MOVEMENT OF CO_2 GAS, INTRODUCED AS SOLID FORMULATION, THROUGH STORED WHEAT BULKS

BY

KARUPPIAH ALAGUSUNDARAM

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

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DEDICATED TO

SRI SATHYA SAI BABA

ABSTRACT

Experiments were conducted in three pilot (1.42-m-diameter) and three farm (5.56-m-diameter) bins to determine the distribution and maintenance of introduced CO_2 gas in bulk wheat. Dry ice was used as a source of CO_2 gas. The pilot-bins were filled with wheat to a height of 1.37 m and the farm bins were either empty or filled with wheat (2.50 m or 2.10 m height) in the experiments. The effects of the floor opening (circular near the centre, rectangular, and circular near the wall), the grain surfaces left open or covered with polyvinylidene chloride (PVC) sheet, and the amount of introduced dry ice on the distribution of CO_2 gas were studied in the pilot bins. The effects of the point of application of dry ice, the amount and frequency of application of dry ice, the grain surface left open or covered with PVC sheet, and sealing various portions of the bin on the distribution and retention of CO_2 gas were studied in the farm bins. In addition to the CO_2 distribution tests the effect of elevated CO_2 concentrations on the mortality of adults in cages of the rusty grain beetle, Cryptolestes ferrugineus (Stephens), was determined in the farm bins.

In the farm bins irrespective of the point of the application of dry ice (on the grain surface, in the aeration duct or in the plenum, or near the central axis of the grain bulk), the observed CO_2 concentrations were higher in the bottom portions of the bulk than in the top portions. For example, at 48 h after introducing dry ice on the grain surface the average CO_2 concentration at the top level was 11.9% compared to 31.6% at the bottom level. Introducing the dry ice on the grain surface gave higher CO_2 concentrations near the top portions of the grain bulk than introducing the dry ice in the plenum or in the aeration duct. For example, at 48 h after the introduction of dry ice the average CO_2 concentrations at the top level was 4.0% when dry ice was introduced in the aeration duct compared to 11.9% when dry ice was introduced on the grain surface.

The efficiency of CO_2 retention ($\eta_{retention}$) was higher in the pilot than in the farm bins. The observed maximum $\eta_{retention}$ in the pilot bin experiments was 54.6% compared to the maximum observed

$\eta_{retention}$ of 27.4% in the farm bin experiments. The $\eta_{retention}$ was higher (on an average by 6%) when the grain surfaces were covered with a PVC sheet than the open grain surfaces. The maximum observed $\eta_{retention}$ was only 54.6% in the pilot-bin experiments because of the sorption of CO_2 gas by wheat. A remarkable decrease in the $\eta_{retention}$ was observed in the farm bins compared with the pilot bins. The uncontrollable loss of CO_2 gas through various leaks in the bin wall and the bin wall to the floor joints might have reduced the $\eta_{retention}$ in the farm bins. In a wheat filled farm bin, the maximum $\eta_{retention}$ was achieved when the dry ice was introduced on the grain surface (26.3%) or near the central axis of the bulk (27.4%), and the grain surface was covered with a PVC sheet. The $\eta_{retention}$ in the empty bin with concrete floor was much higher than that in wheat-filled bins with provision for aeration. Sorption of CO_2 by wheat and unsealable leaks at the joints between the aeration duct or the fully perforated floor reduced the $\eta_{retention}$ in these bins.

An attempt was made to model the movement of CO_2 gas through wheat bulks by solving a three-dimensional diffusion equation in the Cartesian coordinate system using the finite element method. The simulation results were compared with the measured CO_2 data in the pilot bins. The predicted CO_2 concentrations were much lower than the measured data. The under predictions were observed because of the mass displacement of CO_2 through wheat when dry ice sublimated into CO_2 gas. To include the mass displacement of CO_2 in the model, an apparent flow coefficient of CO_2 (D_{app}) was determined by physically simulating the pilot-bin experiments in a laboratory apparatus. The CO_2 concentrations predicted using D_{app} values were closer to the measured data than when pure diffusion was assumed. The importance of including the sorption of CO_2 by wheat in the model was also demonstrated.

Based on the results, it is suggested that a bin with no aeration duct or perforated floor should be used for controlled atmosphere (CA) treatment in non-airtight bins, and the grain surface should be covered with a PVC sheet to reduce the loss of CO_2 through the grain surface. To improve the model predictions a model of forced convective mass transport should be used during the dry ice sublimation period and the diffusion model should be used afterwards.

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a, b	empirical constants (eq.6.6)
A	cross sectional area of the grain chamber (m^2)
[B]	matrix of derivatives of interpolating functions
c	CO_2 concentration ($g\ m^{-3}$)
c_i	initial nodal CO_2 concentration ($g\ m^{-3}$)
C_{th}	CO_2 concentration created by one domain volume of CO_2 gas (%)
C_n	average predicted CO_2 concentration of an element at the present time step ($g\ m^{-3}$)
C_{n-1}	average predicted CO_2 concentration of an element at the previous time step ($g\ m^{-3}$)
{C}	vector of CO_2 concentrations
$(CO2)_i$	measured CO_2 concentration at sampling point i (%)
c_{s1}	specified CO_2 concentration on the boundary S1 ($g\ m_{-3}$)
C_w^{ts}	weighted-volume-average CO_2 concentration for the sampling time ts (%)
C_w^{ts+1}	weighted-volume-average CO_2 concentration for the sampling time ts+1 (%)
D_{app}	apparent flow coefficient of CO_2 through wheat bulk ($m^2\ s^{-1}$)
[D]	material property matrix
Dx	diffusion coefficient of CO_2 through wheat bulk in x-coordinate direction($m^2\ s^{-1}$)
Dy	diffusion coefficient of CO_2 through wheat bulk in y-coordinate direction($m^2\ s^{-1}$)
Dz	diffusion coefficient of CO_2 through wheat bulk in z-coordinate direction($m^2\ s^{-1}$)
e	mean relative percent error of prediction (%)
{f}	element load vector
[F]	global load vector
[K1]	global capacitance matrix
[K2]	global stiffness matrix

L	length of the grain chamber (m)
Mi	measured CO_2 concentration at node i ($g\ m^{-3}$)
[N]	matrix of interpolating functions
NDV CO_2	number of domain volumes of CO_2
P	pressure created by dry ice sublimation in the gas chamber (Pa)
Pi	predicted CO_2 concentration at node i ($g\ m^{-3}$)
q	amount of CO_2 sorbed by wheat ($g\ m^{-3}\ s^{-1}$)
Q	total surface flux across the boundary ($g\ m^{-2}\ s^{-1}$)
Q_m	mass flow rate of CO_2 ($g\ s^{-1}$)
R	gas constant for CO_2; 0.1889 $kJ\ kg^{-1}\ K^{-1}$
S1	surface on which CO_2 concentration is specified
S2	surface on which loss of CO_2 gas is specified
S_{CO2}	rate of sorption of CO_2 by wheat ($g\ kg^{-1}\ d^{-1}$)
V_d	total volume of the grain bulk (m^3)
V_i	volume of a divided region representing one or more sampling points (m^3)

Greek Symbols

Ω	domain consisting of stored-grain bulk
Φ	porosity of wheat (decimal)
τ	time (s)
ρ_{CO2}	density of CO_2 ($g\ m^{-3}$)
ρ_w	density of wheat ($g\ m^{-3}$)

Superscripts

T	transpose of a matrix
(e)	the matrix or the vector is for an element

1. INTRODUCTION

Canada's average annual production of grains and oilseeds from 1982 to 1991 was 52.5 Mt (million tonnes) worth 6.6 billion dollars (Anonymous 1992). Most of the grain harvested in Canada goes into farm storage before being moved for sale or use. The total amount of grains and oilseeds carried over in storage in Canada from one crop year to the next averaged 14.0 Mt annually over a 10 year period from 1982 to 1991 (Anonymous 1992). Most farms must have on-farm storage capacity of about 1.5 to 2.0 times their average annual production because of large carryovers or large harvests (Muir 1980). Common on-farm storage facilities in Canada are corrugated galvanized steel bins of 33- to 545-t capacity (White et al. 1990). The quality of the grains and oilseeds stored in these granaries must be maintained during the period of storage, which sometimes may exceed two or more years (Muir 1980).

Losses to stored product may be of quantity or quality and may occur separately or together (Hall 1970). The quantity loss results from weight loss due to the evaporation of moisture from the food grain, metabolization of food components such as carbohydrates into water and carbon dioxide by microflora and grain enzymes and direct consumption of grain by insects and rodents. The quality loss can result in lower grade for grain due to sprouting, discoloration moulding and rotting, decrease in germinative power and nutritive value or the presence of contaminants such as body parts of insects or rodents.

Several biological (insects, mites and microorganisms) and non-biological (grain temperature and moisture content and gaseous composition of intergranular air) factors interact to cause damage to the stored grain (Oxley 1948, Muir 1980). The growth and development of the biological organisms are optimum at certain temperature, moisture content and intergranular gas composition ranges. For example, at near ambient gas compositions of intergranular air, the development of the insects and mites that attack the stored grain occur at well defined temperature ranges of about 15 to 38°C and 5 to 40°C, respectively and have narrow optimum ranges near 30°C (Sinha and Watters 1985), and the development of most storage fungi occur in high moisture grains (>17% moisture content for wheat, Loschiavo 1984).

Stored grain can be protected from insects and mites by lethal chemicals such as contact insecticides, acaricides, and fumigants (Freeman 1973). These chemicals leave objectionable residues on the grain and are hazardous to handle and apply. Also many stored-product pests are developing resistance to chemicals (White and Loschiavo 1985). Champ (1986) lists 31 species of insects and mites that have developed resistance to various chemicals, worldwide. Due to perceived carcinogenicity to mammals, ethylene dibromide was banned by the Canadian regulatory agencies in 1984 for use in the milling industry, followed by a continued regulatory review of many other chemical fumigants. Currently, methyl bromide and phosphine are the only fumigants used on or near stored products in Canada (White and Jayas 1992). Therefore alternative ways of protecting stored grain against pests should be explored.

Controlled atmosphere (CA) storage is a potential alternative method of insect control (Banks and Annis 1977). CA storage, in principle, is an artificially created intergranular gas composition. Hermetic storage relies on the respiratory activities of grain, insects, mites, and molds to alter the intergranular gas composition in air-tight storage facilities, while in CA storage the gaseous composition of the intergranular air is altered by injecting either CO_2 to create high CO_2 atmospheres, or N_2 to create low O_2 atmospheres lethal to insect pests (Banks and Annis 1977). Effectiveness of controlled atmospheres for controlling various stored-product pests depends on several factors: temperature and moisture content of the grain, gaseous composition used, species and life stages of pests, and the exposure time.

For successful control of pests using controlled atmospheres, gases should be introduced at optimum grain temperature and moisture content and uniformly distributed in the grain bulk to maintain adequate gas levels for the required exposure time in all locations of the bin. Uniform distribution of the introduced gases is dependant on the rate of movement of these gases through the grain bulk which, in turn, depends on the rate of diffusion (Singh et al. 1983, Jayas et al. 1988) and on natural convection currents in the bulk (Bond et al. 1977, Navarro et al. 1986). The maintenance of the required gas levels with minimal use of the introduced gas depends on the loss of the intergranular gas to the ambient air through the leaks in the structure (Banks and Annis 1980). In Australia, a decay time for applied excessive pressure of 5 min for a pressure drop of 2500 to 1500 Pa, 1500 to 750 Pa, or 500 to 250 Pa is regarded as a satisfactory measure of sealing of a structure (Banks and Annis 1980). In the structure that meets these gas tightness specification, 'one-shot' treatment of CO_2 was found to give effective insect control (Banks et al. 1980).

The first large scale application of controlled atmospheres for disinfesting stored grain was done in Australia during 1917-1919 (Winterbottom 1922; cited by Banks et al. 1980). Since then numerous research studies, both in the laboratory and in large grain bulks, have been undertaken to determine the effectiveness of controlled atmospheres for controlling stored-product insects (Annis 1987). Most field tests on the CA storage of grain bulks have been conducted in airtight bins. The on-farm storage bins in Canada are not airtight and the lack of airtightness is a problem when high concentrations of gas must be maintained (White et al. 1990). Sealing these farm bins to make them airtight will interfere with the natural ventilation that helps in reducing temperature gradients and the moisture migration that may occur in large grain bulks (Mcgaughey and Akins 1989). Furthermore, it is not practically feasible to convert the existing bins into completely leak free enclosures (Banks and Annis 1980). Thus, while CA treatment would be most effective in airtight bins, it would be more useful if it could be effectively applied in bins that are not well sealed. An understanding of the distribution and loss of CA gases in non-airtight bins should assist in efficient design and successful application of the CA storage for control of pests in grain stored in such bins.

The movement of gases in a stored grain mass can be studied using two methods: (i) by collecting empirical data in grain bins of various shapes and sizes, and filled with different grains; and (ii) by developing mathematical models, based on physical principles, for predicting the distribution of gases in the grain bulk. The former method requires a lot of time, is costly, and is labour intensive. Although, in the absence of any other empirical data for validating the models, it is essential to collect the empirical data for validating the mathematical model and for understanding the distribution of gases in the grain bulks. To my knowledge, there has been no extensive experimental study on the movement of CO_2 through wheat stored in bolted metal bins, and except for an axisymmetric model for predicting the CO_2 diffusion in stored wheat (Singh et al. 1983, Jayas et al. 1988), no other study was conducted to mathematically describe the movement of gases in stored-grain bulks. This work was undertaken to study the movement of CO_2 gas through stored wheat in pilot and non-airtight farm bins and to develop a finite element model for predicting the three dimensional distribution of CO_2 in a stored-wheat bulk.

2. OBJECTIVES

The specific objectives of this study were:

1. To determine the distribution of CO_2 gas through bulk wheat contained in pilot scale bins of 1.42-m-diameter with different partially perforated floors,
2. To determine the distribution of CO_2 gas through bulk wheat contained in bolted metal bins of 5.56-m-diameter,
3. To develop a three-dimensional finite element solution of a mathematical model of CO_2 diffusion for predicting the movement of CO_2 within the stored grain bulk.
4. To compare the predictions of the model against the measured CO_2 data from the pilot bins.

3. LITERATURE REVIEW

3.1 Factors Affecting the Efficacy of CA Storage

The objective of CA treatment of grains is to kill all insects and mites with minimal use of gases. The efficacy of CA storage depends on the temperature and moisture content of the grain, gas composition of the intergranular atmosphere, exposure time, pest species, and life stages, initial pest population, and distribution of insects in a grain bulk. Numerous laboratory studies have been conducted to determine the effect of various combinations of CA gases on the mortality (the number of insects killed after exposing to a controlled atmosphere and allowing them to potentially recover at optimum conditions) of stored product insects. Results of published studies related to the effect of the abiotic factors on the mortality of insects in a CA storage are reviewed.

Furthermore, the success of CA treatment in controlling insects depends on the uniformity of distribution of the introduced gases and the retention of the gases in the grain bin until all the insects are killed. The adsorption of CO_2 gas by the grain and the production of CO_2 gas by the respiration of insects and grain and loss of gases through various possible leaks in the storage structure are important to determine the amount of gas required to kill the insects, and for accurate prediction of CO_2 distribution using mathematical models. Literature related to the sorption of CO_2 gas, and the distribution and loss of the introduced gas in grain bulks are reviewed next.

Mathematical models, based on physical principles, are useful tools to study the distribution and maintenance of gases in a CA storage and to design cost efficient CA storage systems. The diffusion coefficients of gases through grain bulks are the essential material property data in these models. Literature related to the mathematical modelling of the movement of CO_2 gas through stored grain bulks and those related to the determination of diffusion coefficient of gases through grain bulks are reviewed last.

3.1.1 Effect of Temperature

The action of low O_2 atmospheres on the mortality of insects is strongly dependent on the grain temperature with the effect being slow at low temperatures (Bailey and Banks 1975). Banks and Annis (1977) stated that as the grain temperature decreased from 35 to 15°C the exposure time increased from 1 to 24 wk in a 1% O_2 and 99% N_2 atmosphere. Bailey and Banks (1980) observed a close to complete mortality (>99.5%) of Sitophilus granarius (Linnaeus) in 2 wk at 29.4°C and in 3 wk at 23.9°C in a 1.5% O_2 in N_2 atmosphere. Only 78% mortality could be achieved at 18.3°C even after an exposure period of 12 wk.

Alianiazee (1971) reported an increase in the rate of mortality of Tribolium castaneum (Herbst) and T. confusum du Val when the temperature of the grain bulk increased from 15.6 to 26.7°C in a 100% CO_2 atmosphere. The exposure time needed for 95% mortality of T. castaneum decreased from 78 to 7 h and that of Rhyzopertha dominica (Fabricius) decreased from 202 to 15 h with an increase in temperature from 15 to 32°C in < 1% O_2 and 8.5-11.5% CO_2 atmosphere (Storey 1975). White et al. (1988) found that to control Cryptolestes ferrugineus (Stephens) in 1 wk at 20°C, 54% CO_2 and < 11% O_2 was sufficient, whereas at 10°C, the CO_2 level had to be increased to >74% with O_2 levels decreased below 5%. They also concluded that a temperature of 2.5°C was too cool for an effective control in 1 wk. Thus, for an effective CA treatment of grains, the treatment should be done when the grain bulk temperature is high (> 20°C). In a large grain bulk, different temperatures are observed at various locations of the bulk (Muir et al. 1980, Alagusundaram et al. 1990), therefore lowest temperature in the bulk should be considered for determining the length of exposure time required for an effective control of insects. The grain temperatures near the bin wall closely follow the ambient air temperature. In Canadian farms if the CA treatment of grains is done in the winter months the length of exposure should be extended based on the grain temperatures near the wall.

3.1.2 Effect of Relative Humidity

For most stored-product insects the reproduction rate is less at low relative humidities, however most of them can survive at very low relative humidities (Howe 1965). Jay et al. (1971) found that the effect of relative humidity on the mortality of insects was due to water loss and eventual desiccation, when the insects open spiracles in response to low O_2 in N_2 or CO_2 atmospheres. They reported that the mortality of T. castaneum and Oryzaephilus surinamensis (Linnaeus) was greater at 9% relative humidity than at 33, 54, and 68% relative humidities, in binary or trinary mixtures of O_2, N_2, and CO_2. Navarro and Calderon (1974) confirmed that due to pronounced water loss, the mortality of Ephestia cautella (Walker) was higher at low relative humidity in 21 to 88% CO_2 atmospheres. Alianiazee (1971) reported that the mortality of T. castaneum and T. confusum in a 45% CO_2 atmosphere decreased when relative humidity increased from 38 to 100%. Rameshbabu et al. (1990) found an increase in the mortality of adults and eggs of C. ferrugineus when the relative humidity was reduced from 84 to 60%.

In a stored-grain ecosystem, moisture content of the stored product is in equilibrium with the intergranular air (Muir 1986). Due to external weather changes, snow or rain water entering the bin through the man hole and the air vents, and moisture migration the moisture content at certain points in a stored-grain bulk may be higher than in other parts of the bulk. Therefore, the maximum moisture content at any point in a stored-grain bulk should be considered in deciding the duration of application of CA storage for an effective control of insects (Navarro and Calderon 1980).

3.1.3 Effect of Gas Compositions

Selection of appropriate gaseous composition that is lethal to stored-product insects is essential for an effective control of insects using a CA treatment. Due to the physiological differences, different insects require different atmospheres for their control. Among the mixtures of 20% O_2 in CO_2, N_2, and

He, only the O_2-CO_2 combination was toxic to adult T. castaneum and T. confusum (Alianiazee 1971). Whereas, when the O_2 level was < 1.7%, all mixtures were equally good in controlling these insects. White et al. (1988) reported that the mortality of C. ferrugineus, an economically important stored-product insect in Canada, increases with an increase in CO_2 level from 54-69% to 92-98% in a < 10% O_2 atmosphere. Although low O_2 in N_2 atmospheres have been found to be effective in controlling stored product pests (Bailey and Banks 1980, Shejbal et al. 1973), a CO_2 atmosphere is more effective because it stimulates insect respiration while displacing O_2 (Jay and Pearman 1971; Krishnamurthy et al. 1986; White et al. 1988, 1990). The superiority of CO_2 atmosphere over N_2 atmosphere was further confirmed by Mitsuda and Yamamoto (1980) who stated that CO_2 restricts the growth of fungi and microorganisms. Jay (1980) stated that in N_2 atmosphere, the O_2 levels in the interstitial spaces should be reduced to < 1% to obtain effective insect control. Creating and maintaining < 1% O_2 is difficult and uneconomical in non-airtight structures. He concluded that CO_2 can be used in situations where leakiness from the storage structure may be a problem (like the on-farm storage bins in Canada) or where it is not economically feasible to seal the storage structure. He further stated that a CO_2 concentration of 60±10% (even down to a low of 35%) gives a good control of insects in stored grain.

3.1.4 Effect of Exposure Time

The controlled atmosphere should be maintained in the grain bulk for a minimum required exposure time to achieve effective insect control. Based on 70 year literature review (1900-1970) of laboratory studies on the mortality of insects in CO_2 atmospheres, Annis (1987) stated that the majority of species showed 95% or greater mortality in less than 10 d at CO_2 levels of 40 to 60%. Only T. castaneum and Trogoderma granarium Everts required more than 10 d for 95% mortality. White et al. (1988) found that at 20°C in a CO_2:O_2 atmosphere (> 54%: < 11%) 1 wk was required for the control of C. ferrugineus. When the CO_2 level was 20% and the temperature was 25°C, 4 to 6 wk were required for an effective control of C. ferrugineus (White et al. 1990). Rameshbabu et al. (1990) observed a linear increase in the mortality of C. ferrugineus adults and eggs with an increase in exposure time and complete control of insects was observed in 4 d in 88-92% CO_2 atmospheres. Although the mortality of C. ferrugineus and other insects increases with an increase in exposure time for a particular atmospheric composition, the minimum required exposure time should be decided based on the minimum temperature and maximum moisture content in a large grain bulk (Banks and Annis 1977, Navarro and Calderon 1980).

3.2 Sorption of CO_2 by Grains

In a stored-grain bulk CO_2 is adsorbed due to the diffusion of CO_2 into the kernels (Mitsuda et al. 1973) and it is also produced by the respiration of the grain, insects, and microorganisms. The desorption of previously adsorbed CO_2 by the grain is not considered as production of CO_2 but is important because it may increase the CO_2 concentration in the intergranular air. In a CA storage, the amounts of adsorbed and produced CO_2 should be taken into account in the design and application of the required gas compositions. Furthermore, the source or sink term (q) appearing in the differential equation governing the movement of CO_2 through the grain bulk (Section 4.1) corresponds to the CO_2 production or sorption by grain, respectively. An understanding of the phenomenon of the sorption and production of CO_2 by the grain is essential in deciding the gas compositions required for an effective control of insects and for accurate prediction of CO_2 concentrations at various locations in a bin (Haugh and Isaacs 1967).

Mitsuda et al. (1973) observed the phenomenon of CO_2 sorption by cereal grains and oilseeds and concluded that the diffusion of CO_2 into the pore tissues of grain is the major mechanism of CO_2 sorption by the grain. Mitsuda and Yamamoto (1980) observed a reduction in pressure of the intergranular air due to the sorption of CO_2 by rice stored in sealed 200 L cans in a CO_2 atmosphere.

The shapes of CO_2 sorption and pressure drop curves were symmetrical with respect to the time axis, indicating that the pressure drop was only because of CO_2 sorption by the grain. Various factors such as the grain temperature and moisture content, porosity of the grain kernel and the type of grain affect the amount of CO_2 adsorbed by the grain (Yamamoto and Mitsuda 1980). Yamamoto and Mitsuda (1980) observed that the sorption of CO_2 by brown rice increased with an increase in moisture content and that of paddy rice decreased with an increase in moisture content of rice up to 20%. On the contrary, Diawara et al. (1986) concluded that the sorption of CO_2 by rice kernels increases with a decrease in moisture content. Yamamoto and Mitsuda (1980) stated that many kinds of cereal grains and pulses (rice, wheat, corn, peanuts, red beans, and sesame seed) showed a similar CO_2 sorption phenomenon. In a later study, Mitsuda and Yamamoto (1980) observed an increase in the CO_2 sorption of rice with an increase in the CO_2 pressure inside the grain bulk for a pressure range of 1 to 10 atmospheres, and the sorption equilibrium was obtained after 7 d of storage. One kilogram of wheat at 20°C adsorbs 75 mL of CO_2 in 3 h (Yamamoto and Mitsuda 1980). Cofie-Agblor et al. (1992) observed an exponential rate of adsorption of CO_2 by wheat with time. The amount of CO_2 adsorbed by wheat decreased with an increase in temperature from 0 to 30°C and an increase in moisture content from 12 to 18%. The maximum amount of CO_2 gas sorbed in 24 h ranged from 0.18 g kg^{-1} of wheat to 0.42 g kg^{-1} of wheat at temperatures 30 and 0°C, respectively, at a moisture content of 18%.

