PREDICTION OF GAS LOSS FROM BOLTED-METAL BINS CAUSED BY CHANGING ENVIRONMENTAL CONDITIONS

BY

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A thesis submitted to the Faculty of Graduate Studies
in partial fulfilment of the
requirements for the degree of

MASTER OF SCIENCE

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DEDICATION

To:

Howard, Dorothy, Shelley, Carolyn,
Gordon, and Darren...

My Family

ABSTRACT

Predicting the loss of controlled atmosphere (CA) gases from bolted-metal bins caused by wind, temperature, and chimney effects will improve the efficiency and effectiveness of CA fumigation of stored grain. Two mathematical models from literature [Lawerance Berkeley Laboratory (LBL); and Banks and Annis (BA)] were evaluated for their capability in predicting gas loss from a pilot bin (1.42 m diameter x 1.47 m height) and a full size bin (5.56 m diameter x 6.60 m height). Experimental tests were conducted using the bins to provide validation data for the models.

The experimental gas loss rates for both the pilot bin and full size bin did not indicate a direct correlation to the effects of wind. This may be because the wind and chimney effects were combined for the pilot bin. Similarily, the loss of CA gases from the full size bin was due to the combined forces of wind, temperature, and chimney effects. In addition, the direction of the prevailing wind is expected to affect the loss rate depending on the location of the leakage sites.

The effective leakage areas (ELA) of the bins were determined using fan pressurization tests. An ELA of 4.60 cm^2 was found for the pilot bin. In the full size bin, a CO_2 impermeable plastic sheet was attached to the inside wall at 2.5 m above the floor. This excluded the upper half of the bin including the roof; resulting in an ELA of approximately 7.69 cm^2.

For the pilot bin, the LBL model overpredicted the wind effect by an average of 58 times compared to average rate of the experimental gas loss tests. For the full size bin, overprediction for the wind effect was on an average of 5.2 times the average rate of the experimental gas loss tests. The predicted temperature effect using the pilot

bin could not be validated because experimental data were not available. For the full size bin, the predicted temperature effect was within 1% of the average combined rate of the experimental gas loss tests. However, an accurate validation of the wind and temperature effects for both the pilot bin and full size bin could not be conducted because the experimental data were for the combined forces of wind, temperature, and chimney effects. Error may also be because the shielding and terrain coefficients used in the model do not account for the direction of the prevailing wind and are subjective for each bin site depending on the assessment of the surrounding area. In addition, overestimation of the ELA would cause significant differences between predicted and experimental data.

Predicting the rate of gas loss caused by wind with the BA model was difficult because the model was sensitive to an unknown pressure coefficient. Determination of this coefficient requires wind tunnel tests for each bin. These wind tunnel tests were not conducted. The predicted chimney effect using the pilot bin overpredicted the average experimental gas loss rate by approximately 75 times. An accurate comparison, however, is not possible without more experimental data. For the full size bin, the predicted gas loss rate due to the chimney effect was approximately 15 times the experimental gas loss rate. Further experimental studies should be conducted to separate the forces of wind, temperature, and chimney effects so that accurate relationships can be developed. This would provide better data which could be used to validate the models more accurately.

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And finally, I thank my Mother and Father, who have helped me to see how much I have already accomplished.

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NOMENCLATURE

a	amplitude of temperature oscillation (K)
b	flow coefficient ($m^{7/2}/kg^{1/2}$)
c_i	initial internal gas concentration (kg/m^3)
c_f	internal gas concentration after time t (%)
f_w	parameter for wind effects (dimensionless)
f_s	parameter for temperature effects (dimensionless)
g	acceleration due to gravity (m/s^2)
h	vertical height between two representitive leak sites (m)
k_{Ths}	airchange rate due to head space temperature fluctuations (s^{-1})
k_{Tb}	airchange rate due to bulk temperature fluctuations (s^{-1})
k_{wind}	airchange rate due to wind (s^{-1})
$k_{chimney}$	airchange rate due to chimney effect (s^{-1})
n	flow coefficient (dimensionless)
t	time (s)
v	velocity (m/s)
v_{eff}	effective velocity (m/s)
A_c	effective leakage area in the ceiling (m^2)
A_f	effective leakage area in the floor (m^2)
A_o	effective leakage area of structure (m^2)

A'_o	effective leakage area of structure and orifice hole (m^2)
$A_{o\cdot orifice}$	effective leakage area of orifice hole (m^2)
$A_{orifice}$	experimental effective leakage area of the orifice hole (m^2)
C	pressure coefficient (dimensionless)
C'	shielding coefficient (dimensionless)
C_d	discharge coefficient (dimensionless)
H	ceiling height of structure above ground (m)
H_{wt}	ceiling height of weather tower above ground (m)
IC	inclined coefficient of manometer (dimensionless)
M	molecular weight
N	porosity of the grain (dimensionless)
P	pressure (Pa)
P_s	pressure due to temperature (Pa)
P_{st}	pressure due to wind (Pa)
Q	volume flow rate of gas loss from structure (m^3/s)
R_o	fraction of horizontal effective leakage area (dimensionless)
R^g	individual gas constant ($J \cdot kg^{-1} \cdot K^{-1}$)
R^u	universal gas constant ($kJ \cdot kmol^{-1} \cdot K^{-1}$)
T	temperature (K)
V	volume of bin (m^3)
X	fractional difference of floor and ceiling leakage areas (dimensionless)

Greek Letters

α	terrain coefficient (dimensionless)
α_{wt}	terrain coefficient at the weather tower (dimensionless)

β	normalized height (dimensionless)
β_o	normalized neutral pressure level height (dimensionless)
γ	terrain coefficient (dimensionless)
γ_{wt}	terrain coefficient at the weather tower (dimensionless)
κ	thermal diffusivity (m^2/s)
ω	frequency of temperature oscillation (Hz)
ρ	gas density (kg/m^3)

Chapter 1

INTRODUCTION

Storage of grains and oilseeds (hereafter referred to as grains) before processing is a common practice in the agricultural industry around the world. Harvested grains in Canada are commonly stored on farms in corrugated bolted-metal bins of 42 - 84 t capacity (Madrid et al. 1990). Storage periods may last two or more years depending on economic conditions.

The market value of grains depends on the quality of the grain at the time of sale. Factors such as colour, odour, foreign material, and kernal damage due to insects determine the grade (quality) of grains. High quality grains yield higher selling prices than low quality grains. Grains that are below minimal standards cannot be sold for human consumption and are usually sold at reduced prices as animal feed.

The quality of stored grains may be affected by biological factors (e.g. mites, insects, and micro-organisms) and nonbiological factors (e.g. grain temperature, moisture content, and gaseous composition of intergranular air) (Jayas et al. 1991). Insects such as the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) feed on the germ part of the seed and can cause severe grain spoilage when heavy infestations occur (Anonymous 1990a). Canadian standards require a zero tolerance for live insects in a sample of grain. It is therefore necessary to take measures to protect the quality of stored grains from insects. Currently, chemical insecticides are used to kill and control insects in storage facilities.

Chemicals fatal to stored grain insects are of the form of contact insecticides or gaseous fumigants. Although chemicals are effective in controlling infestations, there are a number of shortcomings to using them. First, the chemicals often leave toxic residues on the grains (Jayas et al. 1991). This may prove detrimental to both the environment and human consumers if the use of chemicals continues. Second, insects develop a resistance to the chemicals (Jayas et al. 1991). Therefore, to obtain 100% mortality of insects, higher fumigant doses will be needed. The consequences of this are increased costs and continued resistance development by the insects. Third, increasing government regulations restrict the use of environmentally damaging chemicals. Currently used insecticides such as methyl bromide and phosphine are under review in Canada. Methyl bromide is a serious atmospheric ozone depleter and will be banned or severely regulated in North America by the year 2001. Therefore, an alternative method to control insect infestations will be needed. Controlled atmosphere (CA) fumigation is a possible alternative to using chemical insecticides.

A controlled atmosphere environment is created by altering the proportions of carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2) in normal atmospheric air. Controlled atmosphere fumigation deprives insects of the O_2 required for respiration and, when used properly, is an effective method to controlling insect infestations (Banks and Annis 1977). The effectiveness, however, depends on several factors: gaseous composition, temperature, moisture content, insect species and life stage, and exposure time.

To obtain adequate insect control, the CA gases should be injected to the storage facility at optimum temperatures, moisture content, and gaseous compostion (Banks and Annis 1977). In addition, the CA gases should be distributed uniformly and maintained for the required exposure time for maximum kill. Herein lies one of the most significant problems of CA fumigation. The distribution and loss of the CA gases depends on the diffusion rate of the CA gas and any convective flows that exist in the grain bulk. A convective flow may be caused by several uncontrollable external factors: wind, temperature variations, barometric pressure fluctuations, and chimney effects (Banks and Annis 1984). These factors create pressure drops across the wall of the bin and act as driving forces for the exchange of internal gases with external ambient air through any existing leaks in the wall (Sherman et al. 1980). If a bin contains cracks or holes in the walls, the CA gases will leak out of the bin and will subsequently be replaced by infiltrating ambient air. If the CA gases leak out before a uniform distribution is obtained and the necessary exposure time has elapsed, the fumigation process will be ineffective (Alagusundaram 1993).

In Australia, effective CA fumigation is possible if a structure has a pressure decay time of approximately 5 min for a pressure drop of 500 Pa to 250 Pa (Banks and Annis 1984). Structures meeting this criterion for airtightness usually require a *one-shot* application of the CA gases for adequate control of insects. This, however, represents a well sealed structure and is not representative of typical storage facilities in Canada and the United States. In North America, two thirds of all grain storage facilities are bolted galvanized steel bins which contain many leaks and do not meet the Australian pressurization guideline (M^{c}Gaughey and Akins 1989). Sealing these bins to make them airtight is not practical; requiring extensive labour and high costs (Alagusundaram 1993). In addition, natural aeration which helps to prevent temperature gradients, moisture migration, and subsequent mould growth would be inhibited (M^c^Gaughey and Akins 1989). Therefore, the application of CA gases to imperfectly sealed bins in North America needs to be studied as a possible alternative to using chemical insecticides. For an effective and efficient use of controlled atmospheres, a method of application must be developed so that there is compensation for any gas loss during fumigation.

M^c^Gaughey and Akins (1989) recommend a two stage process for controlling insects in leaky grain bins. The initial stage purges the bin of the existing atmosphere, replacing it with the controlled atmosphere. The second stage is the maintenance stage which compensates for any gas loss that may occur during the process. The rate of replenishing the CA gases during this stage depends on the amount that is lost. Currently, the only method of quantifying the loss rate of CA gases is by continuous monitoring of the gas concentration. This method is called the passive ventilation measurement technique (Anonymous 1993a). The difficulty with this method is that many time consuming field experiments are required to collect reasonable data and the tests would have to be conducted on every bin that is to be treated with CAs. This is impractical considering the number of storage facilities in North America. A more practical solution is to predict what losses are expected under particular environmental conditions for any bin. From these predictions, guidelines recommending the amount of CA gases required to compensate for the expected losses could be developed. Mathematical models may be used for predicting the loss of CA gases from the storage facilities.

Two mathematical models that specifically predict CA gas loss from treated enclosures caused by changing environmental conditions have been reported in the literature (Banks and Annis 1994; Navarro et al. 1990). These models have not been tested for North America's climate and contain assumptions that are inconsistent with the proposed application. A third model predicts the infiltration-exfiltration from a building (Sherman and Grimsrud 1980). This model was designed for simplicity and ease of application to many different structures. To the best of my knowledge, this model has not been used to predict CA gas loss from bolted-metal grain bins.

Once the loss rate of CA gases is known for given weather conditions, the transient distribution of the CA gases can be determined using a finite element analysis. A program has been written to determine the movement and distribution of CA gases in an airtight structure (Alagusundaram 1993). However, allowing for a loss of internal gases through the bin walls better represents a field situation. Quantifying the rates of gas loss is the purpose of the mathematical models.

Chapter 2

OBJECTIVES

The objectives of this study were:

1. to obtain experimental gas loss rates from a pilot and full size bin which could be used as validation data for the mathematical models,
2. to determine the applicability of using the fan pressurization test to estimate the effective leakage area of a pilot and full size bin,
3. to evaluate existing mathematical models for predicting rates of gas loss from a pilot and full size bin caused by wind, internal-external temperature differences, and internal-external density differences,
4. to validate predicted gas loss rates with the experimental data.

Chapter 3

LITERATURE REVIEW

3.1 Overview

Determining the rate of CA gas loss (natural ventilation rate or rate of gas loss) for given weather conditions is crucial to the successful application of CA fumigation to stored grain. The minimum exposure time to effectively control the rusty grain beetle adult is 4 d with a CO_2 concentration greater than 70 % under warm conditions (Banks and Annis 1977). During exposure, the wind and ambient temperature may vary from insignificant (no wind; internal-external temperature difference $< 15^oC$) to significant (wind speeds > 8 km/h; temperature difference $> 15^oC$) (Anonymous 1993b). Knowledge of expected losses caused by changing weather conditions will allow the CA gases to be replenished, thereby ensuring a sufficient gas concentration and distribution for adequate insect control. The ventilation rates can be quantified either by experiments or by mathematical modeling. This chapter discusses the work that has been previously conducted to determine the loss of gases from an enclosure and the relevance of this work to predicting the loss of CA gases from a bolted-metal bin.

3.2 Experimental Studies

Several experimental methods may be employed to determine natural ventilation rates from a building envelope. Ventilation means both infiltration and exfiltration, is synonymous to gas loss rate, and has units of m^3/s. The building envelope is defined as the barrier that separates the interior volume of a building from the external environment (Anonymous 1993a). Building envelopes are classified as either single zone (no partitions within the envelope) (Sherman 1990) or multizone (partitions in the envelope) (Feustel and Sherman 1989). Some of the methods that can be used to determine ventilation rates are:

1. Australian Coordinating Committee on Silo Sealants - Pressure decay test guideline for fumigable structures (Banks and Annis 1984),
2. ASTM E 741-93, Test method for measuring air leakage rate by tracer dilution (Anonymous 1993a),
3. ASTM E 779-87, Test method for measuring air leakage rate by fan pressurization (Anonymous 1993b).

These references should be consulted for detailed explanations. However, a brief discussion of each method is provided in the following paragraphs.

The guideline used to determine airtightness of grain storage facilities in Australia is a pressure decay test (Banks and Annis 1984). This guideline states that a storage bin is considered airtight if, after being pressurized to 500 Pa, the interior pressure drops a maximum of 250 Pa in 5 min. The ventilation rate (Q) is the volumetric flow rate of gas loss from a structure. The ventilation rate constant or airchange rate, k, is defined as the ratio of the volumetric flow rate to the volume of the structure (Banks and Annis 1984). The airchange rate has base units of s^{-1} and is a measure of the effect of various forces such as wind, temperature, and density. For *one-shot* treatment using a CO_2 based CA, a maximum ventilation rate constant of 0.07 d^{-1} is recommended (Banks and Annis 1984). This rate is only obtainable if costly measures such as intensive sealing are undertaken. In addition, they found the guideline resulted in rate constants that are *excessive* for silo bins, typically made of concrete, and *inexcessive* for farm bins, which are typically constructed from welded steel panels.

Another problem with the pressure decay test is that the ventilation rate is dependent on weather conditions, providing their influence is significant. The method is therefore considered passive, making it difficult to compare the airtightness of different structures. The guideline appears to be subject to uncertainty and should perhaps only be used for storage facilities that can be assumed airtight with a high level of confidence. Unlike the common storage facilities in Australia, typical storage bins in the USA and Canada are not airtight. Sealing them to the level of airtightness required for the Australian guideline is impractical (Alagusundaram 1993) and inhibits natural ventilation which helps prevent temperature gradients and moisture migration (M^c^Gaughey and Akins 1989). Due to these conditions, the Australian guideline could not be adhered to for the purposes of determining ventilation rates in existing bolted-metal bins on Canadian farms.

The tracer dilution method requires extensive instrumentation and intensive labour to collect sufficient data to determine ventilation rates (Alagusundaram 1993; Anonymous 1993a). In addition, the method is subject to variations due to uncontrollable weather conditions (Sherman 1989). Therefore, relationships between gas loss and wind, gas loss and temperature, and gas loss and density are difficult to develop in field situations.

The fan pressurization method indirectly relates the ventilation rate to the effective leakage area (ELA) of the structure (Anonymous 1993b). The ELA is defined as the flow area of cracks and openings in the building envelope (Grimsrud et al. 1982). A quantitative estimate of building tightness is determined by estimating the ELA of a structure (Anonymous 1993b). The ELA is determined experimentally and the resulting value can be used in mathematical models to predict ventilation rates for given weather conditions. Due to its simplicity, the fan pressurization method is ideal for quantifying building tightness of many different structures such as different types of grain bins. However, the resulting ELA should be considered as an estimate (Anonymous 1993b).

The fan pressurization test is active in that the ventilation rate is quantified using a mechanically controlled airflow (i.e. using an electric fan). Under moderate weather conditions (wind speeds < 7 km/h and outside temperatures of 5 to 35°C) the driving forces are insignificant compared with the force of the mechanically supplied airflow (Anonymous 1985a; and Anonymous 1993b). This allows the relative ventilation rate (i.e. ELA) to be isolated from weather influences.

3.3 Mathematical Modeling

Predicting ventilation rates across building envelopes has long been a concern of mechanical engineers who design heating, ventilation, and air conditioning (HVAC) systems. This knowledge allows engineers to design environment control systems that can maintain a comfortable environment and compensate for losses due to natural ventilation. Bantle (1990) reported mathematical models that were developed for the purposes of improving the design of HVAC systems. Until recently the models had not been used in the agriculture industry (Bantle 1990). The models reviewed ranged in complexity from single-zone to multi-zone. An example of a single-zone building is a storage shed; whereas a building that contains many subdivided areas (i.e. two story home or apartment block) is classified as multi-zone. Considering the simple shape and open internal space of a typical bolted-metal grain bin, it can be assumed a single-zone structure (building). Bantle (1990) recommended a mathematical model to predict air leakage from a livestock building.

Many air ventilation models exist but most are highly complex, require mainframe computers, are not available to average users because they are research tools, and are not user friendly (Feustel and Sherman 1989). The National Research Council of Canada (NRC) has developed a model which, like most models, uses the wind and the indoor-outdoor temperature difference as the driving forces (Bantle 1990). The NRC model, however, was developed for multi-cell structures and is not well suited for use in a single-cell building such as a grain bin. Of the other models reviewed, Bantle (1990) suggested that the Lawrence Berkeley Laboratory (LBL) model (Sherman and Grimsrud 1980) is the most suitable for predicting ventilation rates of a single-cell structure. The recognition of the LBL model as one of the most useable ventilation models available is supported by other researchers (Palmiter and Brown 1989; Yuill and Wilson 1985). Two other ventilation models not reviewed by Bantle (1990) were developed by researchers in Australia (Banks and Annis 1984) and Israel (Navarro et al. 1990). These models were probably omitted because they specifically determine the loss of CA gases from a treated enclosure. The LBL model and the models developed in Australia and Israel are discussed in detail as to their application and validation for use under typical Canadian weather conditions.

3.3.1 The Lawrence Berkeley Laboratory Model

The LBL infiltration model is one of the most widely known models for predicting air leakage from buildings (Sherman 1987). The model is also easy to use and is available to average users for estimating air ventilation rates. The main theoretical principle of the model is that the flow through the cracks and holes in the building envelope can be modeled mathematically as flow through an orifice (Sherman and Grimsrud 1980). With this assumption, the flow can be expressed as a power law function of the form (Sherman and Grimsrud 1980; Anonymous 1985a):

$$Q = b(\Delta P)^n \tag{3.1}$$

where: Q = ventilation (gas loss) rate (m^3/s),

Δ P = internal-external pressure drop across building envelope (Pa),

b = flow coefficient ($m^{7/2}/kg^{1/2}$), and

n = flow coefficient (dimensionless).

The coefficients b and n depend on physical conditions specific to each flow regime (i.e. laminar or turbulent) and leakage geometry (White 1986). The value of b is a function of the effective leakage area and the air density and is given by:

$$b = A_o\sqrt{(\frac{2}{\rho})} \tag{3.2}$$

where: A_o = effective leakage area (m^2), and

ρ = gas density (kg/m^3).

The flow coefficient (b) is derived from the Bernoulli equation with the exception that a discharge coefficient is absent from the expression (White 1986). The discharge (orifice) coefficient (C_d) compensates for the assumptions made when using Bernoulli's equation. The leakage area, A_o, in Eq. 3.2 is not the actual physical area of all cracks and holes in the building envelope. Instead, it is an effective area and is equivalent to the physical area of all openings multiplied by C_d. Sherman (1994) and Palmiter and Brown (1989) confirm that the ELA includes the discharge coefficient which is assumed equal to 0.61 for turbulent (orifice) flow (Rouse 1946). An approximate value of the physical area of all openings in a building envelope may be found by dividing the ELA by C_d. For performing infiltration studies, the ELA is better suited because it is easier to measure than the physical area of all the openings in a building envelope (Anonymous 1993b).

