20.6
12	20.1	20.7	20.7	20.0	20.3	20.3	20.1	20.6	20.7	19.9	20.1	20.1	20.0	20.6	20.6
13	20.4	20.4	19.7	20.2	20.3	20.3	20.5	20.6	20.2	19.9	19.9	20.3	21.2	19.6	20.4
14	20.9	21.0	21.0	20.8	20.8	20.7	20.8	20.9	20.9	20.8	20.7	20.6	20.8	20.9	20.8

Day	Replicate 1 - 1.1 mm dia			Replicate 2 - 1.1 mm dia			Replicate 3 - 1.1 mm dia			Replicate 4 - 1.1 mm dia			Replicate 5 - 1.1 mm dia		
	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot
	CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)		
1	72.7	77.2	80.9	72.0	77.9	73.6	74.9	69.7	77.4	63.7	63.2	66.3	63.8	62.2	67.3
2	68.6	72.9	73.3	70.6	72.9	73.0	71.0	71.8	68.1	62.5	65.3	62.9	57.6	56.7	56.0
3	67.1	68.9	72.0	72.4	72.8	72.0	66.2	66.0	68.2	59.8	63.6	64.2	51.3	55.6	54.6
4	65.4	69.1	66.9	70.4	69.5	71.3	65.3	63.1	66.1	62.5	61.5	61.9	49.8	49.2	56.2
5	63.0	66.2	67.9	66.5	67.8	66.6	64.8	65.1	63.2	61.1	60.5	61.9	51.0	50.7	50.7
6	66.0	67.5	65.0	67.7	64.3	66.2	60.4	63.6	64.2	59.3	61.0	59.3	51.5	52.5	53.8
7	63.8	65.7	64.6	67.0	61.9	64.3	62.2	63.4	62.7	59.9	59.1	57.9	49.7	51.7	50.1
8	62.6	62.7	57.8	63.1	60.9	64.1	61.5	59.1	61.6	56.1	55.1	52.8	49.1	51.7	49.6
9	59.1	62.5	62.3	63.3	62.5	61.5	60.9	59.4	61.4	57.5	54.9	59.2	48.0	50.2	49.1
10	56.6	60.9	60.9	57.5	58.4	59.6	56.6	56.0	59.6	55.4	55.4	54.9	45.6	46.4	47.0
11	56.7	59.0	56.7	55.0	58.1	57.2	53.2	55.2	57.2	54.8	53.6	55.4	45.8	46.2	45.9
12	55.1	57.8	56.4	55.4	55.5	56.6	53.3	55.9	52.9	53.8	52.9	55.1	45.5	45.0	44.8
13	52.8	54.1	52.8	54.2	50.5	54.1	55.9	51.1	50.7	47.2	48.8	48.1	43.2	46.4	41.2
14	51.6	52.2	51.9	52.2	47.6	49.9	54.2	50.7	49.1	46.4	46.4	45.9	40.7	45.3	39.7
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)		
1	22.8	21.9	21.7	22.8	22.0	21.9	22.8	21.9	21.6	22.8	22.2	22.1	22.9	22.1	21.7
2	22.6	22.7	22.7	22.6	22.8	22.5	22.5	22.7	22.5	22.4	22.7	22.3	22.6	22.8	22.6
3	23.1	23.2	23.2	22.9	23.0	22.8	22.9	23.0	22.8	22.8	22.8	22.5	22.9	23.2	23.1
4	21.2	22.2	22.2	21.2	21.5	21.5	21.3	22.1	22.2	21.2	21.5	21.1	21.4	22.0	21.8
5	22.8	23.1	23.0	22.8	22.8	22.7	22.7	22.9	22.8	22.7	22.8	22.4	22.8	23.0	22.8
6	23.0	23.6	23.6	22.9	23.3	23.1	23.0	23.6	23.4	22.9	23.2	22.7	23.0	23.7	23.4
7	22.9	23.0	23.0	22.9	23.1	23.0	23.2	23.3	22.9	22.9	23.1	23.3	23.0	23.3	23.4
8	22.2	23.2	23.1	22.1	22.6	22.5	22.2	23.0	23.0	21.9	22.3	21.9	22.1	23.0	22.7
9	21.9	22.7	22.7	21.8	22.3	22.1	21.8	22.6	22.6	21.8	22.1	21.6	21.7	22.5	22.3
10	19.9	21.2	21.2	19.9	20.5	20.4	20.0	21.1	21.3	19.8	20.2	20.1	19.9	20.7	20.7
11	18.5	19.7	19.7	18.3	18.6	18.9	18.4	19.6	19.6	18.2	18.8	18.6	18.7	19.2	19.2
12	18.8	19.5	19.6	19.0	19.1	19.2	19.0	19.4	19.8	18.9	18.9	18.9	19.0	19.4	19.4
13	20.3	20.7	20.7	20.2	20.4	20.4	20.3	20.6	20.6	20.3	20.3	20.2	20.3	20.6	20.6
14	18.0	19.1	19.1	17.9	18.1	18.2	18.0	19.0	19.1	17.8	18.0	18.1	18.0	18.7	18.7