3.3 Production of CO_2 by Grains

3.3.1 Respiration of Grain

Carbon dioxide is produced in a stored-grain ecosystem due to the respiration of the grain, insects, and microorganisms. The intensity of respiration in a stored-grain bulk is affected by the temperature and moisture content of the grain, mechanical damage, type and degree of microfloral infection, mites, and insects (White et al. 1982, Srour 1988).

The complete combustion of a typical carbohydrate is represented by the following equation:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + Heat \tag{3.1}$$

For each gram of dry matter broken down 1.47 g of CO_2 is produced. Carbon dioxide produced by grains increases with an increase in temperature and moisture content (Bailey 1940, Milthorpe and Robertson 1948, White et al. 1982, Srour 1988). In cereal grains, the CO_2 production doubles for every 5°C rise in temperature up to a temperature of 28°C and for every 1.5 percentage point increase in moisture content up to a moisture content of 20% (wet basis) (Srour 1988). Bailey (1940) found that wheat at 11% moisture content produced 0.2 mg of CO_2 per kg of dry matter in 24 h and 11.0 mg for wheat at 17% moisture content. White et al. (1982) measured CO_2 production by wheat at various moisture contents (14% to 25%) and at various temperatures (10 to 40°C) and related the amount of CO_2 produced to the spoilage of the grain. They found that the rate of CO_2 production increased with an increase in temperature and an increase in moisture content. One kilogram of wheat at 16.5% moisture content and 10°C produced 28 mg of CO_2 and 1 kg wheat at 16.5% moisture content and 40°C produced 793 mg of CO_2 in 21 d. Milthorpe and Robertson (1948), measured a CO_2 production rate of 0.22 g kg^{-1} d^{-1} for 9-10% moisture content wheat at a temperature of 27°C. White et al. (1982) concluded that CO_2 production by wheat at $\leq$ 14% moisture content is negligible at < 30°C.

3.3.2 Respiration of Insects and Microorganisms

Milthorpe and Robertson (1948) stated that higher respiration rates are always associated with insect infestation. Although insects are only a small fraction of the total mass of grain, they contribute a very large proportion of the total CO_2 produced. This is because the grain kernels, although living, are in a resting stage and their metabolism is slow, while insects are very active and their metabolism is very high for their body weight (Oxley 1948). Sinha et al. (1986a) observed elevated intergranular CO_2 levels of 2% or more in nine insect infested bins containing corn, barley, and wheat situated in Western Canada and in the Mid-northern United States; whereas in non-infested bins, the CO_2 levels were at atmospheric level (0.03%). In a subsequent study, Sinha et al. (1986b) determined the rates of CO_2 production of T. castaneum and C. ferrugineus at 27.5°C and 33°C. An empirical relationship of the following form was found to describe the amount of CO_2 produced by various life stages of these insects:

$$\% \, CO_2 = a(\text{Larvae}) + b(\text{Adults}) + c(\text{Pupae}) \qquad (3.2)$$

where a, b, and c are empirical constants whose values for both insects are given in their paper.

White et al. (1982) found that moisture content of the grain and the presence storage fungi like Aspergillus glaucus group had a significant positive role in the production of CO_2 by wheat. High bacterial infection was usually associated with low CO_2 production caused by reduction of fungal infection by competition. Thus, for predicting the CO_2 distribution in a high moisture grain or an infested grain bulk, the source term (q in eq. 4.1) can not be ignored.

3.4 Distribution of Introduced Gases in Grain Bulk

In addition to the effects of temperature, moisture content, gas composition, and the exposure time, the efficacy of a CA treatment of large grain bulks also depends on the uniform distribution of the injected gases in the bulk and maintenance of the required atmospheric compositions for the minimum required exposure time for complete kill of insects. The uniformity of gas distribution depends on the movement of CO_2 inside the grain mass and the maintenance depends on the level of sealing of the silos against the loss of gases through the leaks in the bin walls or through the grain surface. In the absence of pressure gradients, the movement of introduced gases through the grain bulk is mainly due to molecular diffusion. In a high CO_2 atmosphere, the CO_2 molecules being heavier than air molecules, settle in the bottom portions of the grain bulk creating lower concentrations in the top portions (Guiffre and Segal 1984). This gravitational penetration of CO_2 gas in stored-grain bulks has been successfully employed to distribute chemical fumigants.

Calderon and Carmi (1973) showed that methyl bromide in the presence of CO_2 gas moved readily to the bottom of 17-m-tall wheat bulks, while confined to the top portions of the bulk when applied alone. Williams et al. (1984) confirmed the observation of Calderon and Carmi (1973), by demonstrating the effective distribution of methyl bromide in the presence of CO_2 gas. Around the same time, Viljoen et al. (1984) used CO_2 in the form of gas, snow, and dry ice, to distribute methyl bromide in wheat, maize, and sorghum bulks contained in 17-m-diameter and 32.3-m-tall bins. Carbon dioxide introduced as gas was found more effective in distributing methyl bromide to the bottom portions of the bulk than snow or solid. No reason for this difference was discussed in their article. When CO_2 was used as a carrier gas less methyl bromide was needed to control insects and because of the use of smaller doses of methyl bromide the aeration of the grain after the treatment was faster.

In an airtight bin, if the CO_2 levels are maintained for sufficiently long periods of time the CO_2 concentrations in the bulk may become uniform due to molecular diffusion. A gas exchange rate of 2 to 5% of the store volume is unavoidable, even in completely airtight bins (Wilson et al. 1980), and in non-airtight bins the gas exchange rates will be very high. Due to the entry of fresh atmospheric air into the grain bulk, it is not possible to attain uniform concentrations throughout the bulk. To achieve uniform concentrations in the bulk, and in relatively short time, usually the intergranular air is recirculated. A recirculation rate of 0.1 times the volume of intergranular air per day was found to adequately distribute the CA gases in large grain bulks (Banks et al. 1980). Wilson et al. (1980) demonstrated the effectiveness of a gas recirculation system on the CO_2 distribution in two 13.9-m-diameter and 18.2-m-tall bins containing wheat. These bins were airtight (a decay time of 3.5 min for pressure drop from 1500 to 750 Pa). The total mass of CO_2 gas, supplied by vaporizing liquid CO_2, was 1 kg t^{-1} of wheat. In a bin with no gas recirculation, the CO_2 concentrations in the head space fell from 80% to 20% in 48 h while in the bottom the concentrations remained >60%. A recirculation rate of 17 m^3 h^{-1} (about 0.17 times the volume of the bin per day) gave CO_2 concentrations of 28 and 32% in the head space and bottom, respectively, after 2.5 d. The adsorption of CO_2 by the wheat and a gas exchange rate of 2.4 to 4% day^{-1} reduced the gas levels by 0.19 kg t^{-1} of wheat in the interstitial space. Navarro et al. (1986), based on a laboratory study using 0.57-m-diameter and 2.60-m-tall wheat bulks, concluded that recirculation is essential to obtain uniform gas distribution in the bulk. They found that about 2.8 times the volume of intergranular air per day was essential to make the CO_2 concentrations in the bulk uniform in 7 h. When a continuous flow of CO_2 was applied at the bottom of a 100-cm-long and 10.4-cm-diameter wheat column, the O_2 concentrations ranged from 0.9% at the bottom to 18.5% at the top, while CO_2 concentrations ranged from 70.5% to 3.3% (Navarro et al. 1981).

3.5 Studies Related to the Use of CO_2 Gas in Grain Bulks

The first reported work on the use of CO_2 for disinfesting stored grain was conducted by Winterbottom (1922), (Cited by Banks et al. 1980). During 1917-1919, he used CO_2 produced by burning coke to disinfest stored bagged grain in Australia. Since then numerous research studies have been carried out to use CO_2 gas for insect control in stored products. In 1942, Oosthuizen and Schmidt (Cited by Banks 1979), used CO_2 to control Callosobruchus chinensis (L.) in old and new galvanized steel tanks of 1.2 m^3 capacity. Carbon dioxide was introduced into the base of the tank filled with cowpeas. In the new bins, CO_2 levels decayed slowly from 70 to 41% in 14 d while in the old bins, due to large leakage the effectiveness of the treatment was very low. Jay et al. (1970) used CO_2 (supplied by vaporizing liquid CO_2 from tanks) to control T. castaneum in inshell peanut bulks contained in 9.1-m-diameter and 34.4-m-tall concrete bins. The bins were equipped with gas recirculation systems. Carbon dioxide concentrations in the bins were uniform around 35% at the end of three separate treatments of 48, 96, and 168 h. But, due to large leakage in the semi-airtight bin, the CO_2 requirement was very high. For a 168 h treatment 2.2 kg CO_2 per m^3 of peanut was used. They hypothesized that regulating CO_2 gas supply using a pressure regulator and a flow meter would reduce the gas requirement. Later Jay and Pearman (1973) studied the effectiveness of elevated CO_2 on the mortality of several insects, including Sitophilus spp., in shelled corn bulks contained in a 7.3-m-diameter and 24.7-m-tall silo. Liquid CO_2 was vaporized and supplied at the base of the bin at a rate of 4.3 kg m^{-3}. The insects were controlled in 96 h at 60-70% CO_2. In the same bin, Jay (1980) observed 80% or more CO_2 concentrations between 0 and 13 m height 10 h after applying 592.7 m^3 of CO_2. Above 13 m the CO_2 concentrations ranged from trace to 22%. Jay and D'Orazio (1984) field tested the effect of CO_2 gas (vaporized liquid CO_2) to disinfest non-airtight concrete and steel bins containing wheat, sorghum, maize and rice. They observed very good control of insects, but with a high rate of CO_2 input (2.6 to 3.8 kg CO_2 m^{-3} of wheat). In an airtight bin with a gas interchange rate of less than 5%, the amount of CO_2 required was 0.8 kg CO_2 m^{-3} of wheat in vertical bins with 5% head space and 1.6 kg CO_2 m^{-3} of wheat in horizontal sheds with 40-45% head space (Banks and Annis 1980).

Point of application of CO_2 gas, although important in terms of convenience of application and availability of duct works or perforated floors, does not reduce the uniformity of distribution in large grain bulks. An efficiency of purging ($\eta_{purging}$) of 73% was observed by Banks et al. (1980) while purging from a single point in a 16 400 t shed containing wheat. The efficiency of purging was calculated by:

$$\eta_{purging} = C_c\left\{\frac{Pore\ volume + Head\ space\ volume}{Volume\ of\ CO_2\ gas\ used}\right\} \qquad (3.3)$$

where: C_c = concentration of CO_2 (%) at termination of gas input.

There are basically three different methods of application: (i) from the top of the grain bulk, (ii) from the bottom of the grain bulk, and (iii) along the grain stream during bin filling (Jay 1980). The choice of the method of application is decided based on the availability of materials and convenience of application for the particular situation rather than based on the consideration that any one method is superior to the other. Except for an experimental study by Jay (1980) who applied CO_2 in the form of snow along the grain stream while the bin was loaded, I could not find any other published article in which the CO_2 was applied along the grain stream. Mcgaughey and Akins (1989) studied the movement of an 86% N_2 and 14% CO_2 atmosphere supplied from a mobile gas generator, in four 4.6-m-diameter bins containing wheat to a depth of 1.5 m. Two of these bins had fully perforated floors and the other two had concrete floors. In the bins with a concrete floor, the atmosphere was introduced through a pipe with the open end at the centre and 30 cm above the floor. The decrease in O_2 concentrations in the bins with the perforated floors was independent of radial position and in the bins with a concrete floor the O_2 concentrations decreased more rapidly from top to bottom along the centre than near the wall. Covering the grain surface with a polyethylene sheet reduced the gas requirement by a factor of 10 compared to a ventilated overhead space, and by a factor of 2 compared to completely sealing the overhead space.

3.6 Use of Dry Ice as a Source for Creating High CO_2 Atmospheres

In most of the studies cited above, high CO_2 atmospheres in grain bulks were created by vaporizing liquid CO_2 or by burning hydrocarbons. Dry ice, the solid form of CO_2 which sublimates into CO_2 gas at temperatures above -78.7°C, has a potential to be used as a source to create controlled atmospheres in stored-grain bulks. Dry ice is easy to handle and can be accurately weighed to introduce the exact amount of gas in the bulk without much waste. Furthermore, it is not essential to buy or rent a high-pressure cylinder and vaporizer required for liquid CO_2 application. In spite of all these advantages, dry ice has not been used extensively, probably because it is more expensive than CO_2 gas

(White and Jayas 1992). In the literature, I could find only a few research works in which dry ice was employed to create a high CO_2 atmosphere.

Mansour (1955) (cited by Banks 1979) treated 180 t of wheat contained in a bin of 240 m^3 capacity with 160 kg of dry ice. The CO_2 levels achieved were not given, but after 25 d of treatment he observed 90% mortality of weevils (the type of weevils was not given in the paper) at temperatures of 11 to 15°C. Banks and Sharp (1979) tested the use of CO_2 introduced in the form of dry ice for disinfesting a freight container holding 19 t of wheat. The container was well sealed and had a leakage rate of $< 6 \times 10^{-3}$ m^3 s^{-1} at 250 Pa excess pressure. Two lots of dry ice were introduced after filling the container. One 30-kg-lot was sprinkled directly on the grain surface and it sublimated quickly and increased the CO_2 concentrations in the bulk. Another 21-kg-lot of dry ice was contained in an insulated box; it slowly sublimated at the rate of 3 kg per day to replenish the lost CO_2. Nine hours after the introduction of dry ice a substantial gradient of CO_2 concentrations existed in the bulk (38% in the top to 55% in the bottom). After 23 h of treatment the concentrations became nearly uniform at 45%. The CO_2 concentrations in the bulk remained between 42 to 52% over a 10 d period and a complete control of artificially induced infestations of R. dominica, and S. oryzae was observed.

Jay and D'Orazio (1984) treated four hopper-type rail cars containing 77 t of bulk wheat flour with 91 or 181 kg of dry ice pellets sprinkled on the flour surface and another 91 kg of dry ice blocks covered in cloth bags pushed into the flour in each car. At the end of 10 d treatment the CO_2 concentrations in the car treated with 181 kg of dry ice ranged from 31% in the top to 40% in the bottom. The CO_2 concentrations in the other cars were not mentioned. They observed 95.2 to 99.1% mortality of T. confusum in cages. The mortality was not increased with the introduction of 181 kg dry ice over 91 kg dry ice.

The transport of gases through the grain bulk, without mechanical recirculation, occurs due to molecular diffusion (Singh et al. 1983, Jayas et al. 1988) and the convection currents (Bond et al. 1977, Gilby 1983, Navarro et al. 1986). Convection currents are developed because of the temperature gradients in a large grain bulk (Muir et al. 1980). To quantify the mass transfer by diffusion the diffusion coefficient of CO_2 in a grain-bulk is required.

3.7 Diffusion Coefficients of Gases Through Agricultural Grains

A diffusion coefficient can be defined as "the flow of current of a substance which passes perpendicularly through a reference plane of unit area, during a unit time under unit concentration gradient" (Jost 1960). The diffusion coefficient of gases through other substances is usually expressed in dimensions of $L^2\ T^{-1}$. Several researchers have reported that the diffusion coefficient of gases through grain is about 1/3 of the diffusion coefficient of gases in air (Henderson and Oxley 1944, Bailey 1959, Haugh and Isaccs 1967). Henderson and Oxley (1944) determined the diffusion coefficient of CO_2 through bulk wheat at 12% moisture content as 0.0415 $cm^2\ s^{-1}$ at room temperature. Bailey (1959) determined the rates of diffusion of O_2 through bulks of wheat, barley, maize, and oats and found a quadratic relationship between the diffusion coefficient and the temperature (in the range of 1.7 to 42°C). The value of the diffusion coefficient of O_2 for wheat at 23°C was 0.067 $cm^2\ s^{-1}$. The diffusion coefficient of O_2 for maize, barley, and oats were 0.0558, 0.0642, and 0.0721 $cm^2\ s^{-1}$, respectively.

Haugh and Isaacs (1967) studied the diffusion coefficient of O_2 through bulks of corn contained in 0.33-m-diameter and 0.66-m-tall steel cylinders. The gas chamber was of the same diameter as the grain column and was above the grain column; it had a length of 0.40 m. They determined the diffusion coefficient at initial O_2 concentrations of 5, 8, 10, 14 and 21% in the gas chamber. Their results indicated that diffusion coefficient of O_2 through corn was a non-linear function of concentration:

$$D = 0.791 - 0.420(CR) + 0.136(CR^2) \tag{3.4}$$

Where; D = diffusion coefficient ($cm^2\ s^{-1}$)

CR = concentration ratio = C/Co

C = concentration of O_2 (g m^{-3})

Co = initial concentration in the gas chamber, $C(x,0)$ (g m^{-3})

Other than Haugh and Isaacs (1967) all other researchers assumed that the diffusion coefficient of gases through grain bulks was independent of concentration.

Adamezyk et al. (1978) found an increase in the diffusion coefficient of H_2, He, Ne, Ar, O_2, and Xe through wheat with an increase in porosity. Singh et al. (1984) studied the effects of flow direction, grain bulk porosity, grain moisture content, and temperature on the diffusion coefficient of CO_2 through wheat, rapeseed, corn, and oats. There was no significant difference in the diffusion coefficient of CO_2 through wheat and rapeseed for the three flow directions studied (vertically upward, horizontally, and vertically downward). They observed a quadratic relationship between the diffusion coefficient of CO_2 through wheat and temperature (range -10 to 30°C):

$$D = [2.245 - 0.0176(T) + 0.00032(T^2)] \times 10^{-2} \tag{3.5}$$

where T is the temperature of the grain bulk in K and D is in $cm^2\ s^{-1}$.

3.8 Gas Loss from Grain Storage Bins

For predicting the CO_2 concentrations accurately in a grain bulk and for estimating the amount of gas required to kill insects, the gas loss from the grain storage structure should be known. According to Blomsterberg and Harrje (1979) the major mechanisms of gas loss from ventilated buildings in the open are the wind and the magnitude of the temperature variations in the surrounding atmospheres. These two factors do not act independently, and the sum of their individual effects would always be less than their combined effect on gas losses (Sinden 1978). For determining the losses of fumigants from sealed grain bins, Barker (1974) considered the effects of temperature and barometric pressure variations in the surrounding atmosphere. He estimated that in a 291 m^3 bulk wheat, for a temperature drop from 20 to 10 °C and a barometric pressure drop of 182 kPa there would be 3.34 m^3 of air exchange with the atmosphere. Sharp et al. (1976) considered the effect of all three mechanisms (i.e. the wind, temperature, and the barometric pressure variations) for estimating the leakage of air into insulated containers. They concluded that the effect of wind was small compared to the effects of temperature and barometric pressure variations, for the gas losses from well sealed containers. An on-farm storage bin which is not sealed is intermediate between well sealed structures like insulated containers and intentionally ventilated dwelling buildings. The following mechanisms might cause gas losses from such on-farm storage bins (Banks and Annis 1984): 1. temperature variation, 2. barometric pressure variation, 3. wind effects, and 4. chimney or stack effect within a grain bulk.

Meiring (1982) gave estimates of rates of gas loss from silos under various levels of sealing, but did not include the wind and chimney effects. He concluded that for proper O_2 control in a metal silo the specific permeability (area of opening per unit volume) should not exceed 0.2 mm^2/m^3 and in a concrete silo the tolerance limit can be as high as 0.4 mm^2/m^3. Based on an estimate of rates of gas loss from four types of grain storage structures (cylindrical farm bin, rectangular bag stack, cylindrical silo bin and rectangular flat store), Banks and Annis (1984) concluded that factors like the long term variation in barometric pressure and diffusion have negligible effect on gas losses.

Navarro et al. (1990) developed a simulation model to determine the gas loss from grain storage bins. They considered the diurnal and seasonal ambient temperature variations to determine the gas loss from the grain storage structure. The simulation results were compared with measured data on CO_2 concentration changes in two welded steel bins of 3.0-m-diameter and 8.75-m-tall containing 52 and 28 t of wheat, respectively. Although the model prediction and measured CO_2 changes in the bulks compared well, they made many questionable assumptions in the model. They assumed: 1) the CO_2 is distributed uniformly in the grain bulk, 2) sorption of CO_2 by the grain will not influence the gas concentration, 3) temperature in the grain mass is uniform, 4) wind effect is negligible, and 5) barometric pressure variation is negligible.

3.9 Previous Models

Singh et al. (1983) solved an axisymmetric diffusion equation for predicting the CO_2 concentrations in the grain mass caused by CO_2 produced in localized area of spoiling grain. They assumed two cases of boundary conditions for the bin wall: 1. infinitely permeable to CO_2 (Dirichlet boundary condition); and 2. impermeable to CO_2 (homogeneous Neumann boundary condition). Based on the assumption that CO_2 leaving the grain mass instantaneously diffuses into the atmosphere, the CO_2 concentration at the surface of the grain was assumed to be equal to the atmospheric CO_2 concentration. They did not compare the model results with experimental data. Later Jayas et al. (1988) used the model of Singh et al. (1983) for predicting the CO_2 concentrations in a 5.8-m-diameter bin containing wheat to a depth of 4.9 m. The CO_2 was injected at the centre and 1 m below the grain surface at a flow rate of 77.4 L/min. The predicted CO_2 concentrations at various locations in the bin were compared with the measured values after 23 h of injection. In the bottom two thirds of the bin CO_2 concentrations predicted by the model (with an impermeable wall) were higher than the measured data. They concluded that the model prediction could be improved by allowing some leakage through the bin wall.

To my knowledge, no other model has been developed to predict the movement of CO_2 through the stored grain mass. The discussed models are axisymmetric models. In most farm bins, CO_2 may be adsorbed and produced at various locations in the bin and CO_2 may be introduced at a point near the wall making the problem of CO_2 movement non-axisymmetric. Furthermore, an axisymmetric model cannot predict the movement of CO_2 in non-circular bins. Therefore, I attempted to develop a three dimensional model for predicting the movement of CO_2 within the grain mass. In the next chapter the solution of the differential equation governing the transport of CO_2 within the grain mass is given.

4. MODEL DEVELOPMENT

4.1 Governing Equation and Boundary Conditions

The partial differential equation governing the unsteady state transport of miscible fluids in an anisotropic porous media in the Cartesian coordinate system is given by (Fried and Combarnous 1971, Huyakorn et al. 1986, Brodkey and Hershey 1988):

$$\frac{\partial}{\partial x}\left(Dx\,\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(Dy\,\frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(Dz\,\frac{\partial c}{\partial z}\right) + q = \frac{\partial c}{\partial \tau} \qquad (4.1)$$

subject to the boundary conditions,

$$c = c_{s1} \qquad \text{on } S1 \qquad (4.2)$$

$$Dx\,\frac{\partial c}{\partial x}\,\ell_x + Dy\,\frac{\partial c}{\partial y}\,\ell_y + Dz\,\frac{\partial c}{\partial z}\,\ell_z = Q \qquad \text{on } S2 \qquad (4.3)$$

and the initial condition:

$$C(x,y,z,\tau) = c_i \qquad \text{on } \Omega \qquad (4.4)$$

For the movement of CO_2 within a stored-grain bulk the various notations used in the above equations are:

c	=	concentration of CO_2 at time $\tau > 0$ (g m^{-3})
c_i	=	initial concentration of CO_2 in the domain Ω (g m^{-3})
c_{s1}	=	concentration specified on the boundaries S1 (g m^{-3}))
Dx, Dy, and Dz	=	diffusion coefficients of CO_2 through the grain in x, y and z coordinate directions, respectively (m^2 s^{-1})
ℓ_x, ℓ_y, and ℓ_z	=	direction cosines of outward drawn normal to the boundary in the x, y, and z directions, respectively

q	=	amount of CO_2 adsorbed or produced by the grain (g m^{-3} s^{-1})
Q	=	total surface flux across the boundary S2 (g m^{-2} s^{-1})
S1 and S2	=	boundary segments
Ω	=	domain consisting of the stored-grain bulk.