The value of the flow exponent, n, ranges between 0.5 (turbulent flow) and 1.0 (fully developed laminar flow) (Sherman 1987; Sherman and Modera 1986b). At low pressure drops, the flow through an opening is laminar, dominated by viscous forces, and proportional to the pressure drop. Conversely, at high pressure drops the flow is turbulent, dominated by inertial forces, and is proportional to the square root of the pressure drop (Sherman and Grimsrud 1980). For typical pressures which drive infiltration (i.e. 4 Pa), the flow resembles turbulent flow and is therefore proportional to the square root of the pressure drop (Sherman and Grimsrud 1980; Banks and Annis 1984; Feustel and Sherman 1989). This suggests a flow coefficient n equal to

0.5 which is consistent with that used to determine the coefficient b. Substituting Eq. 3.2 into Eq. 3.1 with a value of n equal to 0.5 yields the expression used by Sherman and Grimsrud (1980) to determine the gas loss rate:

$$Q = A_o \sqrt{\frac{2}{\rho} \Delta P} \tag{3.3}$$

A pressure drop across an opening in a building envelope is the driving force for ventilation. The principle causes of such pressure drops are wind, internal-external temperature difference, and internal-external density differences. The temperature effect of the LBL model is also called the stack effect (Anonymous 1985a). The pressure drop due to wind is caused by a stream of air impinging on the building envelope. The pressure drop due to the stack effect is due to density differences between the internal and external air which is created by differences in air temperatures (Sherman and Grimsrud 1980). The wind and stack effects do not act independently, thereby complicating the process of modeling ventilation. For simplicity, Sherman and Grimsrud (1980) assumed the two parameters can be separated and treated independently. The respective flow rates are then added by quadrature (vector addition), which is consistent with ASHRAE standards (Anonymous 1985a).

The corresponding pressure drops for the wind (ΔP_{st}) and temperature (ΔP_s) are derived from first principles (Sherman and Modera 1986a; Sherman and Grimsrud 1980):

$$\Delta P_{st} = \frac{1}{2} \rho v_{eff}^2 \tag{3.4}$$

$$\Delta P_s = \rho g h \frac{\Delta T}{T_{int}} (\beta_o - \beta) \tag{3.5}$$

where: v_{eff} = effective velocity (m/s),

ρ = gas density (kg/m^3),

g = gravitational acceleration (m/s^2),

h = stack height (m),

T = temperature (K),

T_{int} = internal temperature (K), and

β_o = normalized neutral pressure level height (dimensionless),

β = normalized height (dimensionless).

Meterological measurements, such as wind speed, are recorded from weather towers which are typically located in open areas and are 10 m above ground (Anonymous 1985a). The wind speed in rural areas, where most grain storage bins are located in Canada, may be less than the value measured from a weather tower (Anonymous 1985a). This would be due to local terrain conditions and shielding obstructions such as rolling hills and other storage facilities (Sherman and Grimsrud 1980). Tables 3.1 and 3.2 present typical terrain and shielding coefficients (Sherman and Grimsrud 1980). Using these coefficients in Eq. 3.6, the wind speed measured at the weather tower can be converted to an effective wind speed to account for terrain and shielding effects. It is the effective velocity that is used in Eq. 3.4 to determine the pressure drop across the building envelope:

Table 3.1: Terrain Coefficients for Standard Terrain Classes (Palmiter and Brown 1989)

Class	γ	α	Description
I	0.10	1.30	Ocean or other large body of water
II	0.15	1.00	Flat terrain with some isolated objects
III	0.20	0.85	Rural areas with low buildings and trees
IV	0.25	0.67	Urban area - industrial or forest
V	0.35	0.47	City centre

Table 3.2: Shielding Coefficients for Standard Shielding Classes (Palmiter and Brown 1989)

Class	C'	Description
I	0.324	No obstructions
II	0.285	Light local shielding, few obstructions
III	0.240	Some obstruction within two house heights
IV	0.185	Obstructions around perimeter
V	0.102	Large obstructions around perimeter, within two house heights

$$v_{eff} = v_{wt} \frac{\alpha \left(\frac{H}{10}\right)^{\gamma}}{\alpha_{wt} \left(\frac{H_{wt}}{10}\right)^{\gamma_{wt}}} \tag{3.6}$$

where: v_{wt} = wind speed measured at the weather tower (m/s),

α, γ = terrain coefficients at bin site (dimensionless),

H = height above ground of structure (m),

α_{wt}, γ_{wt} = terrain coefficients at weather tower site (dimensionless).

H_{wt} = height above ground of the weather tower (m),

The stack effect pressure difference (ΔP_s) is a function of temperature and height above the neutral pressure level (NPL) (Sherman and Modera 1986a; Anonymous 1985a). Equation 3.5 yields the pressure difference for a given internal-external temperature difference. The stack height, h, is often assumed to be the height of the building (Sherman and Grimsrud 1980). Detailed analysis of leak location is not possible considering the number and size of leaks present in a building envelope. Therefore, Sherman and Grimsrud (1980) group the total leakage area into three components: floor, wall, and ceiling. The NPL can then be related to the variables R_o and X (Sherman and Grimsrud 1980).

$$R_o = \frac{A_c + A_f}{A_o} \tag{3.7}$$

and

$$X = \frac{A_c - A_f}{A_o} \tag{3.8}$$

where: R_o = fraction of effective leakage area that is horizontal,

A_c = effective leakage area in the ceiling (m^2),

A_f = effective leakage area in the floor (m^2), and

X = fractional difference between floor and ceiling leakage areas.

The simplified expressions for the wind and stack coefficients become (Sherman and Grimsrud 1980):

$$f_w = C'(1 - R_o)^{\frac{1}{3}} \tag{3.9}$$

and

$$f_s = \frac{1}{3}(1 + \frac{R_o}{2})[1 - \frac{X^2}{(2 - R_o)^2}]^{\frac{3}{2}} \tag{3.10}$$

where: f_w = wind effect parameter (dimensionless), and

f_s = stack effect parameter (dimensionless).

Using these expressions, the locations of the neutral pressure level and leakage sites are not required. This reduces the accuracy of the model because it is assumed that the leakage area is evenly distributed in each component (wall, ceiling, and floor) (Sherman and Modera 1986a). However, this loss in accuracy may be insignificant compared to the extensive work necessary to detail the size and location of every leak in a typical grain bin. In addition, the relative ease of the LBL model appears to suit the application of quantifying gas loss rates from many different types and sizes of grain storage structures. The final simplified expressions for the individual flow rates are (Sherman and Grimsrud 1980):

$$Q_{wind} = f_w A_o v_{eff} \tag{3.11}$$

and

$$Q_{stack} = f_s A_o \sqrt{gh \frac{\Delta T}{T_{int}}} \tag{3.12}$$

In the derivation of these equations, Sherman and Grimsrud (1980) made the following assumptions to simplify the model:

- flow is dominated by orifice flow,
- floor and ceiling are well shielded,
- wind and temperature effects can be separated,
- neutral pressure level is approximately half way up the structure,
- directional wind effects are negligible,
- the structure is typically shielded,
- the internal pressure coefficient is constant,
- the infiltration is independent of the sign of ΔT,
- the gases inside the structure are fully mixed (Feustel and Sherman 1989), and
- there are no internal flow restrictions (Feustel and Sherman 1989)

The intended application of the LBL model is to estimate expected ventilation rates across building envelopes. To the best of my knowledge, it has never been used to predict CA gas loss from a circular grain bin filled with a porous medium (grain). The use of the LBL model for this application violates some of the simplifying assumptions. Therefore, before the model is used to predict CA gas loss, a discussion regarding some of the assumptions is necessary.

First, locating the NPL at the mid-height of the bin wall may be invalid. With the addition of the grain to the internal zone and the presence of two gases, it is difficult to simply assume the location of the NPL. Second, the assumption of a fully mixed zone does not hold true for a bin filled with grain. Alagusundaram (1993) has shown that the concentration of CA gases is stratified in a treated bin that is full of grain. This is mostly due to the density differences between the CO_2 and air that are both present in the intergranular space. Third, the assumption of no internal flow restrictions does not apply to a bin filled with a porous medium. The movement of the internal gas is inhibited by the grain and can only pass through the small intergranular spaces. Modification of the LBL model may be needed to minimize inaccuracies due to the violation of these assumptions.

3.3.2 Banks and Annis Model

The Banks and Annis (1984) (BA) model specifically determines the loss of CA gases from a treated enclosure. The total gas loss rate is calculated from the maximum rates of the contributing individual driving forces (Banks and Annis 1984). These forces include: temperature variation (headspace and bulk), wind, chimney (density) effect, and diffusion (Banks and Annis 1984). The driving forces of interest are the wind and chimney effects. This model is theoretically based on the orifice flow equation (Eq. 3.1). However, unlike the LBL model which solves for the flow rate explicitly, the BA model determines the ventilation rate constant for each contributing driving force. The simplest form of this equation is (Banks and Annis 1984):

$$k = \frac{Q}{V} \tag{3.13}$$

where: k = ventilation rate constant (s^{-1}).

The ventilation rate constant for each contributing factor is determined from gas laws. Banks and Annis (1984) state that the ventilation rate constants due to the wind and chimney effects are dependent on the level of sealing (leakage area). Conversely, the ventilation rate constants produced by temperature effects and barometric pressure are less sensitive to the level of sealing. With the exception of headspace temperature and barometric pressure effects, all the other driving forces require knowledge of the leakage area.

A method for determining the leakage area of a grain bin is not provided by Banks and Annis (1984). It is, however, required to determine ventilation rate constants for wind, bulk temperature variations, chimney effects, and diffusion or permeation. Banks and Annis (1984) relate pressure decay times, τ, to the flow coefficient b, which includes the leakage area. This avoids the need for determining the leakage area. Instead of using the effective leakage area as a measure of airtightness of a treated storage bin, the pressure decay times are used. However, Banks and Annis (1984) show that the pressure decay tests are ambiguous and only serve as an approximate indication of the *possible* gas loss rate. A more accurate method of indicating the airtightness of a structure would be to use the effective leakage area (Anonymous 1993b). This value could then be used in the BA model to improve prediction of the gas loss rates.

The area used by Banks and Annis (1984) in the equation for the flow coefficient b is not the effective leakage area but rather is the actual physical area of the leakage sites. Although they do not explicitly say this, it is assumed true because the expression for b used by Banks and Annis (1984) includes the orifice coefficient. Equation 3.2 is rewritten as:

$$b = C_d A \sqrt{(\frac{2}{\rho})} \tag{3.14}$$

where: C_d = orifice (discharge) coefficient (dimensionless),
A = physical leakage area (m^2).

The inclusion of the orifice coefficient in this equation indicates that the physical leakage area is being used instead of the effective leakage area (Sherman 1994). If it was possible to physically measure the actual area of all leakage sites, then the orifice coefficient would be necessary. Using this approach, Banks and Annis (1984) appear to choose a value of C_d = 0.76. This value is for flow through short capillary tubes at low Reynolds numbers of 100 to 800 (Krieth and Eisenstadt 1957). This is inconsistent with the assumption that infiltration occurs in the transitional to turbulent flow regime (Sherman and Grimsrud 1980; Banks and Annis 1984). Furthermore, Banks and Annis (1984) use a flow exponent (n) equal to 0.50 which implies turbulent flow. It appears they have combined a coefficient for turbulent flow (n) with a coefficient representative of laminar flow (b). Their justifications for doing this are not discussed in their work. It also appears that these values were chosen to simply illustrate the model and do not represent an accurate indication of a field situation. Obvious discrepancies are apparent with the choice of orifice coefficient. Due to these uncertainties, the difficulty in measuring the actual physical area of the leakage sites, and the inconclusive data from the pressure decay tests, the BA model should be used with caution and should perhaps be modified to provide a better prediction of natural ventilation rates.

For the BA model, the most significant driving forces are the wind and the chimney effect. The gas loss rate caused by the wind effects is derived from Eq. 3.4 with the inclusion of a pressure coefficient, C. Equation 3.4 then becomes (Banks and Annis 1984):

$$\Delta P_{st} = C\frac{1}{2}\rho v^2 \tag{3.15}$$

where: C = pressure coefficient (dimensionless).

The pressure coefficient varies with the location of measurement and orientation to wind direction (Banks and Annis 1984). The value of C is also dependent on the flow regime, laminar or turbulent (White 1986), and will have different values all over the surface of the bin wall (Banks and Annis 1984). The difference in pressure coefficients, ΔC, is required to calculate the ventilation rate constant for wind (Banks and Annis 1984):

$$k_{wind} = \frac{b}{2^{n+1}V}(\frac{\Delta C \rho v^2}{2})^n \tag{3.16}$$

where: V = internal volume of structure (m^3).

The value of ΔC could range from 0.0 to $\pm$ 4.0 (Banks and Annis 1984). Determining the value of ΔC experimentally is inconceivable for every grain bin that is to be treated with CA gases. A better method may be to incorporate the shielding coefficient of the LBL model into the BA model (i.e. Eq. 3.9).

The term, 2^{n+1}, is derived from the assumption that the total leakage area can be represented by two leaks in series with equal values of n (Banks and Annis 1984). With this assumption, the first leak site can be placed at the bottom of the structure while the second leak site can be located at the top of the structure. This placement of the leakage sites would provide a maximum prediction of gas loss from the bin.

Missing from the BA model are the terrain and shielding adjustments to wind velocities recorded at weather towers. As discussed previously, the precise measurement of the wind velocity in the vinicity of every bin to be treated is impractical. Therefore, the wind velocities recorded at a weather tower should be adjusted to help reduce the error involved in predicting gas loss rates.

The effect due to temperature is separated into three components: temperature variation in the headspace, temperature variation in the grain bulk, and the chimney effect (Banks and Annis 1984). The effect of headspace temperature variation can be assumed to be negligible providing the grain is covered with a CA impermeable plastic sheet. The practice of isolating the grain bulk from the headspace with a plastic covering has been recommended by M^{c}Gaughey and Akins (1989) and Alagusundaram (1993). The effect due to bulk temperature variation yields a small component to the overall loss (Banks and Annis 1984). The greatest temperature gradients in a grain bulk will be located near the wall and therefore, the bulk temperature effect will be negligible compared the wind and chimney effects.

The chimney effect of the BA model is the effect due to compositional differences. The expression for the ventilation rate due to the chimney effect is given as (Banks and Annis 1984):

$$k_{chimney} = \frac{1}{2V}\int_{0}^{2\pi}\frac{b}{2^{n+1}}\left(gh\left(\frac{MP}{R_u T_{ave}\left(1+a\cos\omega t\right)} - \rho_{int}\right)\right)^{n} d(\omega t) \tag{3.17}$$

where: h = vertical height between two representative leak sites (m),

M = molecular weight of air in the pore space of the grain, and

R_u = universal gas constant (kJ·kmol^{-1}·K^{-1}).

a = amplitude of temperature oscillation (K),

κ = thermal diffusivity (m^2/s),

t = time (s), and

ω = frequency of temperature fluctuation (Hz).

Included in Eq. 3.17 is the vertical height, h, between two representative leak sites. As discussed previously, detailed knowledge of the leakage sites is difficult to obtain; especially with grain bins because so many finite openings exist in the envelope. Quantifying h for every treatable bin is impractical and would be based on user judgement. In addition, reference to the neutral pressure level is absent from the BA model, which only adds to the uncertainty. This problem might be simplified by assuming that h represents the height of the structure and incorporating the shielding coefficient and Eqs 3.7, 3.8, and 3.10 from the LBL model into the BA model.

A number of simplifying assumptions are made by Banks and Annis (1984) which may invalidate the model. The first of these is the assumption of a well mixed zone which was also assumed by Sherman and Grimsrud (1980). A second assumption made by Banks and Annis (1984) is the additive correlation among the independently acting driving forces. Sherman and Grimsrud (1980) and Anonymous (1985a) recommend adding the independent effects by quadrature. Finally, the total leakage area is represented by two composite leaks with similar flow characteristics, separated by a vertical distance h (Banks and Annis 1984). Equation 3.17 omits any influence that can be caused by the location of the NPL. For example: if the NPL is located below, above, or between the two representative leak sites, what effect does this have on the ventilation rate? This question is not addressed by Banks and Annis (1984). Sherman and Grimsrud (1980) addressed this concern and developed coeffcients that eliminate the requirement of the NPL location.

3.3.3 Other CA Gas Loss Models

The only other model developed to predict the loss of CA gas from an enclosure was developed by Navarro et al. (1990). Their model simulated gas loss from a grain bin subjected to internal-external temperature differences. This was the only driving force considered and was separated into two components: diurnal and seasonal. Other assumptions included: uniform CA gas distribution in the grain bulk (i.e. fully mixed), negligible CO_2 sorption and desorption from the grain, uniform bulk temperature, and negligible wind and barometric pressure effects (Navarro et al. 1990). The model results were compared with experimental data of CO_2 concentration levels. The experiments were conducted using two welded steel bins (3.0 m dia., 8.75 m tall) which contained 52 and 28 t of wheat, respectively. Both the numerical model and the experimental conditions are not representative of the situation in Canada. First, the use of welded bins, which would have a very small effective leakage area, are not comparable to bolted-metal bins commonly used in Canada. Second, the effect of wind on infiltration can be the most significant factor for bins with substantial effective leakage area (Banks and Annis 1984; Sherman and Grimsrud 1980). The omission of this effect in the model of Navarro et al. (1990) is justified because they used welded steel bins. The Navarro et al. (1990) model may therefore be applicable to welded steel bins (which are becoming more popular on Canadian farms) and concrete bins which are typically used in primary elevators on the Canadian prairies. However, the model of Navarro et al. (1990) is not a viable method to predict CA gas loss from bolted-metal bins subject to wind, temperature, and chimney effects.

3.4 Final Remarks

The literature reviewed to date indicates that the LBL model has never been used for predicting the ventilation of CA gases from bolted-metal grain bins. The only use of this model in the agricultural field was by Bantle (1990). However, this work was not validated against field tests. For the LBL model to be used, a number of input parameters must be determined specifically for each test site. The model can then be tested as to its ease and accuracy for determining the loss rate of CA gases from treated enclosures.

The BA model presents a second method for determining CA gas loss from treated enclosures. A number of their assumptions, however, do not hold for the application on Canadian prairies and modification of the model may improve its accuracy. This model also requires a number of site specific input parameters before it can be field tested.

Chapter 4

MATERIALS AND METHODS

4.1 Overview

The work in this thesis was based on both mathematical modeling and experimental tests. The purpose of the mathematical modeling was to develop a method of predicting the loss rate of the CA gases from the storage facility. The experiments served two purposes. First, to determine the effective leakage area of the bins which would be later required as input data for the mathematical models. Second, experimental data of the transient CA gas concentration levels in the bins are required to validate the mathematical models. This chapter outlines the materials and methods followed for both types of measurements.

4.2 Mathematical Model Parameters

The models evaluated (LBL and BA) required a number of user specified parameters which are specific for each bin tested (Banks and Annis 1984; Sherman and Grimsrud

1980). These parameters included the physical dimensions of the bins, shielding and terrain coefficients, pressure coefficients, wind speeds, temperatures, and densities. The details of these are discussed below.

The storage structures used in the experimental tests and model simulations were a pilot bin and a full size bin. The pilot bin had dimensions of 1.42 m dia. and 1.47 m height with no headspace. The plenum on the pilot bin measured 1.14 m x 0.36 m x 0.2 m and was welded underneath the bin floor. The full size bin was 5.56 m dia. with a height to eaves of 5.70 m. This bin had a coned roof with a headspace volume of 7.28 m^3. The full size bin was located 20 km south of Winnipeg, Manitoba.

The CA gas introduced comprised of approximately 60% CO_2, <2% O_2, and 38% N_2. The density of CO_2 and the diffusion coefficient (carbon dioxide into air) at STP were 1.977 kg/m^3 and 13.8 mm^2/s, respectively (Perry and Green 1984).

The ambient temperatures and wind speeds used in this thesis were set similar to those commonly expected on the Canadian prairies. The average conditions for Winnipeg, Manitoba, Canada were used as a guideline for the prairie region. Environment Canada (1992) provided yearly averages of 2.4°C and 18 km/h for the Winnipeg area. Wind speeds of 5 to 35 km/h with increments of 10 km/h were used in the models. These values were selected to provide a distinct indication of the effects of wind. Internal-external temperature differences ranging from 0.0 to 50.0°C were used to study the effects of temperature.

Standardized coefficients for terrain and shielding (Sherman and Grimsrud 1980) were used to adjust the wind speed and the temperature effect. Most grain storage sites in Canada are located on farms in rural areas. Terrain parameters of α=0.85 and γ=0.20 are recommended for this class of terrain (Class III, Sherman and Grimsrud 1980). The recommended shielding coefficient for a structure located within two house heights of some obstructions is C'=0.285.

The flow coefficients for the LBL model in the power law equation (Eq. 3.1) were chosen for turbulent flow through an orifice. The exponent, n, of this equation was therefore set to 0.50. The b coefficient must be determined for each test bin and is dependent on the effective leakage area. The ELA for each bin must be estimated experimentally.