Day	Replicate 1 - 1.3 mm dia			Replicate 2 - 1.3 mm dia			Replicate 3 - 1.3 mm dia			Replicate 4 - 1.3 mm dia			Replicate 5 - 1.3 mm dia		
	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot
	CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)		
1	73.8	72.9	75.2	74.6	71.2	77.6	67.7	69.8	75.2	65.1	67.0	62.2	58.0	53.2	54.0
2	73.4	77.9	77.9	78.6	72.2	74.9	71.5	72.6	72.0	66.4	63.6	64.3	56.4	55.1	58.4
3	72.4	74.9	71.3	72.6	73.5	73.0	71.5	69.9	71.9	66.0	59.9	64.9	50.5	53.8	57.5
4	68.2	71.7	71.6	70.9	70.7	69.0	67.2	68.9	69.7	64.8	59.7	57.7	53.9	55.1	53.4
5	64.1	66.1	68.4	65.0	68.9	66.8	65.8	66.6	68.4	62.5	61.5	55.1	54.4	56.1	49.7
6	62.8	63.2	63.8	64.9	65.5	64.6	61.8	64.9	66.2	55.4	59.6	57.9	48.7	53.3	47.3
7	60.1	68.3	67.7	67.8	63.2	66.8	63.5	64.6	66.9	62.8	58.3	61.4	54.5	52.8	52.0
8	65.1	68.4	67.8	67.1	63.7	64.8	59.4	59.7	65.3	57.9	54.0	59.0	52.6	49.9	54.4
9	64.8	64.4	64.6	67.6	61.8	66.3	57.9	57.2	65.0	56.3	57.0	58.6	49.3	47.7	51.4
10	62.3	60.6	64.2	63.6	64.2	63.7	63.4	63.8	64.2	59.7	59.0	58.1	51.7	51.9	51.6
11	62.2	56.9	62.7	62.5	62.6	61.1	62.0	61.1	62.4	57.0	56.6	57.2	50.0	47.1	48.3
12	62.0	55.8	60.3	61.8	60.9	60.8	61.1	58.7	62.1	54.9	56.4	55.5	48.3	46.9	47.0
13	60.9	55.5	56.3	58.8	57.7	57.8	56.9	56.6	58.4	52.2	53.8	55.0	47.1	45.2	46.2
14	58.8	54.7	55.0	57.4	55.1	56.5	52.9	55.6	57.3	50.0	52.1	50.4	44.1	46.6	45.6
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)		
1	18.6	19.1	19.1	18.6	18.7	18.8	18.6	18.9	19.1	18.6	18.7	18.7	18.6	18.9	19.0
2	19.6	19.8	19.8	19.6	19.7	19.7	19.6	19.7	19.7	19.6	19.6	19.5	19.6	19.7	19.7
3	20.9	21.0	20.9	20.9	21.0	20.9	20.9	20.8	20.7	20.7	20.8	20.7	20.8	20.8	20.9
4	24.1	23.2	22.9	24.1	23.6	23.4	24.0	23.0	22.3	24.1	23.7	23.5	24.1	23.5	23.2
5	24.1	24.1	23.9	24.0	24.1	23.9	24.0	24.0	23.4	24.1	24.1	23.7	24.1	24.1	23.8
6	23.3	23.4	23.3	23.3	23.2	23.1	23.3	23.3	23.2	23.2	23.2	23.0	23.2	23.2	23.3
7	22.9	23.6	23.5	22.8	23.3	23.1	22.9	23.6	23.4	22.8	23.1	22.7	22.8	23.6	23.3
8	22.6	23.4	23.3	22.6	23.1	22.8	22.7	23.4	23.2	22.6	22.8	22.6	22.8	23.3	23.1
9	23.6	24.1	23.9	23.6	23.8	23.7	23.7	24.0	23.8	23.4	23.7	23.2	23.6	23.9	23.7
10	23.5	24.5	24.3	23.4	23.9	23.8	23.5	24.3	24.1	23.3	23.6	23.2	23.3	24.2	23.9
11	24.1	24.6	24.5	24.1	24.3	24.2	24.1	24.7	24.3	24.0	24.2	23.7	24.1	24.5	24.3
12	23.8	23.7	23.9	24.7	24.8	24.3	24.3	24.8	23.9	23.8	24.2	23.5	24.5	24.5	24.4
13	24.1	23.8	23.9	23.6	24.6	24.3	24.7	24.6	24.0	23.9	24.1	24.0	24.7	24.6	24.5
14	22.7	22.8	22.9	22.7	22.6	22.6	22.6	23.0	23.0	22.7	22.6	22.4	24.3	24.3	24.4