The segment S1 represents the portion of the boundary where concentration of CO_2 may be specified. It may consist of more than one segment of the boundary. For example, part of S1 may represent the surface of the grain where concentration may be specified as constant at the atmospheric level in a ventilated head space. Another portion of S1 may represent the portion of a grain boundary where CO_2 is injected and thus maintained at a constant concentration. Similarly S2 may be made of more than one segment of the boundary. For example, the bin floor may be assumed to be impermeable to the flow of CO_2, whereas bin walls may have a specified flux of CO_2 to the surroundings depending on the rate of loss through the bin wall. The segments S1 and S2 together make the total boundary of the domain Ω. The specified CO_2 concentration along the boundary S1 is known as the Dirichlet boundary condition and specified flux across the boundary S2 is know as the Newmann boundary condition. When the surface flux Q becomes zero, then eq. 4.3 represents a homogenous Newmann boundary.

4.2 Finite Element Formulation

In the finite element method the problem domain is divided into interconnected smaller regions known as elements. The element equations are developed from the governing partial differential equation by using variational or weighted residual methods. Details of these methods are given in Segerlind (1976, 1984), respectively. To use the variational approach a functional is required whereas the weighted residual method is more general and can be used with any partial differential equation. I used the weighted residual method.

In the weighted residual method, an approximate solution is substituted in the governing equation and a weighted residual over the entire domain is minimized with respect to the unknown coefficients in the approximate solution. Depending on the weighting function used for weighting the residual, there are various weighted residual methods. When the weighting function is the same as the interpolating (approximating) function of the field variable, it is known as the Galerkin method. The solution of eq. 4.1 along with the associated boundary conditions (eqs. 4.2, 4.3, and 4.4) is derived next using the Galerkin's weighted residual method.

Let the field variable, c, in each element of the domain be approximated by:

$$c(x,y,z,\tau) = \sum_{i=1}^{p} [N_i^{(e)}(x,y,z)]\ \{C^{(e)}\} \tag{4.5}$$

where:

$\{C^{(e)}\}$	=	the vector of nodal CO_2 concentrations of an element,
$[N_i^{(e)}(x,y,z)]$	=	the vector of interpolating functions, and
p	=	total number of nodes in an element.

Using interpolating function N_i (eq. 4.5), as the weighting function the weighted residual form of eq. 4.1 can be written as:

$$\int_V [N]^T\{\frac{\partial}{\partial x}(Dx\frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(Dy\frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(Dz\frac{\partial c}{\partial z}) +$$

$$q - \frac{\partial c}{\partial \tau}\}\ dV = 0 \tag{4.6}$$

(Use of the superscript (e) to represent individual element is dropped for simplicity).

Now, using Green's theorem (Rao 1982), the integral involving the diffusion terms can be evaluated as follows:

$$\int_V [N]^T \frac{\partial}{\partial x} (Dx \frac{\partial c}{\partial x})\ dV = -\int_V \frac{\partial [N]^T}{\partial x} Dx \frac{\partial c}{\partial x}\ dV + \int_S [N]^T Dx \frac{\partial c}{\partial x} \ell_x\ dS$$

(4.7)

where S represents the surface of the element and ℓ_x is the x-direction cosine of the outward drawn normal to the boundary.

The integral in y and z coordinate directions can also be evaluated in a similar way. Substituting these integrals in eq. (4.6) results in:

$$\int_V [N]^T \{-\frac{\partial [N]^T}{\partial x} (Dx \frac{\partial c}{\partial x}) - \frac{\partial [N]^T}{\partial y} (Dy \frac{\partial c}{\partial y}) - \frac{\partial [N]^T}{\partial z} (Dz \frac{\partial c}{\partial z})\} dV +$$

$$\int_V [N]^T (q - \frac{\partial c}{\partial \tau})\ dV + \int_S [N]^T \{Dx \frac{\partial c}{\partial x} \ell_x + Dy \frac{\partial c}{\partial y} \ell_y + Dz \frac{\partial c}{\partial z} \ell_z\}\ dS = 0$$

(4.8)

where ℓ_y and ℓ_z are the y- and z-direction cosines, respectively, of the outward drawn normal to the boundary.

Defining the material property matrix [D]:

$$[D] = \begin{bmatrix} Dx & 0 & 0 \\ 0 & Dy & 0 \\ 0 & 0 & Dz \end{bmatrix} \qquad (4.9)$$

and the gradient vector as:

$$\{g\} = \begin{Bmatrix} \frac{\partial c}{\partial x} \\ \frac{\partial c}{\partial y} \\ \frac{\partial c}{\partial z} \end{Bmatrix} = \begin{bmatrix} \frac{\partial N1}{\partial x} & \frac{\partial N2}{\partial x} & \cdots & \frac{\partial Np}{\partial x} \\ \frac{\partial N1}{\partial y} & \frac{\partial N2}{\partial y} & \cdots & \frac{\partial Np}{\partial y} \\ \frac{\partial N1}{\partial z} & \frac{\partial N2}{\partial z} & \cdots & \frac{\partial Np}{\partial z} \end{bmatrix} \begin{Bmatrix} c1 \\ c2 \\ \cdot \\ \cdot \\ \cdot \\ cp \end{Bmatrix} \qquad (4.10)$$

$$= [B]\ \{C\} \qquad (4.11)$$

and, substituting for c from eq. 4.5, eq. 4.8 can be written as:

$$\int_V [B]^T \ [D] \ [B]\{C\} \ dV + \int_V [N]^T \ [N] \ \frac{\partial c}{\partial \tau} \ dV - \int_V q[N]^T \ dV -$$

$$\int_s [N]^T \{Dx \frac{\partial c}{\partial x} l_x + Dy \frac{\partial c}{\partial y} l_y + Dz \frac{\partial c}{\partial z} l_z\} \ ds = 0 \tag{4.12}$$

and substituting from eq. 4.3 for the surface integral terms results in:

$$\int_V [B]^T \ [D] \ [B] \ \{C\} \ dV + \int_V [N]^T \ [N] \ \frac{\partial c}{\partial \tau} \ dV - \int_V q \ [N]^T \ dV - \int_S [N]^T \ Q \ ds = 0 \tag{4.13}$$

Eq. 4.13 can be written in a short form as:

$$[k1]\{\frac{\partial c}{\partial \tau}\} + [k2]\{C\} = \{f\} \tag{4.14}$$

where:

$$[k1] = \int_V [N]^T \ [N] \ dV$$

$$[k2] = \int_V [B]^T \ [D] \ [B] \ dV$$

and

$$\{f\} = \int_V q \ [N]^T \ dV + \int_S Q \ [N]^T \ dS$$

The surface integral S corresponds to the boundary S2 only. Eq. 4.14 is for an element in the domain. Adding the element matrices, [k1] and [k2], and the force vector {f} of individual elements in the domain yields the global equation:

$$[K1]\{\frac{\partial c}{\partial \tau}\} + [K2]\{c\} = \{F\} \tag{4.15}$$

where, [K1] and [K2] are the global matrices and {F} is the global vector.

4.3 Time Integration of eq. 4.15

To solve eq. 4.15 in the time domain, a ϕ family of approximations, which approximates a weighted average of the time derivative, is introduced:

$$\phi\{\dot{c}\}_{n+1} + (1-\phi)\,\{\dot{c}\}_n = \frac{\{c\}_{n+1} - \{c\}_n}{\Delta\tau}\,; \qquad 0 < \phi < 1 \tag{4.16}$$

where subscript n+1 corresponds to time $\tau+\Delta\tau$ and the subscript n corresponds to time τ.

A number of different schemes can be obtained by choosing the value of ϕ as follows (Wood and Lewis 1975):

ϕ	= 0	forward difference scheme
	= 0.5	Crank-Nicholson scheme
	= 0.667	Galerkin's scheme
	= 1.0	backward difference scheme

The finite difference recurrence relationship is stable for any value of ϕ between 0.5 and 1.0. Assuming,

$$\{\dot{c}\}_{n+1} = \{\dot{c}\}_n = \{\dot{c}\} \tag{4.17}$$

which means the slopes at time τ_{n+1} and τ_n are equal; rearranging the terms in eq. 4.16 results in:

$$\{\dot{c}\} = \frac{\{c\}_{n+1} - \{c\}_n}{\Delta\tau}\,\frac{1}{[\phi + (1-\phi)]} \tag{4.18}$$

substituting the values of {c} in eq. 4.15 yields:

$$[K1]\,\{c\}_{n+1} = [K1]\,\{c\}_n + \Delta\tau[\phi + (1-\phi)]\,[\{F\} - [K2]\,\{c\}] \tag{4.19}$$

Accounting for the time change in the boundary condition vector {F}, the above equation can be written as:

$$[K1]\ \{c\}_{n+1} = [K1]\ \{c\}_n + \phi\Delta\tau\ [\{F\}_{n+1} - [K2]\ \{c\}_{n+1}] +$$

$$(1 - \phi)\ \Delta\tau\ [\{F\}_n - [K2]\ \{c\}_n] \qquad (4.20)$$

Rearranging eq. 4.20 to obtain $\{c\}_{n+1}$ in terms of $\{c\}_n$ and dividing by $\Delta\tau$ yields:

$$\left[\frac{[K1]}{\Delta\tau} + \phi\ [K2]\right] \{c\}_{n+1} = \left[\frac{[K1]}{\Delta\tau} - (1-\phi)\ [K2]\right] \{c\}_n +$$

$$\left[\phi\ \{F\}_{n+1} + (1 - \phi)\ \{F\}_n\right] \qquad (4.21)$$

Eq. 4.21 can be solved to obtain the CO_2 concentrations at time $\tau+\Delta\tau$ by using the CO_2 concentrations at time τ.

5. MATERIALS AND METHODS

5.1 Pilot Bin Experiments

5.1.1 Test Bins

Three 1.42-m-diameter and 1.47-m-tall bins were obtained from a local manufacturer (Westeel, Winnipeg, Manitoba). A bin was made by soldering two plain galvanized steel sheets along the height and rolled to form 1.42-m-diameter cylinders. Two cylinders were bolted together to give 1.47-m-tall bins. Three different partially perforated floors were installed in the three bins. The floor openings were: a 0.3-m-diameter opening at the centre, a 1.14 m x 0.36 m rectangular opening, and a 0.3-m-diameter opening near the wall (Figs. 5.1, 5.2, and 5.3, respectively). Metal boxes of volumes 0.0925 m^3 for bins 1 and 3 and 0.202 m^3 for bin 2 were fabricated using 0.9-mm-thick sheet metal and mounted directly under the perforated floor openings of the bins. A known quantity of dry ice was placed in these boxes to create CO_2 gas. The boxes were equipped with a 7.5-cm-diameter PVC pipe fitting and a screw cap for placing the dry ice and for aerating the grain after each replication. The bins were placed on 50-cm-high wooden platforms. All the joints and bolt holes in the bins were sealed using silicon sealant.

To draw gas samples, semirigid nylon tubing 3.2-mm-outside diameter were installed at five levels, spaced 0.33 m apart in the vertical direction. There were 11, 13, and 12 sampling points at each level for Bins 1, 2, and 3, respectively (Figs. 5.1, 5.2 and 5.3). The gas sampling tubes were taken out of the bins through 6.4-mm-diameter copper nipples soldered to the bin wall at each radius and at each level. The outer end of the gas sampling tubes were fitted with rubber septa. Gas samples, collected using 10-mL syringes, were analyzed for CO_2 concentrations using a gas chromatograph (Perkin-Elmer model Sigma 3B) with a thermal conductivity detector and a 1-mL fixed volume injection loop.

In addition to gas samples the grain temperatures were also recorded. To monitor the grain

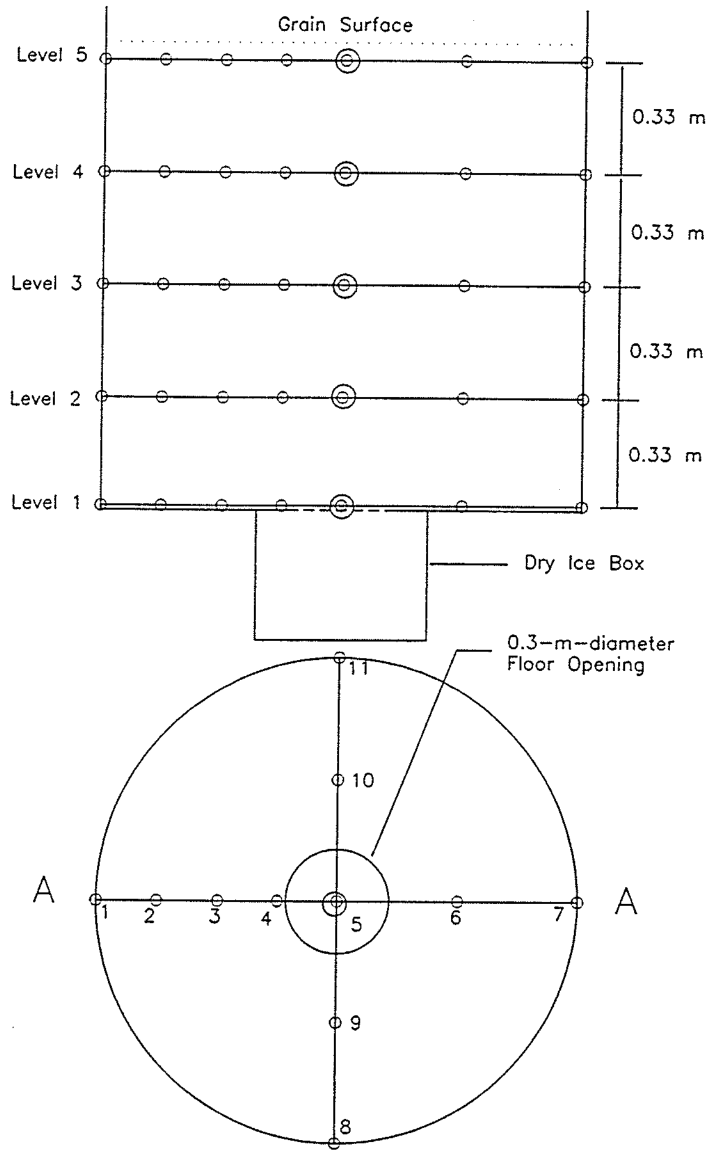

Fig. 5.1. Schematic diagram of the gas (o) and both gas and temperature (◎) sampling locations in a 1.42-m-diameter and 1.47-m-tall bin with a 0.3-m-diameter perforated floor opening at the centre (Bin 1).

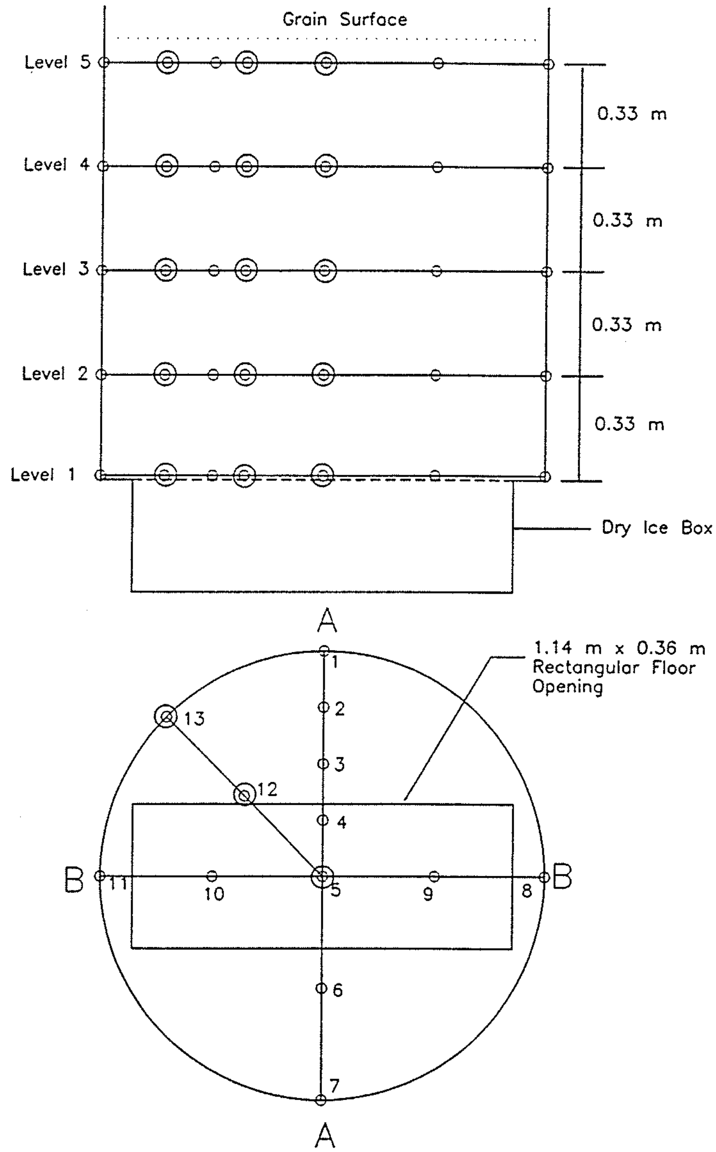

Fig. 5.2. Schematic diagram of the gas (o) and both gas and temperature (◎) sampling locations in a 1.42-m-diameter and 1.47-tall bin with a 1.14 x 0.36 m rectangular perforated floor opening (Bin 2).

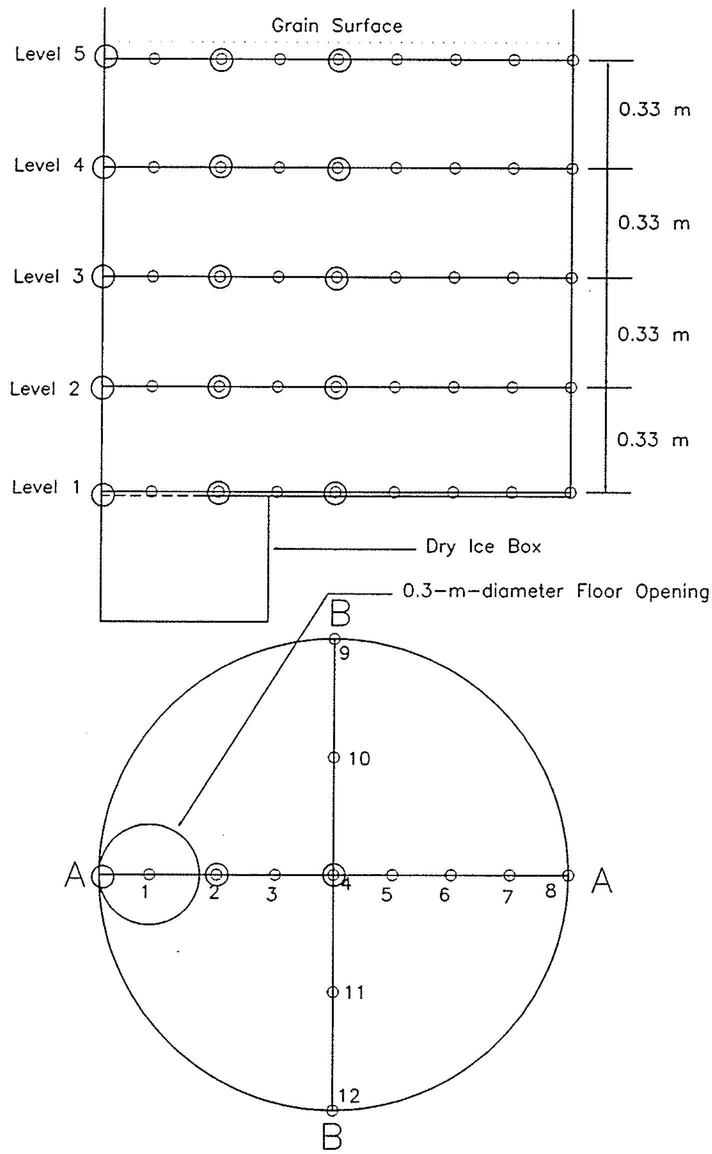

Fig. 5.3. Schematic diagram of the gas (o) and both gas and temperature (◎) sampling locations in a 1.42-m-diameter and 1.47-m-tall bin with a 0.3-m-diameter perforated floor opening near the wall (Bin 3).

temperatures, copper-constantan thermocouples were installed at 5 locations along the central axis of Bin 1 and at 15 locations in each of the Bins 2 and 3. The thermocouples were connected to a multichannel switch board and then to a temperature indicator.

5.1.2 Experimental Procedure

The bins were filled with Canadian Hard Red Spring wheat (cv. 'Katepwa'), graded No. 1 by the Canadian Grain Commission. The wheat which was obtained from a local farmer had 0.5% dockage by volume and 12.8% moisture content (all the moisture contents quoted in this thesis are on a wet mass basis). The bins were filled to a depth of 1.37 m by manually pouring the wheat from buckets. For Bins 1 and 3, 180 g of dry ice, which with perfect purging and mixing would create an average CO_2 concentration of approximately 10% in the intergranular air space of the wheat bulk, was placed in the box and for Bin 2, 370 g of dry ice, which would create an average CO_2 concentration of approximately 20%, was used. Samples of intergranular air for determining CO_2 concentration were collected using a 10-mL syringe and the grain temperatures were recorded at 1, 3, 6, 9, 12 and 21 h after the introduction of the dry ice (Tables A1 to A9). Before collecting gas samples, the gas sampling tubes were flushed out by drawing 2 to 6 mL gas and discharging it into the room air. After flushing, about 8-mL of gas samples were withdrawn for analysis. In all the bins experiments were conducted with open and covered grain surfaces. For covering the grain surface a polyvinylidene chloride sheet (made of 3 layers of nylon and 4 layers of polyethylene), which had a CO_2 permeability rate of < 0.1 cm^3 m^{-2} d^{-1} (Winpak, Winnipeg, Manitoba) was used. The covering sheet was taped to the bin wall using duct tape. Various experiments conducted in the pilot bins are given in Table 5.1.

After each replicate, the grain was aerated using a 1.5 kW centrifugal fan (General Blower Co., Wheeling, IL), for about 1h to bring the intergranular CO_2 concentrations to atmospheric level, and left undisturbed for about 24 h before the start of the next experiment. The blower was run for another 15 min just before the start of the next experiment to make sure the intergranular CO_2 concentration

Table 5.1. Summary details of experiments conducted in 1.42-m-diameter bins containing wheat to a depth of 1.37 m.

Experiment No.	Bin No.	Grain Surface	Amount of Dry Ice (g)
Pilot 1	1	Open	180
Pilot 2	1	Open**	180
Pilot 3	1	Covered	180
Pilot 4	2	Open	370
Pilot 5	2	Covered	370
Pilot 6	3	Open	180
Pilot 7	3	Covered	180
Pilot 8	1	Open	540
Pilot 9	2	Covered	740

** The bin was emptied and refilled after each of the three replicates. In other tests bin was filled once for three replicates but grain was aerated in between replicates.

reached the atmospheric level. In the first few experiments, gas samples were collected at a few random sampling locations and analyzed for CO_2 concentrations before introducing the dry ice for the next experiment. Grain samples were collected after each experiment for determining the moisture content. The moisture contents of the wheat samples were determined by drying triplicate samples of about 15 g each in an air convection oven at 130°C for 19 h (ASAE 1992). The moisture contents of wheat samples used in all other experiments throughout this thesis were also determined using the same procedure. The moisture content of the wheat did not vary appreciably during the course of the experiments. The average moisture content of the wheat used in the pilot bin experiments was 12.6±0.4%.