The flow coefficients for the BA model were similar to those of the LBL model with the exception that the b coefficient included the orifice discharge coefficient (C_d). The discharge coefficient is a function of the Reynolds number (Rouse 1946). As stated previously, the flow through a building envelope is dominated by turbulent flow. Therefore, a more accurate discharge coefficient would be 0.61 for an orifice ratio of 0.475 in the turbulent flow regime (Rouse 1946) which is inconsistent with the value Banks and Annis (1984) appear to assume. This discrepancy was simply overcome by using Eq. 3.1 in the BA model instead of Eq. 3.15.

4.3 Experimental Procedures

4.3.1 Effective Leakage Area Tests

The ELA of the test bins was measured by conducting fan pressurization tests according to the ASTM Standard practice of determining the air leakage rate through a building envelope (Anonymous 1993b). A schematic diagram of the apparatus is illustrated in Figure 4.1. The procedure consisted of: (i) pressurization of the bin using a fan; (ii) measurement of the airflow rate; and (iii) measurement of static pressure drop that was created across the building envelope. Several flow rates and corresponding pressure drops were measured. The data were used to determine the experimental flow coefficients n and b by conducting a two parameter fit to a power law function (Eq. 3.1) using procedure GLM of SAS (SAS 1982). The ASTM Standard (Anonymous 1993b) recommends a depressurization test in addition to the pressurization test. Due to the limitations of the equipment, the depressurizaton tests were not conducted.

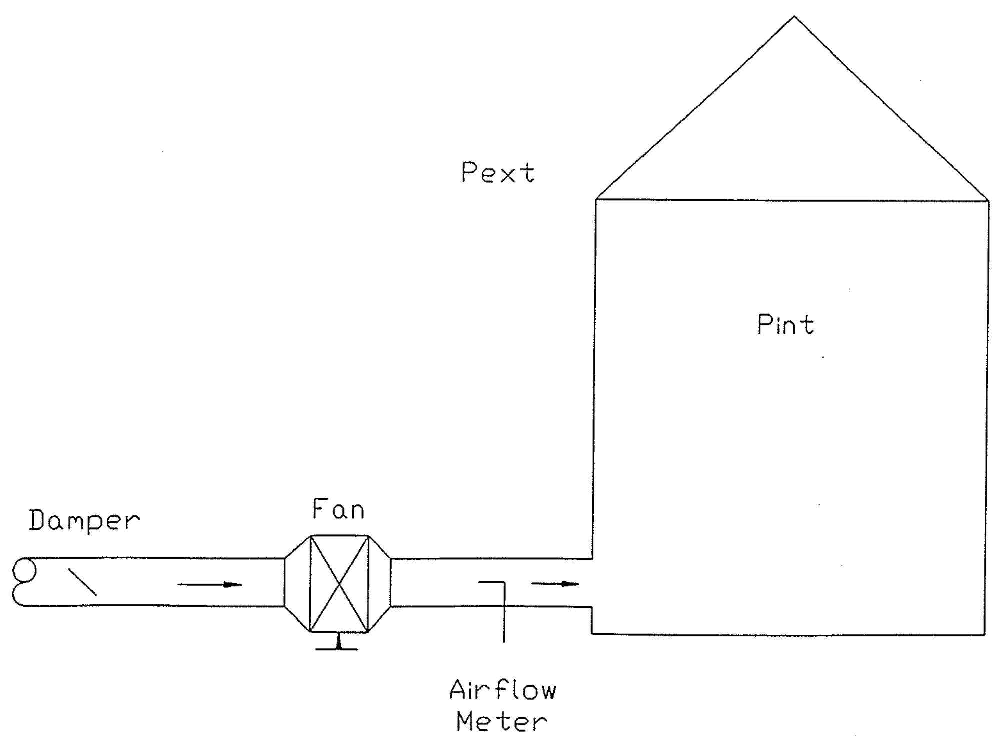

Figure 4.1: Schematic diagram of the fan pressurization equipment.

Once the flow coefficients were known, Eq. 3.1 was used with a reference pressure of 4 Pa to determine the ventilation rate, Q_{4Pa}. The effective leakage area of the bin was then found by using this rate (Q_{4Pa}) and the reference pressure (4 Pa) in Eq. 3.3 and solving for A_o. This leakage area represented the total effective leakage area in the bin envelope including cracks and holes.

The estimated ELA was calibrated by mounting a thin flat plate which contained an orifice hole into an opening of the building envelope. The plate must be less than 1.60 mm thick and the orifice hole must have a known diameter with a tolerance of $\pm$ 0.80 mm (Anonymous 1985b). The effective orifice area ($A_{o \cdot orifice}$) is the physical area of the orifice hole multiplied by the orifice coefficient, $C_d = 0.61$. The value of $A_{o \cdot orifice}$ must be greater than A_o of the structure being tested. This ensures that measurement errors do not dominate the ELA estimate. The effective leakage area of the structure when the orifice hole was mounted in the building envelope, A'_o, was determined using the fan pressurization method. The following equation was then used to determine the experimental effective leakage area of the orifice hole.

$$A_{orifice} = A'_o - A_o \tag{4.1}$$

This value was compared to $A_{o \cdot orifice}$ for calibration. The acceptable percent error between the experimentally measured ($A_{orifice}$) and the effective orifice area ($A_{o \cdot orifice}$) is $\pm$ 25% (Anonymous 1985b).

Details for the Pilot Bin

The pilot bin was constructed of 2 steel panels, rolled into a cylinder, and bolted horizontally and welded vertically. The bolted horizontal seam was covered with a layer of silicone and the complete wall was welded to the bin floor. The top was sealed with an impermeable polyvinylidene chloride (PVDC) sheet which consisted of 3 layers of nylon and 4 layers of polyethylene. This PVDC sheet had a CO_2 permeability rate < 0.1 $\mathrm{cm}^3 \cdot m^{-2} \cdot d^{-1}$.

A sealed 0.746 kW fan was connected to the inlet of a 9.8 cm internal diameter (i.d.) pipe that measured 5.77 m long. The pipe outlet was secured to the inlet of the bin plenum. The flow rate of the incoming air was adjusted by placing air blockage plates of various openings at the fan inlet. The blockage plates had openings of the following diameters: 1.0, 1.2, 1.5, 2.0, 2.4, 3.4, 4.5, 6.0 cm. An orifice plate (orifice ratio = 0.475) and a manometer were set up 4.14 m from the fan inlet and measured the average pressure drop across the orifice plate for the various airflows. The average pressure drops were converted to airflow rates in units of m^3/s.

A second manometer was used to measure the induced average pressure drop across the bin wall for each flow rate. Semi-rigid nylon tubes (3.22 mm outside diameter, 2.54-cm long) were located through the bin wall at five different vertical levels (0.0, 0.33, 0.66, 0.99, 1.32 m above the floor) and at four equi-spaced radial positions (A-B-C-D). The inlet of the manometer was connected to the outlet of the nylon tubes and the internal-external pressure difference was measured. The ASTM Standard recommends induced envelope pressure drops ranging from 12.5 Pa to 75 Pa (Anonymous 1993b). Due to the pressure limitations of the Standard and the available measuring equipment, only four different envelope pressure drops were obtainable.

The ELA of the pilot bin was calibrated using three different plates with orifice openings of 1.29, 5.72, and 8.26 cm diameters. Each plate with an orifice opening was mounted separately over a hole in the PVDC plastic cover on top of the bin. The plates were secured with duct tape and fan pressurization tests were conducted using each plate. The flow coefficients were determined from the measured flow rate and pressure drop. The resulting ELA (A_o') was determined and used in Eq. 4.1 to determine $A_{orifice}$.

Details for the Full Size Bin

The full size bin was constructed of corrugated panels of galvanized steel that were bolted together. Most seams contained a rubber gasket and silicone to improve the seal; however, holes and cracks were visible in the bin wall and roof. The bin had a concrete floor and was equipped with a 0.46 dia. x 4.7 m long circular duct located on the floor. This duct had perforations for a length of 3.3 m beginning from the far end of the duct. The bin was empty for the fan pressurization tests.

A circular duct (0.75 m dia. x 7 m long) was connected to the inlet of a sealed 3.73 kW axial fan. A flow straightener (0.48 m dia. x 1 m long) was later added to the inlet of the duct to reduce fluctuations in the manometer readings. A pitot tube was used to measure the airflow rate and was located 6 m downstream of the duct inlet and 1 m upstream of the fan. The velocity pressure was measured with a manometer at eight sampling locations and was converted to velocity (m/s) and averaged by dividing by the number of sampling points. The flow rate was determined using the area of the duct and the calculated average velocity. As with the pilot bin, four different induced envelope pressure drops and corresponding airflow rates were measured. The air blockage plates for these tests had openings of 30.5, 40.6, 48.3, and 50.8 cm dia.

Semi-rigid nylon tubes (3.22 mm outside diameter, 5 cm long) located at three different heights (0.55, 1.30, and 2.05 m above the floor) and four equi-spaced radial positions in the bin wall were used to measure the envelope pressure drop. The manometer inlet was connected to the tubes and the induced pressure drops across the bin wall were measured. For each flow rate, 12 measurements were taken and the average envelope pressure drop was determined.

A second pressurization test was conducted which included a PVDC sheet taped to the wall of the full size bin at a height of 2.5 m above the floor. This was done in accordance with the CO_2 experiments conducted by Alagusundaram (1993) which contained a PVDC sheet on the top surface of the grain. The PVDC sheet eliminates the effects of the roof during the fan pressurization tests. The resulting ELA was for 2.5 m of the bin wall and any leakage area contained in the floor.

4.3.2 Experimental Gas Loss Tests

The pilot bin was located outdoors in an open area that contained only a few obstructions located at least two bin heights away. The bin was empty and the top was sealed with a PVDC sheet. Approximately 2.5 kg of dry ice was placed in the plenum of the bin at the start of each test. Assuming perfect purging and mixing in the bin, this amount of dry ice should create a concentration of approximately 60% of CO_2, based on average temperatures of approximately -25.0°C. Samples of the gas in the bin were taken at 14, 17.5, and 21 h after the introduction of the dry ice.

The samples of gas were withdrawn from the bin through nylon tubes that were 2.5, 17.8, 35.6, and 71.1 cm long. These tubes were connected across two perpendicular diameters and supported by steel wires at the same vertical levels as the tubes used for the fan pressurization tests (Fig. 4.2). Wind speeds and ambient temperatures during the tests were obtained from Environment Canada (1994).

To measure the concentration of gas in the bin, the tubes were initially flushed by withdrawing 4-6 mL of gas and releasing it to the ambient air. Approximately 8 mL were then taken from 31 sampling points using 10 mL syringes. These samples were then analyzed for CO_2 concentration using a gas chromatograph (Perkin-Elmer Model Sigma 3B) equipped with a thermal conductivity detector held at 150°C, a 1 mL fixed volume injection loop, and a steel column (183 cm x 0.3 cm o.d.) containing poropak N (50/80 mesh). The oven temperature was held at 65°C and the carrier gas was helium.

Similar tests for CO_2 concentration levels using the full size bin had been previously completed by Alagusundaram (1993). Therefore, it was not necessary to repeat these tests as the data were readily available for comparison with the mathematical models.

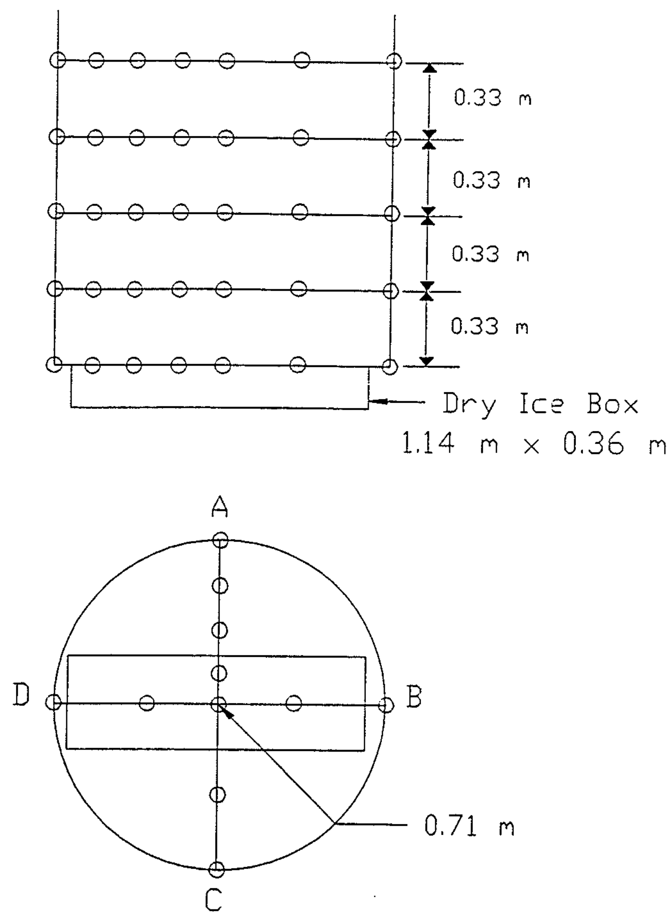

Figure 4.2: Schematic diagram of the pilot bin (gas sampling points represented by o).

Chapter 5

RESULTS AND DISCUSSION

5.1 Overview

Before the mathematical models could be evaluated, the effective leakage area of both bins had to be determined experimentally. In addition, experimental loss rates for CO_2 gas using the pilot bin were obtained. Similar data using the full size bin were obtained by Alagusundaram (1993). These experimental results were compared to gas loss rates predicted by the mathematical models. This chapter presents and discusses the results of the work.

5.2 Pilot Bin

5.2.1 Effective Leakage Area

The airflows and pressure drops from the fan pressurization tests on the pilot bin are summarized in Tables 5.1 and 5.2. A depressurization test was not conducted because of the unsuitability of the experimental equipment. Although the pressure drops for Test A1 are above the recommended range of 12 - 75 Pa (Anonymous 1993b), coefficients b and n are comparable to the other tests, and the resulting r^2 value (Table 5.3) from the two parameter fit equation is in agreement with published results (Anonymous 1993b; Anonymous 1985b). Reduced airflow in Tests A2 through A4 yielded satisfactory pressure drops and r^2 values. Most of the pressure drops for Tests A5 and A6 were below the lower limit: this was due to the small capacity of the fan. Even with the largest inlet opening, the maximum pressure drop across the bin wall was less than 27 and 8 Pa for Tests A5 and A6, respectively. However, the b and n coefficients as well as the r^2 value compare well to the other tests (Table 5.3).

The coefficient n (Table 5.3) represents the flow exponent of Eq. 3.1. Flow dominated by turbulence (inertial effects) yields a flow exponent of 0.5 (Sherman 1987; Sherman and Grimsrud 1980). For all of the tests conducted, the flow exponent indicates that the flow through the bin wall was close to the turbulent regime. As the effective leakage area increases (Tests A5 and A6), the flow is expected to become more laminar, resulting in an increase in the flow exponent. This did not occur for the pilot bin tests which may be because of the narrow range of developed pressures.

The effective leakage area of the pilot bin was approximately 4.60 cm^2 for Tests A1 through A3 (Table 5.4). Tests A4 through A6 provide calibration data for determining

Table 5.1: Measured airflow rate and corresponding pressure drops across the bin wall in the pilot bin. The top of the bin was sealed using a PVDC sheet.

Fan Inlet	Test A1		Test A2		Test A3	
Opening dia. (cm)	Airflow (m^3/h)	Pres. Drop (Pa)	Airflow (m^3/h)	Pres. Drop (Pa)	Airflow (m^3/h)	Pres. Drop (Pa)
6.00	27.50	128.24	—	—	—	—
4.50	26.47	121.26	—	—	—	—
3.40	24.77	106.07	—	—	—	—
2.40	21.38	80.18	20.15	78.80	21.67	79.50
2.00	—	—	18.11	59.76	17.74	59.18
1.50	—	—	13.60	33.62	13.11	34.19
1.20	—	—	10.04	18.43	9.70	19.25
1.00	—	—	7.49	12.70	8.33	14.22

the ELA. Although, the r^2 value for Test A4 is good, the resulting effective leakage area (A'_o, which includes the ELA of the orifice hole and the ELA of the bin envelope) did not show an increase as expected (Table 5.5). This may be because the diameter of the orifice was too small. It is recommended (Anonymous 1985b) that the orifice hole be comparable to the estimated ELA of the structure being tested. The ELA of the pilot bin was estimated to be 4.60 cm^2, whereas the orifice hole for Test A4 had an area of 1.28 cm^2 which corresponds to an effective leakage area of 0.78 cm^2. This is significantly below the estimated ELA. The results using larger orifice holes (Tests A5 and A6) indicated that the experimental estimation of the orifice hole ELA ($A_{orifice}$) was within 15 to 26% of the actual orifice hole ELA ($A_{o \cdot orifice}$). It is expected that if the orifice area was significantly larger than the ELA of the bin envelope such that the envelope ELA was negligible, the errors of the calculated ELA may be higher. Conversely, if orifice holes that were greater than the ELA but smaller than those of Test A5 were used and higher pressure drops were obtained, then the per

Table 5.2: Measured airflow rate and corresponding pressure drops across the bin wall in the pilot bin. The top of the bin was sealed using a PVDC sheet which included different size orifice openings.

	Orifice Opening					
	1.28 cm dia.		5.78 cm dia.		8.23 cm dia.	
Fan Inlet	Test A4		Test A5		Test A6	
Opening dia. (cm)	Airflow (m^3/h)	Pres. Drop (Pa)	Airflow (m^3/h)	Pres. Drop (Pa)	Airflow (m^3/h)	Pres. Drop (Pa)
6.00	—	—	39.72	26.14	42.94	7.84
4.50	—	—	31.14	16.31	32.29	4.601
3.40	—	—	19.67	6.72	19.95	1.87
2.40	—	—	13.60	3.24	13.60	0.87
2.00	—	—	—	—	—	—
1.50	15.50	42.34	—	—	—	—
1.20	10.65	21.35	—	—	—	—
1.00	7.40	11.15	—	—	—	—

Table 5.3: Coefficients of Eq. 3.1 for the pilot bin obtained from fan pressurization tests.

Test #	r^2	b	n
A1	0.999	2.10	0.529
A2	0.994	1.93	0.551
A3	0.999	2.03	0.530
A4	0.999	1.94	0.556
A5	0.999	7.42	0.514
A6	0.999	14.53	0.524

cent difference may decrease improving the calibration. Nonetheless, the calibration results give reasonable confidence in the method used for determining the ELA. Based on the results, it can be stated that the ELA's obtained by the fan pressurization test are accurate within 25%. However, this may produce significant errors in predicted gas loss rates.

Table 5.4: Effective leakage area from the pilot bin tests.

Test #	A_o (cm^2)
A1	4.61
A2	4.46
A3	4.56
Avg. $\pm\sigma$	4.60 $\pm$ 0.1

Table 5.5: Calibration results for the effective leakage area using various orifice holes in the pilot bin.

Test #	A'_o (cm^2)	$A_{orifice}$* (cm^2)	$A_{o\cdot orifice}$ (cm^2)	% Difference $(\frac{A_{o\cdot orifice}-A_{orifice}}{A_{o\cdot orifice}})$ x 100
A4	4.50	-0.10	0.78	112.8
A5	16.27	11.67	15.68	25.6
A6	32.29	27.69	32.45	14.6

*$A_{orifice} = A'_o - A_o$

Figure 5.1 illustrates the linear relationship between the bin wall pressure drop and the airflow into the pilot bin. The slopes of all curves are similar and the only effect of increasing the ELA by adding orifice holes of progressively larger diameters was a shift in the intercept. This shift implies that an increase in the ELA creates a

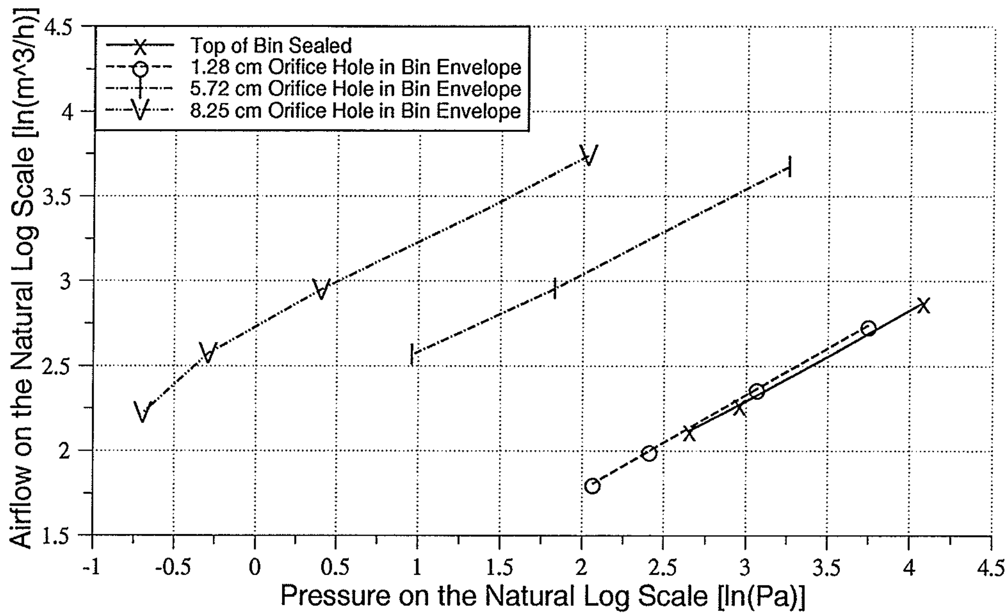

Figure 5.1: The relationship between natural logarithms of airflow into the pilot bin and pressure drops across the bin wall.

less tight structure which increases the airflow rate for an equal pressure difference. Consequently, the flow coefficient b increases which increases the gas loss rate, Q. This effect is consistent with published results (Anonymous 1985a). It is expected that if the ELA increases, the pressure decreases and viscous forces begin to dominate as the flow regime through the bin wall becomes laminar (Sherman and Modera 1986b). Consequently, the exponent n should also increase from 0.5 to 1.0. However, the results do not indicate an increase in the exponent which may imply that the orifice hole was not large enough to change the flow regime.