Day	Replicate 1 - 1.5 mm dia Top	Mid	Bot	Replicate 2 - 1.5 mm dia Top	Mid	Bot	Replicate 3 - 1.5 mm dia Top	Mid	Bot	Replicate 4 - 1.5 mm dia Top	Mid	Bot	Replicate 5 - 1.5 mm dia Top	Mid	Bot
	CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)		
1	81.1	83.2	78.7	74.6	80.1	79.7	77.1	78.2	73.4	64.9	70.2	70.5	60.1	52.8	60.0
2	75.9	72.1	75.0	76.8	73.2	74.5	72.6	72.2	71.9	70.3	68.2	68.3	63.6	61.9	60.6
3	78.4	70.1	73.4	78.9	75.3	71.6	69.8	74.2	74.9	67.8	68.2	64.8	61.5	59.6	61.8
4	76.7	73.7	71.3	73.9	74.7	71.8	75.2	66.3	68.3	65.9	63.2	67.0	56.7	60.7	58.7
5	71.2	68.7	71.1	72.3	69.8	72.6	72.1	72.0	73.1	66.4	64.0	61.4	50.3	59.7	54.9
6	67.6	69.0	71.8	71.9	68.8	70.2	70.4	70.5	69.7	64.9	63.0	58.3	47.7	59.2	53.1
7	64.9	66.5	68.6	69.8	69.2	69.4	68.5	65.4	69.3	61.4	61.4	59.5	53.7	53.2	51.5
8	66.1	66.7	68.8	67.4	66.5	66.8	68.1	68.2	65.9	61.3	59.8	61.1	55.3	55.3	55.5
9	64.2	67.1	66.5	66.0	67.8	69.1	68.4	68.2	67.7	58.5	59.3	61.2	52.1	53.9	54.0
10	62.2	64.0	65.1	64.8	61.2	66.7	62.9	64.3	62.6	59.3	58.1	57.4	51.1	52.1	49.9
11	62.7	64.1	64.2	63.1	57.8	63.6	62.5	59.5	64.1	59.5	59.5	58.9	52.5	52.4	51.9
12	61.0	60.7	63.5	62.1	63.7	63.4	63.5	63.9	64.5	55.7	58.2	58.5	51.4	49.7	49.4
13	59.7	59.1	62.4	61.6	60.0	61.8	62.4	63.4	61.5	56.4	58.6	57.0	51.3	48.4	49.8
14	57.1	61.3	60.8	59.1	59.8	60.0	59.2	61.6	60.7	56.2	55.5	55.5	50.8	48.4	48.2
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)		
1	23.2	23.7	23.7	23.5	23.5	23.4	23.3	23.6	23.4	23.2	23.3	23.1	23.1	23.6	23.4
2	23.7	23.9	23.9	23.7	23.8	23.7	23.7	23.8	23.7	23.6	23.7	23.5	23.7	23.8	23.7
3	24.0	24.2	24.2	24.0	24.1	23.9	24.1	24.2	24.0	24.0	23.9	23.8	24.1	24.2	24.0
4	24.1	24.7	24.6	24.2	24.4	24.3	24.3	24.6	24.4	24.2	24.3	24.1	24.2	24.6	24.4
5	23.0	24.0	23.9	23.0	23.3	23.2	23.1	23.9	23.9	22.8	23.0	22.8	22.9	23.6	23.4
6	22.3	23.3	23.3	22.3	22.8	22.6	22.4	23.3	23.3	22.2	22.5	22.2	22.3	23.1	22.9
7	21.9	23.0	22.9	21.8	22.3	22.3	21.9	22.9	23.0	21.8	22.1	21.8	21.8	22.8	22.6
8	22.2	23.1	23.1	22.2	22.7	22.6	22.2	22.9	23.0	22.0	22.4	22.1	23.0	22.8	22.8
9	23.3	23.4	23.6	23.3	23.3	23.3	23.4	23.4	23.4	23.2	23.3	23.1	23.4	23.5	23.3
10	22.8	23.6	23.6	22.7	23.4	23.1	22.8	23.2	23.4	22.7	23.1	22.7	22.7	23.4	23.3
11	23.3	23.6	23.7	23.4	23.4	23.3	23.3	23.6	23.7	23.3	23.3	23.2	23.3	23.6	23.5
12	23.2	23.7	23.7	23.1	23.4	23.3	23.2	23.7	23.7	23.1	23.3	23.0	23.2	23.6	23.4
13	22.9	23.4	23.4	22.8	23.0	22.9	22.9	23.3	23.3	22.8	22.9	22.7	22.8	23.3	23.2
14	22.6	23.2	23.3	22.6	22.9	22.8	22.7	23.3	23.3	22.5	22.8	22.4	22.6	23.1	23.0