5.2 Farm Bin Experiments

5.2.1 CO_2 Distribution Tests

5.2.1.1 Test Bins

Three 5.56-m-diameter bins were used for the CO_2 distribution tests. The bins were made of corrugated galvanized steel sections bolted together. One bin (farm Bin 1) was equipped with a 0.46-m-diameter and 4.7-m-long circular duct on its concrete floor (Fig.5.4). The duct had perforations for a length of 3.3-m from the end inside the grain bin. The second bin (farm Bin 2) had a fully perforated floor (Fig.5.5) and the third bin (farm Bin 3) had a concrete floor (Fig.5.6). These bins were instrumented with gas sampling tubes for drawing intergranular gas samples to determine CO_2 concentration, and copper-constantan thermocouples to monitor the grain temperatures. Semi-rigid nylon tubes of 3.2-mm-outside diameter were used as gas sampling tubes. In farm Bin 1 and farm Bin 3 the gas sampling tubes and thermocouple wires were installed at three different levels (0.55-m, 1.30-m, and 2.05-m- from the concrete floor) (Fig. 5.4 and 5.6). In farm Bin 2 the gas sampling tubes and thermocouple wires were installed at four different levels (near the perforated floor and at 0.43-m,

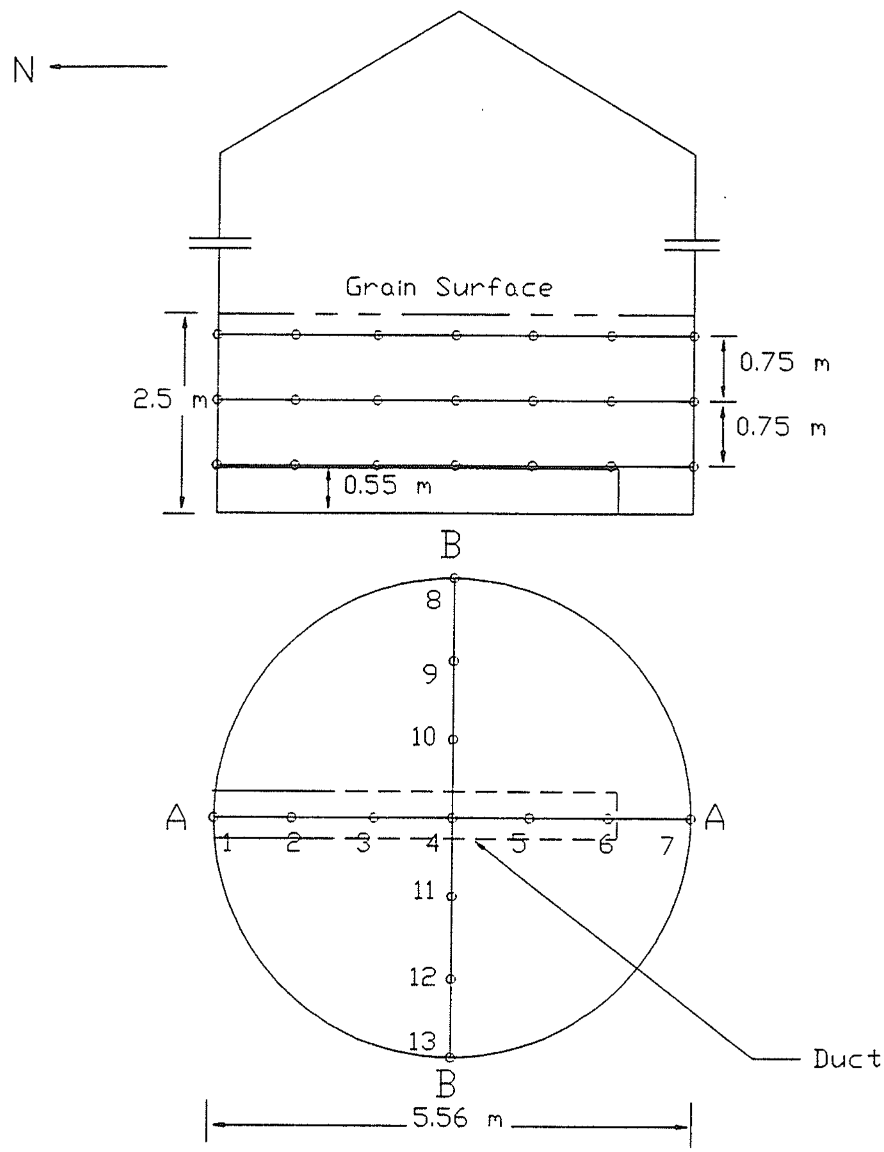

Fig. 5.4. Schematic diagram of the temperature and gas sampling locations (o) in a 5.56-m-diameter bin a circular duct on the floor (farm Bin 1).

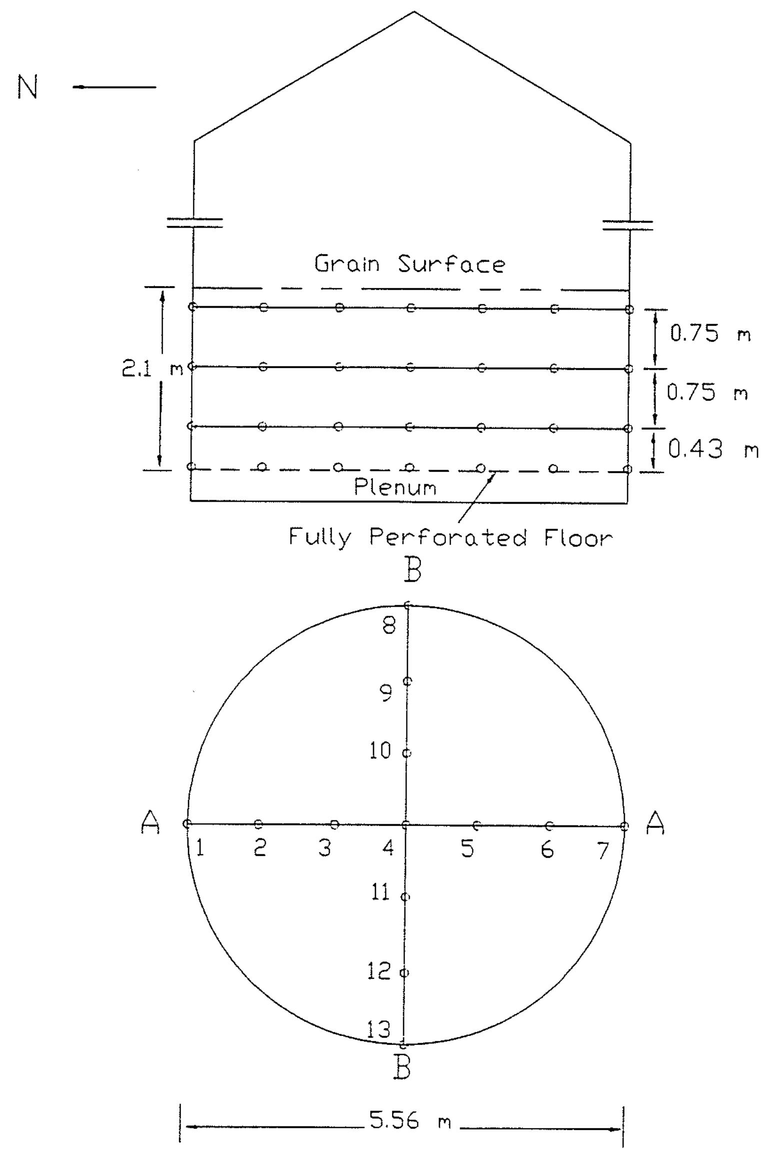

Fig. 5.5. Schematic diagram of the temperature and gas sampling locations (o) in a 5.56-m-diameter bin with a fully perforated floor (farm Bin 2).

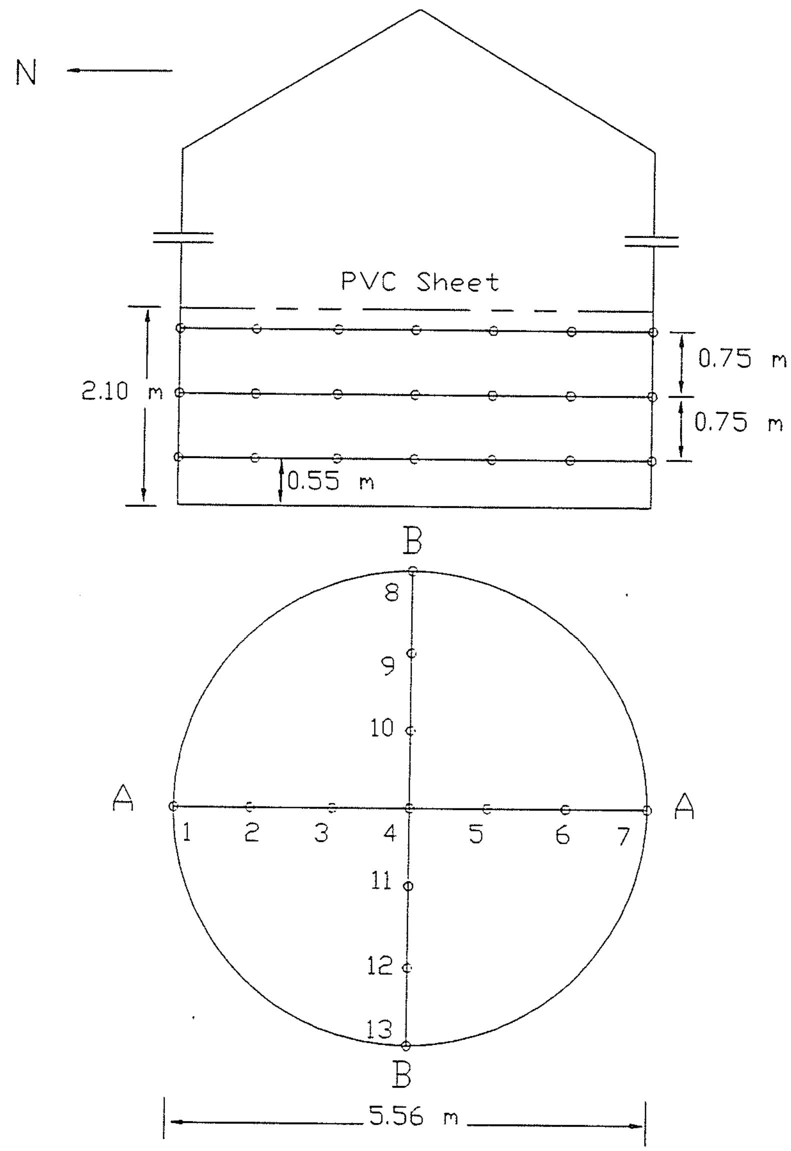

Fig. 5.6. Schematic diagram of the temperature and gas sampling locations (o) in a 5.56-m-diameter bin with a concrete floor (farm Bin 3).

1.18-m, and 1.93-m from the perforated floor) (Fig. 5.5). In all the farm bins, there were 13 sampling locations for gas samples and temperatures at each level (Fig. 5.4, 5.5, and 5.6). The gas sampling tubes and thermocouple wires were held in place by taping them to 1.6-mm-diameter steel wires extending across two perpendicular diameters. Both the gas sampling tubes and thermocouple wires were taken out of the bin through small holes made in the wall at each radius and at each level. The gas sampling tubes were fitted with rubber septa at the outer end. The thermocouple wires were connected to a multichannel switch box which in turn was connected to a temperature indicator. The visible holes in the bin wall and the holes made for inserting thermocouple wires and gas sampling tubes were all sealed using silicon sealant. A polyvinylidene chloride sheet was spread on the inside face of the door and taped to the wall to reduce the escape of gases through door to wall joints.

5.2.1.2 Experimental Procedure

Farm Bins 1 and 2 were filled with Canadian Hard Red Spring wheat purchased from a local farmer. An auger was used to fill the bins. While loading the grain into the bins, about 0.5 kg wheat samples were collected at regular intervals for a total of 20 kg. This sample was reduced to 1.0 kg using a Boerner divider and was sent to the Canadian Grain Commission for grading. Wheat had 1.0% dockage by mass and 11.8% moisture content and was graded No. 1.

The levelled height of the wheat bulk in farm Bin 1 was 2.50 m and that in farm Bin 2 was 2.1 m. Dry ice was used to create high levels of CO_2 in the grain bulk. The effects on the distribution of CO_2 in the grain bulk of the point of application of dry ice, the amount and frequency of application of dry ice, and the grain surface left open or covered with a polyvinylidene chloride sheet were studied. The details of various experimental combinations are summarised in Table 5.2. To determine the amount of CO_2 loss through various possible leaks in the bin, experiments were conducted in an empty bin with concrete floor (farm Bin 3). A (50 mm x 50 mm square) lumber frame 2.1-m-tall was

Table 5.2. **Summary details of experiments conducted in 5.56-m-diameter bolted metal bins.**

Experiment No.	Bin No.	Grain Surface	Amount and Frequency of Dry Ice Application	Duration of Experiment (h)	Point of Application of Dry Ice
1	1	Open	28 kg at 0 and 24 h	48	In the duct
2	1	Covered	28 kg at 0 and 24 h	48	In the duct
3	1	Covered	54 kg at 0 h, 56 kg at 24 h and 52 kg at 48 h	72	In the duct
4	1	Covered	30 kg at 0, 24, 48, and 60 h, 15 kg at 12 h, and 28 kg at 36 h	73	In the duct
5	1	Covered	27 kg at 0 and 24 h	48	On the grain surface under the PVC sheet
6	1	Covered	17.5 kg at 0 h, and 16.3 kg at 24 h	48	In a 10.0-cm-diameter perforated tube along the central axis
7	2	Open	28 kg at 0 and 24 h	48	In the plenum under the fully perforated floor
8	2	Covered	28 kg at 0 and 24 h	48	In the plenum under the fully perforated floor
9*	3	Empty Bin	28 kg at 0 and 24 h	48	On the concrete floor
10#	3	Empty Bin	28 kg at 0 and 24 h	48	On the concrete floor
11&	3	Empty Bin	28 kg at 0 and 24 h	48	On a PVC sheet spread on the floor
12	1	Covered	28 kg at 0, 24, 48, 72, 96, 152, 168, 192, and 216 h	240 h	14 kg in the duct and 14 kg on the grain surface under the PVC sheet

* A PVC sheet was spread at a height of 2.10 m from the floor and taped to the wall. The door was sealed using a PVC sheet.
\# In addition to the sealing in Experiment 9, the bin wall to concrete floor joints were sealed using silicone sealant.
& In addition to the sealing in Experiment 9, a PVC sheet was spread on the floor and taped to the bin wall.

constructed inside farm Bin 3. A polyvinylidene chloride sheet was spread on the frame and taped to the bin wall using duct tape to create the experimental domain underneath. Three experiments were conducted in this bin by progressively sealing: (i) the door using a polyvinylidene chloride sheet (Experiment 9), (ii) bin wall to concrete floor joints using silicon sealant (Experiment 10), and (iii) excluding the concrete floor by spreading a polyvinylidene sheet on the floor (Experiment 11) (Table 5.1).

The temperature and gas samples for CO_2 were obtained at 3, 6, 9, 24, 27, 30, 33, and 48 h after the first introduction of dry ice except for the following experiments:

1. Experiment 1: at 2, 4, 6, 8, 10, 24, 27, 30, 33, and 48 h after the first introduction of dry ice.
2. Experiment 3: at 3, 6, 9, 25, 27, 30, 33, 48, 51, 54, 57, and 72 h after the first introduction of dry ice;
3. Experiment 4: at 3, 6, 9, 12, 15, 21, 24, 30, 33, 36, 39, 42, 48, 51, 57, 60, 70 and 73 h after the first introduction of dry ice;
4. Experiment 12: every 24 h for 10 days; and

Before drawing the gas samples for analysis the sampling tubes were flushed by drawing 10 mL to 20 mL gas and discharging it to the atmosphere. Then gas samples were collected using 10-mL syringes. The gas samples were analyzed for CO_2 concentrations using gas chromatographs (a Perkin-Elmer model Sigma 3B gas chromatograph or a Hewlett Packard 5890 gas chromatograph). Both gas chromatographs were equipped with a thermal conductivity detector and a 1-mL fixed volume injection loop.

After each experiment, the wheat-filled bins (Bins 1 and 3) were aerated for about an hour to bring down the CO_2 concentrations in the intergranular air to atmospheric level, and left undisturbed until the next experiment. Prior to the start of the next experiment the grain was again aerated for about

15 min. Prior to the start of another experiment, a few random gas samples were drawn to check whether the initial CO_2 concentration had dropped to the atmospheric level.

5.2.2 Bioassay

Instrumented farm Bins 1 and 3 filled with wheat to a height of 2.50 m were used to study the mortality of 4- to 8-wk-old rusty grain beetle, C. ferrugineus, adults under elevated CO_2 levels. Farm Bin 1 with the cylindrical duct on the floor was used as the test bin and farm Bin 3 with the concrete floor was used as a control bin. The door of the test bin was sealed by spreading a PVC sheet on the inside face of the door and taping it to the bin wall. The door of the control bin was not sealed. The grain surfaces in both the test and control bins were covered with PVC sheets that were taped to the wall.

Fifty rusty grain beetle adults and about 10 g of wheat germ were put in each small bag made of honey straining cloth (0.02 mm^2 aperture openings). These bags were placed in metal tubes of 16.0-mm-inside diameter (hereafter referred to as insect tubes). Perforations for an easy entry of CO_2 to the insect bags were made in the insect tubes at points where the insect bags were placed (Fig. 5.7). The insect tubes were inserted into the bins through 19.0-mm-inside diameter and 88.9-mm-long nipples bolted to the wall. The joints between the nipples and the bin wall were sealed with silicon sealant to prevent the escape of intergranular gases to the atmosphere. Sixty tubes were inserted in each of the test and control bins. There were 12 different locations along four equally spaced radii at 0.55-m, 1.30-m, and 2.05-m-from the floor through which the insect tubes were inserted. The sampling locations for the insects were the same as for CO_2 except that at sampling location 4 (Figs. 5.4 and 5.6) there were two insect bags. In total there were 210 insect bags inserted in each bin (10,500 insects per bin).

The experiment was run for 10 d starting from 15 September, 1992. In the test bin, 28 kg of dry ice (14 kg through the perforated duct on the floor and 14 kg above the grain surface underneath

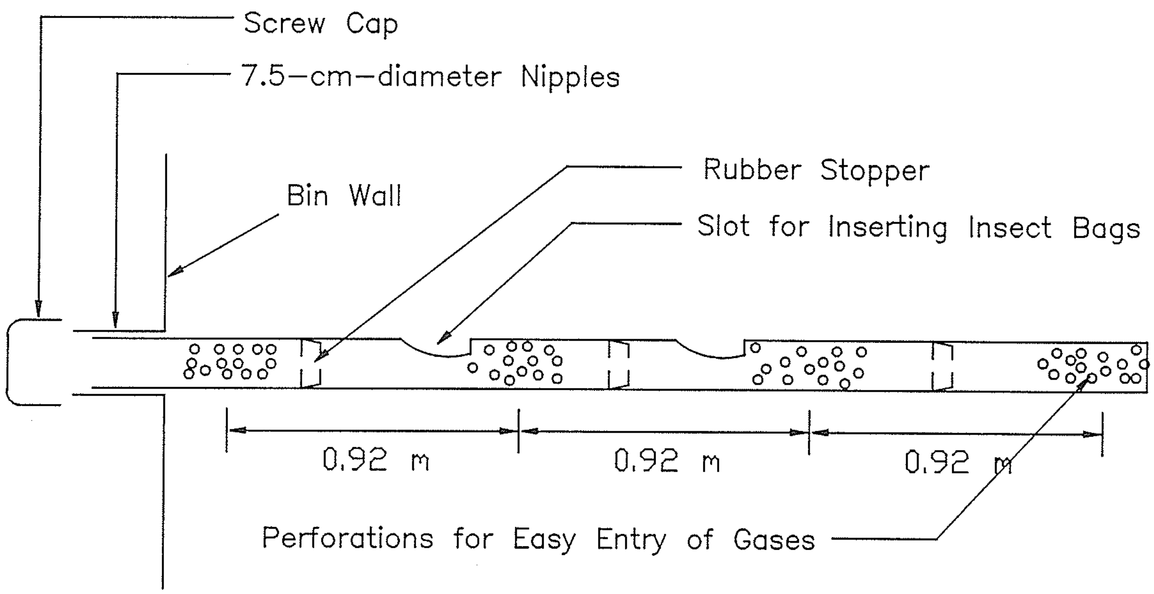

Fig. 5.7. Schematic diagram of an insect tube.

the PVC sheet), was introduced at 0, 24, 48, 72, 96, 152, 168, 192, and 216 h. Gas samples and temperatures were taken every 24 h and the insect samples were taken every 48 h from both the test and control bins. In the laboratory, the insects were allowed to potentially recover at 25±2°C for 48 to 72 h before counting dead and live insects.

5.3 Determination of Apparent Flow Coefficient of CO_2 Through Wheat Bulks

5.3.1 The Apparatus

The apparatus used for determining the apparent flow coefficient of CO_2 through a wheat bulk was similar to the one used by Singh et al. (1984). Two main components of the apparatus are: (i) a cubical gas chamber of 0.35 m x 0.35 m x 0.35 m inside dimensions, and (ii) a 0.164-m-inside diameter and 0.5-m-long grain chamber (Fig. 5.8). The gas chamber was fabricated using 9 mm thick plexiglass acrylic sheet and the cylindrical grain chamber was cut from a plexiglass acrylic tube of 6 mm wall thickness. On one face of the gas chamber a 0.176-m-diameter hole was drilled and the grain chamber was joined to it using 3M adhesive (3M Canada Ltd., London, Canada). On the inner end of the cylinder a fixed screen and on the outer end a detachable screen were attached to hold the grain in the cylinder. On one side of the gas chamber a 0.1-m-diameter hole was drilled through which the dry ice could be introduced. This hole was closed by a detachable cover during experiments. Three plexiglas acrylic tubes of 6.2-mm-inside diameter and 20-mm-length were fitted to three faces of the gas chamber (ports 1-3, Fig. 5.8). About 10 mm of the tube length projected out of the faces. The projected length of the tube was cut to a 9.5-mm-outside diameter so that a rubber septum, 9.5-mm-inside diameter, could be tightly fitted to close the ports during experiments. Four similar ports (ports 6-9, Fig. 5.8) were located along the length of the grain chamber. Additionally, two other ports were installed near the inlet end of the grain chamber. Two 3.2-mm-outside diameter semi-rigid nylon tubes were inserted through rubber septa fitted to these ports, to take gas samples from the grain and gas chamber near the

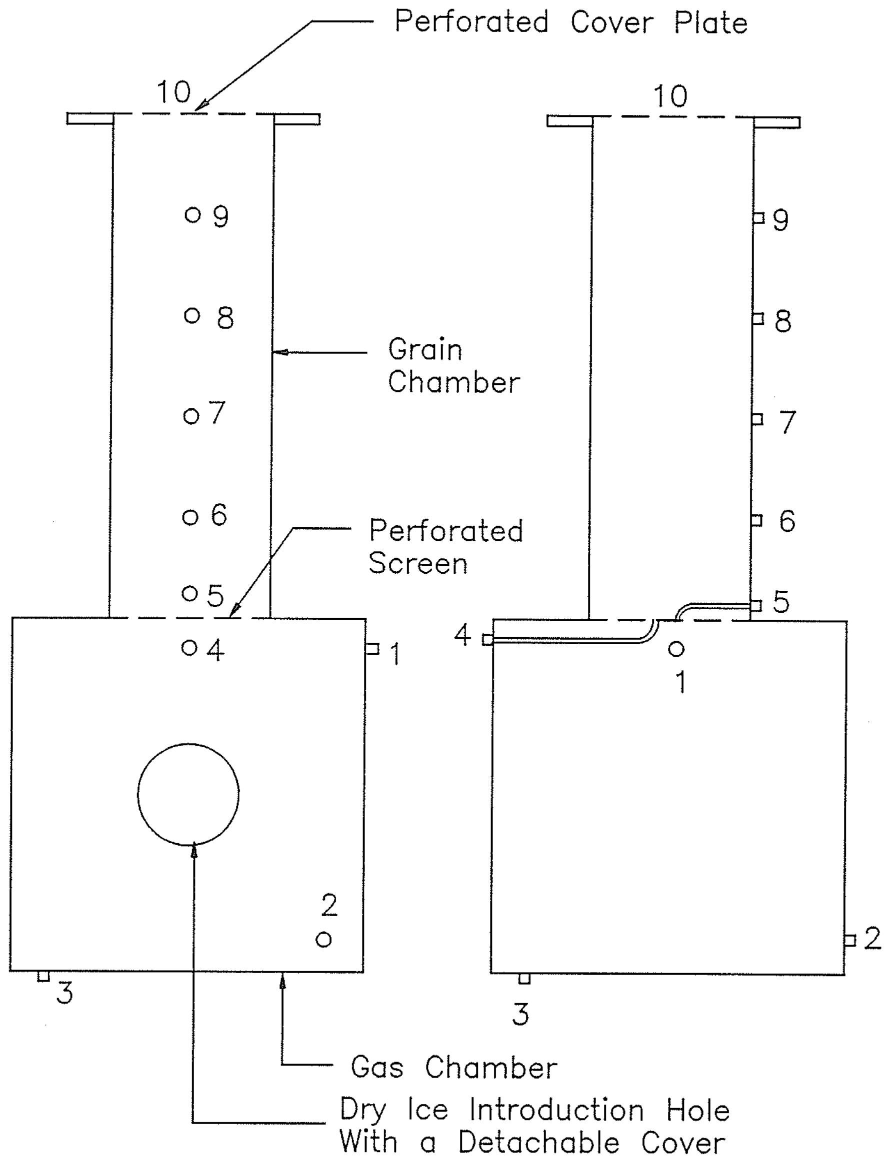

Fig. 5.8. Schematic diagram of the apparatus used for measuring the apparent flow coefficient of CO_2 through wheat bulks.

perforated screen (ports 4 and 5, Fig. 5.8).