5.2.2 Experimental Gas Loss Tests

Table 5.6 presents a summary of the average concentrations of CO_2 gas in the pilot bin for several experiments. Temperature effects were not a driving force of the gas loss for these experiments because the bin was empty and the internal and external temperatures were assumed equal (Appendix B). The only driving forces of gas loss were assumed to be wind and chimney effects. It can also be assumed, with an empty bin, that the CO_2 gas mixed completely with the internal air and concentrations were nearly uniform (Appendix B).

Table 5.6: Experimental gas concentration levels in the pilot bin.

Test #	c_1 % CO_2	c_2 % CO_2	c_3 % CO_2
B1	56.87	54.22	37.66
B2	75.53	71.80	64.61
B3	60.29	55.60	51.69
B4	51.37	49.48	43.84
B5	48.02	46.64	43.07
B6	41.24	41.27	39.22

The rate of gas loss was determined using the following equation:

$$Q = \frac{(c_i - c_f) \cdot V}{100 \cdot \Delta t} \tag{5.1}$$

For wind speeds ranging from 8 to 27 km/h, the average gas loss rate was approximately 7.33 x10^{-6} m^3/s (Table 5.7). This corresponds to 0.23 airchanges per day.

Table 5.7: Experimental gas loss rates of CO_2 from the pilot bin.

Test #	Wind Speed (km/h)	$c_i - c_f$ (% CO_2)	Δ t (h)	Q x10^{+6} (m^3/s)
$B1_{c1-c2}$	24.0	2.65	5.0	3.7
$B1_{c2-c3}$	27.0	16.56	17.0	6.9
$B2_{c1-c2}$	17.0	3.73	3.5	7.5
$B2_{c2-c3}$	13.0	6.95	3.5	14.3
$B3_{c1-c2}$	16.0	4.609	4.0	8.2
$B3_{c2-c3}$	18.0	3.91	3.5	7.9
$B4_{c1-c2}$	13.0	1.89	3.5	3.8
$B4_{c2-c3}$	14.0	5.64	3.5	11.3
$B5_{c1-c2}$	17.0	1.38	3.5	2.8
$B5_{c2-c3}$	17.0	3.57	3.5	7.2
$B6_{c1-c2}$	9.0	-0.03	3.5	0.0
$B6_{c2-c3}$	8.0	2.05	3.5	7.2

Banks and Annis (1984) recommended an airchange rate no greater than 0.07 d^{-1} for *one-shot* CA control of insects in a concrete silo. The pilot bin yielded an airchange rate 3.30 times this value. The increased rate was because the construction of the pilot bin was not similar to the silo and the pilot bin probably has more leakage sites. Also, Banks and Annis (1984) state that the 0.07 d^{-1} rate is *inexcessive* for farm bins and therefore, a larger airchange rate is expected for a bolted-metal bin. Based on these results, it can be concluded that the pilot bin is not an airtight structure and contains sufficient effective leakage area to allow substantial loss of CO_2 gases. The fan pressurization tests yielded an ELA of 4.60 cm^2 which seems reasonable compared to a surface area of approximately 10.0 m^2.

The results of Table 5.7 do not indicate a direct correlation between the wind speed and rate of gas loss. This may be because of the combined effects of the wind and chimney driving forces. In addition, the direction of the wind may have a significant effect depending on the location of the leakage sites which were unknown.

5.2.3 Mathematical Modeling

LBL Model

Typical gas loss rates using the LBL (Sherman and Grimsrud 1980) model with various wind speeds are presented in Table 5.8. The shielding coefficient (C') and terrain coefficients (α and γ) selected represent the local conditions surrounding the pilot bin during the experimental gas loss tests. It was assumed that all of the effective leakage area in the pilot bin existed in the wall. Therefore, the R_o and X values (Eqs. 3.7 and 3.8, respectively) were set to 0.0. These values are more pertinent to the full size bin which is expected to have leakage areas in the roof, wall, and ceiling.

The predicted gas loss rate for an ELA of 4.60 cm^2 was on average 58 times the average experimental gas loss rate (Tables 5.8 and 5.7, respectively). Over estimating the effective leakage area could cause significant error in the predicted gas loss rates. Conducting a detailed visual inspection of the bin with a filler gauge to estimate the ELA between the seams is impossible because the seams were either welded or completely covered with silicone sealant. If an ELA of 4.60 mm^2 was used in the model instead of 4.60 cm^2, then the predicted rates of gas loss would be 0.01 times the values given in Table 5.8 and would more closely match the experimental data.

Table 5.8: Predicted gas loss rates for various wind speeds from the pilot bin with the LBL model (A_o = 4.60 cm^2, C' = 0.285, α = 0.85, γ = 0.20).

Wind Speed (km/h)	Q_{wind} x10^{+6} (m^3/s)
5	105.5
15	316.4
25	527.4
35	738.3

The experimental data for wind speeds ranging from 8 to 27 km/h indicated no direct correlation between gas loss and wind speed. The experimental gas loss rates are scattered whereas the predicted rates show an increase with increasing wind speed. It can be concluded that the LBL model did not provide accurate estimates of the gas loss rate compared to the experimental results. Further experimental tests under controlled conditions should be conducted to progressively validate the LBL model.

Other sources of error may be the choice of terrain and shielding coefficients. Figures 5.2 and 5.3 illustrate the effects of different values of coefficients for various wind speeds. For an ELA of 4.60 cm^2, a wind speed of 25 km/h, and a shielding coefficient of 0.285, increasing the terrain class from 2 to 3 (i.e. $\alpha = 1.0$, $\gamma = 0.15$ to $\alpha = 0.85$, $\gamma = 0.20$), decreased the rate of gas loss from 682.3 x10^{-6} to 527.4 x10^{-6} m^3/s. Conducting a similar test for the shielding effects with A_o = 4.60 cm^2, wind speed = 25 km/h, α = 0.85, and γ = 0.20, and increasing the shielding class from 2 to 3 (i.e. C' = 0.285 to C' = 0.240); the gas loss rate decreased from 527.4 x10^{-6} to 445.1 x10^{-6} m^3/s. The selection of the shielding and terrain coefficients is subjective and can lead to errors in predicted gas loss rates. Palmiter and Brown (1989) found that the choice of coefficients differed between several contractors for the same site. This subjectivity can cause significant error for wind speeds greater than 15 km/h. This is because above this speed, the predicted gas loss rates are more sensitive to the choice of coefficients (Figs. 5.2 and 5.3). Below 15 km/h, the subjectivity becomes less important as the gas loss rates are less sensitive. Therefore, at low wind speeds the predicted gas loss rates are more reliable because the model is less sensitive to the subjectivity of the shielding and terrain classes.

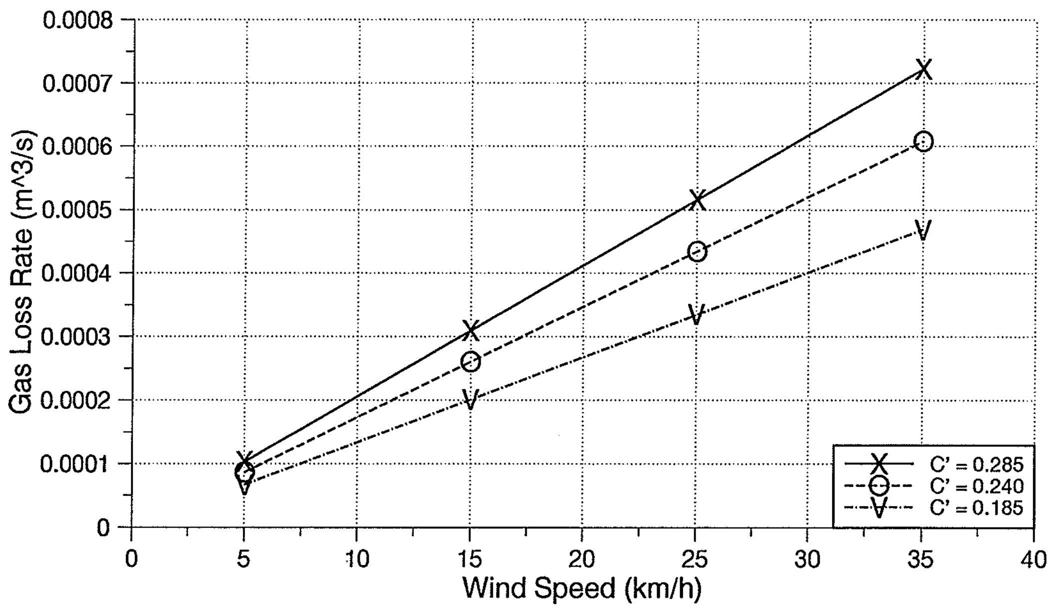

Figure 5.2: Predicted influence of shielding effects on gas loss rate for the pilot bin ($A_o = 4.60$ cm^2, $\alpha = 0.85$, $\gamma = 0.20$).

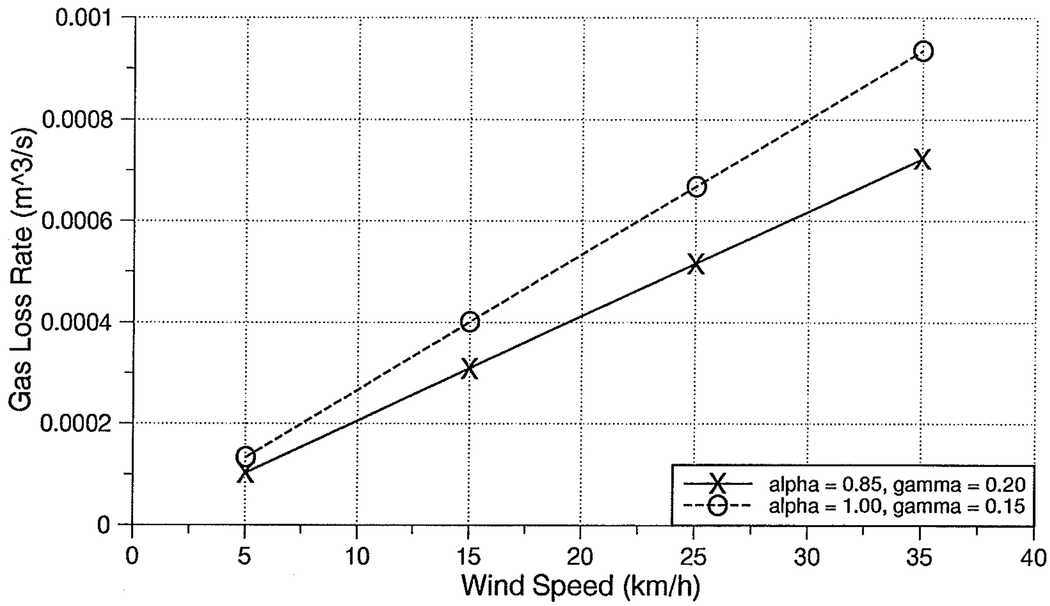

Figure 5.3: Predicted influence of terrain effects on gas loss rate for the pilot bin ($A_o = 4.60$ cm^2, $C' = 0.285$).

BA Model

The wind component of the BA (Banks and Annis 1984) model contains the differential pressure coefficient ΔC. Banks and Annis (1984) state that the value of ΔC can range from approximately 0.0 to 4.0. However, they do not discuss how this coefficient is to be determined for each grain bin in which CAs are to be used. Therefore, values ranging from 0.5 to 4.0 were set to study the effect of this coefficient. The results for an ELA of 4.60 cm^2 are presented in Table 5.9. The choice of ΔC can have a significant effect on ventilation. An increase in ΔC from 0.5 to 4.0 increased the gas loss rate by 2.8 times for all wind speeds.

Table 5.9: Predicted gas loss rates [Q x10^{+6} (m^3/s)] for various pressure coefficients for the pilot bin with the BA model.

Wind Speed	Pressure Coefficients				
(km/h)	0.5	1.0	2.0	3.0	4.0
5.00	159.7	225.9	319.4	391.2	451.8
15.00	479.2	677.6	958.3	1173.4	1355.3
25.00	798.6	1129.4	1597.2	1956.2	2258.8
35.00	1118.1	1581.2	2236.1	2738.7	3162.3

* For an ELA of 4.60 mm^2 the gas loss rates would be 0.01 times these values.

An estimate of ΔC can be obtained from the experimental gas loss rates by calculating backwards using Eq. 3.16. Using the experimental data of Table 5.7 (average gas loss rate of 7.33 x 10^{-6} m^3/s and average wind speed of 16 km/h), $A_o = 4.60$ cm^2, and $n = 0.50$; the value of ΔC was 1.03 x10^{-4}. Replacing the average wind speed of 16 km/h with an adjusted effective wind speed of 9.2 km/h (terrain and shielding coefficients: $\alpha = 0.85$, $\gamma = 0.20$, and $C' = 0.285$, respectively), the value of ΔC was calculated as

3.11 x10^{-4}. The calculated ΔC values appear very small and without experimentally determining ΔC, this method cannot be assumed valid. In addition, this method is impractical because it requires experimental gas loss rates for each bin to be treated.

Parameters such as: bin size, wall smoothness, roof shape, doors, grain loading and aeration equipment, and surrounding obstructions and terrain affect the value of ΔC (Mulhearn et al. 1976). Considering that ΔC has a major influence on the predicted rate of gas loss, wind tunnel tests using models of typical grain bins used in Canada should be conducted under controlled conditions. A relationship should be developed to provide an estimate of a general pressure coefficient for particular types of bins. Mulhearn et al. (1976) conducted wind tunnel tests using scale models of 2000 t grain bins which are 23.8 times the largest typical farm bin found in Canada. The values of ΔC found by Mulhearn et al. (1976) ranged from 1.6 to 2.4. These values are substantially larger than the values of ΔC found from the experimental gas loss rates of Table 5.7. This may be because of the difference in size of the bins and the uncertainty in the ΔC values found using the data of Table 5.7.

A second problem with the wind component of the BA model is the wind speed used in Eq. 3.16. The BA model does not include parameters that account for a reduction in the wind speed due to terrain and shielding effects. The shielding and terrain coefficients along with the appropriate equations from the LBL model can be incorporated into the BA model. Table 5.10 presents the rates of gas loss for the unadjusted and adjusted wind speeds. The adjusted wind speeds reduce the rate of gas loss by 3.45 times.

By adding these wind reduction parameters to the BA model, the predicted gas loss rates from the pilot bin were closer to the experimental values. However, it cannot be

Table 5.10: Predicted gas loss rates for unadjusted and adjusted wind speeds for the pilot bin with the BA model (A_o = 4.60 cm^2).

Unadjusted[1] Wind Speed (km/h)	$Q_{unadjusted}$ x10^{+6} (m^3/s)	Adjusted[2] Wind Speed (km/h)	$Q_{adjusted}$ x 10^{+6} (m^3/s)
5.0	2.4	2.90	0.7
15.0	6.8	8.9	2.0
25.0	11.4	14.5	3.3
35.0	16.0	20.3	4.6

[1] ΔC = 1.03 x10^{-4}

[2] ΔC = 3.11 x10^{-4}, C' = 0.285, α = 0.85, γ = 0.20

concluded that the accuracy of the model has improved because (i) the exact pressure coefficient is unknown; and (ii) the experimental gas loss rates do not indicate a direct relationship to the effects of wind.

The chimney effect for the BA model can be simplified because the average internal temperatures were recorded by Alagusundaram (1993). Using the gas law equation:

$$P = \rho R^g T \tag{5.2}$$

where: R^g = individual gas constant (J kg^{-1} K^{-1}),

the interior and exterior densities can be calculated for each temperature condition. These densities can then be used in the following equation:

$$\Delta P = (\rho_{int} - \rho_{ext})gh \tag{5.3}$$

to determine the pressure drop due to the internal-external temperature difference. Equation 5.3 replaces the term:

$$\frac{1}{2}\int_0^{2\pi} \left(gh \left(\frac{MP}{R_u T_{ave} \left(1 + a \cos \omega t\right)} - \rho_{int} \right) \right)^n d(\omega t) \tag{5.4}$$

of Eq. 3.17. The simplified equation to determine the gas loss due to the chimney effect becomes:

$$Q_{chimney} = \frac{b}{2^{n+1}} (\Delta P)^n \tag{5.5}$$

Using an internal density of 1.977 kg/m^3 and an external density of 1.202 kg/m^3, the gas loss rate due to the chimney effect for the pilot bin is 547.2 x10^{-6} m^3/s. This overpredicts the average experimental gas loss rate (7.33 x10^{-6} m^3/s) by approximately 75 times. This rate seems unreasonably large for a density difference of only 0.78 kg/m^3. Further experimental data are required before the chimney effect of the model can be accurately validated.

5.3 Full Size Bin

5.3.1 Effective Leakage Area

The results of the fan pressurization test using the flow straightener are presented in Table 5.11. Similar to the pilot bin, a depressurization test was not conducted. To conform to the pressure drop requirements of the ASTM Standard (Anonymous 1993b), only three data points were obtainable. This is because the bin envelope pressure drops did not fall within the range of the standard. Reduced airflows were used to lower the envelope pressure drop. However, measurement difficulties using the pitot tube prevented the airflow pressures to be recorded. The smallest inlet opening that yielded a measurable airflow was 30.48 cm. The other two tests, with increased airflows, yielded pressure drops which exceeded the upper limit of the standard. Nonetheless, the natural logrithmic pressure drops and airflow rates were plotted (Fig.5.4) and are consistent with published data (Anonymous 1993b).

Table 5.11: Measured airflow rates and corresponding pressure drops across the bin wall of the full size bin. A flow straightener was mounted to the inlet of the fan duct.

	Airflow Velocity (m/s)										
Fan Inlet	Pitot Tube Traverse Positions								Avg. Vel.	Airflow	ΔP
dia. (cm)	1	2	3	4	5	6	7	8	(m/s)	(m^3/h)	(Pa)
30.48	4.37	4.606	4.609	4.607	4.71	4.80	4.607	4.31	4.601	4824.00	63.05
40.64	6.45	6.82	6.91	6.91	6.88	6.83	6.65	6.19	6.71	7020.00	111.40
48.26	6.99	7.70	8.16	8.49	8.45	8.03	7.57	6.88	7.78	8174.51	131.53

Sherman and Grimsrud (1980) present hypothetical airflows and corresponding envelope pressure drops which fall within the range of the ASTM Standard (Anonymous

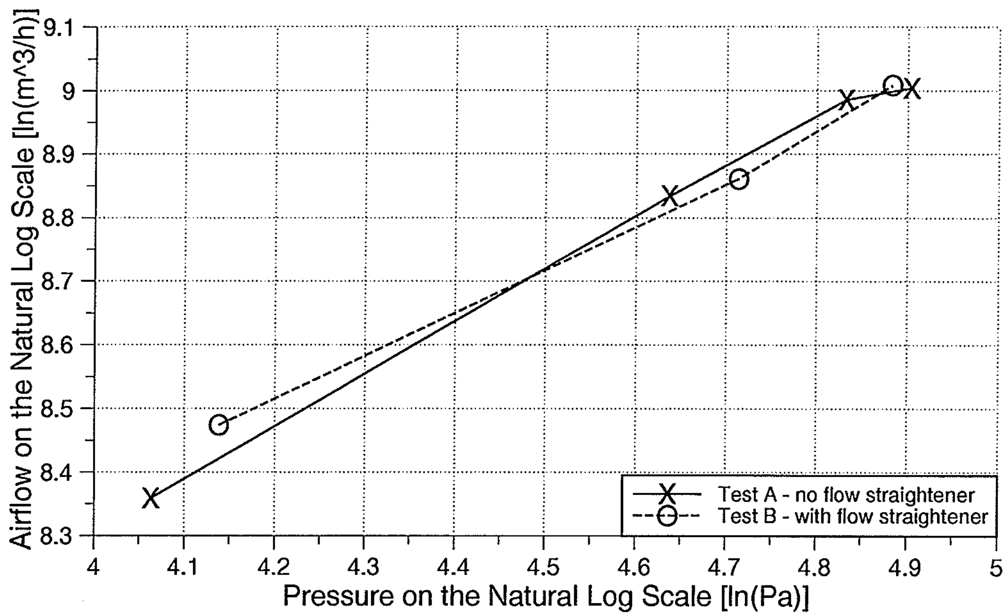

Figure 5.4: The relationship between natural logarithms of airflow into the full size bin and pressure drops across the bin wall.