Day	Replicate 1 - 12.7mm dia Top	Mid	Bot	Replicate 2 - 12.7mm dia Top	Mid	Bot	Replicate 3 - 12.7mm dia Top	Mid	Bot	Replicate 4 - 12.7mm dia Top	Mid	Bot	Replicate 5 - 12.7mm dia Top	Mid	Bot
	CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)			CO_2 (%)		
1	83.3	82.9	85.1	81.2	85.3	87.5	79.3	83.0	86.7	78.5	76.1	78.1	70.1	71.7	71.9
2	78.9	80.1	81.3	78.7	81.0	81.9	81.2	80.6	81.4	73.7	74.3	75.0	65.6	69.4	67.6
3	76.4	75.0	75.9	74.1	74.4	75.9	74.9	75.9	75.6	71.4	70.8	72.5	63.5	62.4	64.1
4	69.3	71.0	74.2	68.4	70.9	68.7	71.3	72.2	72.4	66.2	67.6	67.7	57.0	58.4	53.9
5	63.9	63.5	66.6	63.8	65.1	66.0	66.7	67.6	64.2	63.5	64.1	60.4	55.7	55.2	53.8
6	53.9	58.5	59.5	59.5	57.4	64.0	58.7	62.3	59.7	59.7	57.8	56.6	52.7	51.7	52.9
7	50.2	57.6	53.1	56.3	54.7	63.7	57.9	59.9	53.8	56.8	56.1	52.3	49.8	46.4	50.1
8	46.2	53.9	50.2	54.1	51.8	59.9	55.5	56.5	49.5	52.2	55.1	47.7	48.1	44.2	45.5
9	49.5	50.3	50.1	47.0	47.9	48.1	52.6	53.6	53.6	51.5	52.2	52.6	39.7	40.0	39.8
10	45.0	46.0	45.9	42.9	43.5	44.9	47.8	48.6	48.6	48.8	49.1	49.5	35.9	36.2	36.2
11	41.0	41.5	41.3	38.7	39.0	39.0	42.3	43.7	44.1	44.2	45.1	44.6	31.8	32.3	31.9
12															
13	36.4	36.9	37.4	34.9	35.2	35.4	38.9	39.6	39.8	41.0	41.6	41.6	28.5	28.8	28.9
14	34.7	34.9	35.0	32.8	33.1	32.8	36.9	37.2	37.3	39.2	39.7	39.6	26.8	27.2	27.2
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)			Temperature (°C)		
1	25.9	23.7	23.3	25.6	24.2	23.9	25.6	23.6	23.1	25.7	24.4	24.5	25.7	23.9	23.5
2	23.6	23.9	24.0	23.6	23.7	23.8	23.7	23.9	23.9	23.6	23.7	23.5	23.5	24.1	23.9
3	24.2	24.7	24.5	24.2	24.3	24.3	24.4	24.6	24.5	24.3	24.3	24.0	24.3	24.6	24.3
4	23.9	24.7	24.6	23.8	24.1	24.1	23.9	24.4	24.6	23.7	24.0	23.7	23.7	24.6	24.3
5	20.2	21.9	22.0	20.1	20.8	21.0	20.3	21.9	22.3	20.1	20.6	20.3	20.3	21.5	21.4
6	20.8	21.0	21.1	20.5	20.4	20.4	20.5	21.1	21.2	20.4	20.3	20.3	20.6	20.6	20.7
7	21.1	21.6	21.7	21.2	21.3	21.3	21.1	21.6	21.7	20.9	21.0	20.9	21.0	21.4	21.5
8	20.2	21.2	21.2	20.1	20.3	20.6	20.3	20.9	21.2	20.1	20.5	20.1	20.1	20.6	21.0
9	20.4	21.1	21.1	20.4	20.6	20.7	20.5	21.2	21.1	20.3	20.5	20.4	20.5	21.1	21.0
10	22.7	22.4	22.2	22.6	22.4	22.3	22.5	22.2	22.2	22.0	22.4	22.5	22.3	22.5	22.6
11	19.9	20.7	20.8	19.8	20.3	20.3	19.8	20.7	20.8	19.7	20.1	19.9	19.8	20.6	20.6
12															
13	19.4	19.8	19.9	19.9	19.4	19.7	19.7	19.4	19.8	19.9	19.4	19.6	19.5	19.4	19.8
14	22.8	22.0	21.8	22.9	22.3	22.2	22.7	21.8	21.3	22.9	22.4	22.3	23.0	22.3	22.1