5.3.2 Sample Preparation

Canadian Hard Red Spring wheat graded No.1 by the Canadian Grain Commission was used in the experiments. The wheat obtained from a local farmer had 0.5% dockage by mass and 12.8% moisture content. The effect of moisture content on the apparent flow coefficient of CO_2 through wheat was studied at five different moisture contents. Wheat samples of about 25 kg each were conditioned to five different moisture contents (11.0, 12.3, 14.0, 16.5 and 18.5% wet basis) by adding a predetermined quantity of distilled water and mixing in a small concrete mixer, or by spreading the wheat on the floor and allowing it to dry until the desired low moisture content was reached. The prepared samples were sealed in plastic bags and allowed to equilibrate at room temperature for about 24 h, and then stored at -20°C until used in the experiments. About 48 h before the start of the experiment the samples were conditioned to the experimental temperature. An environmental chamber with a relative humidity (RH) controller was used to create the required experimental temperatures. The RH of the environmental chamber was set at 75%.

5.3.3 Experimental Procedure

The wheat sample was filled in the grain chamber by manually pouring it from the top end of the grain chamber. In most experiments the mass of the grain filling in the grain chamber was measured to calculate the in-situ bulk density of the wheat. The particle density of various moisture content wheat samples was determined using a toluene displacement method (Mohsenin 1970). Using the in-situ bulk density and the particle density, the porosity of the wheat bulk in the grain chamber was estimated (Mohsenin 1970).

A known quantity of dry ice was placed in the gas chamber and the opening was sealed using the detachable lid. Gas samples were taken at 10 min, and at 1 h intervals for 8 h after the introduction of dry ice. When drawing gas samples about 5-mL of gas was flushed out and about 8-mL of gas was taken in 10-mL syringes. These gas samples were analyzed for CO_2 concentrations using a gas chromatograph (Hewlett Packard 5890) with a thermal conductivity detector and 1-mL fixed volume injection loop.

A total of 16 experiments were conducted (five different moisture contents at 20°C and using 40 g dry ice, five different temperatures at 12.3% moisture content and using 40 g dry ice and six different amounts of dry ice at 20°C and at 12.3% moisture content). Each experiment was repeated three times.

6. RESULTS AND DISCUSSION

6.1 CO_2 Distribution in Pilot Bins

6.1.1 Iso-Concentration Lines

Lines of constant CO_2 concentrations along section A-A of Bin 1 (Fig. 5.1), and along sections A-A and B-B of Bins 2 and 3 (Figs. 5.2 and 5.3, respectively) were drawn by interpolating the measured CO_2 concentrations at various locations, separately at all sampling times. These plots, drawn using the CALCOMP plotting subroutines (University of Manitoba Computer services), are for the mean CO_2 concentrations of three replicates at various experimental conditions (Figs. 6.1 to 6.13). The iso-concentration lines of measured CO_2 concentrations of individual replicates are shown in Appendix Figs. B.1 to B.39. The measured CO_2 concentrations along with the mean, standard deviations, and coefficient of variations among three replicates for various experiments are shown in Appendix Table A.1 to Table A.9. The coefficient of variation among three replicates was less than 10% in 74.5% of the samples in all the experiments. In 97.6% of the samples the deviation among replicates was less than 25%. Maximum deviations were observed at level 5 (Figs. 5.1, 5.2, and 5.3) where the CO_2 concentrations were usually low. At level 5, which is at a distance of 0.05 m from the grain surface, small undulations in the grain surface might cause large differences in the measured CO_2 concentrations which would have resulted in larger coefficients of variation among replicates in that level. The grain temperatures did not vary much during the three replicates of any experimental combination. The maximum observed deviation in the grain temperature in any experiment was ±2.7°C (Table A.10).

During the initial few hours after the introduction of dry ice, the CO_2 gas flooded along the floor in the bins. In Bin 1, for example, 1 h after the introduction of dry ice the CO_2 concentrations near the wall in the horizontal direction reached about 10% while a point at the same distance in the vertical direction had a concentration of only about 2% (the 10 and 2% concentration lines in Fig. 6.1). In Bin

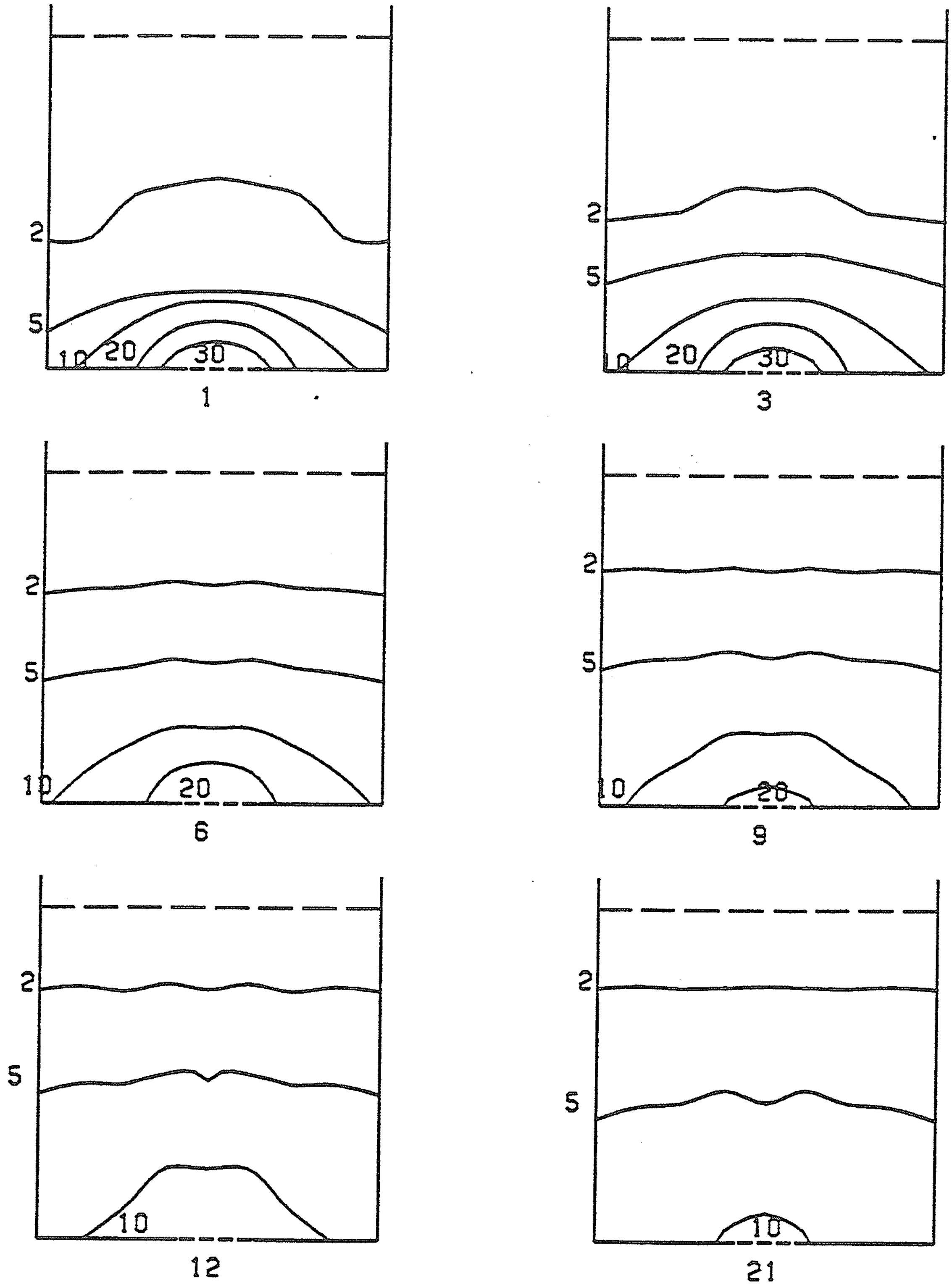

Fig. 6.1. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.1) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with open top surface at various sampling times after the introduction of 180 g of dry ice under a 0.3-m-diameter perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

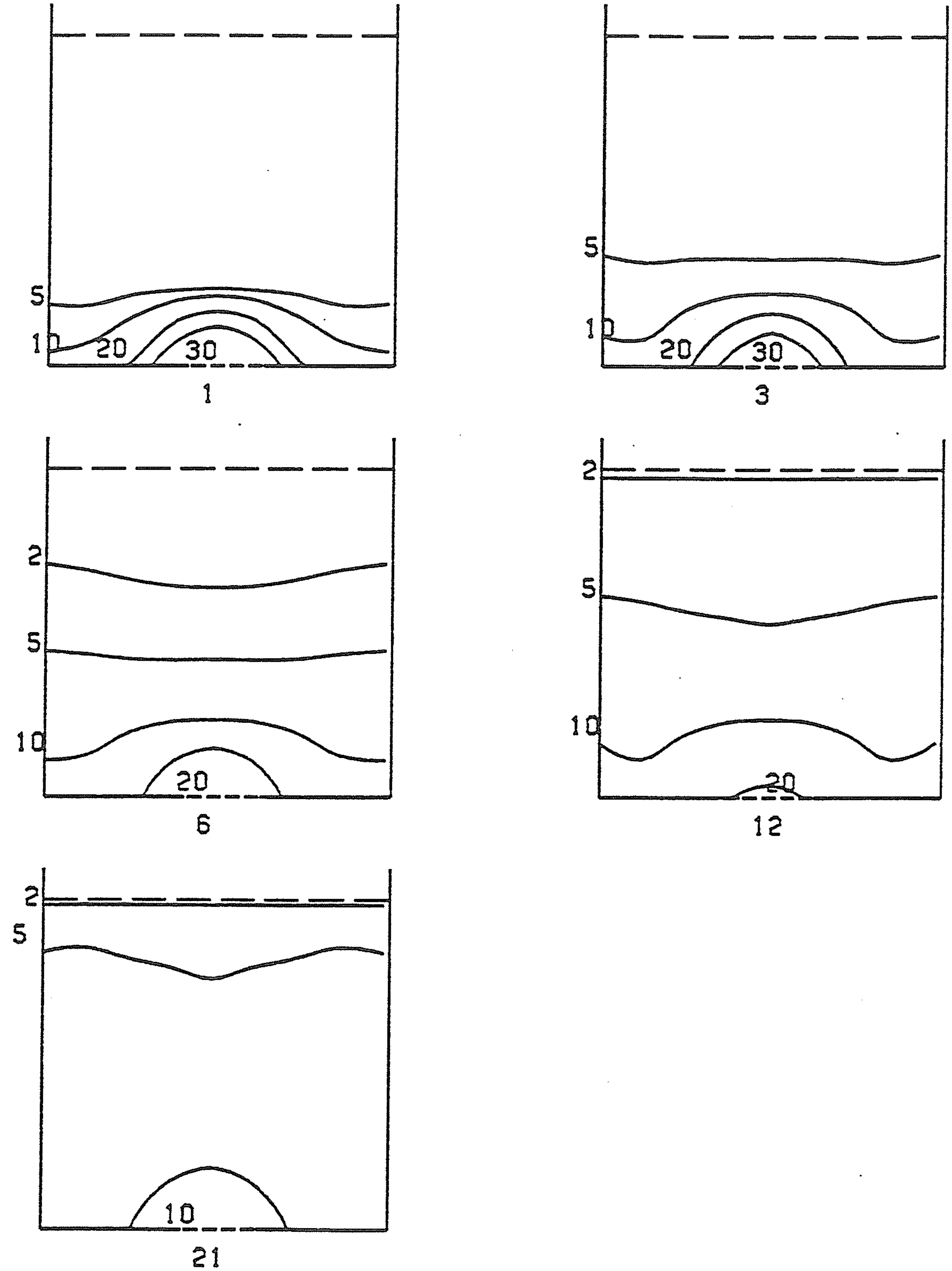

Fig. 6.2. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.1) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with covered top surface at various sampling times after the introduction of 180 g of dry ice under a 0.3-m-diameter perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

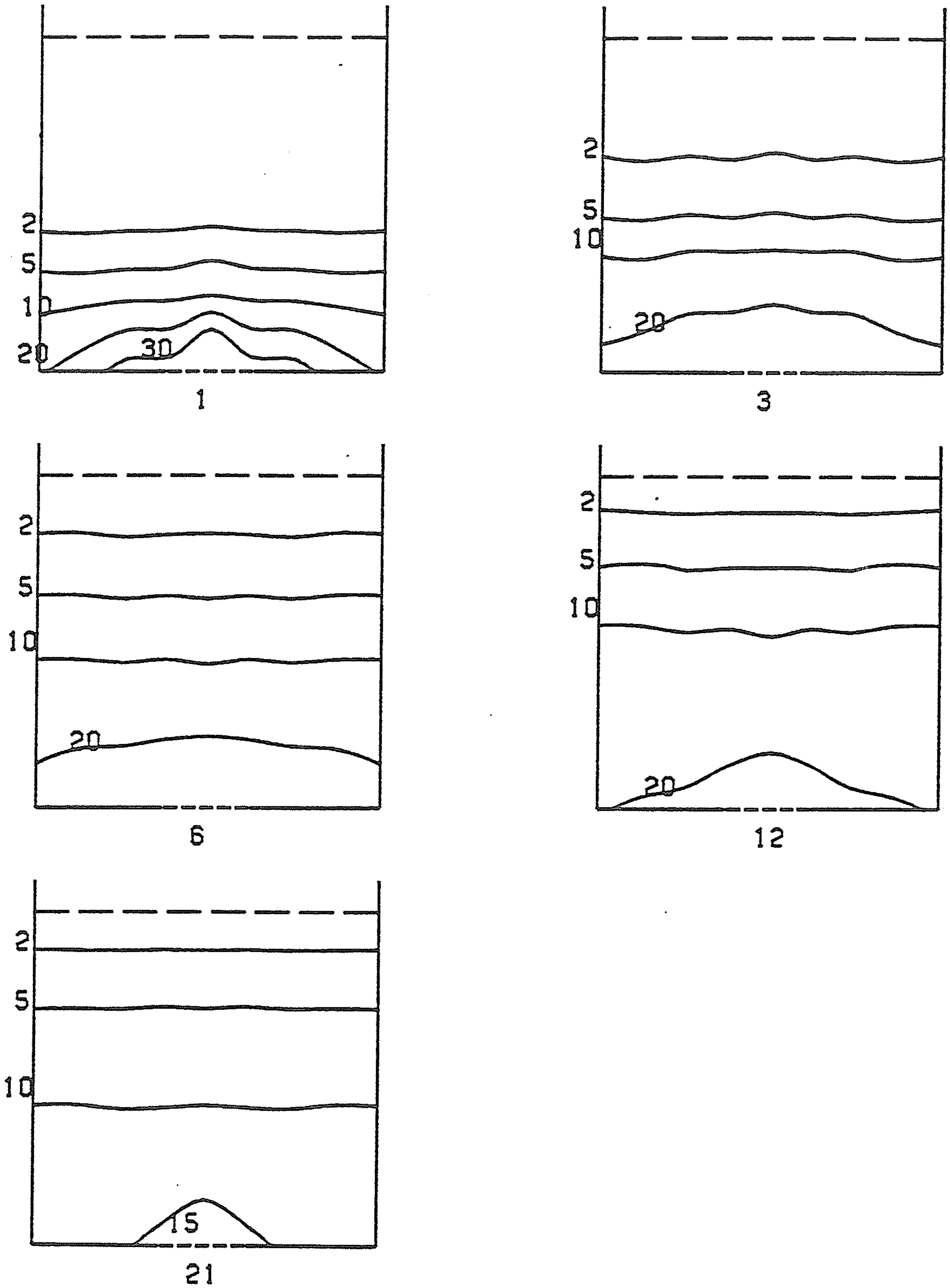

Fig. 6.3. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.2) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with open top surface at various sampling times after the introduction of 370 g of dry ice under a 1.14 x 0.36 m perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

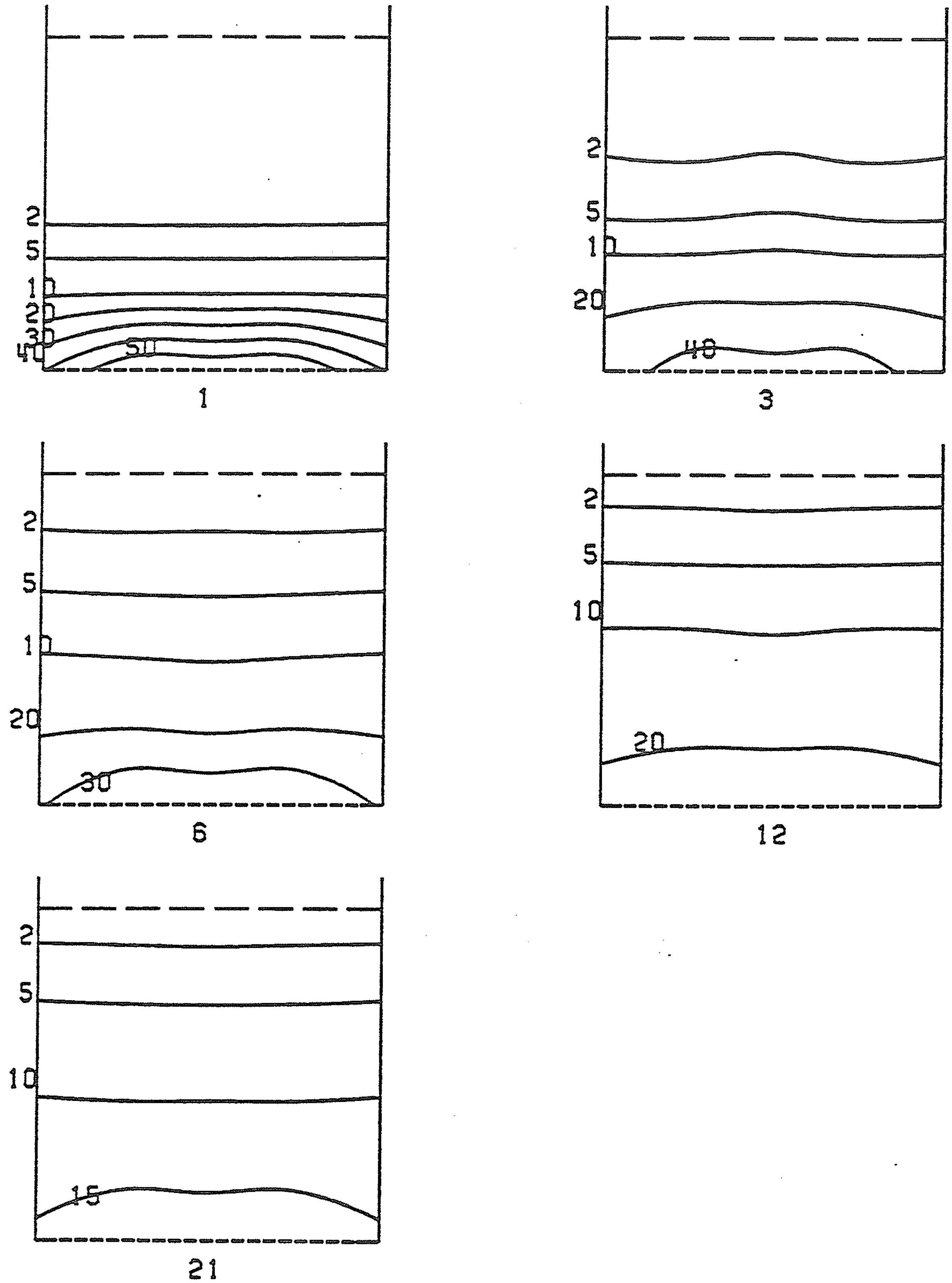

Fig. 6.4. Lines of constant CO_2 concentrations (%) along section B-B (Fig. 5.2) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with open top surface at various sampling times after the introduction of 370 g of dry ice under a 1.14 x 0.36 m perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

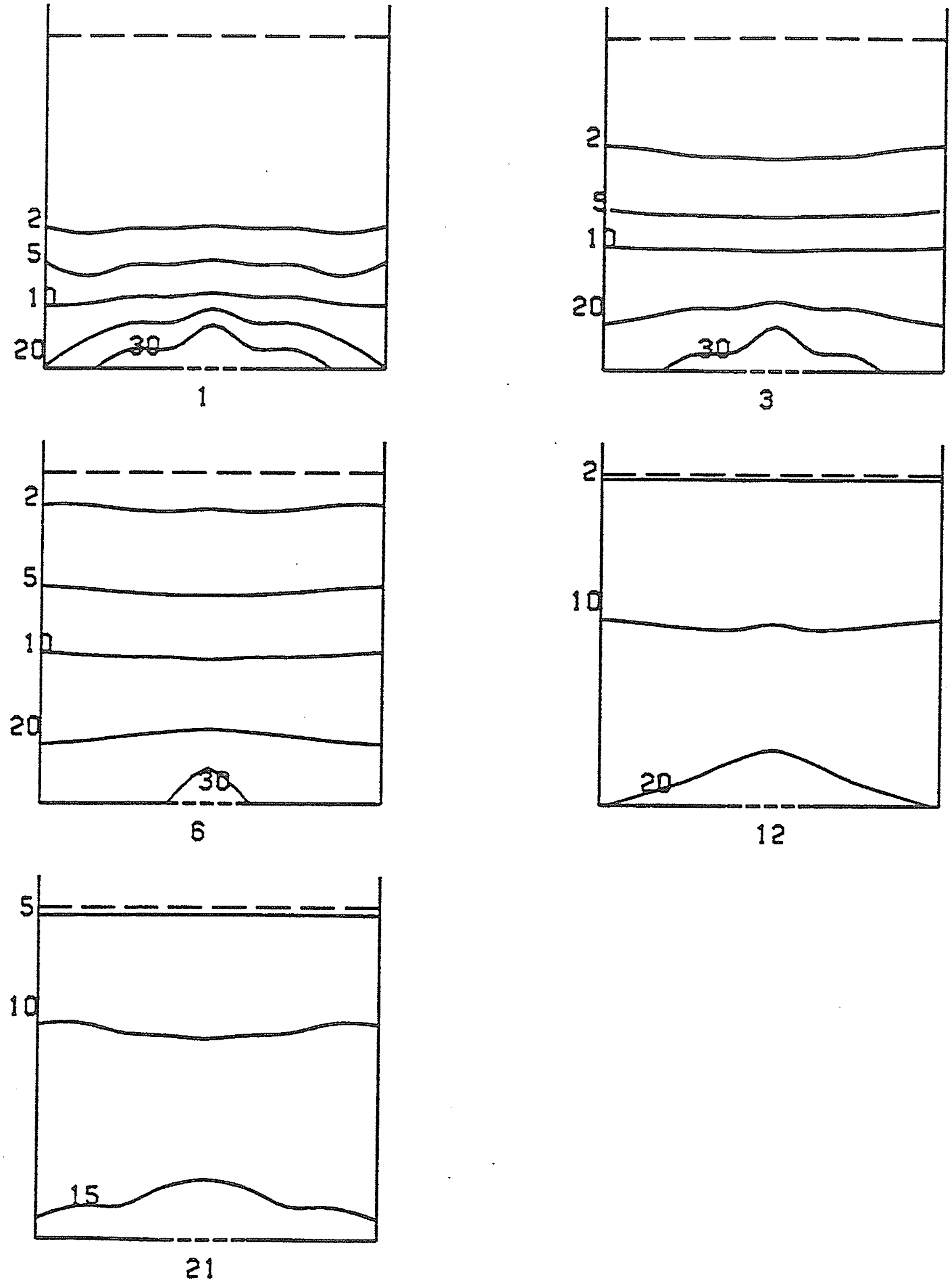

Fig. 6.5. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.2) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with covered top surface at various sampling times after the introduction of 370 g of dry ice under a 1.14 x 0.36 m perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