Table 5.12: Coefficients of Eq. 3.1 for the full size bin obtained from fan pressurization tests.

Test	r^2	b	n
without flow straightener	0.996	174.7	0.79
with flow straightener	0.998	255.7	0.71

1993b). The flow coefficients calculated from their data yielded $b = 202.0$ and $n = 0.6$. Table 5.12 presents the coefficients of Eq. 3.1 for the full size bin. Although only three data points were obtainable, the resulting flow coefficients are reasonable (Sherman and Grimsrud 1980). In addition, the r^2 value was within the recommended range of 0.99 to 1.0 (Anonymous 1985b).

The ELA of the full size bin was estimated to be 746 cm^2 (Table 5.13). Considering that the wall to roof joint of the bin contained several large gaps and that the roof contained an open air vent (approximately 750 cm^2), the estimated ELA was reasonable. However, the total ELA of the bin is not necessary because the CO_2 gas loss experiments were conducted by covering the top surface of the grain with a PVDC sheet and attaching it to the bin wall at 2.5 m above the bin floor (Alagusundaram 1993). The lower door of the bin was also sealed with a PVDC sheet. Therefore, the only leakage area that the CA gases could escape through during these experiments must be located in the wall to floor joint, the seams of the bolted panels for a height of 2.5 m above the bin floor, and any gaps in the bolt holes.

A fan pressurization experiment that included PVDC sheet taped to the bin wall at 2.5 m above the bin floor was attempted. These tests indicated an envelope pressure drop in excess of 120 Pa when a 10 cm dia. opening was mounted at the duct inlet. At this pressure, the tape began to peel and, if allowed to continue, the PVDC sheet would have completely peeled off of the bin wall. Not only did this create an unsafe testing environment, but the bin wall pressure drop decreased progressively as more of the PVDC sheet pulled off of the wall. This made it impossible to record airflow data with corresponding pressure drop because the pressure drop would not remain constant for the duration of the experiment.

An attempt was made to reduce the airflow entering the bin, thereby reducing the pressure drop across the bin wall. This test also proved unsuccessful. These tests did, however, provide a clear indication that most of the leakage area was contained in the roof and not in the seams of the bolted wall panels. This is evident because a much lower flow rate (10 cm dia. opening at the duct inlet) created a pressure drop which would have exceeded that of a 48 cm dia. opening when the PVDC sheet was not used. It could be concluded then, that if an ELA of 746 cm^2 was to be used in the mathematical models, the predicted gas loss rates would be greatly overestimated compared to those found by Alagusundaram (1993). It was therefore necessary to estimate the ELA for this small portion of the bin wall which included the floor to wall seam.

An alternative to using fan pressurization tests to estimate the ELA of a structure is to physically measure the leakage area and then multiply the value by a discharge coefficient of 0.61. For this procedure, a filler gauge was used to measure the width of any gaps that were present between the seam of two bolted panels. For the bin wall surface area of interest, all of the horizontal seams were completely covered with silicone sealant and the filler gauge could not be used. These seams were therefore assumed to be perfectly sealed. Of the 26 vertical seams, all but five were completely covered with silicone sealant. These seams were also considered to be perfectly sealed. Using the filler gauge on the five unsealed vertical seams, it was found that the panels contained approximately the same number of gaps with similar openings. For each seam there were 12 gaps that were 2.54 cm long, 0.813 mm wide and 12 gaps that were 2.54 cm long, 0.012 mm wide. The total physical leakage area for the five seams was calculated to be 12.6 cm^2. Multiplying this value by an orifice coefficient of 0.61 gave an effective leakage area of 7.69 cm^2. This ELA was used in the mathematical models to compare predicted gas loss rates with experimental gas loss rates. This method of determining the ELA of a structure is impractical and does not provide a true estimate because only holes and cracks that are visible are accounted for and these are assumed uniform in size.

5.3.2 Experimental Gas Loss Tests

The experimental tests of CO_2 gas loss were conducted previously by Alagusundaram (1993). For these tests, the bin contained wheat which filled the bin 2.5 m above the floor. The driving forces for the loss of gas were the wind, temperature, and chimney effect. To prevent CA gases from escaping to the headspace of the bin, the top surface of the grain was covered and sealed with a PVDC sheet. Carbon dioxide gas was introduced as dry ice in the air duct and samples were taken and analyzed using the same method as with the pilot bin experiments. The average wind speeds and ambient temperatures which were measured at the Winnipeg International Airport were obtained from Environment Canada (1992) weather service. A summary of these data is presented in Table 5.13.

Similar to the pilot bin, there appears to be no direct correlation between the wind speed and gas loss rate. The experimental results, however, provide a guideline for estimating the loss of CO_2 gas from a typical bolted-metal bin.

When filled with wheat to a height of 2.5 m and assuming a porosity of 40%, a pore volume of 24.3 m^3 is present in the bin. Taking the average gas loss rate (73.7 $\times 10^{-6}$ m^3/s) and dividing by the pore volume gives an airchange rate of 0.26 d^{-1}. The experimental rate is approximately 3.75 times the maximum recommended rate of 0.07 d^{-1} for silos. A larger rate is expected because the full size bolted-metal bin

Table 5.13: Wind, temperature, CO_2 gas levels, and gas loss rates for experimental tests using the full size bin (Alagusundaram 1993).

Test #	Avg. Wind Speed (km/h)	Avg. Ambient Temp. (°C)	Avg. Grain Temp (°C)	c_i (%)	c_f (%)	Δt (h)	Q x10^{+6} (m^3/s)
1	10.9	14.93	14.47	22.27	10.19	15.0	54.3
2	3.2	15.39	14.47	25.44	6.58	18.0	70.7
3	8.3	16.43	15.95	21.86	7.00	16.0	62.6
4	18.3	16.96	15.95	52.59	34.18	15.0	82.8
5	16.9	16.92	15.95	56.91	26.29	15.0	137.7
6	5.3	16.18	17.36	48.36	38.96	9.0	70.4
7	8.2	16.95	17.36	49.50	39.75	16.0	41.1
8	11.1	17.75	15.16	32.39	21.22	15.0	50.2
9	12.9	19.43	15.16	43.05	22.32	15.0	93.2

contains more effective leakage area than a concrete silo (Banks and Annis 1984).

5.3.3 Mathematical Modeling

LBL Model

Compared to the experimental rates of gas loss from the full size bin, the LBL model (ELA = 7.69 cm^2) overpredicted the rates by an average of 5.2 times (Table 5.14). As with the pilot bin, the effective leakage area of the full size bin is suspect and may be too large. The visual inspection of the structure is crude and should only be used as a guide in determining the ELA. It would also be a difficult task to detail the leakage sites of a large bin such as one with a capacity of 82 t. Better designed equipment for the fan pressurization test would provide a more accurate estimate of the ELA of the full size bin. A blower door assembly to pressurize and

Table 5.14: Predicted gas loss rates for various wind speeds using the full size bin with the LBL model (A_o = 7.69 cm^2, C' = 0.185, α = 0.85, and γ = 0.20).

Wind Speed (km/h)	Q_{wind} x10^{+6} (m^3/s)
5.0	127.3
15.0	381.9
25.0	636.4
35.0	891.0

depressurize the structure is recommended (Anonymous 1993b; Palmiter and Brown 1989; and Anonymous 1988). In addition, several orifice holes should be mounted on the bin wall to calibrate the effective leakage area. The use of a plastic sheet that is impermeable to CO_2 gases to prevent losses through the roof is essential to the effective application of controlled atmospheres in bolted-metal bins (M^{c}Gaughey and Akins 1989; Alagusundaram 1993). Therefore, sealing off the roof with an effective seal that will hold during the fan pressurization test is essential to determining the ELA of just the bin wall and floor.

Another possible cause for the error in the predicted gas loss rates, is the reduced wind speed used in Eq. 3.11. This effective velocity is the reduced wind speed to the height of the structure. However, the height of the grain bin was not used in the model; instead, the height above ground of the PVDC plastic was used. Also, Palmiter and Brown (1989) state that the equations used by Sherman and Grimsrud (1980) to estimate the effect of height on wind speed are valid at heights only above 12 m. A review of four different methods for reducing wind speeds for terrain and shielding effects recommend that further studies be conducted (Anonymous 1990b).

As discussed with the pilot bin, the terrain and shielding coefficients are subject to uncertainty due to the ambiguous descriptions and the subjectivity of their selection by each user (Sherman and Grimsrud 1980; Palmiter and Brown 1989). Sherman and Grimsrud (1980) assume that the directional wind effects are negligible. However, the location of the full size bin and the obstructions surrounding it suggest that three different shielding classes could be selected depending on the direction of the prevailing wind. In addition, the experimental CO_2 gas loss tests for both the pilot bin and full size bin indicate that the prevailing winds can change direction significantly in the course of several hours (Environment Canada 1992; Environment Canada 1994). To improve the accuracy of the models, it may be necessary to either average the coefficients or incorporate a term into the model that would account for the directional wind effects. It is questionable, however, as to whether or not this level of accuracy is necessary since the experimental results of the CO_2 gas loss indicate no correlation to the wind speed.

The predicted gas loss rates caused by the stack effect could be studied for the full size bin because the tests conducted by Alagusundaram (1993) contained wheat and therefore an internal-external temperature difference existed. Unfortunately, the average grain temperature (16.8°C) was very close to the average ambient temperature (15.8°C) during the experiments. Also, losses caused by temperature cannot be studied experimentally on the full size bin independent of the wind effects. Therefore, a direct comparison of the predicted losses with the experimental losses caused by internal-external temperature differences is not possible. Nonetheless, the stack effect of the LBL model and the effects of the coefficients R_o and X are reviewed in the following paragraph.

Assuming that all of the leakage area is in the wall (i.e. $R_o = 0.0$ and $X = 0.0$), the predicted gas loss rate is 74.7 x10^{-6} m^3/s. Isolating the roof and floor using plastic sheets is the only way to quantify R_o and X. If, for example, $A_c = A_f = (1/3)A_o$ with internal and external temperatures of 16.8 °C and 15.8 °C, respectively, then the gas loss rate increases by 1.3 times to 99.9 x10^{-6} m^3/s. Setting $A_c = 0.0$ and $A_f = (1/3)A_o$ with the same temperatures as above, the rate of gas loss is 82.2 x10^{-6} m^3/s. The same rate is found if $A_f = 0.0$ and $A_c = (1/3)A_o$. Setting $A_c = (1/2)A_o$ and $A_f = (1/3)A_o$ with the same temperatures as above, the rate of gas loss is 102.9 x10^{-6} m^3/s. The same rate is found if $A_f = (1/2)A_o$ and $A_c = (1/3)A_o$. It can be concluded from these results that the lowest gas loss rate will be predicted if the ELA in the floor and ceiling are as small as possible (i.e. 0.0).

As a further study of the stack effect using the LBL model, Tables 5.15 and 5.16 present results for hypothetical temperature differences. A small temperature gradient of 10°C is significant enough to cause a rate of gas loss comparable to a 10 km/h wind in a structure that contains an ELA of 7.69 cm^2. By adding in quadrature the gas losses for wind (35 km/h) and temperature ($\Delta T = 50$°C), the total gas loss rate would be 1029.0 x10^{-6} m^3/s or an airchange rate of 3.7 d^{-1}.

Table 5.15: Predicted gas loss rates caused by internal-external temperature differences for the full size bin with the LBL model for assumed parameters: T_{int} = -20.0°C, A_o = 7.69 cm^2, C' = 0.185, α = 0.85, γ = 0.20.

T_{ext} (°C)	ΔT (°C)	Q_{stack} x10^{+6} (m^3/s)
-20.00	0.00	0.00
-10.00	10.00	252.17
0.00	20.00	356.62
10.00	30.00	436.77
20.00	40.00	504.34
30.00	50.00	563.87

Table 5.16: Predicted gas loss rates caused by internal-external temperature differences for the full size bin with the LBL model for assumed parameters: T_{int} = 30.0°C, A_o = 7.69 cm^2, C' = 0.185, α = 0.85, γ = 0.20.

T_{ext} (°C)	ΔT (°C)	Q_{stack} x10^{+6} (m^3/s)
-20.00	50.00	515.28
-10.00	40.00	460.88
0.00	30.00	399.13
10.00	20.00	325.89
20.00	10.00	230.44
30.00	0.00	0.00

BA Model

The pressure coefficient ΔC for the full size bin was found by working backwards through Eq. 3.16. Using the average experimental gas loss rate (73.7 x10^{-6} m^3/s), the corresponding average wind speed (10.6 km/h), and $A_o = 7.69$ cm^2; the value of ΔC was 8.54 x10^{-3}. As with the pilot bin, determining the pressure coefficient in this manner cannot be assumed accurate and wind tunnel tests of an exact model and surrounding conditions are required to validate the value. Compared to the range of values found by Mulhearn et al. (1976), the calculated value of ΔC for the full size bin is very small. However, the models used by Mulhearn et al. (1976) were free standing (i.e. no other structures in the surrounding area) and represented 2000 t bins which are approximately 50 times the full size bin. Whereas the surrounding area of the full size bin used for this work contained another bin as well as a large machinery storage shed. When modeling the bin in a wind tunnel, the surroundings should also be scaled and used to determine their influence on the bin being tested. Generalized shielding and terrain conditions may provide reasonable values for typical bins used in Canada. If the calculated value of ΔC (8.54 x10^{-3}) is used, the BA model overpredicts the rates of gas loss caused by wind ($Q_{unadjusted}$) compared to the experimental results (Tables 5.17 and 5.13, respectively).

Adjusting the weather tower recorded wind speeds to effective wind speeds reduces the predicted rates of gas loss by 5.4 times for the full size bin (Table 5.17). A new pressure coefficient was used in the model for the adjusted gas loss rates. This value ($\Delta C = 20.4$ x10^{-3}) was calculated by adjusting the average experimental wind speed (10.7 km/h) to a reduced value (6.8 km/h) to account for shielding and terrain effects. The effect of adding the wind reduction parameters to the BA model is significant as the model now underpredicts the gas loss rates compared to the experimental results

Table 5.17: Predicted gas loss rates for unadjusted and adjusted wind speeds for the full size bin with the BA model ($A_o = 7.69$ cm^2).

Unadjusted[1] Wind Speed (km/h)	$Q_{unadjusted}$ x10^{+6} (m^3/s)	Adjusted[2] Wind Speed (km/h)	$Q_{adjusted}$ x 10^{+6} (m^3/s)
5.0	34.9	3.2	6.4
15.0	104.7	9.7	19.3
25.0	174.4	16.1	32.1
35.0	244.2	22.5	45.0

[1] $\Delta C = 8.54$ x10^{-3}

[2] $\Delta C = 20.4$ x10^{-3}, $C' = 0.185$, $\alpha = 0.85$, $\gamma = 0.20$

of Table 5.13.

For the chimney effect of the BA model; assuming an internal and external pressure of 101.3 kPa and using gas constants of $R^g_{CO_2} = 188.9$ (J kg^{-1} K^{-1}) and $R^g_{air} = 287.0$ (J kg^{-1} K^{-1}) with internal and external temperatures of 16.8 and 15.8^{o}C, respectively, the internal and external densities are 1.85 and 1.22 kg/m^3, respectively. This corresponds to a pressure drop of 15.45 Pa and a gas loss rate of 1074.0 x10^{-6} m^3/s. For only a 1^{o}C temperature difference, this loss rate seems unreasonably large. If this is indeed the case, then the effect of the wind is negligible because Q_{wind} and $Q_{chimney}$ are added in quadrature. As with the pilot bin further experimental data of the chimney effect are required before the model predictions can be accurately validated. The theoretical development of the chimney effect used in the model should also be studied further.

Chapter 6

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The experimental gas loss rates for the pilot and full size bin did not indicate a correlation with wind speed; rather the results were scattered. This may be because the loss rates were caused by the combined forces of the wind, temperature, and chimney effects. Also, the experimental rate of gas loss may be dependent on the wind direction and location of the leakage sites.

2. The experimental airchange rates from the pilot bin and full size bin were 0.23 and 0.26 d^{-1}, respectively.

3. Correctly determining the effective leakage area of a structure was paramount in using the mathematical models to predict the loss of CA gases from an enclosure.

4. Using orifice holes of known effective leakage area provided a method for calibrating the ELA of the pilot bin.

5. A typical roof of a bolted-metal bin contains most of the effective leakage area due to natural aeration vents and doors. Excluding the roof by attaching an impermeable plastic sheet to the inside bin wall reduced the ELA significantly and resulted in lower predicted rates of gas loss.

6. For the pilot bin, the wind component of the LBL model overpredicted the rates of gas loss by an average of 58 times the average experimental rate. For the full size bin, the model overpredicted by an average of 5 times the average experimental rate of gas loss.

7. For the full size bin, the predicted rate of gas loss caused by a 1.0°C temperature difference using the LBL model was within 1% of the average experimental rate.

8. Care should be taken when selecting shielding and terrain coefficients for wind speeds above 15 km/h. Above this speed the LBL model was highly sensitive to these coefficients.

9. The arbitrary choice of pressure coefficients for use in the wind component of the BA model was not an accurate method of determining the value of this coefficient for each bin to be tested. Without knowledge of this coefficient, the wind component of the BA model cannot be used.

10. The predicted gas loss rate due to the chimney effect of the BA model for the pilot bin was approximately 75 times the average experimental rate.

11. For the full size bin, using a 1°C temperature difference with the chimney effect resulted in a predicted gas loss 14.6 times the average experimental rate.

12. A high level of accuracy of the predicted rates of gas loss cannot be expected until experimental relationships are developed between (i) gas loss and wind, (ii) gas loss and temperature effects, and (iii) gas loss and density effects.

Chapter 7

RECOMMENDATIONS

The following recommendations are made from this study:

1. Conducting fan pressurization tests should include both pressurization and depressurization. This will account for any leakage sites that act as gate valves and will also provide a second estimation of the ELA. In addition, it is recommended that orifice holes be used as a standard practice to calibrate the estimated ELA.

2. More detailed studies in controlled environments dealing with the forces of the wind, temperature, and chimney effects should be conducted. Scaled models of typical grain bins should be studied using a wind tunnel. This may provide better estimations of the pressure coefficients and shielding and terrain effects.

3. The experimental rates of gas loss caused by wind, temperature, and chimney effects should be separated to provide better validation data for the models. For example, conducting CO_2 concentration tests with no wind and no temperature effects will separate the parameters and provide data specific to the chimney

effect. A similar test should be conducted for the wind effects. For the temperature effects, a pilot bin of similar construction to the full size bin could be constructed and used to study the effects of temperature differences, i.e. warm grain (25°C) with a cold external environment (-25°C); and cold grain (-20°C) with a warm external environment (30°C).

4. The influence of the neutral pressure level should be studied to determine if the presence of grain in the bin affects the location of the NPL. In addition, the effect of the NPL location on the R_o and X coefficients of the LBL model should be examined. Locating the NPL is done by placing more pressure taps vertically along the bin wall and determining the location of the sign change (i.e. $\pm$ ΔP) of the pressure drop (Anonymous 1988).

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Appendix A

Fan Pressurization Tests - Pilot Bin

The following tables contain the data taken for the fan pressurization tests conducted on the pilot bin. Tables A.1.1 to A.4.2 are for tests when the PVDC cover was sealed. Tables A.5.1 to A8.2 contain the data for the test which included a plate with a 1.28 cm diameter orifice opening mounted in the PVDC cover. Tables A.9.1 to A.12.2 contain the data for the test which included a a plate with a 5.72 cm orifice opening in the PVDC cover. Tables A.13.1 to A.17.2 contain the data for the test which included a plate with a 8.26 cm orifice opening in the PVDC cover. Tables A.18 to A.20 contain the results from three tests (sealed and 5.72, and 8.26 orifice openings) for only 1 replicate.