Appendix L - Pressure Decay Data for Full-size Bins

Pressure decay data collected from the full-size welded-steel hopper bins during the summer of 1996. Pressure decay tests were conducted before all fumigation experiments, except when caged insects were present in the bins (i.e., experiments F4.3, F4.4, F4.5, F4.8, and F4.9).

Experiment:	F1.1	
Replicate:	1	
Date:	May 13, 1996	
Bin:	A	
Amb. temp.:	14.5°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
End:	0.75	28:13

Experiment:	F1.1	
Replicate:	2	
Date:	May 13, 1996	
Bin:	A	
Amb. temp.:	14.5°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
End:	0.75	20:45

Experiment:	F1.1	
Replicate:	3	
Date:	May 13, 1996	
Bin:	A	
Amb. temp.:	14.5°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
End:	0.75	26:30

Experiment:	F1.1	
Replicate:	4	
Date:	May 13, 1996	
Bin:	A	
Amb. temp.:	14.5°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
End:	0.75	24:26

Experiment:	F2.1	
Replicate:	1	
Date:	May 27, 1996	
Bin:	B	
Amb. temp.:	22.5°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	0.92	05:00
End:	0.75	07:00

Experiment:	F2.1	
Replicate:	2	
Date:	May 27, 1996	
Bin:	B	
Amb. temp.:	22.5°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.14	05:00
	0.81	10:00
End:	0.75	13:45

Experiment:	F2.1	
Replicate:	3	
Date:	May 27, 1996	
Bin:	B	
Amb. temp.:	22.5°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.23	05:00
	0.96	10:00
End:	0.75	14:43

Experiment:	F2.1	
Replicate:	4	
Date:	May 28, 1996	
Bin:	B	
Amb. temp.:	16.8°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.00	05:00
	0.81	10:00
End:	0.75	11:20

Experiment:	F3.1	
Replicate:	1	
Date:	June 7, 1996	
Bin:	A	
Amb. temp.:	23.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.49	00:00
	1.31	05:00
	1.12	10:00
	0.98	15:00
	0.87	20:00
	0.84	25:00
End:	0.74	30:00

Experiment:	F3.1	
Replicate:	2	
Date:	June 7, 1996	
Bin:	A	
Amb. temp.:	23.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.49	00:00
	1.39	05:00
	1.27	10:00
	1.10	15:00
	0.96	20:00
	0.85	25:00
	0.77	30:00
End:	0.74	31:10