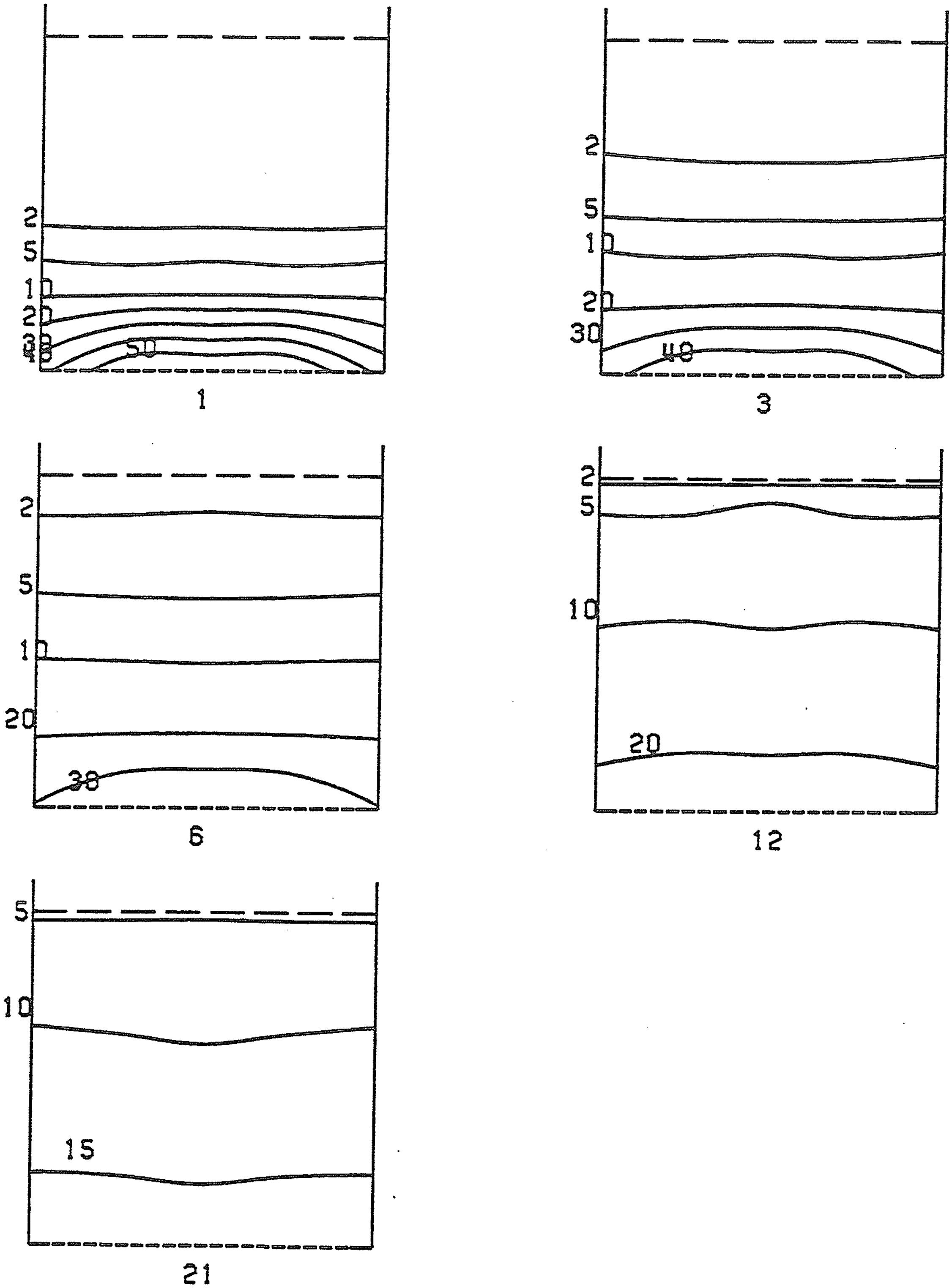

Fig. 6.6. Lines of constant CO_2 concentrations (%) along section B-B (Fig. 5.2) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with covered top surface at various sampling times after the introduction of 370 g of dry ice under a 1.14 x 0.36 m perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

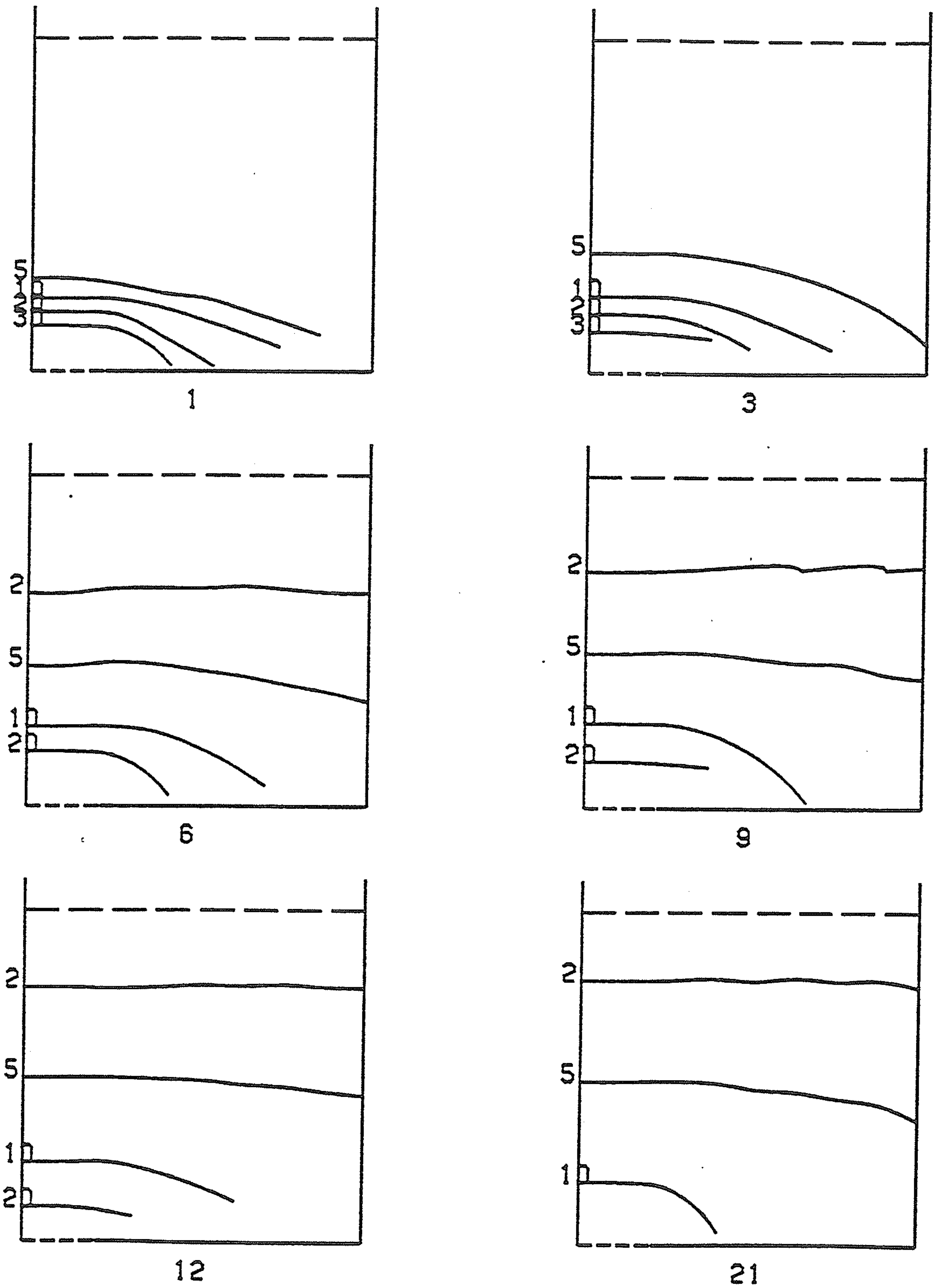

Fig. 6.7. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.3) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with open top surface at various sampling times after the introduction of 180 g of dry ice under a 0.3-m-diameter perforated floor opening near the wall. (The numbers beneath each bin indicate the sampling times (h)).

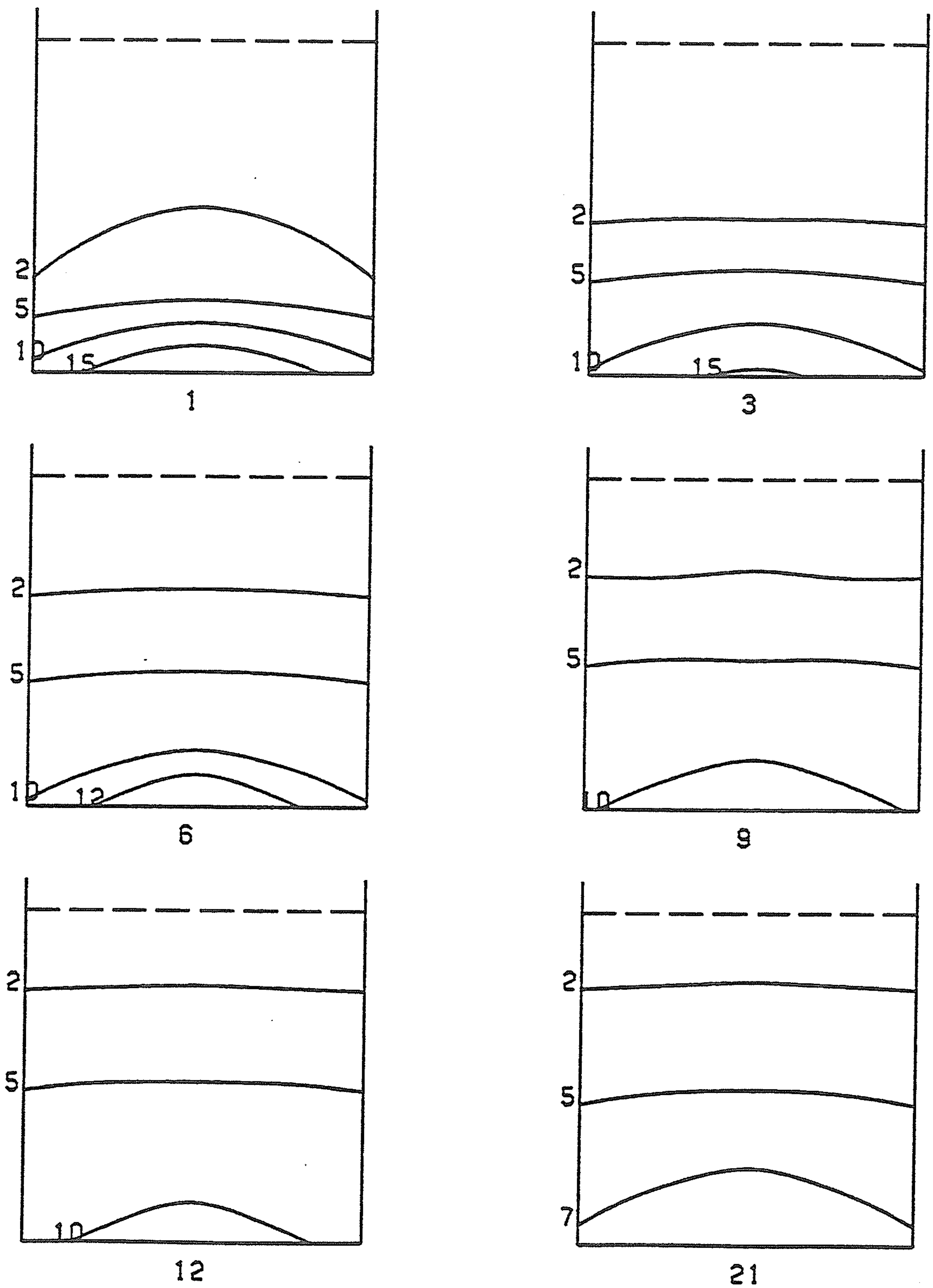

Fig. 6.8. Lines of constant CO_2 concentrations (%) along section B-B (Fig. 5.3) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with open top surface at various sampling times after the introduction of 180 g of dry ice under a 0.3-m-diameter perforated floor opening near the wall. (The numbers beneath each bin indicate the sampling times (h)).

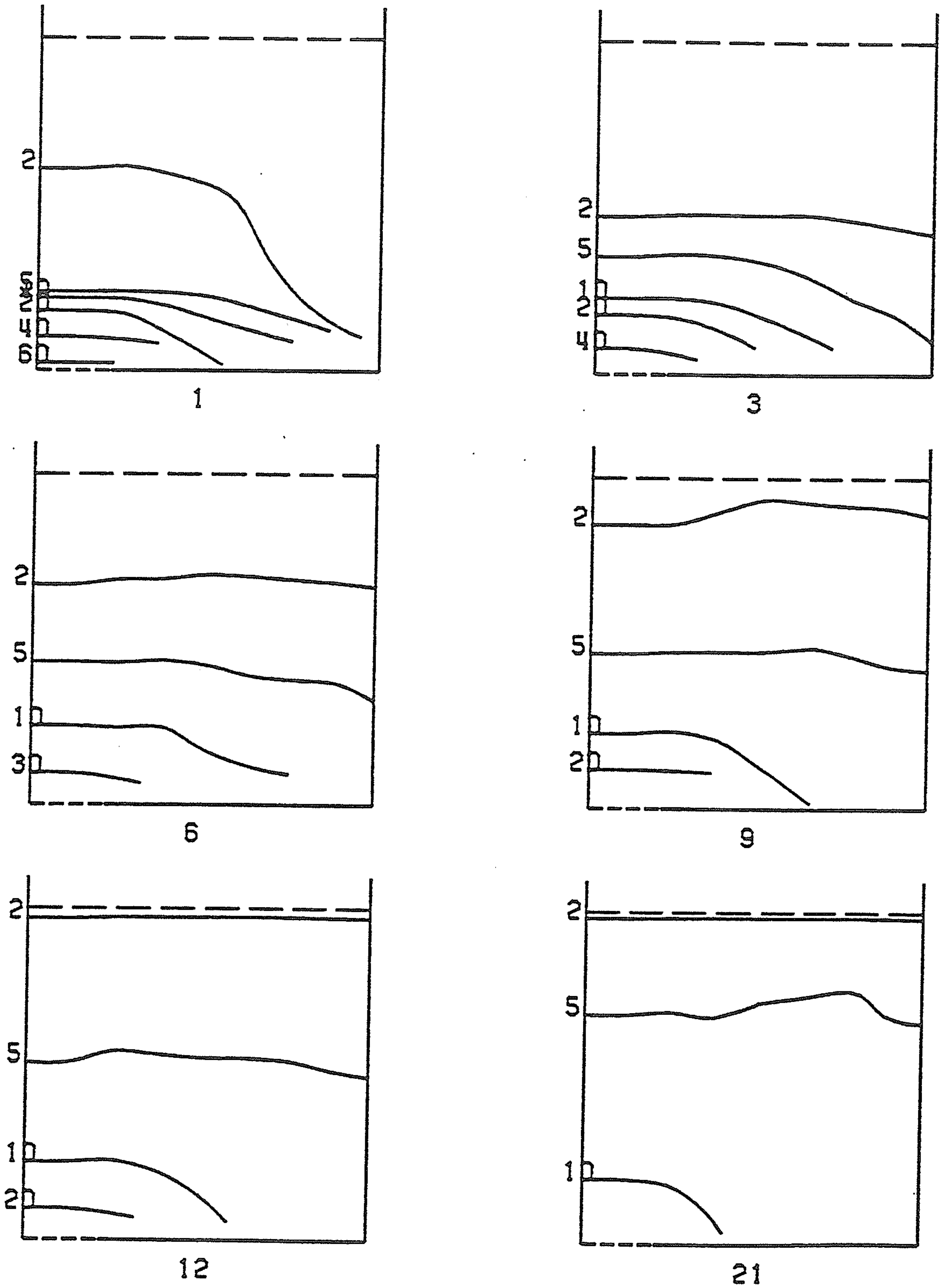

Fig. 6.9. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.3) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with covered top surface at various sampling times after the introduction of 180 g of dry ice under a 0.3-m-diameter perforated floor opening near the wall. (The numbers beneath each bin indicate the sampling times (h)).

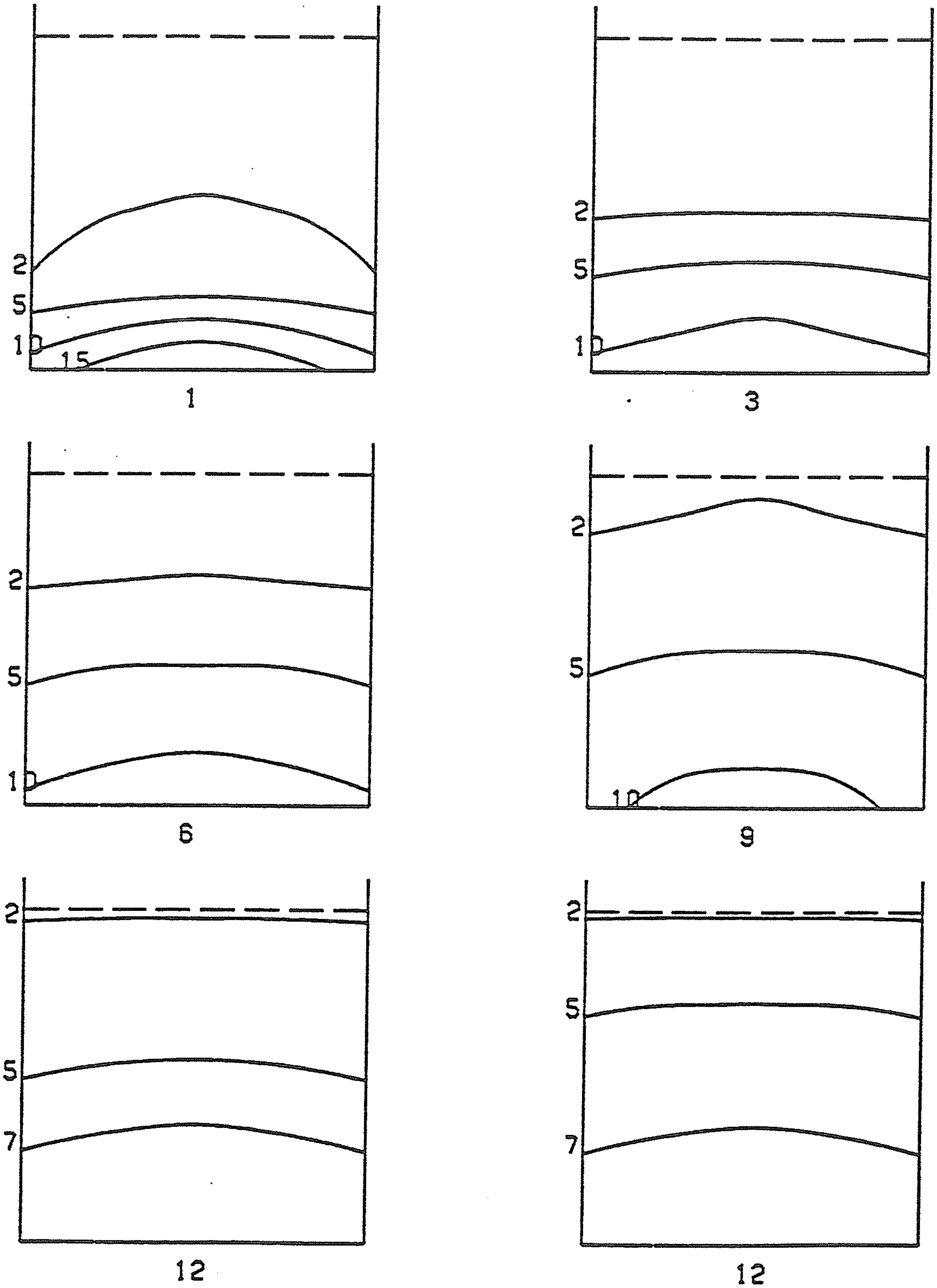

Fig. 6.10. Lines of constant CO_2 concentrations (%) along section B-B (Fig. 5.3) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with covered top surface at various sampling times after the introduction of 180 g of dry ice under a 0.3-m-diameter perforated floor opening near the wall. (The numbers beneath each bin indicate the sampling times (h)).

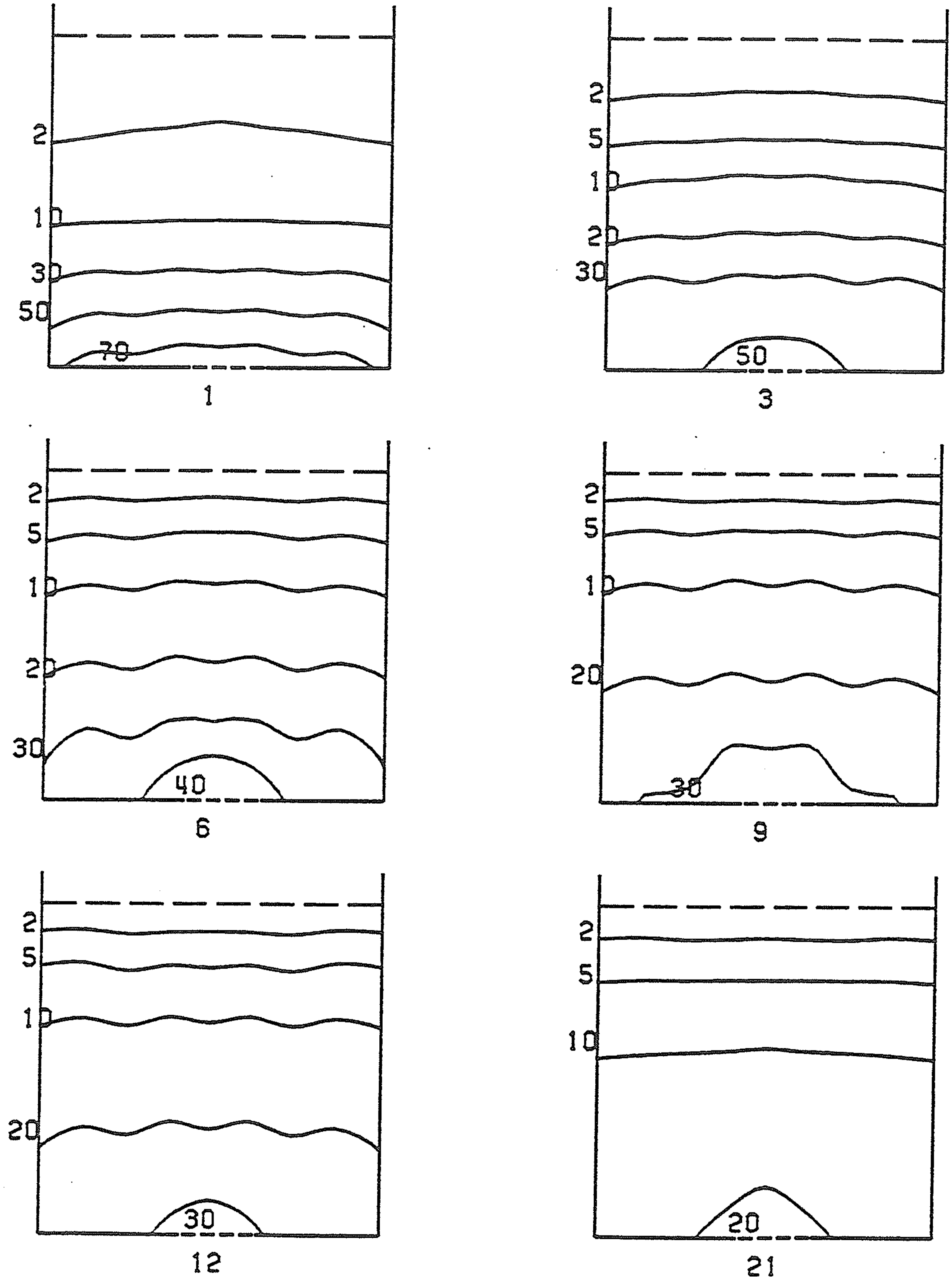

Fig. 6.11. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.1) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with open top surface at various sampling times after the introduction of 540 g of dry ice under a 0.3-m-diameter perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