Table A.1.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	1.12	1.13	1.13	1.14	1.14
	2	1.17	1.16	1.16	1.16	1.16
	3	1.16	1.16	1.16	1.16	1.16
B	1	—	1.14	1.13	1.14	1.14
	2	—	1.14	1.14	1.15	1.14
	3	—	1.14	1.16	1.16	1.16
C	1	1.12	1.12	1.12	1.12	1.10
	2	1.14	1.14	1.14	1.14	1.11
	3	1.14	1.15	1.16	1.16	1.13
D	1	1.12	1.12	1.12	1.12	1.14
	2	1.16	1.15	1.16	1.14	1.16
	3	1.14	1.14	1.14	1.14	1.15
Inclined manometer coefficient: 0.05						

Air blockage plate with 1.00 cm opening - Top of bin sealed

Table A.1.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.049	22.0	74.79
2	0.049	22.0	74.79
3	0.049	22.1	74.79
Inclined manometer coefficient: 0.05			

Table A.2.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	1.58	1.58	1.58	1.58	1.58
A	2	1.57	1.57	1.57	1.56	1.56
	3	1.54	1.54	1.54	1.54	1.54
	1	—	1.55	1.55	1.56	1.56
B	2	—	1.53	1.53	1.54	1.54
	3	—	1.54	1.53	1.54	1.54
	1	1.54	1.54	1.55	1.54	1.51
C	2	1.53	1.53	1.54	1.53	1.49
	3	1.53	1.54	1.54	1.54	1.51
	1	1.57	1.57	1.57	1.56	1.58
D	2	1.54	1.54	1.53	1.52	1.54
	3	1.53	1.54	1.54	1.53	1.54
Inclined manometer coefficient: 0.05						

Air blockage plate with 1.20 cm opening - Top of bin sealed

Table A.2.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.069	21.1	74.79
2	0.065	21.4	74.79
3	0.066	21.6	74.79
Inclined manometer coefficient: 0.05			

Table A.3.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	2.76	2.76	2.77	2.76	2.78
	2	2.75	2.74	2.74	2.77	2.78
	3	2.76	2.76	2.76	2.74	2.76
B	1	—	2.73	2.74	2.74	2.74
	2	—	2.70	2.70	2.71	2.70
	3	—	2.77	2.77	2.78	2.78
C	1	2.74	2.74	2.74	2.74	2.70
	2	2.72	2.72	2.72	2.69	2.64
	3	2.74	2.76	2.76	2.75	2.72
D	1	2.74	2.72	2.74	2.72	2.75
	2	2.74	2.70	2.74	2.72	2.76
	3	2.73	2.73	2.74	2.72	2.78
Inclined manometer coefficient: 0.05						

Air blockage plate with 1.50 cm opening - Top of bin sealed

Table A.3.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.120	21.5	74.79
2	0.120	21.4	74.79
3	0.125	21.6	74.79
Inclined manometer coefficient: 0.05			

Table A.4.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	4.80	4.78	4.79	4.80	4.82
A	2	4.85	4.83	4.83	4.83	4.83
	3	4.81	4.80	4.80	4.80	4.82
	1	—	4.78	4.76	4.80	4.80
B	2	—	4.73	4.74	4.76	4.76
	3	—	4.71	4.70	4.72	4.72
	1	4.72	4.72	4.78	4.75	4.68
C	2	4.74	4.73	4.76	4.74	4.61
	3	4.67	4.66	4.72	4.68	4.60
	1	4.76	4.72	4.73	4.72	4.80
D	2	4.72	4.75	4.76	4.75	4.81
	3	4.72	4.72	4.74	4.72	4.79
Inclined manometer coefficient: 0.05						

Air blockage plate with 2.00 cm opening - Top of bin sealed

Table A.4.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.225	20.0	74.70
2	0.225	20.7	74.79
3	0.220	21.3	74.79
Inclined manometer coefficient: 0.05			

Table A.5.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	0.64	0.64	0.64	0.64	0.64
A	2	0.63	0.64	0.64	0.64	0.64
	3	0.64	0.64	0.63	0.63	0.64
	1	—	0.64	0.63	0.63	0.64
B	2	—	0.63	0.64	0.64	0.63
	3	—	0.63	0.63	0.63	0.63
	1	0.64	0.63	0.64	0.64	0.64
C	2	0.63	0.63	0.63	0.63	0.62
	3	0.61	0.62	0.61	0.61	0.61
	1	0.64	0.64	0.63	0.64	0.64
D	2	0.64	0.64	0.64	0.63	0.64
	3	0.63	0.62	0.63	0.62	0.63
Inclined manometer coefficient: 0.05						

Air blockage plate with 1.00 cm opening - 1.28 cm dia. orifice hole in bin envelope

Table A.5.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.025	21.4	74.65
2	0.025	21.2	74.69
3	0.029	20.9	74.70
Inclined manometer coefficient: 0.05			

Table A.6.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	0.90	0.90	0.90	0.89	0.90
	2	0.91	0.91	0.90	0.89	0.90
	3	0.91	0.91	0.91	0.90	0.91
B	1	—	0.88	0.89	0.89	0.89
	2	—	0.89	0.90	0.91	0.91
	3	—	0.89	0.89	0.89	0.90
C	1	0.89	0.89	0.89	0.89	0.88
	2	0.89	0.90	0.90	0.90	0.89
	3	0.87	0.88	0.89	0.88	0.86
D	1	0.89	0.89	0.89	0.89	0.89
	2	0.91	0.90	0.91	0.90	0.91
	3	0.90	0.89	0.90	0.89	0.90

Inclined manometer coefficient: 0.05

Air blockage plate with 1.20 cm opening - 1.28 cm dia. orifice hole in bin envelope

Table A.6.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.039	22.2	74.55
2	0.039	22.0	74.60
3	0.038	21.7	74.65

Inclined manometer coefficient: 0.05

Table A.7.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	1.73	1.73	1.73	1.72	1.73
	2	1.74	1.73	1.73	1.73	1.73
	3	1.73	1.72	1.72	1.72	1.72
B	1	—	1.72	1.72	1.73	1.72
	2	—	1.71	1.70	1.71	1.72
	3	—	1.72	1.72	1.72	1.71
C	1	1.71	1.71	1.72	1.71	1.69
	2	1.68	1.68	1.70	1.69	1.65
	3	1.71	1.69	1.68	1.71	1.69
D	1	1.72	1.72	1.73	1.72	1.73
	2	1.72	1.72	1.71	1.71	1.72
	3	1.72	1.72	1.72	1.72	1.73
Inclined manometer coefficient: 0.05						

Air blockage plate with 1.50 cm opening - 1.28 cm dia. orifice hole in bin envelope

Table A.7.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature ^oC	Ambient Pressure cm Hg
1	0.080	22.5	74.50
2	0.080	22.6	74.50
3	0.080	22.9	74.50
Inclined manometer coefficient: 0.05			

Table A.8.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	3.44	3.44	3.40	3.38	3.41
A	2	3.45	3.42	3.40	3.40	3.44
	3	3.48	3.44	3.46	3.47	3.47
	1	—	3.37	3.39	3.41	3.41
B	2	—	3.41	3.41	3.41	3.43
	3	—	3.38	3.38	3.39	3.40
	1	3.39	3.40	3.40	3.38	3.33
C	2	3.36	3.34	3.38	3.40	3.35
	3	3.32	3.36	3.38	3.38	3.30
	1	3.40	3.40	3.40	3.39	3.42
D	2	3.40	3.40	3.40	3.36	3.44
	3	3.43	3.40	3.41	3.39	3.42
Inclined manometer coefficient: 0.05						

Air blockage plate with 2.00 cm opening - 1.28 cm dia. orifice hole in bin envelope

Table A.8.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature ^oC	Ambient Pressure cm Hg
1	0.169	23.2	74.50
2	0.169	23.4	74.50
3	0.169	23.7	74.50
Inclined manometer coefficient: 0.05			

Table A.9.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	—	0.21	—	—	—
	2	0.21	—	—	—	—
	3	—	—	—	0.21	—
B	1	—	—	—	0.21	—
	2	—	0.21	—	—	—
	3	—	—	0.21	—	—
C	1	0.21	—	—	—	—
	2	—	—	0.21	—	0.21
	3	—	0.21	—	—	0.21
D	1	—	—	0.21	—	0.21
	2	—	—	—	0.21	—
	3	0.21	—	—	—	—
Inclined manometer coefficient: 0.05						

Air blockage plate with 2.40 cm opening - 5.72 cm dia. orifice hole in bin envelope

Table A.9.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.115	22.5	76.41
2	0.115	22.5	76.41
3	0.120	22.5	76.41
Inclined manometer coefficient: 0.05			

Table A.10.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	—	—	0.52	—	—
A	2	—	—	0.50	—	—
	3	—	—	—	0.50	—
	1	—	—	—	—	0.51
B	2	—	0.50	—	—	0.50
	3	—	—	0.50	—	0.50
	1	0.50	—	—	—	—
C	2	—	—	—	0.50	—
	3	0.50	—	—	—	—
	1	—	0.52	—	0.51	—
D	2	0.50	—	0.50	—	—
	3	—	0.50	—	—	—
Inclined manometer coefficient: 0.05						

Air blockage plate with 3.40 cm opening - 5.72 cm dia. orifice hole in bin envelope

Table A.10.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature ^oC	Ambient Pressure cm Hg
1	0.26	22.5	76.41
2	0.26	22.5	76.41
3	0.26	22.5	76.41
Inclined manometer coefficient: 0.05			

Table A.11.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	1.23	—	—	—	1.23
A	2	—	1.23	—	—	—
	3	—	1.24	—	1.23	—
	1	—	1.23	—	—	—
B	2	—	—	—	1.23	—
	3	—	—	1.23	—	—
	1	—	—	1.23	—	—
C	2	1.23	—	1.23	—	—
	3	—	—	—	—	1.23
	1	—	—	—	1.23	—
D	2	—	—	—	—	1.23
	3	1.23	—	—	—	—
Inclined manometer coefficient: 0.05						

Air blockage plate with 4.50 cm opening - 5.72 cm dia. orifice hole in bin envelope

Table A.11.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.645	22.5	76.49
2	0.640	22.5	76.45
3	0.080	22.5	76.41
Inclined manometer coefficient: 0.05			

Table A.12.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	—	2.08	—	—	2.10
A	2	2.06	—	—	2.07	—
	3	2.08	—	—	—	2.07
	1	—	—	2.06	2.08	—
B	2	—	2.07	—	—	2.07
	3	—	2.06	—	—	—
	1	2.06	—	—	—	2.07
C	2	—	2.07	—	—	—
	3	—	—	—	2.07	—
	1	—	2.08	—	2.06	—
D	2	—	—	2.07	—	—
	3	—	—	2.07	—	—
Inclined manometer coefficient: 0.05						

Air blockage plate with 6.00 cm opening - 5.72 cm dia. orifice hole in bin envelope

Table A.12.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	1.10	22.5	76.45
2	1.09	22.6	76.45
3	1.10	22.7	76.45
Inclined manometer coefficient: 0.05			

Table A.13.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	0.04	0.04	—	0.04	0.04
A	2	0.04	—	0.04	—	0.04
	3	0.04	—	0.04	—	0.04
	1	—	0.04	—	0.04	—
B	2	—	0.04	—	0.04	—
	3	—	0.04	—	0.04	—
	1	0.04	—	0.04	—	0.04
C	2	—	0.04	—	0.04	—
	3	—	0.04	—	0.04	—
	1	0.04	—	0.04	—	0.04
D	2	0.04	—	0.04	—	0.04
	3	0.04	—	0.04	—	0.04
Inclined manometer coefficient: 0.05						

Air Blockage Plate with 2.00 cm opening - 8.255 cm dia. orifice hole in bin envelope

Table A.13.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.060	24.1	75.00
2	0.060	24.8	75.00
3	0.060	25.3	75.10
Inclined manometer coefficient: 0.05			

Table A.14.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
	1	0.06	—	0.06	—	0.06
A	2	—	—	0.06	—	—
	3	—	—	0.06	—	0.06
	1	—	0.06	—	0.06	—
B	2	—	0.06	—	0.06	—
	3	—	0.06	—	0.06	—
	1	—	0.06	—	0.06	—
C	2	—	0.06	—	0.06	—
	3	—	0.06	—	—	0.06
	1	0.06	—	0.06	0.06	0.06
D	2	0.06	—	0.06	—	0.06
	3	0.06	—	—	0.06	—
Inclined manometer coefficient: 0.05						

Air blockage plate with 2.40 cm opening - 8.255 cm dia. orifice hole in bin envelope

Table A.14.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature ^oC	Ambient Pressure cm Hg
1	0.120	25.8	75.10
2	0.120	25.4	75.10
3	0.120	25.1	75.20
Inclined manometer coefficient: 0.05			

Table A.15.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	0.12	—	—	0.12	—
	2	0.12	—	—	—	0.12
	3	0.12	—	—	0.12	—
B	1	—	0.12	—	0.12	—
	2	—	0.12	—	0.12	—
	3	—	0.12	—	—	0.12
C	1	0.12	—	—	—	0.12
	2	0.12	—	0.12	—	—
	3	0.12	—	—	0.12	—
D	1	—	0.12	0.12	—	0.12
	2	—	0.12	—	0.12	—
	3	—	—	0.12	—	0.12
Inclined manometer coefficient: 0.05						

Air blockage plate with 3.40 cm opening - 8.255 cm dia. orifice hole in bin envelope

Table A.15.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.255	24.8	75.20
2	0.255	24.6	75.20
3	0.257	24.4	75.20
Inclined manometer coefficient: 0.05			

Table A.16.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	0.34	0.34	—	—	—
	2	0.34	—	—	—	0.34
	3	0.34	—	—	0.34	—
B	1	—	0.34	—	—	0.34
	2	—	0.34	—	—	0.34
	3	—	0.34	—	—	0.34
C	1	0.34	—	—	0.34	—
	2	0.34	—	0.34	—	—
	3	0.34	—	0.34	—	—
D	1	—	0.34	—	—	0.34
	2	—	0.34	—	0.34	—
	3	—	0.34	—	—	0.34
Inclined manometer coefficient: 0.05						

Air blockage plate with 4.50 cm opening - 8.255 cm dia. orifice hole in bin envelope

Table A.16.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	0.680	23.4	75.20
2	0.685	23.4	75.20
3	0.685	23.1	75.20
Inclined manometer coefficient: 0.05			

Table A.17.1: Pilot Bin Internal - External Pressure Drop

Radial Position	Test #	Presssure Drop (in. H_2O) Vertical Position				
-	-	1	2	3	4	5
A	1	—	0.62	—	0.62	—
	2	0.62	—	—	—	0.62
	3	—	0.61	—	0.61	—
B	1	—	0.62	—	—	0.62
	2	—	0.62	—	—	0.62
	3	—	0.61	—	—	0.61
C	1	0.62	—	—	0.62	—
	2	—	0.62	—	0.62	—
	3	0.61	—	—	0.62	—
D	1	0.62	—	0.62	—	—
	2	0.62	—	—	—	—
	3	0.61	—	0.61	—	—
Inclined manometer coefficient: 0.05						

Air blockage plate with 6.00 cm opening - 8.255 cm dia. orifice hole in bin envelope

Table A.17.2: Pilot Bin Air Flow

Test #	Air Flow Pressure kPa	Air Flow Temperature °C	Ambient Pressure cm Hg
1	1.250	22.5	75.20
2	1.250	22.8	75.20
3	1.250	23.0	75.20
Inclined manometer coefficient: 0.05			

Table A.18: Pilot Bin: Air Flow and Pressure Drop

	Air Blockage Plate #							
	1	2	3	4	5	6	7	8 (open)
Air Flow (kPa) IC = 0.05	0.04	0.07	0.13	0.23	0.32	0.43	0.49	0.53
Δ P (in. H_2O) IC = 0.10	0.51	0.74	1.35	2.40	3.22	4.26	4.87	5.15

Top of Bin Sealed

Table A.19: Pilot Bin: Air Flow and Pressure Drop

	Air Blockage Plate #			
	5	6	7	8 (open)
Air Flow (kPa) IC = 0.05	0.13	0.27	0.68	1.10
Δ P (in. H_2O) IC = 0.05	0.26	0.54	1.31	2.10

Orifice Hole (5.72 cm dia) - in bin envelope

Table A.20: Pilot Bin: Air Flow and Pressure Drop

	Air Blockage Plate #			
	5	6	7	8 (open)
Air Flow (kPa) IC = 0.05	0.13	0.28	0.73	1.29
Δ P (in. H_2O) IC = 0.05	0.07	0.15	0.37	0.63

Orifice Hole (8.255 cm dia) - in bin envelope

Appendix B

CO_2 Concentration Tests - Pilot Bin

The following tables (B.1 to B.18) contain the results of the CO_2 gas concentration tests conducted using the pilot bin. Refer to Fig. 4.2 for sampling locations.

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 17-18, 1994

CO_2 Input: 4.81 kg @ 0700 h, January 17, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1100

Wind speed: W 13 km/h — Ambient Pres.: 103.01 kPa

Ambient Temp.: -33°C — Rel. Humidity: 64%

Table B.1: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	—	87.10	—	89.04	—
B-1	—	—	87.37	—	—
C-1	88.24	—	—	—	87.50
D-1	93.97	—	83.26	—	—
A-3	—	48.63	—	49.77	—
B-3	—	—	50.44	—	—
C-3	46.65	—	—	—	53.17
D-3	58.45	—	57.04	—	—
A-5	—	30.05	—	28.86	—
B-5	—	—	28.76	—	—
C-5	31.75	—	—	—	30.65
D-5	32.98	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 17-18, 1994

CO_2 Input: 4.81 kg @ 0700 h, January 17, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1600

Wind speed: NW 35 km/h

Ambient Temp.: -30°C

Ambient Pres.: 102.96 kPa

Rel. Humidity: 57%

Table B.2: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	—	56.41	—	57.87	—
B-1	—	—	53.63	—	—
C-1	57.74	—	—	—	57.15
D-1	56.32	—	53.71	—	—
A-3	—	52.99	—	55.64	—
B-3	—	—	51.02	—	—
C-3	52.87	—	—	—	53.51
D-3	53.52	—	53.71	—	—
A-5	—	51.32	—	53.55	—
B-5	—	—	53.94	—	—
C-5	53.52	—	—	—	51.68
D-5	54.96	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 17-18, 1994

CO_2 Input: 4.81 kg @ 0700 h, January 17, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 0900 January 18, 1994

Wind speed: W 19 km/h
Ambient Pres.: 103.32 kPa

Ambient Temp.: -34°C
Rel. Humidity: 63%

Table B.3: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	—	39.28	—	40.01	—
B-1	—	—	36.64	—	—
C-1	38.66	—	—	—	41.17
D-1	40.34	—	38.26	—	—
A-3	—	37.83	—	38.60	—
B-3	—	—	35.97	—	—
C-3	38.36	—	—	—	36.53
D-3	37.94	—	39.17	—	—
A-5	—	35.50	—	35.61	—
B-5	—	—	31.18	—	—
C-5	36.94	—	—	—	39.65
D-5	37.32	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 19, 1994

CO_2 Input: 6.2 kg @ 2300 h, January 18, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 0900

Wind speed: W 19 km/h

Ambient Pres.: 103.08 kPa

Ambient Temp.: -32°C

Rel. Humidity: 65%

Table B.4: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	—	89.99	—	91.32	—
B-1	—	—	81.22	—	—
C-1	87.33	—	—	—	90.66
D-1	89.22	—	85.01	—	—
A-3	—	71.70	—	72.81	—
B-3	—	—	67.45	—	—
C-3	70.99	—	—	—	70.61
D-3	72.57	—	70.41	—	—
A-5	—	66.25	—	68.32	—
B-5	—	—	64.09	—	—
C-5	68.97	—	—	—	70.12
D-5	69.41	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 19, 1994

CO_2 Input: 6.2 kg @ 2300 h, January 18, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1230

Wind speed: WSW 15 km/h

Ambient Pres.: 103.20 kPa

Ambient Temp.: -27°C

Rel. Humidity: 58%

Table B.5: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	—	73.22	—	75.03	—
B-1	—	—	74.06	—	—
C-1	74.49	—	—	—	71.40
D-1	73.50	—	69.84	—	—
A-3	—	74.12	—	72.29	—
B-3	—	—	70.63	—	—
C-3	71.75	—	—	—	72.69
D-3	71.89	—	70.61	—	—
A-5	—	67.86	—	71.43	—
B-5	—	—	71.70	—	—
C-5	68.97	—	—	—	71.58
D-5	70.43	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 19, 1994

CO_2 Input: 6.2 kg @ 2300 h, January 18, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1600

Wind speed: SW 11 km/h

Ambient Pres.: 103.21 kPa

Ambient Temp.: -25°C

Rel. Humidity: 51%

Table B.6: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	—	63.84	—	67.67	—
B-1	—	—	66.50	—	—
C-1	66.72	—	—	—	64.51
D-1	63.39	—	62.41	—	—
A-3	—	67.05	—	68.41	—
B-3	—	—	61.92	—	—
C-3	64.12	—	—	—	64.68
D-3	65.57	—	65.85	—	—
A-5	—	63.31	—	62.68	—
B-5	—	—	63.26	—	—
C-5	62.41	—	—	—	65.78
D-5	64.12	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 21, 1994

CO_2 Input: 6.2 kg @ 2100 h, January 20, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 0900

Wind speed: WNW 15 km/h

Ambient Pres.: 102.48 kPa

Ambient Temp.: -16°C

Rel. Humidity: 63%

Table B.7: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	78.75	74.63	—	73.26	—
B-1	—	—	71.50	—	—
C-1	78.37	—	76.86	—	76.20
D-1	74.57	—	69.83	—	—
A-3	62.18	59.65	—	62.00	—
B-3	—	—	57.98	—	—
C-3	62.30	—	61.88	—	59.12
D-3	60.65	—	57.39	—	—
A-5	49.48	45.34	—	47.71	—
B-5	—	—	34.48	—	—
C-5	51.93	—	46.13	—	44.65
D-5	45.35	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 21, 1994

CO_2 Input: 6.2 kg @ 2100 h, January 20, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1300