Experiment:	F3.1	
Replicate:	3	
Date:	June 10, 1996	
Bin:	A	
Amb. temp.:	26.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.37	00:00
	1.29	05:00
	1.14	10:00
	0.96	15:00
	0.84	20:00
	0.72	25:00
End:	0.69	27:02

Experiment:	F4.1	
Replicate:	1	
Date:	June 24, 1996	
Bin:	B	
Amb. temp.:	13.2°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.00	05:00
End:	0.75	08:52

Experiment:	F4.1	
Replicate:	2	
Date:	June 24, 1996	
Bin:	B	
Amb. temp.:	13.2°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.04	05:00
End:	0.75	09:33

Experiment:	F4.1	
Replicate:	3	
Date:	June 24, 1996	
Bin:	B	
Amb. temp.:	13.2°C	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.00	05:00
End:	0.75	08:04

Experiment:	F4.2	
Replicate:	1	
Date:	July 8, 1996	
Bin:	A	
Amb. temp.:	N/A	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.26	05:00
	1.03	10:00
	0.82	15:00
End:	0.75	17:11

Experiment:	F4.2	
Replicate:	2	
Date:	July 8, 1996	
Bin:	A	
Amb. temp.:	N/A	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.25	05:00
	1.02	10:00
	0.82	15:00
	0.75	16:56

Experiment:	F4.2	
Replicate:	3	
Date:	July 8, 1996	
Bin:	A	
Amb. temp.:	N/A	
	Pressure (kPa)	Time (min:s)
Start:	1.51	00:00
	1.25	05:00
	1.02	10:00
	0.80	15:00
End:	0.75	16:30

Experiment:	F4.6	
Replicate:	1	
Date:	Aug. 6, 1996	
Bin:	A	
Amb. temp.:	19.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.41	00:00
	1.21	05:00
	1.02	10:00
	0.86	15:00
	0.71	20:00
End:	0.70	20:32

Experiment:	F4.6	
Replicate:	2	
Date:	Aug. 6, 1996	
Bin:	A	
Amb. temp.:	19.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.41	00:00
	1.19	05:00
	0.98	10:00
	0.82	15:00
End:	0.70	19:27

Experiment:	F4.6	
Replicate:	3	
Date:	Aug. 6, 1996	
Bin:	A	
Amb. temp.:	19.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.41	00:00
	1.17	05:00
	0.99	10:00
	0.84	15:00
End:	0.70	19:19

Experiment:	F4.7	
Replicate:	1	
Date:	Aug. 12, 1996	
Bin:	B	
Amb. temp.:	23.6°C	
	Pressure (kPa)	Time (min:s)
Start:	1.41	00:00
	0.72	05:00
End:	0.70	05:20

Experiment:	F4.7	
Replicate:	2	
Date:	Aug.12, 1996	
Bin:	B	
Amb. temp.:	23.6°C	
	Pressure (kPa)	Time (min:s)
Start:	1.41	00:00
	0.78	05:00
End:	0.70	06:09

Experiment:	F4.7	
Replicate:	3	
Date:	Aug. 13, 1996	
Bin:	B	
Amb. temp.:	14.6°C	
	Pressure (kPa)	Time (min:s)
Start:	1.50	00:00
	0.84	05:00
End:	0.75	06:03

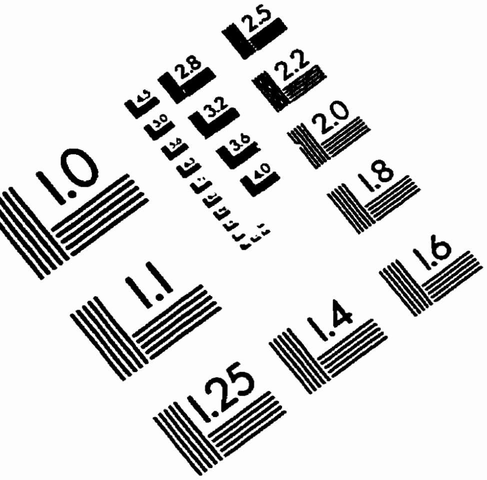
Experiment:	F4.7	
Replicate:	4	
Date:	Aug. 13, 1996	
Bin:	B	
Amb. temp.:	14.6°C	
	Pressure (kPa)	Time (min:s)
Start:	1.50	00:00
	0.88	05:00
End:	0.75	06:19