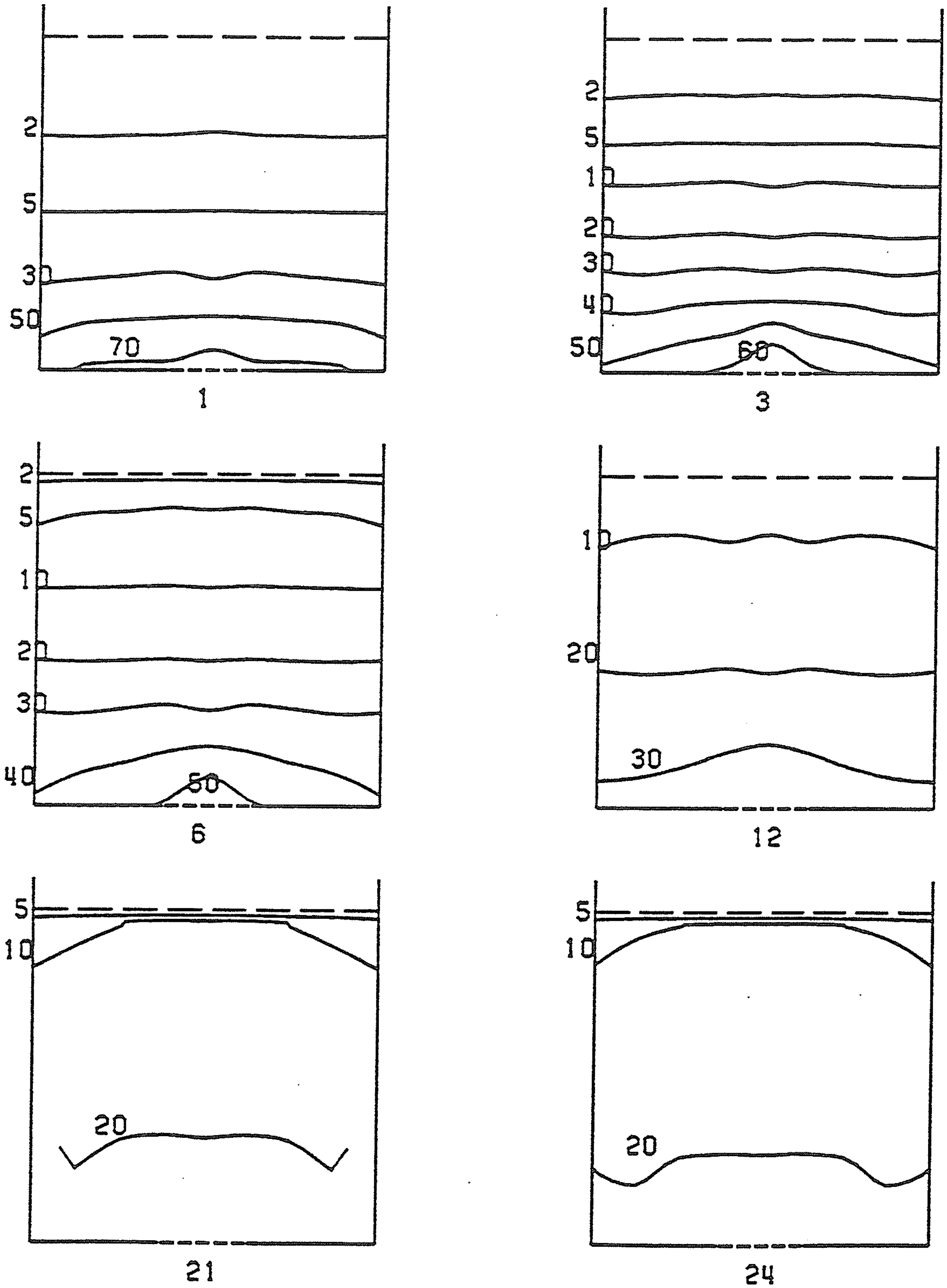

Fig. 6.12. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.2) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with covered top surface at various sampling times after the introduction of 740 g of dry ice under a 1.14 x 0.36 m perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

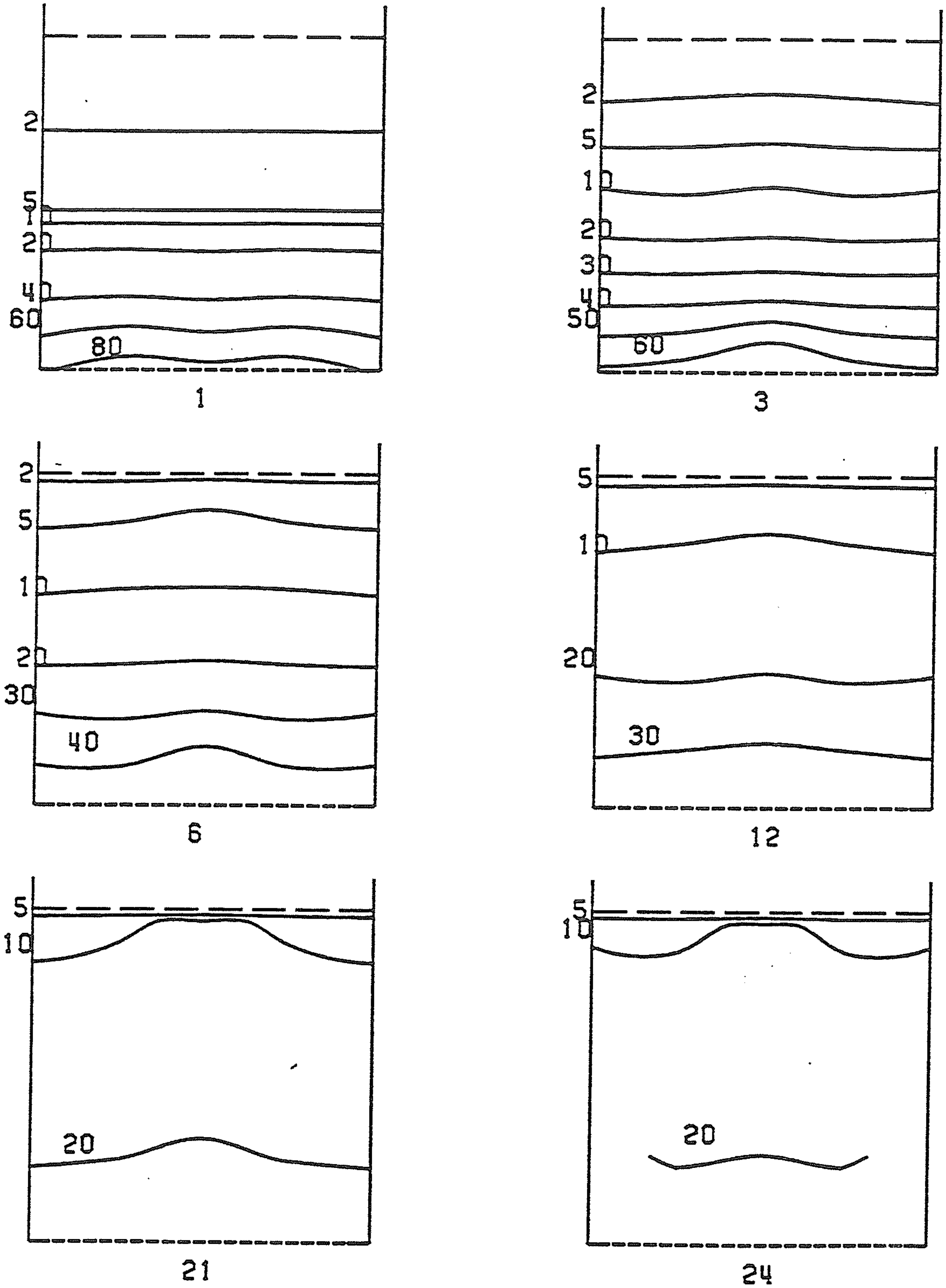

Fig. 6.13. Lines of constant CO_2 concentrations (%) along section B-B (Fig. 5.2) of a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with covered top surface at various sampling times after the introduction of 740 g of dry ice under a 1.14 x 0.36 m perforated floor opening near the centre. (The numbers beneath each bin indicate the sampling times (h)).

2, with an input of 370 g of dry ice, the lower corners (0.53-m-from the floor opening) of the bulks reached about 22% CO_2 along section A-A at 3 h while at a point about 0.66-m above the floor along the central axis the concentration reached only about 5% (Figs.6.3, and 6.5). Similar high CO_2 concentrations in the lower portions of the wheat bulk were observed with 540 g dry ice in Bin 1 and 740 g dry ice in Bin 2. (Figs. 6.11, 6.12 and 6.13). Guiffre and Seagal (1984), while discussing the practical aspects of CA storage, cautions against the layering of CO_2 in the bottom portions of the grain bulk thus creating reduced concentrations in the top portions. To attain uniform CO_2 concentrations throughout the grain bulk in large silos, it is often essential to recirculate the intergranular air from bottom to top using a fan and piping system (Jay et al. 1970, Wilson et al. 1980, Navarro et al. 1986). The flooding of CO_2 in the lower regions of the wheat bulks might be because of the following reasons:

(i) CO_2 is about 1.5 times heavier than air (the density of CO_2 at a temperature of 20°C is 1.815 kg m^{-3} compared with the density of air of 1.189 kg m^{-3} at the same temperature). The gravity forces acting on the heavier CO_2 molecules tend to reduce their rate of movement in the vertical direction.

(ii) When dry ice sublimates into CO_2 gas it creates a slow releasing pressure. For example, 180 g dry ice will create an absolute pressure of 107.8 kPa at 20°C in the dry ice box of Bin 1 (Fig. 5.1), if the box was perfectly sealed. This pressure causes a mass movement of CO_2 through the grain mass. The resistance of grains and oilseeds to bulk flow of air is lower in the horizontal direction than in the vertical direction (Kumar and Muir 1986, Jayas et al. 1987, Alagusundaram et al. 1992). Wheat has about 30 to 60% higher resistance to airflow in the vertical direction than in the horizontal direction (Kumar and Muir 1986). Because of the low resistance to flow in the horizontal direction the bulk movement of CO_2 gas might be more in the horizontal direction than in the vertical direction.

Once the pressure created by the dry ice sublimation is dissipated, the CO_2 gas starts moving into the bulk due to molecular diffusion. At atmospheric pressure, the coefficient of diffusion is the same in both the horizontal and the vertical directions (Singh et al. 1984). Six hours or later after the introduction of dry ice the CO_2 concentrations in the top 2/3 height of the wheat bulks were nearly uniform along the bin diameter in all the three bins and along both the cross sections (Figs. 6.1 to 6.13). There were gradients in the vertical direction. For an effective control of insects using modified atmospheres the introduced gases should be uniformly distributed in the grain bulk and a minimum required CO_2 concentration (about 35%) should be maintained at all locations in the grain bulk. Although CO_2 was not distributed uniformly along the bin cross sections in the bottom portions, the concentrations were higher than in the top portions. When using CO_2 gas to kill insects in a farm bin, care should be taken to check the CO_2 levels in the top portions of the grain bulk. The pilot bin experiments indicate that reduced area for CO_2 inlet (0.071 m^2 in Bins 1 and 3 and 0.41 m^2 opening in Bin 2), or the location of the floor opening (near the centre in Bin 1 and near the wall in Bin 3), did not reduce the uniformity of CO_2 distribution along the horizontal bin cross sections in the top regions of the bulk (Figs. 6.1 to 6.13). Therefore, in an existing farm bin with a concrete floor, it will be possible to introduce the dry ice through the auger inlet hole in the door to create lethal concentrations at every location in the bulk.

Statistical t tests were performed to compare the means of the measured CO_2 concentrations at various locations and at various times in different experiments. The CO_2 concentrations in a bulk that was refilled after each replicate were not significantly different (the level of significance for this comparison and all that are to follow was $\alpha=0.05$) from a bulk that was not refilled after each replicate. Out of 264 sample measurements, 212 were not significantly different. The wheat used in the experiments was relatively free of foreign material (0.5% foreign material), and each time the bins were filled by pouring the wheat from buckets. In a farm bin, however, the in-situ bulk density of grain in a bin filled, with canola, using a spreader is more than that of a spout-filled bin (which in turn reduces the porosity of the bulk), and the fine materials tend to fall near the centre and near the wall of the bin and the chaff is distributed near the bin wall (Singh 1987). The reduced porosity or the different porosity in different regions of the bulk will alter the pattern and the rate of movement of the CO_2 gas through the bulk. Jay and Pearman (1973) in their study on controlling natural infestations in a corn bulk observed low CO_2 concentrations at locations where the accumulation of dust and foreign material were highest. They hypothesized that uniform CO_2 concentrations in the bulk could be achieved quickly if the foreign material content were less. Further experiments in large grain bulks with different foreign material contents should be conducted to study the effect of filling method and the distribution of foreign material on the distribution of CO_2.

Although the CO_2 gas distributed nearly uniformly along the horizontal bin cross sections in the top portions of the grain bulk, the concentrations in uncovered grain bulks were low near the top compared to the other portions of the grain bulk (Figs. 6.1, 6.3, 6.4, 6.7, 6.8, and 6.11), due to an immediate dissipation of CO_2 to the atmosphere above the grain surface. For an uncovered grain bulk, if a 100% CO_2 concentration is maintained over a long period of time under a fully perforated floor, the concentration gradient under steady state condition will be linear along the bulk height, indicating that it will not be feasible to create a concentration of over 35% in the top 1/3 height of the bulk. Covering the grain surface with a PVC sheet, however, considerably increased the concentrations near the top portions of the bulk (Figs. 6.2, 6.5, 6.6, 6.9, 6.10, 6.12, and 6.13). For example, at 21 h after the introduction of dry ice in Bin 1, the 2% concentration line was about 1/4 height below the grain surface in an open top grain surface, whereas it was just near the grain surface in the covered grain bulk (Figs 6.1 and 6.2).

The means of the measured CO_2 concentrations at various locations in open and covered grain surfaces were compared using statistical t-tests. In Bin 1, 159 out of 209 CO_2 samples, in Bin 2, 110 out of 247 samples, and in Bin 3, 123 out of 288 samples in a grain bulk with open grain surface were significantly different from samples in the grain bulk with covered grain surface. The major effect of covering the grain surface was to increase the CO_2 concentrations near the top portions of the bulk. In all three bins most CO_2 samples at levels 3, 4 and 5 (97% of samples in bin 1, 92% in Bin 2 and 94% in Bin 3) were significantly different, with the observed concentrations in the covered bulks always being higher than the uncovered bulks (Appendix A). For example, 21 h after the introduction of dry ice the average CO_2 concentration at the level 5 with 370 g of dry ice in Bin 2 with open grain surface was 0.72% compared to 8.93% when the grain surface was covered with a PVC sheet. Thus, covering the grain surface is an efficient way of retaining the CO_2 gas within the grain bulk. As expected, increasing the amount of dry ice increased the CO_2 concentrations significantly. In Bin 1, with 540 g of dry ice the CO_2 concentrations in 242 out of 264 samples were higher than with 180 g dry ice and in Bin 2, 740 g dry ice increased CO_2 concentrations at 259 out of 286 samples over the 370 g dry ice. McGaughey and Akins (1989), based on their study on CA treatment of grains in corrugated steel bins, found that the gas requirement in an uncovered grain bulk was 10 times more than the gas requirement in a covered grain bulk for creating the same levels of CO_2 concentrations in both the grain bulks. For a CA treatment in non-airtight bins, it will be necessary to cover the grain surface with a PVC sheet to achieve high concentrations in the top portions of the bulk.

6.2 CO_2 Distribution in Farm Bins

6.2.1 Iso-Concentration Lines

The measured CO_2 concentrations at various sampling points and at different times are given in Appendix C (Tables C.1. to C.12.) Lines of constant CO_2 concentrations were drawn by linearly interpolating the measured concentrations at various sampling locations and at different sampling times. A typical plot of iso-concentration lines of measured CO_2 at various sampling times in Experiment 1

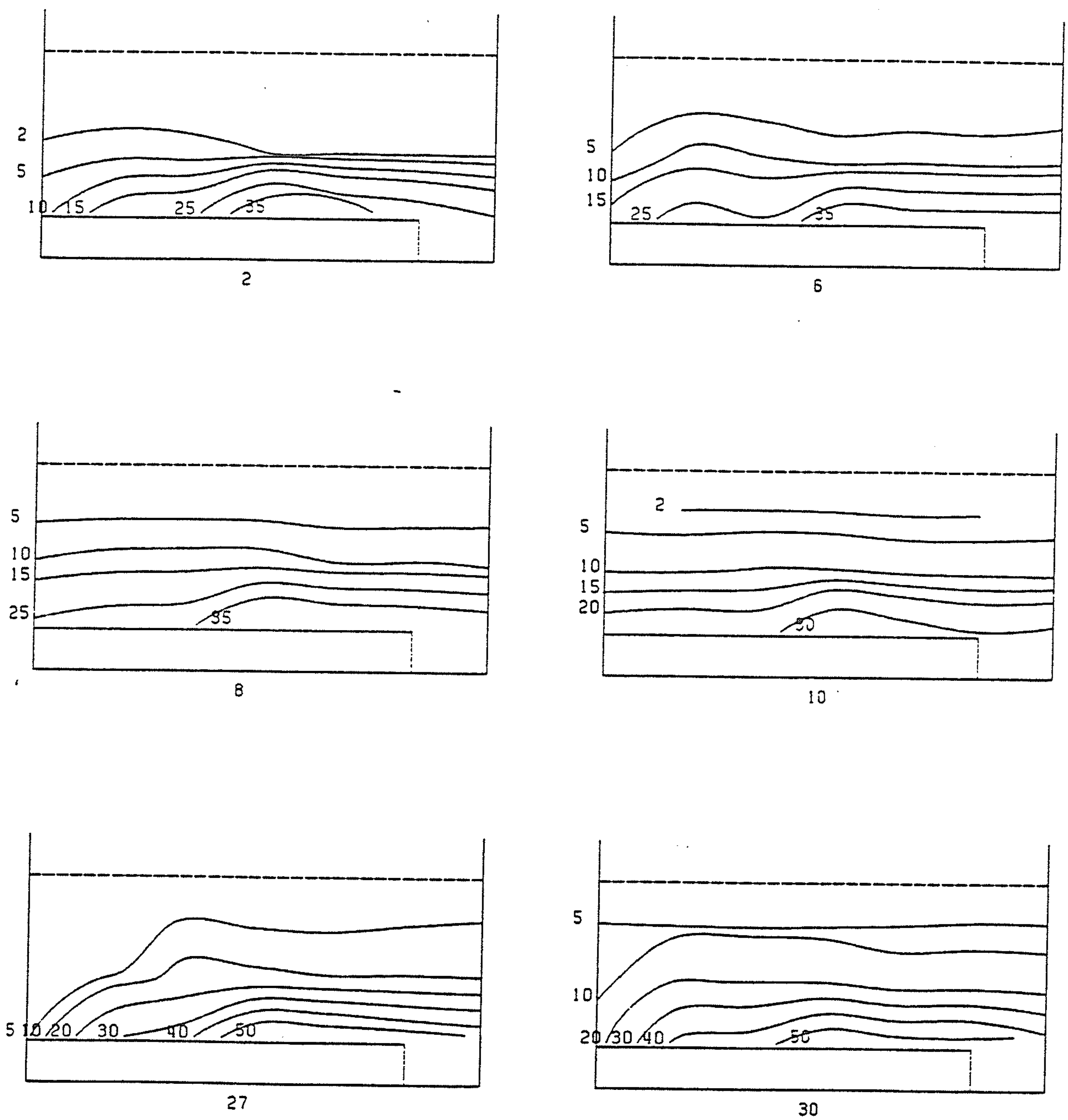

Fig. 6.14. Lines of constant CO_2 concentrations (%) along section A-A (Fig. 5.4) of a 5.56-m-diameter bin containing wheat to a depth of 2.50 m with open top surface at various sampling times after the introduction of dry ice (28 kg each at 0 and 24 h) in the aeration duct. (The numbers beneath each bin indicate the sampling times (h)).

along section A-A (Fig 5.4) of farm Bin 1 with an open grain surface is shown in Fig. 6.14. The iso-concentration plots for all other experiments are shown in Appendix D (Figs. D.1. to D.22). Irrespective of the point of application of dry ice (through the circular duct on the floor as in Experiment 2, on the grain surface underneath the plastic sheet as in Experiment 5, or near the central axis of the grain bulk as in Experiment 6), the CO_2 concentrations were higher in the bottom portions of the wheat bulk than in the top portions (Figs. D.3, D.4, D.9, D.10, D.11 and D.12, and Tables C.2, C.5, and C.6). For example at 48 h in Experiment 2, the average CO_2 concentration at 2.05-m-height from the floor was 4.04% compared to 8.72% at a height of 0.55-m from the floor. The average CO_2 concentrations at heights of 2.05-m and 0.55-m from the floor in Experiment 5 were 11.87 and 31.63%, respectively and in Experiment 6 were 11.65 and 26.65%, respectively. As explained in Section 6.1.1 the accumulation of CO_2 in the bottom portions of the bulk was mainly due to the gravity forces acting on the heavier CO_2 molecules. Jay (1980) stated that, in a non-airtight storage bin the heavier CO_2 molecules will sink from the top to bottom. In an airtight bin, if sufficiently long time is allowed, the CO_2 concentration throughout the bulk will become nearly uniform due to molecular diffusion. This hypothesis, however, should be validated. The rapid downward movement of CO_2 gas has been effectively used for distributing chemical fumigants in stored grain bulks (Gilby 1983). Calderon and Carmi (1973) showed that methyl bromide can be readily moved to the bottom of a 17-m-tall wheat bulk when CO_2 in the form of dry ice is used as a carrier gas.

For nearly the same amount of dry ice input in Experiment 5 (the dry ice introduced on the grain surface underneath the covering sheet) the CO_2 concentrations in the top portions of the grain bulk were higher than the CO_2 concentrations in Experiment 2 (dry ice introduced through the duct on the floor). For example, the location of the 35% concentration line in Experiment 5 (Figs. D.9 and D.10) was nearly the same as the location of the 10% concentration line in Experiment 2 (Fig. D.3 and D.4) at 33 h after the introduction of dry ice. It is possible that a certain amount of air in the top portions of the grain bulk was mixed with CO_2 gas during the movement of the CO_2 molecules from the surface to the bottom, thus creating higher CO_2 concentrations in the top portions of the bulk in Experiment 5 than in Experiment 2. In an airtight bin with no gas recirculation system or in a non-airtight bin, CO_2 can be introduced at the top of the grain surface to create high concentrations in the top portions of the bulk. The observed CO_2 concentrations in Experiment 6 (34 kg of dry ice introduced through a 10-cm-diameter tube near the central axis of the grain bulk), were comparable to the CO_2 concentrations in Experiment 5 (56 kg of dry ice introduced on the grain surface underneath the PVC sheet), (the location of 15 and 20% concentration lines in Figs. D.9, D.10, D.11 and D.12 at 48 h). Although the mass of dry ice required to create the same levels of CO_2 concentrations were lower (about 60% lower) when dry ice was introduced through the central axis (using an inseted perforated tube) rather than on the grain surface, there are practical difficulties in introducing dry ice along the central axis of the bulk because existing bins do not have ducts at their centre and installing the central ducts just for CA treatment would require changing the philosophy of bin design. Because of these practical difficulties this method of introducing dry ice was not considered further.

The CO_2 concentrations at 48 h in farm Bin 2 with fully perforated floor (Fig 5.5) were very low compared to the concentrations in farm Bin 1 with cylindrical aeration duct (Fig. 5.4) (either with open or covered grain surface, Appendix Tables C.1, C.2, C.7 and C.8). In the bin with fully perforated floor, it was not possible to seal the joints in the plenum between the concrete floor and the bin wall, which might have caused a higher rate of loss of CO_2 in this bin. If an existing bin is to be sealed for CA treatment, a bin with no perforated floor or duct should easier to seal.