Wind speed: W 17 km/h

Ambient Pres.: 102.65 kPa

Ambient Temp.: -11°C

Rel. Humidity: 78%

Table B.8: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	62.40	60.54	—	57.00	—
B-1	—	—	58.83	—	—
C-1	58.21	—	58.85	—	59.95
D-1	55.65	—	59.04	—	—
A-3	61.70	54.14	—	56.97	—
B-3	—	—	55.51	—	—
C-3	57.61	—	58.71	—	53.40
D-3	57.41	—	56.15	—	—
A-5	54.37	54.89	—	52.63	—
B-5	—	—	39.32	—	—
C-5	53.61	—	53.20	—	53.67
D-5	46.38	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 21, 1994

CO_2 Input: 6.2 kg @ 2100 h, January 20, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1630

Wind speed: WNW 20 km/h

Ambient Pres.: 102.76 kPa

Ambient Temp.: -11°C

Rel. Humidity: 71%

Table B.9: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	54.96	55.36	—	55.70	—
B-1	—	—	52.21	—	—
C-1	53.98	—	54.55	—	54.78
D-1	51.26	—	51.03	—	—
A-3	52.65	54.02	—	55.17	—
B-3	—	—	50.90	—	—
C-3	50.34	—	55.35	—	52.50
D-3	48.61	—	55.17	—	—
A-5	50.55	50.81	—	50.10	—
B-5	—	—	39.39	—	—
C-5	50.73	—	48.32	—	48.76
D-5	49.85	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 24, 1994

CO_2 Input: 4.5 kg @ 2200 h, January 23, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 0900

Wind speed: NNE 13 km/h

Ambient Pres.: 103.15 kPa

Ambient Temp.: -24°C

Rel. Humidity: 69%

Table B.10: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	64.81	65.88	—	65.03	—
B-1	—	—	64.37	—	—
C-1	63.07	—	64.38	—	65.22
D-1	61.00	—	65.94	—	—
A-3	48.85	49.73	—	49.65	—
B-3	—	—	50.10	—	—
C-3	46.30	—	48.28	—	45.59
D-3	52.71	—	50.85	—	—
A-5	42.39	43.35	—	40.03	—
B-5	—	—	29.40	—	—
C-5	44.26	—	40.20	—	41.75
D-5	43.45	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 24, 1994

CO_2 Input: 4.5 kg @ 2200 h, January 23, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1230

Wind speed: NNE 13 km/h

Ambient Pres.: 103.28 kPa

Ambient Temp.: -22°C

Rel. Humidity: 66%

Table B.11: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	50.82	52.29	—	48.69	—
B-1	—	—	48.34	—	—
C-1	51.87	—	50.96	—	51.91
D-1	50.38	—	44.69	—	—
A-3	52.01	48.41	—	52.43	—
B-3	—	—	48.35	—	—
C-3	49.72	—	51.93	—	49.92
D-3	50.15	—	50.61	—	—
A-5	51.87	48.39	—	48.40	—
B-5	—	—	39.69	—	—
C-5	51.16	—	48.57	—	48.81
D-5	47.71	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 24, 1994

CO_2 Input: 4.5 kg @ 2200 h, January 23, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1600

Wind speed: NNE 15 km/h

Ambient Pres.: 103.33 kPa

Ambient Temp.: -21°C

Rel. Humidity: 62%

Table B.12: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	46.15	45.59	—	45.06	—
B-1	—	—	43.71	—	—
C-1	46.06	—	46.43	—	45.01
D-1	44.31	—	46.06	—	—
A-3	43.47	43.74	—	45.78	—
B-3	—	—	42.43	—	—
C-3	43.45	—	44.94	—	43.42
D-3	42.81	—	41.15	—	—
A-5	45.25	40.73	—	41.76	—
B-5	—	—	37.89	—	—
C-5	44.00	—	40.84	—	43.85
D-5	46.99	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 25, 1994

CO_2 Input: 4.1 kg @ 1930 h, January 24, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 0900

Wind speed: ENE 17 km/h   Ambient Pres.: 103.72 kPa

Ambient Temp.: -21°C   Rel. Humidity: 59%

Table B.13: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	60.45	62.01	—	61.23	—
B-1	—	—	60.17	—	—
C-1	60.34	—	60.14	—	61.49
D-1	59.69	—	59.26	—	—
A-3	49.07	46.37	—	49.17	—
B-3	—	—	49.61	—	—
C-3	50.32	—	50.39	—	50.75
D-3	49.50	—	47.70	—	—
A-5	38.13	33.19	—	35.50	—
B-5	—	—	22.03	—	—
C-5	37.98	—	36.53	—	35.02
D-5	36.24	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 25, 1994

CO_2 Input: 4.1 kg @ 1930 h, January 24, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 01230

Wind speed: NE 17 km/h Ambient Pres.: 103.71 kPa

Ambient Temp.: -19°C Rel. Humidity: 56%

Table B.14: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	47.71	50.04	—	48.08	—
B-1	—	—	46.65	—	—
C-1	47.93	—	49.73	—	48.71
D-1	47.28	—	46.12	—	—
A-3	47.40	46.58	—	46.68	—
B-3	—	—	44.44	—	—
C-3	46.27	—	48.92	—	46.45
D-3	46.72	—	46.06	—	—
A-5	48.41	43.16	—	46.11	—
B-5	—	—	35.16	—	—
C-5	48.34	—	47.15	—	46.80
D-5	47.02	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 25, 1994

CO_2 Input: 4.1 kg @ 1930 h, January 24, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1600

Wind speed: ENE 17 km/h

Ambient Pres.: 103.61 kPa

Ambient Temp.: -17°C

Rel. Humidity: 51%

Table B.15: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	45.67	46.61	—	43.90	—
B-1	—	—	42.04	—	—
C-1	44.13	—	45.36	—	44.27
D-1	42.43	—	41.68	—	—
A-3	43.64	44.84	—	43.55	—
B-3	—	—	42.30	—	—
C-3	43.63	—	44.65	—	42.86
D-3	41.15	—	41.12	—	—
A-5	46.15	41.89	—	40.77	—
B-5	—	—	33.95	—	—
C-5	44.63	—	42.71	—	42.33
D-5	44.54	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 27, 1994

CO_2 Input: 2.5 kg @ 1730 h, January 26, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 0900

Wind speed: S 11 km/h   Ambient Pres.: 102.28 kPa

Ambient Temp.: -10°C   Rel. Humidity: 89%

Table B.16: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	44.44	49.45	—	46.53	—
B-1	—	—	46.37	—	—
C-1	49.91	—	49.24	—	47.26
D-1	44.31	—	49.99	—	—
A-3	42.10	42.53	—	43.66	—
B-3	—	—	41.81	—	—
C-3	42.31	—	44.41	—	44.52
D-3	43.62	—	42.65	—	—
A-5	34.95	33.70	—	34.65	—
B-5	—	—	25.73	—	—
C-5	34.12	—	33.76	—	33.40
D-5	34.95	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 27, 1994

CO_2 Input: 2.5 kg @ 1730 h, January 26, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1230

Wind speed: W 7 km/h — Ambient Pres.: 102.20 kPa

Ambient Temp.: -8°C — Rel. Humidity: 85%

Table B.17: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	40.76	43.30	—	41.14	—
B-1	—	—	40.63	—	—
C-1	43.26	—	42.80	—	43.36
D-1	42.16	—	43.75	—	—
A-3	42.22	41.59	—	41.95	—
B-3	—	—	39.87	—	—
C-3	39.71	—	42.80	—	41.13
D-3	41.96	—	41.03	—	—
A-5	42.45	39.07	—	41.30	—
B-5	—	—	33.95	—	—
C-5	43.27	—	40.92	—	37.26
D-5	42.61	—	—	—	—

CO_2 GAS LOSS TEST - PILOT BIN

Date of test: January 27, 1994

CO_2 Input: 2.5 kg @ 1730 h, January 26, 1994

WEATHER CONDITIONS AT SAMPLE TIME

Sample time: 1600

Wind speed: WNW 9 km/h
Ambient Pres.: 102.02 kPa

Ambient Temp.: -8°C
Rel. Humidity: 84%

Table B.18: Pilot Bin: CO_2 Concentration Test

CO_2 CONCENTRATION (%)					
Sampling Location	Distance from Bin Wall (cm)				
Level	0.0	17.8	35.6	53.3	71.1
A-1	38.12	41.87	—	38.65	—
B-1	—	—	38.17	—	—
C-1	40.85	—	41.63	—	39.45
D-1	40.00	—	41.31	—	—
A-3	39.65	38.56	—	39.55	—
B-3	—	—	36.18	—	—
C-3	39.18	—	40.56	—	40.04
D-3	39.03	—	38.72	—	—
A-5	40.79	37.25	—	38.71	—
B-5	—	—	34.27	—	—
C-5	39.83	—	39.21	—	38.87
D-5	40.09	—	—	—	—

Appendix C

Fan Pressurization Tests - Full Size Bin

The following tables contain the data taken for the fan pressurization tests conducted on the full size bin. Tables C.1.1 to C.3.2 are the results for the experiment that did not include the flow straightener. Tables C.4.1 to C.6.2 are the results for the experiment that included the flow straightener.

Date of test: March 30, 1994

Weather Conditions During Experiment

Average Wind Speed: 17.12 km/h Ambient Pres.: 101.8 kPa

Average Ambient Temp.: 4.0°C

Table C.1.1: Full Size Bin - Bin Envelope Pressure Drop

Vertical Level	Rep. #	Pressure Drop (kPa) Radial Location 1 (NW)	7 (SE)	8 (NE)	13 (SW)
L11	1	0.29	0.29	0.29	0.29
	2	0.29	0.29	0.29	0.29
	3	0.30	0.29	0.29	0.30
L21	1	0.29	0.29	0.29	0.29
	2	0.29	0.29	0.29	0.29
	3	0.29	0.30	0.29	0.29
L31	1	0.30	0.29	0.29	0.29
	2	0.30	0.29	0.29	0.29
	3	0.30	0.29	0.29	0.29
Inclined Coefficient = 0.20					

Air Blockage Plate: 30.5 cm Opening

Table C.1.2: Full Size Bin - Airflow Measurement

Rep. #	Airflow Measurement (in. H_2O) Pitot Tube Traverse Position 1	2	3	4
1	0.60 - 0.80	0.70 - 0.90	0.80 - 0.90	0.80 - 0.90
2	0.60 - 0.70	0.70 - 0.80	0.80 - 0.90	0.80 - 0.95
3	0.60 - 0.70	0.70 - 0.80	0.80 - 0.90	0.85 - 0.95
	5	6	7	8
1	0.80 - 0.90	0.75 - 0.85	0.75 - 0.85	0.65 - 0.80
2	0.80 - 0.90	0.70 - 0.90	0.70 - 0.90	0.70 - 0.80
3	0.85 - 0.95	0.75 - 0.85	0.75 - 0.85	0.70 - 0.80
Inclined Coefficient = 0.05				

Air Blockage Plate: 30.5 cm Opening

Date of test: March 30, 1994

Weather Conditions During Experiment

Average Wind Speed: 17.12 km/h Ambient Pres.: 101.8 kPa

Average Ambient Temp.: 4.0°C

Table C.2.1: Full Size Bin - Bin Envelope Pressure Drop

Vertical Level	Rep. #	Pressure Drop (kPa) Radial Location 1 (NW)	7 (SE)	8 (NE)	13 (SW)
L11	1	0.50	0.51	0.52	0.52
	2	0.50	0.51	0.52	0.51
	3	0.51	0.51	0.51	0.52
L21	1	0.52	0.52	0.51	0.52
	2	0.51	0.51	0.52	0.52
	3	0.52	0.51	0.51	0.52
L31	1	0.52	0.52	0.51	0.52
	2	0.51	0.51	0.52	0.52
	3	0.52	0.52	0.52	0.51
Inclined Coefficient = 0.20					

Air Blockage Plate: 40.6 cm Opening

Table C.2.2: Full Size Bin - Airflow Measurement

Rep. #	Airflow Measurement (in. H_2O) Pitot Tube Traverse Position 1	2	3	4
1	1.70 - 2.00	1.90 - 2.30	2.10 - 2.30	2.10 - 2.30
2	1.60 - 1.90	1.90 - 2.10	1.90 - 2.20	2.00 - 2.20
3	1.70 - 2.00	1.80 - 2.10	2.00 - 2.30	2.10 - 2.30
	5	6	7	8
1	2.00 - 2.10	2.00 - 2.20	1.90 - 2.20	1.80 - 2.00
2	2.00 - 2.20	2.00 - 2.30	1.90 - 2.20	1.60 - 1.90
3	2.10 - 2.30	2.10 - 2.30	2.00 - 2.20	1.80 - 2.00
Inclined Coefficient = 0.05				

Air Blockage Plate: 40.6 cm Opening

Date of test: March 30, 1994

Weather Conditions During Experiment

Average Wind Speed: 17.12 km/h Ambient Pres.: 101.8 kPa

Average Ambient Temp.: 4.0°C

Table C.3.1: Full Size Bin - Bin Envelope Pressure Drop

Vertical Level	Rep. #	Pressure Drop (kPa) Radial Location 1 (NW)	7 (SE)	8 (NE)	13 (SW)
L11	1	0.63	0.62	0.62	0.63
	2	0.64	0.63	0.63	0.63
	3	0.62	0.62	0.63	0.63
L21	1	0.63	0.63	0.62	0.63
	2	0.64	0.62	0.63	0.63
	3	0.63	0.62	0.63	0.63
L31	1	0.63	0.62	0.62	0.64
	2	0.65	0.63	0.64	0.63
	3	0.63	0.63	0.63	0.62
Inclined Coefficient = 0.20					

Air Blockage Plate: 50.8 cm Opening

Table C.3.2: Full Size Bin - Airflow Measurement

Rep. #	Airflow Measurement (in. H_2O) Pitot Tube Traverse Position 1	2	3	4
1	2.30 - 2.60	2.80 - 3.10	2.80 - 3.10	2.70 - 3.00
2	2.20 - 2.60	2.30 - 2.50	2.30 - 2.60	2.60 - 2.90
3	2.30 - 2.60	2.80 - 3.00	2.50 - 3.00	2.70 - 3.10
	5	6	7	8
1	2.60 - 2.90	2.70 - 3.00	2.70 - 3.00	2.50 - 2.80
2	2.60 - 2.90	2.80 - 3.10	2.50 - 2.80	2.50 - 2.70
3	2.70 - 3.00	2.70 - 3.10	2.60 - 2.80	2.40 - 2.70
Inclined Coefficient = 0.05				

Air Blockage Plate: 50.8 cm Opening

Date of test: April 6, 1994

Weather Conditions During Experiment

Average Wind Speed: 9 km/h Ambient Pres.: 102.10 kPa

Average Ambient Temp.: 0.0°C

Table C.4.1: Full Size Bin - Bin Envelope Pressure Drop

Vertical Level	Rep. #	Pressure Drop (kPa) Radial Location 1 (NW)	7 (SE)	8 (NE)	13 (SW)
L11	1	0.32	0.32	0.31	0.32
	2	0.31	0.33	0.30	0.31
	3	0.32	0.30	0.31	0.31
L21	1	0.33	0.32	0.31	0.32
	2	0.33	0.31	0.31	0.32
	3	0.30	0.32	0.32	0.31
L31	1	0.32	0.32	0.33	0.33
	2	0.32	0.31	0.32	0.30
	3	0.30	0.32	0.31	0.31
Inclined Coefficient = 0.20					

Air Blockage Plate: 30.5 cm Opening

Table C.4.2: Full Size Bin - Airflow Measurement

Rep. #	Airflow Measurement (in. H_2O) Pitot Tube Traverse Position 1	2	3	4
1	0.75 - 0.85	0.85 - 0.95	0.85 - 0.95	0.85 - 0.95
2	0.90 - 1.00	1.15 - 1.25	1.20 - 1.30	1.20 - 1.30
3	0.95 - 1.00	1.00 - 1.10	1.00 - 1.10	1.00 - 1.05
	5	6	7	8
1	0.90 - 1.00	0.90 - 1.00	0.90 - 1.00	0.75 - 0.85
2	1.20 - 1.30	1.30 - 1.40	1.20 - 1.30	1.00 - 1.10
3	1.00 - 1.05	1.00 - 1.10	0.95 - 1.00	0.80 - 0.90
Inclined Coefficient = 0.05				

Air Blockage Plate: 30.5 cm Opening

Date of test: April 6, 1994

Weather Conditions During Experiment

Average Wind Speed: 9 km/h Ambient Pres.: 102.10 kPa

Average Ambient Temp.: 0.0°C

Table C.5.1: Full Size Bin - Bin Envelope Pressure Drop

Vertical Level	Rep. #	Pressure Drop (kPa) Radial Location 1 (NW)	7 (SE)	8 (NE)	13 (SW)
L11	1	0.56	0.55	0.56	0.56
	2	0.55	0.54	0.55	0.56
	3	0.54	0.54	0.56	0.56
L21	1	0.56	0.57	0.56	0.56
	2	0.56	0.55	0.55	0.56
	3	0.57	0.56	0.56	0.56
L31	1	0.56	0.56	0.56	0.56
	2	0.56	0.56	0.55	0.56
	3	0.56	0.56	0.56	0.55
Inclined Coefficient = 0.20					

Air Blockage Plate: 40.6 cm Opening

Table C.5.2: Full Size Bin - Airflow Measurement

Rep. #	Airflow Measurement (in. H_2O) Pitot Tube Traverse Position 1	2	3	4
1	1.95 - 2.10	2.15 - 2.30	2.20 - 2.30	2.25 - 2.30
2	1.90 - 2.10	2.20 - 2.30	2.20 - 2.35	2.30 - 2.40
3	1.90 - 2.10	2.20 - 2.30	2.30 - 2.35	2.25 - 2.35
	5	6	7	8
1	2.25 - 2.35	2.20 - 2.30	2.10 - 2.20	1.70 - 1.85
2	2.25 - 2.35	2.20 - 2.30	2.00 - 2.20	1.80 - 1.90
3	2.20 - 2.30	2.20 - 2.30	2.10 - 2.20	1.80 - 2.00
Inclined Coefficient = 0.05				

Air Blockage Plate: 40.6 cm Opening

Date of test: April 6, 1994

Weather Conditions During Experiment

Average Wind Speed: 9 km/h   Ambient Pres.: 102.10 kPa

Average Ambient Temp.: 0.0°C

Table C.6.1: Full Size Bin - Bin Envelope Pressure Drop

		Pressure Drop (kPa)			
Vertical	Rep.	Radial Location			
Level	#	1 (NW)	7 (SE)	8 (NE)	13 (SW)
L11	1	0.66	0.66	0.66	0.66
	2	0.63	0.65	0.66	0.66
	3	0.65	0.65	0.66	0.67
L21	1	0.66	0.67	0.66	0.66
	2	0.63	0.65	0.66	0.66
	3	0.67	0.67	0.66	0.67
L31	1	0.66	0.66	0.65	0.66
	2	0.67	0.65	0.65	0.66
	3	0.67	0.66	0.66	0.66
Inclined Coefficient = 0.20					

Air Blockage Plate: 48.3 cm Opening

Table C.6.2: Full Size Bin - Airflow Measurement

	Airflow Measurement (in. H_2O)			
Rep.	Pitot Tube Traverse Position			
#	1	2	3	4
1	2.30 - 2.45	2.80 - 3.00	3.20 - 3.30	3.40 - 3.50
2	2.30 - 2.40	2.80 - 2.90	3.25 - 3.35	3.50 - 3.60
3	2.30 - 2.40	2.80 - 2.90	3.00 - 3.20	3.40 - 3.50
	5	6	7	8
1	3.40 - 3.50	3.00 - 3.20	2.70 - 2.80	2.10 - 2.30
2	3.40 - 3.60	3.10 - 3.20	2.80 - 2.90	2.20 - 2.40
3	3.30 - 3.50	3.00 - 3.20	2.60 - 2.80	2.30 - 2.40
Inclined Coefficient = 0.05				