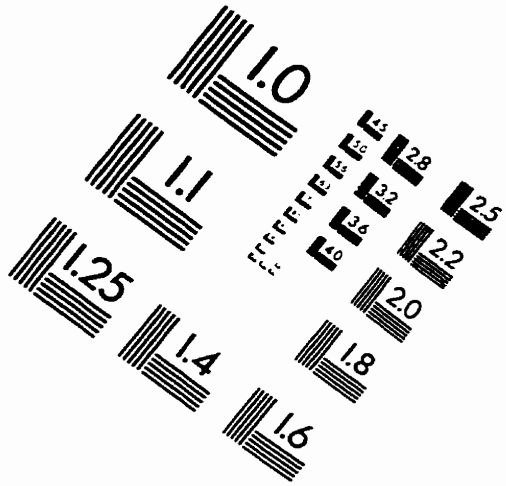
Experiment:	F4.7	
Replicate:	5	
Date:	Aug. 13, 1996	
Bin:	B	
Amb. temp.:	14.6°C	
	Pressure (kPa)	Time (min:s)
Start:	1.50	00:00
	0.84	05:00
End:	0.75	06:04

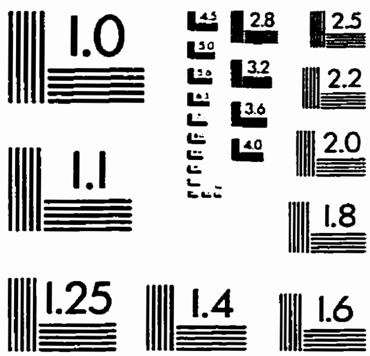
Experiment:	F4.10	
Replicate:	1	
Date:	July 17, 1996	
Bin:	C	
Amb. temp.:	21.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.37	00:00
	1.16	05:00
	1.04	10:00
	0.94	15:00
	0.84	20:00
	0.76	25:00
	0.70	30:00
End:	0.69	32:00

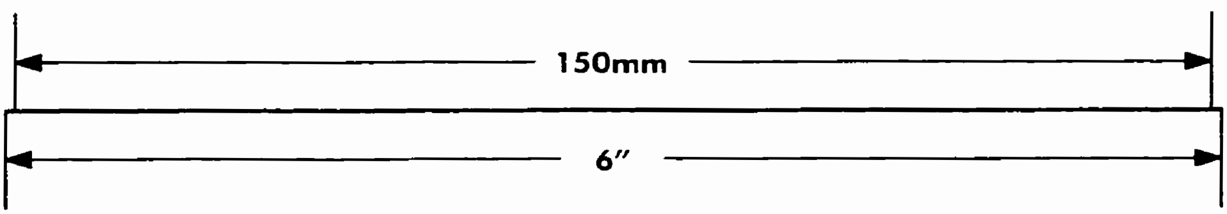
Experiment:	F4.10	
Replicate:	2	
Date:	July 17, 1996	
Bin:	C	
Amb. temp.:	21.0°C	
	Pressure (kPa)	Time (min:s)
Start:	1.37	00:00
	1.17	05:00
	1.08	10:00
	0.98	15:00
	0.88	20:00
	0.78	25:00
	0.70	30:00
End:	0.69	32:00

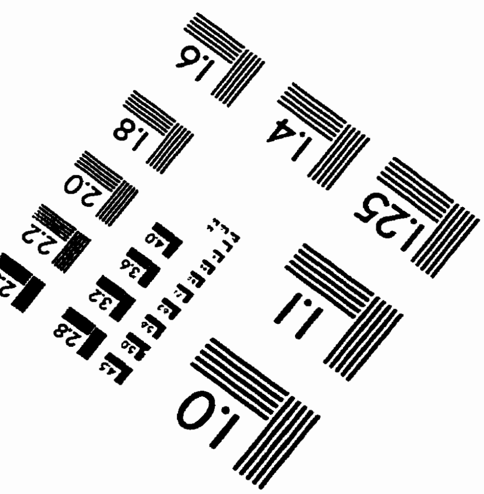
IMAGE EVALUATION TEST TARGET (QA-3)











APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989