Air Blockage Plate: 48.3 cm Opening

Appendix D

Mathematical Model Computer Programs

The following appendix contains computer programs of the LBL and BA models as well as sample input and output files.

```
      PROGRAM lblinfil
C
C
C
C  The equations for this program were incorporated from the work of
C                    Max H. Sherman and David T. Grimsrud,
C                        Lawerence Berkeley Laboratory
C                                    1980
C
C
C
C
C *****************************************************************************
C         THIS PROGRAM DETERMINES THE INFILTRATION OF A GAS THROUGH A
C         STRUCTURE.  THE DRIVING FORCES OF THE INFILTRATION ARE WIND
C         AND TEMPERATURE DIFFERENCES BETWEEN THE INTERNAL ENVIRONMENT
C                TEMPERATURE AND THE AMBIENT TEMPERATURE.
C *****************************************************************************
C
C
C
C---VARIABLE DICTIONARY
C
C   C      - GENERALIZED SHIELDING COEFFICIENT
C   H      - HEIGHT OF GRAIN BIN [m]
C   HP     - HEIGHT OF WIND MEASUREMENT TOWER
C   ATEMPC - AMBIENT TEMPERATURE [Celcius]
C   ATEMPK - AMBIENT TEMPERATURE [Kelvin]
C   GTEMPC - INTERNAL GRAIN TEMPERATURE [Celcius]
C   GTEMPK - INTERNAL GRAIN TEMPERATURE [Kelvin]
C   DELTAT - TEMPERATURE DIFFERENCE
C   R      - FRACTION OF LEAKAGE AREA IN THE FLOOR AND ROOF
C   X      - EFFECTIVE LEAKAGE DISTRIBUTION PARAMETER
C   GAMMA  - TERRAIN CLASS COEFFICIENT FOR STORAGE BIN SITE
C   ALPHA  - TERRAIN CLASS COEFFICIENT FOR STORAGE BIN SITE
C   GAMMAP - TERRAIN CLASS COEFFICIENT FOR STORAGE AT WIND MEASURING STATION
C   ALPHAP - TERRAIN CLASS COEFFICIENT FOR STORAGE AT WIND MEASURING STATION
C   DIA    - DIAMETER OF THE STORAGE BIN [m]
C   TELA   - TOTAL EFFECTIVE LEAKAGE AREA OF STORAGE BIN [m2]
C   TFLA   - TOTAL LEAKAGE AREA IN THE FLOOR OF THE STORAGE BIN [m2]
C   TRLA   - TOTAL LEAKAGE AREA IN THE ROOF OF THE STORAGE BIN [m2]
C   VELK   - WIND VELOCITY MEASURED AT THE MEASURING TOWER [km/h]
C   VELM   - WIND VELOCITY MEASURED AT THE MEASURING TOWER [m/s]
C   FS     - STACK PARAMETER
C   FW     - WIND PARAMETER
C   QS     - EXFILTRATION RATE DUE TO STACK EFFECT [m3/s]
C   QW     - EXFILTRATION RATE DUE TO STACK EFFECT [m3/s]
C   QTOT   - TOTAL EXFILTRATION RATE [m3/s]
C
C
C---VARIABLE DECLARATIONS
C
      IMPLICIT REAL*8(A-H,O-Z)
      CHARACTER OUTPFN*12
C
C
      OPEN(UNIT=6,FILE='input.dat')
      READ(6,100) OUTPFN
      READ(6,101) DIA,H,TELA
      READ(6,102) ATEMPC,GTEMPC
      READ(6,103) VELK
      READ(6,104) C,ALPHA,GAMMA
      READ(6,105) ALPHAP,GAMMAP,HP
C
100   FORMAT(A12)
101   FORMAT(E11.8/E11.8/E11.8)
```

```
102   FORMAT(E11.8/E11.8)
103   FORMAT(E11.8)
104   FORMAT(E11.8/E11.8/E11.8)
105   FORMAT(E11.8/E11.8/E11.8)
      CLOSE(UNIT=6)

C
C---CONVERTION CALCULATIONS
C
      ATEMPK=ATEMPC+273.15
      GTEMPK=GTEMPC+273.15
      DELTAT=ABS(GTEMPK-ATEMPK)
      VELM=VELK*1000.0/3600.0

      g=9.81
      trla=0.0
      tfla=0.0

C
C---CALCULATE LEAKAGE AREA FRACTIONS
C
      X=TRLA-TFLA/TELA
      R=TRLA+TFLA/TELA

C
C---CALCULATE STACK AND WIND PARAMETERS
C

      FS=(1.0/3.0)*(1.0+(R/2.0))*((1.0-(X**2/(2.0-R)**2))**(3.0/2.0))*
     &      SQRT(G*H/GTEMPK)
C
      FW=C*((1.0-R)**(1.0/3.0))*((ALPHA*((H/10.0)**GAMMA))/
     &       (ALPHAP*((HP/10.0)**GAMMAP)))


C       WRITE(*,*) R,C,H,ALPHA,GAMMA,HP,ALPHAP,GAMMAP,FW,velm
C
C---CALCULATE THE EXFILTRATION RATES
C


      QS=TELA*FS*SQRT(DELTAT)
      QW=TELA*FW*VELM
      QTOT=SQRT((QS**2.0)+(QW**2.0))

C
C---PRINT THE RESULTS TO AN OUTPUT FILE
C
      OPEN(UNIT=7,FILE=OUTPFN)
      WRITE(7,*)
      WRITE(7,190) '====== WEATHER DATA ======'
      WRITE(7,205) VELK,GTEMPC,ATEMPC
      WRITE(7,200)
      WRITE(7,*)
      WRITE(7,191) '====== PHYSICAL PARAMETERS ======'
      WRITE(7,210) H,DIA,TELA
      WRITE(7,200)
      WRITE(7,*)
      WRITE(7,192) '====== INPUT COEFFICIENTS ======'
      WRITE(7,215) C,ALPHA,GAMMA,ALPHAP,GAMMAP
      WRITE(7,200)
      WRITE(7,*)
      WRITE(7,193) '====== OUTPUT DATA ======'
      WRITE(7,220) FW,FS,QW,QS,QTOT
      WRITE(7,200)
      WRITE(7,*)
```

```
      WRITE(7,198) '* Values From Table 3.1 of Thesis'
      WRITE(7,198) '** Values From Table 3.2 of Thesis'
      WRITE(7,*)
C      WRITE(7,198) 'D.T. Grimsrud, et al. 1982. A Predictive Air-'
C      WRITE(7,198) 'Infiltration Model - Long Term Field Test'
C      WRITE(7,198) 'Validation, ASHRAE Trans. Ho-82-16 No.1. 1351-1371'
C
190   FORMAT(26X,A,/)
191   FORMAT(22X,A,/)
192   FORMAT(22X,A,/)
193   FORMAT(26X,A,/)
198   FORMAT(2X,A)
200   FORMAT(1X,76('*'))
205   FORMAT(1X,T2,'Wind Velocity          = ',E9.3,2X,'[km/hr]',/
     K          ,T2,'Inside Temperature     = ',E9.3,2X,'[Celcius]',/
     K          ,T2,'Outside Temperature    = ',E9.3,2x,'[Celcius]')
210   FORMAT(1X,T2,'Height Of Bin          = ',E9.3,2X,'[m]',/
     K          ,T2,'Diameter Of Bin        = ',E9.3,2X,'[m]',/
     K          ,T2,'Effective Leakage Area = ',E9.3,2x,'[m^2]')
215   FORMAT(1X,T2,'Shielding Coefficient** = ',E9.3,/
     K          ,T2,'Alpha Terrain Coefficient at Bin Site* = ',E9.3,/
     K          ,T2,'Gamma Terrain Coefficient at Bin Site* = ',E9.3,/
     K          ,T2,'Alpha Terrain Coefficient at Wind Measurement Site*
     K = ',E9.3,/
     K          ,T2,'Gamma Terrain Coefficient at Wind Measurement Site*
     K = ',E9.3)
220   FORMAT(1X,T2,'Reduced Wind Parameter, fw*           = ',E11.5,/
     K          ,T2,'Reduced Stack Parameter, fs*          = ',E11.5,/
     K          ,T2,'Volume Flow Rate Due to Wind Effect  = ',E11.5,2X,
     K                      '[m^3/s]',/
     K          ,T2,'Volume Flow Rate Due to Temp. Effect = ',
     K                        E11.5,2X,'[m^3/s]',/
     K          ,T2,'Total Volumetric Flow Rate           = ',E11.5,2X,
     K                      '[m^3/s]')

      CLOSE(UNIT=7)
C
C
      STOP
      END
```

```
LBLFS05.out       ! output file name
+5.560e+00        ! bin diameter [m]
+2.500e+00        ! bin height [m]
+7.690e-04        ! total effective leakage area [m2]
+1.000e+00        ! ambient temperature [Celcius]
+1.000e+00        ! grain temperature [Celcius]
+0.500e+01        ! wind velocity [kph]
+0.185e+00        ! shielding coefficient
+0.850e+00        ! terrain coefficient (alpha) at bin site
+0.200e+00        ! terrain coefficient (gamma) at bin site
+1.000e+00        ! terrain coefficient (alpha) at wind measurement location
+0.150e+00        ! terrain coefficient (gamma) at wind measurement location
+10.00e+00        ! wind measurement height [m]
```

```
                  ====== WEATHER DATA ======

Wind Velocity              = 0.150E+02  [km/hr]
Inside Temperature         = 0.100E+01  [Celcius]
Outside Temperature        = 0.100E+01  [Celcius]
****************************************************************************

              ====== PHYSICAL PARAMETERS ======

Height Of Bin              = 0.250E+01  [m]
Diameter Of Bin            = 0.556E+01  [m]
Effective Leakage Area = 0.769E-03  [m^2]
****************************************************************************

              ====== INPUT COEFFICIENTS ======

Shielding Coefficient** = 0.185E+00
Alpha Terrain Coefficient at Bin Site* = 0.850E+00
Gamma Terrain Coefficient at Bin Site* = 0.200E+00
Alpha Terrain Coefficient at Wind Measurement Site*  = 0.100E+01
Gamma Terrain Coefficient at Wind Measurement Site*  = 0.150E+00
****************************************************************************

                  ====== OUTPUT DATA ======

Reduced Wind Parameter, fw*            = 0.11917E+00
Reduced Stack Parameter, fs*           = 0.99699E-01
Volume Flow Rate Due to Wind Effect  = 0.38185E-03  [m^3/s]
Volume Flow Rate Due to Temp. Effect = 0.00000E+00  [m^3/s]
Total Volumetric Flow Rate             = 0.38185E-03  [m^3/s]
****************************************************************************

 * Values From Table 3.1 of Thesis
 ** Values From Table 3.2 of Thesis
```

```fortran
      PROGRAM banks
C
C
C
C  The equations for this program were incorporated from the work of
C                          H.J. Banks and P.C. Annis,
C            CSIRO, Division of Entomology, Canberra Australia
C                                       1984
C
C
C
C
C ****************************************************************************
C           THIS PROGRAM DETERMINES THE INFILTRATION OF A GAS THROUGH A
C           GRAIN BIN.  THE DRIVING FORCES OF THE INFILTRATION ARE WIND
C           AND TEMPERATURE DIFFERENCES BETWEEN THE INTERNAL ENVIRONMENT
C                  TEMPERATURE AND THE AMBIENT TEMPERATURE.
C ****************************************************************************
C
C
C
C---VARIABLE DICTIONARY
C
C   APLA    - ACTUAL PHYSICAL LEAKAGE AREA
C   ALPHA   - ORIFICE COEFFICIENT
C   AMPLC   - AMPLITUDE OF GRAIN TEMPERATURE VARIATION [Celcius]
C   AMPLK   - AMPLITUDE OF GRAIN TEMPERATURE VARIATION [Kelvin]
C   BDIA    - DIAMETER OF GRAIN BIN [m**2]
C   BHGT    - HEIGHT OF GRAIN BIN [m]
C   CINIT   - INITIAL CONCENTRATION OF THE CA GASES IN THE GRAIN BIN [%vol]
C   CFINL   - FINAL CONCENTRATION OF THE CA GASES IN THE GRAIN BIN [%vol]
C   CEXTR   - AMBIENT CONCENTRATION OF THE CA GASES [%vol]
C   DIFFK   - THERMAL DIFFUSIVITY OF THE CA GASES [watts/(m*Kelvin)]
C   DELC    - DIFFERENCE IN PRESSURE COEFFICIENTS
C   FLOWB   - FLOW COEFFICIENT
C   FLOWN   - FLOW EXPONENT
C   GRAV    - ACCELERATION DUE TO GRAVITY [m/s**2]
C   OMEGA   - FREQUENCY OF OSILLATION [Hz]
C   POROS   - POROSITY COEFFICIENT OF THE GRAIN
C   QFLOW   - FLOW RATE OF INFILTRATION [m**3/s]
C   RHO     - DENSITY OF THE CA GASES [kg/m**3]
C   TELA    - TOTAL EFFECTIVE LEAKAGE AREA [m**2]
C   TIMEH   - TIME DURATION OF TREATMENT [hours]
C   TIMES   - TIME DURATION OF TREATMENT [seconds]
C   TAVGC   - AVERAGE GRAIN TEMPERATURE [Celcius]
C   TAVGK   - AVERAGE GRAIN TEMPERATURE [Kelvin]
C   VELK    - WIND VELOCITY MEASURED AT THE WEATHER TOWER [kph]
C   VELM    - WIND VELOCITY MEASURED AT THE WEATHER TOWER [m/s]
C   VOL     - VOLUME OF STORAGE BIN [m**3]
C   VOLHS   - HEAD SPACE VOLUME OF THE STORAGE BIN [m**3]
C   VRWIND  - VENTILATION RATE DUE TO WIND EFFECTS [seconds**-1]
C   VRBTMP  - VENTILATION RATE DUE TO BULK TEMPERATURE EFFECTS [seconds**-1]
C   VRHSTP  - VENTILATION RATE DUE TO HEAD SPACE TEMPERATURE EFFECTS [sec**-1]
C
C ****************************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      CHARACTER OUTPFN*12
C
C
      OPEN(UNIT=6,FILE='input.dat')
      READ(6,100) OUTPFN
      READ(6,101) BDIA,BHGT,TELA,VOLHS
      READ(6,102) TAVGC,TMINC,DELTC,OMEGA,VELK,TIMEH
      READ(6,103) POROS,DIFFK,RHO
      READ(6,104) DELC,FLOWN,ALPHA
```

```
C
100   FORMAT(A12)
101   FORMAT(E11.8/E11.8/E11.8/E11.8)
102   FORMAT(E11.8/E11.8/E11.8/E11.8/E11.8/E11.8)
103   FORMAT(E11.8/E11.8/E11.8)
104   FORMAT(E11.8/E11.8/E11.8)
      CLOSE(UNIT=6)

C
C---CONVERTION CALCULATIONS
C
      GRAV=9.81
      PI=3.14159637
      VOL=(PI/4.0)*(BDIA**2)*BHGT+0.20+VOLHS

      DELTK=DELTC+273.15
      TMINK=TMINC+273.15
      TAVGK=TAVGC+273.15
      VELM=VELK*1000.0/3600.0
      TIMES=TIMEH*3600.0

C
C
C
C ************************** INFILTRATION DUE TO WIND *************************
C
      FLOWB=TELA*SQRT(2.0/RHO)
C
      QFLWND=(FLOWB/(2.0**(FLOWN+1.0)))*
     K           (((DELC*RHO/2.0)*(VELM**2.0))**FLOWN)
C
      VRWND=QFLWND/VOL
      VRTRB=VRWND*0.2
C
C
C *********************** INFILTRATION DUE TO TEMPERATURE *********************
C
c      IF (DELTK.GE.0.0 .AND. TMINK.NE.0.0 ) THEN
c          VRHSTP=(VOLHS*DELTK)/(VOL*TMINK*TIMES)
c      ENDIF
C
C
c      IF (OMEGA.NE.0.0) THEN
c          VRBKTP=(2.0*AMPLK*POROS*TELA)/(TAVGK*VOL*TIMES)*
c     K                    SQRT(DIFFK/OMEGA)
c      ENDIF
C
C
C ************ INFILTRATION DUE TO BAROMETRIC PRESSURE VARIATIONS ************
C
c      VRBPF=DPRES/(PRESMX*TIME)
C
C
C ****************************************************************************
C
C
C----PRINT THE RESULTS TO AN OUTPUT FILE
C
      OPEN(UNIT=7,FILE=OUTPFN)
      WRITE(7,*)
      WRITE(7,190) '====== ENVIRONMENTAL DATA ======'
      WRITE(7,205) VELK,DELTC,OMEGA,TIMEH
      WRITE(7,200)
      WRITE(7,*)
      WRITE(7,191) '====== PHYSICAL PARAMETERS ======'
      WRITE(7,210) BHGT,BDIA,VOL,VOLHS,DELC,TELA
```

```
      WRITE(7,200)
      WRITE(7,*)
      WRITE(7,192) '====== INPUT COEFFICIENTS AND CONSTANTS ======'
      WRITE(7,215) POROS,DIFFK,ALPHA,FLOWB,FLOWN
      WRITE(7,200)
      WRITE(7,*)
      WRITE(7,193) '====== OUTPUT DATA ======'
      WRITE(7,220) QFLWND,VRWND,VRTRB,VRHSTP,VRBKTP
      WRITE(7,200)
      WRITE(7,*)
190   FORMAT(23X,A,/)
191   FORMAT(22X,A,/)
192   FORMAT(15X,A,/)
193   FORMAT(26X,A,/)
198   FORMAT(2X,A)
200   FORMAT(1X,76('*'))
C
205   FORMAT(1X,T2,'Wind Velocity                      = ',E9.3,2X,
     K '[km/hr]',/
     K          ,T2,'Amplitude of  Fluctuation         = ',E9.3,2X,
     K '[Celcius]',/
     K          ,T2,'Frequency of Temp. Oscillation    = ',E9.3,2x,
     K '[Hz]',/
     K          ,T2,'Time Duration of Treatment        = ',E9.3,2x,
     K '[seconds]')
C
210   FORMAT(1X,T2,'Height Of Bin                      = ',E9.3,2X,
     K '[m]',/
     K          ,T2,'Diameter Of Bin                   = ',E9.3,2X,
     K '[m]',/
     K          ,T2,'Volume of Bin                     = ',E9.3,2x,
     K '[m^3]',/
     K          ,T2,'Volume of Headspace               = ',E9.3,2x,
     K '[m^3]',/
     K          ,T2,'Pressure Coefficient              = ',E9.3,2x,
     K '',/
     K          ,T2,'Total Effective Leakage Area      = ',E9.3,2x,
     K '[m^2]')
C
215   FORMAT(1X,T2,'Porosity of the Grain              = ',E9.3,/
     K          ,T2,'Thermal Diffusivity               = ',E9.3,2x,
     K '[m2/s]',/
     K          ,T2,'Orifice Coefficient               = ',E9.3,2X,/
     K          ,T2,'Flow Coefficient  (b)             = ',E9.3,2X,/
     K          ,T2,'Flow Coefficient  (n)             = ',E9.3)

220   FORMAT(1X,T2,'Volume Flow Rate Due to Wind
     K = ',E11.5,2X,'[m^3/sec]',/
     K          ,T2,'Ventilation Rate Due to Wind
     K = ',E11.5,2X,'[sec^-1]',/
     K          ,T2,'Ventilation Rate Due to Turbulence
     K = ',E11.5,2X,'[sec^-1]',/
     K          ,T2,'Ventilation Rate Due to Headspace Temp. Fluctuations
     K = ',E11.5,2X,'[sec^-1]',/
     K          ,T2,'Ventilation Rate Due to Bulk Temp. Fluctuations
     K = ',E11.5,2X,'[sec^-1]')
C
      CLOSE(UNIT=7)
C
C
      STOP
      END
```

```
dc35.out           ! output filename
+1.420e+00           ! bin diameter [m]
+1.470e+00           ! bin height [m]
+4.600e-04           ! leakage area [m2]
+0.000E+00           ! headspace volume [m2]
+1.500e+01           ! average temperature [Celcius]
+1.500E+01           ! minimum temperature [Celcius]
+0.000e+00           ! amplitude of temperature oscillation
+0.000e+00           ! frequency of oscillation [Hz]
+3.500e+01           ! wind speed [kph]
+1.260e+04           ! time duration [seconds]
+0.400e-00           ! grain porosity
+1.380e-06           ! thermal diffusivity [m2/s] [W/mK]
+1.977e-00           ! density [kg/m3]
+1.020e-04           ! pressure coefficient (delc)
+0.500e-00           ! flow exponent
+6.100e-01           ! orifice coefficient
```

====== ENVIRONMENTAL DATA ======

Wind Velocity	=	0.150E+02	[km/hr]
Amplitude of Fluctuation	=	0.000E+00	[Celcius]
Frequency of Temp. Oscillation	=	0.000E+00	[Hz]
Time Duration of Treatment	=	0.126E+05	[seconds]

****

====== PHYSICAL PARAMETERS ======

Height Of Bin	=	0.147E+01	[m]
Diameter Of Bin	=	0.142E+01	[m]
Volume of Bin	=	0.253E+01	[m^3]
Volume of Headspace	=	0.000E+00	[m^3]
Pressure Coefficient	=	0.200E+01	
Total Effective Leakage Area	=	0.460E-03	[m^2]

****

====== INPUT COEFFICIENTS AND CONSTANTS ======

Porosity of the Grain	=	0.400E+00	
Thermal Diffusivity	=	0.138E-05	[m2/s]
Orifice Coefficient	=	0.610E+00	
Flow Coefficient (b)	=	0.463E-03	
Flow Coefficient (n)	=	0.500E+00	

****

====== OUTPUT DATA ======

Volume Flow Rate Due to Wind	=	0.95833E-03	[m^3/sec]
Ventilation Rate Due to Wind	=	0.37909E-03	[sec^-1]
Ventilation Rate Due to Turbulence	=	0.75817E-04	[sec^-1]
Ventilation Rate Due to Headspace Temp. Fluctuations	=	0.00000E+00	[sec^-1]
Ventilation Rate Due to Bulk Temp. Fluctuations	=	0.00000E+00	[sec^-1]

****