In an empty bin (farm Bin 3) the CO_2 concentrations became nearly uniform along the horizontal cross sections in a short time (< 3 h). The contour plots for sampling times 24 h and 48 h are not given for the experiments in the empty bin (Figs. D.17 to D.22) because at these sampling times the CO_2 concentrations became nearly uniform throughout the space (Tables C.9, C.10 and C.11). In a bin filled with wheat, the CO_2 concentrations never became uniform throughout the bulk. Because the coefficient of diffusion of CO_2 through air is about 3 times greater than that in a grain bulk (Henderson and Oxley 1944, Bailey 1959, Haugh and Isaccs 1967, Singh et al. 1985) the distribution of CO_2 in an empty space became uniform in a short time. If a wheat filled bin was perfectly sealed and undisturbed for a long duration, the concentrations may become uniform throughout the bulk. In a non-airtight bin, ingress of air through leaks reduces the possibility of the uniformity of CO_2 distribution (Jay 1980).

6.3 Weighted-Volume Average CO_2 Concentrations

6.3.1 Definition

The amount of measured CO_2 concentration data in the pilot and farm bin experiments was very large (the CO_2 at numerous sampling locations in each bin (Sections 5.1, and 5.2), was recorded at several times in each experiment). For easy graphical representation of the measured CO_2 data and for estimating the concentration x time products (ct-products) (Section 6.4), the weighted-volume average CO_2 concentrations for each experiment were calculated using the following procedure.

Weighted-volume average CO_2 was defined as the sum of the product of measured CO_2 concentration at a sampling point and the space volume represented by this sampling point divided by the total volume of the grain bulk. The equation for it is given by:

$$C_w^{ts} = \frac{1}{V_d} \sum_{i=1}^{n} (CO_2)_i \, V_i \qquad (6.1)$$

where:

C_w^{ts} = weighted-volume average CO_2 concentration for the sampling time ts (%),

V_d = total volume of the grain bulk including intergranular air and grain (m^3),

n = number of component volumes represented by one or more sampling points,

$(CO_2)_i$	=	measured CO_2 concentration at a sampling point in volume i (%). If more than one sampling points were present in a subvolume i the arithmetic average of the measured CO_2 concentrations at these sampling points was taken as $(CO_2)_i$,
V_i	=	volume of the component region i (m^3).

6.3.2 Pilot Bins

To estimate the weighted-volume average concentrations for the pilot bin experiments the grain bulks were divided into smaller volumes each represented by one or more sampling points (Figs. 6.15 and 6.16). The bin floor cross sections were divided into smaller areas giving consideration to the pattern of the CO_2 movement. In Bin 1, which was symmetric around the vertical axis, concentric circles were drawn from the bin centre in such a way that the sampling point falls midway between two concentric rings. In Bin 3, concentric circles were drawn from the point where the floor opening touches the bin wall and Bin 2 was divided into rectangular regions. The division along the height of the grain bulk was the same for all the three bins and is shown for Bin 1 in Fig. 6.15. Using the divided volumes and the measured CO_2 concentrations, the weighted-volume average CO_2 concentration for a given sampling time was estimated using eq. 6.1.

6.3.3 Farm Bins

The grain bulks or the empty bin were divided into 39 smaller volumes in farm Bins 1 and 3 (Fig.6.17) and 52 smaller volumes in farm Bin 2 in such a way that the sampling points are at the geometric centre of the sub-divided region in the horizontal direction. The widths of the regions near the wall were half of the width of the regions in the rest of the bulk. The division of the grain bulk in farm Bin 2 was similar to that shown for farm Bins 1 and 3 except that there were 4 levels in farm Bin 2. The weighted-volume average CO_2 concentration for each sampling level and for the whole bin at

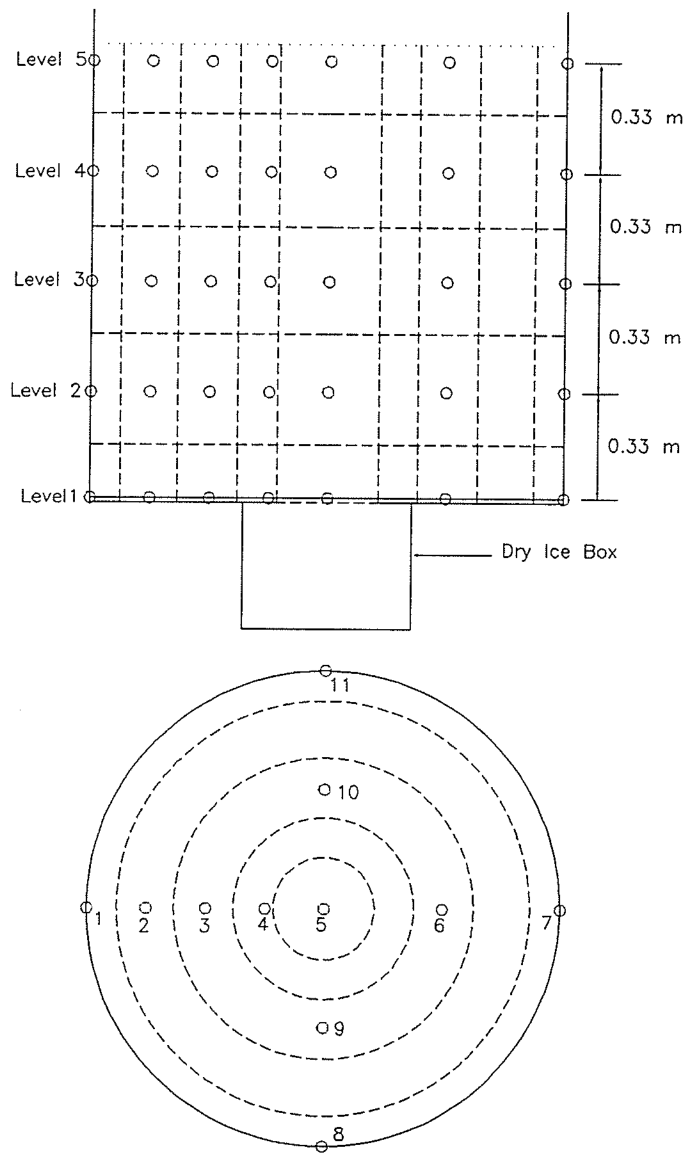

Fig. 6.15. Pilot Bin 1 divided into smaller volumes for determining the weighted-volume average CO_2 concentrations.

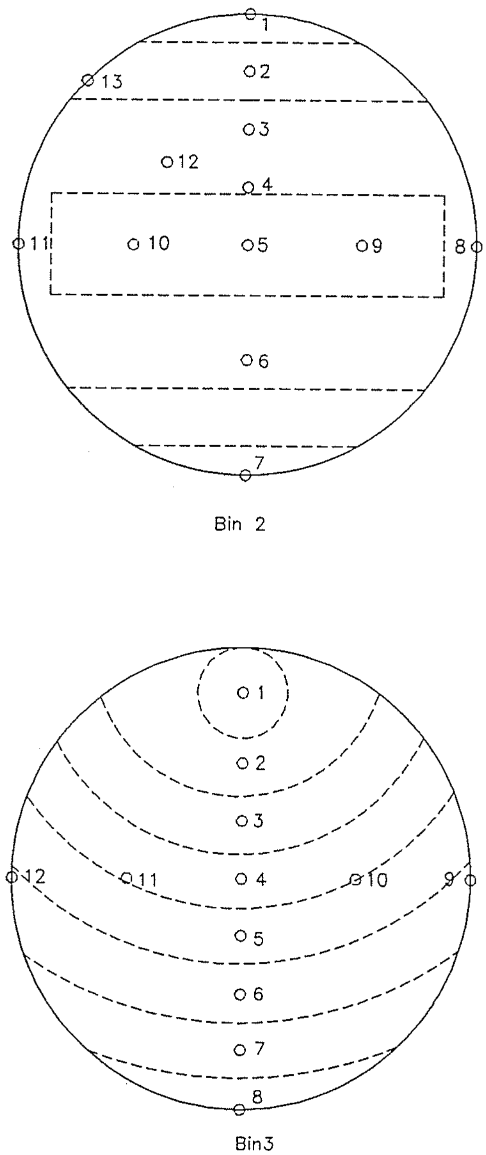

Fig. 6.16. Plan view of the pilot Bins 2 and 3 divided into smaller areas for determining the weighted-volume average CO_2 concentrations (the division in the vertical direction was the same as in Bin 1 shown in Fig. 6.15).

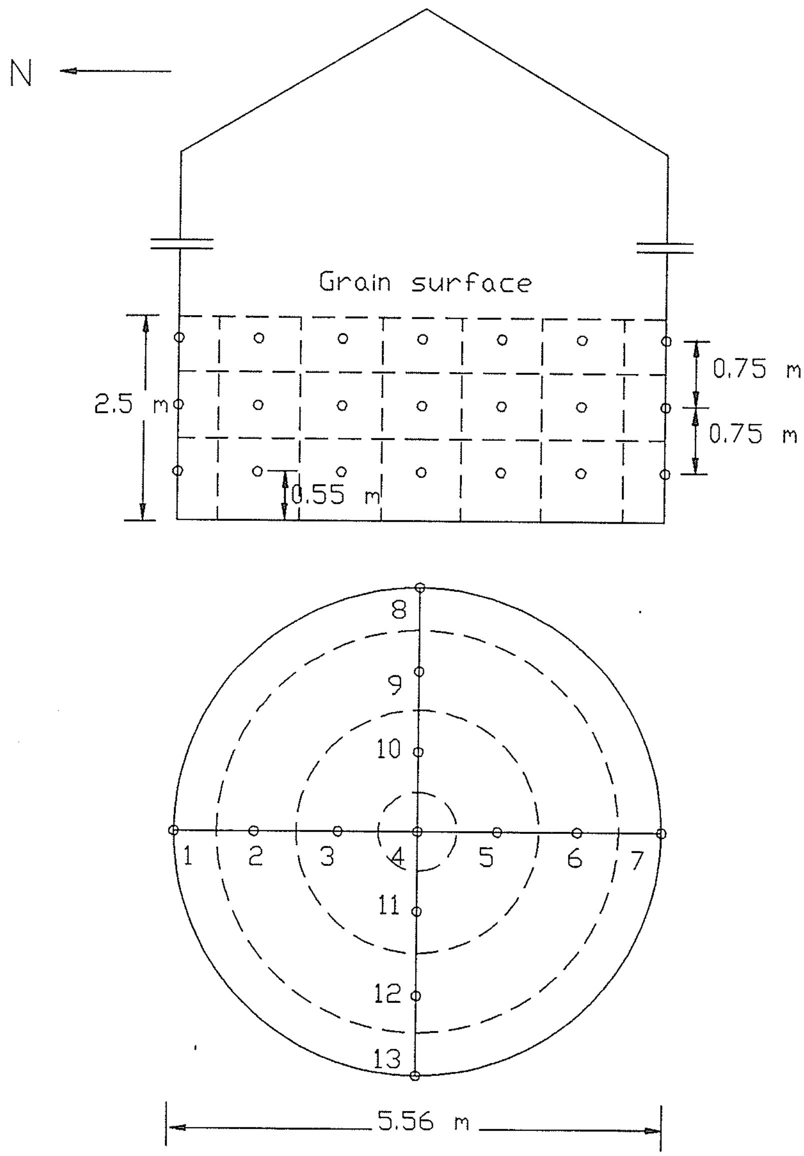

Fig. 6.17. Farm Bin 1 divided into smaller volumes for determining the weighted-volume average CO_2 concentrations. Farm Bins 2 and 3 were divided similarly, but farm Bin 2 had 4 levels and farm Bin 3 had a height of 2.10 m.

every sampling time were estimated using eq. 6.1.

The change in the weighted-volume average CO_2 concentration with time for various experiments in farm Bins 1, 2 and 3 are shown in Figs. 6.18, 6.19, and 6.20, respectively. The CO_2 concentrations in the bulk rose to a peak within the first few hours after the introduction of dry ice and started to decline afterwards. For example, at 24 h in Experiment 2, the average CO_2 concentration in the bin fell to nearly 10% from over 20% at 9 h (Experiment 2 in Fig. 6.18). When larger amounts of dry ice were introduced (as in Experiment 3) or when the frequency of application was increased (as in Experiment 4), the CO_2 concentrations in the bulk were higher. For nearly the same amount of dry ice introduced (162 kg in Experiment 3 and 163 kg in Experiment 4), the weighted-volume average CO_2 concentrations 72 h after the first introduction of dry ice in Experiment 3 was much lower than that observed in Experiment 4 (Experiment 3 and 4 in Fig. 6.18). Due to the high labour requirement, introducing dry ice every 12 h in a farm bin may not be practical. Progressively sealing the bin increased the CO_2 concentrations in the bin (Fig. 6.20). For example, in farm Bin 3, the weighted-volume average CO_2 concentration for the whole experimental space at sampling time 48 h after the first introduction of dry ice increased from 13.20% in Experiment 9 to 15.06% in Experiment 10 to 23.54% in Experiment 11. This is also obvious from the iso-concentration lines of CO_2 (Appendix Figs. D.17 to D.22). At 33 h after the first introduction of dry ice the location of the 30% concentration line in Experiment 9 (Appendix Figs. D.17 and D.18) was the same as that of the 35% concentration line in Experiment 10 (Appendix Figs. D19 and D.20) and that of the 40% concentration line in Experiment 11 (Appendix Figs. D.21 and D.22). Covering the concrete floor had a greater effect than sealing the wall-floor joint. To increase the CO_2 retention in a bin a PVC sheet can be spread on the concrete floor and taped to the bin wall before loading. This will also reduce the corrosion of the reinforcing steel in concrete when CO_2 is adsorbed by the concrete (Banks and McCabe 1988). This approach may not be practically feasible because the insect infestation may occur when the grain is already in the bin.

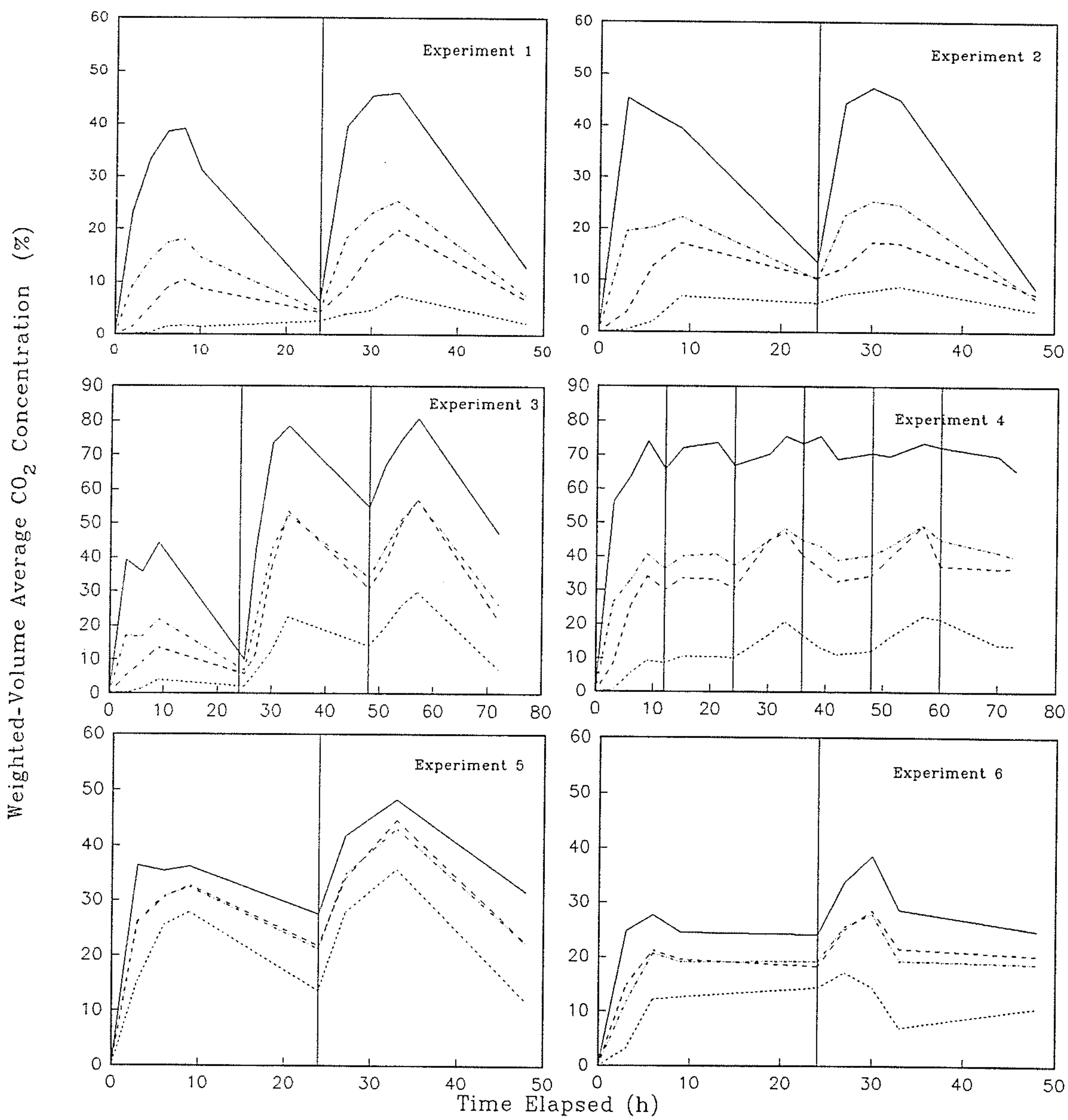

Fig. 6.18. Change in weighted–volume average CO_2 concentrations with time in farm Bin 1 (Table 5.2). Vertical lines indicate the time at which dry ice was introduced

(—— 0.55; ----- 1.30; and ······· 2.05 m from the floor and ·-·-· average for the whole bin)

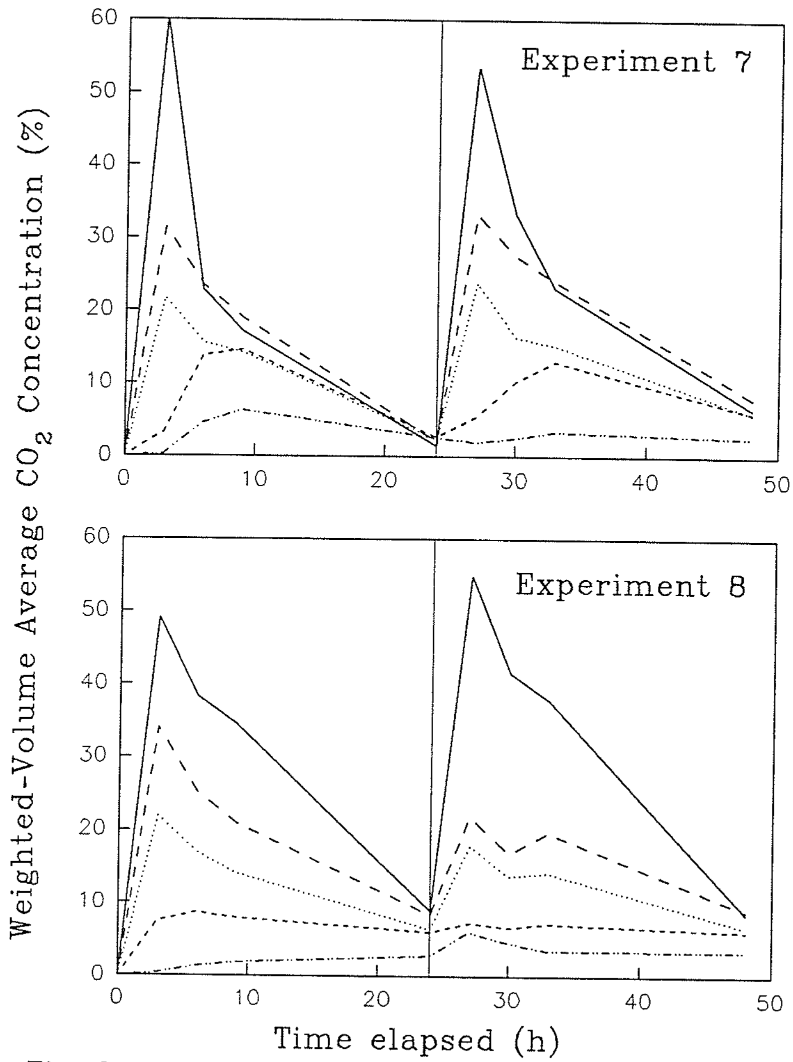

Fig. 6.19. Change in weighted–volume average CO_2 concentrations with time at various levels in farm Bin 2 (Table 5.2). Vertical lines indicate the time at which dry ice was introduced

(—— Near the floor; - - - 0.53; ----- 1.26; and ·-·-·- 1.99 m from the floor and ········ average for the whole bin)

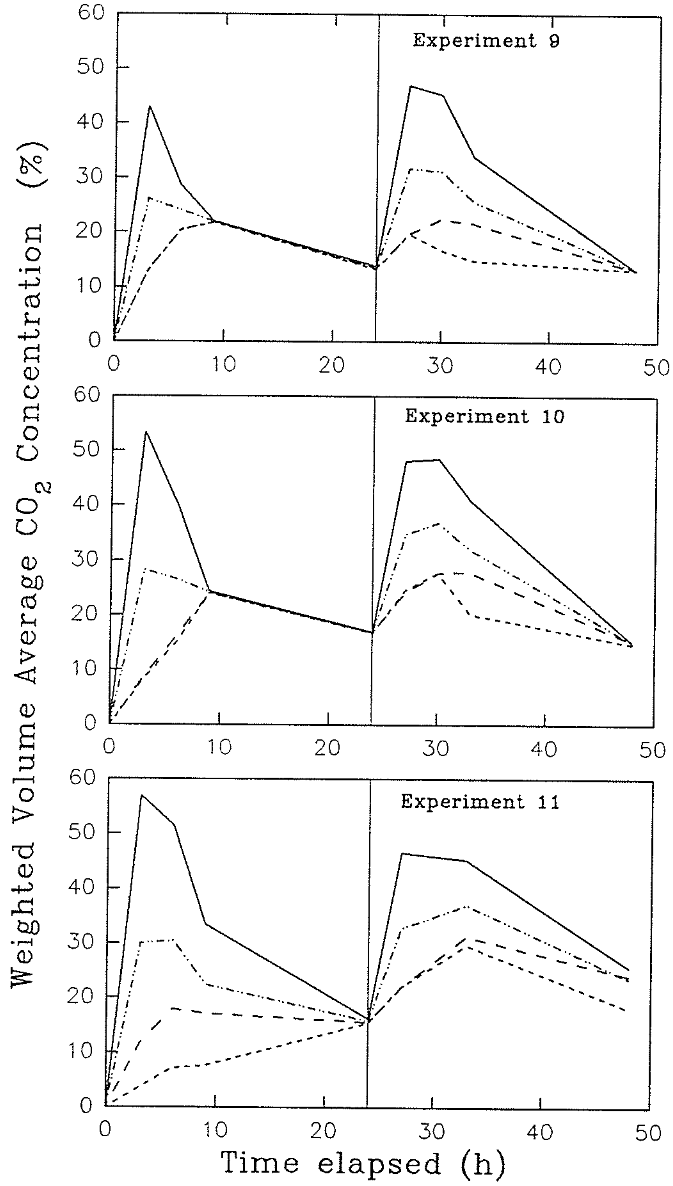

Fig. 6.20. Change in weighted-volume average CO_2 concentrations with time at various levels in farm Bin 3 (Table 5.2). Vertical lines indicate the time at which dry ice was introduced.

(—— 0.55; - - - 1.30; and ······ 2.05 m from the floor; and ·-·-·- average for the whole bin)

In an airtight bin "one-shot" application of CO_2 was effective in killing all the insects (Banks and Annis 1980). Assuming that the CO_2 sorption by wheat is negligible and there is no leakage from the bin, 50 kg of dry ice creates approximately 100% CO_2 concentration in farm Bin 1 (2.50-m-tall wheat bulk), and 40 kg of dry ice should create approximately a 100% CO_2 concentration in farm Bin 2 (2.10-m-tall wheat bulk). The CO_2 concentrations observed in the bolted metal bins were much lower than the expected concentrations. This was probably because of large leaks in these non-airtight bins. These bins should be sealed for a successful CA treatment. In temperate climatic regions, as in Canada, during fall and winter months the air exchange between the grain bulk and the surrounding atmosphere through the leaks in the bin wall and through the eaves helps in reducing the temperature gradients, and the subsequent moisture relocation in the grain bulks (Mcgaughey and Akins 1989). Complete sealing of farm bins would hamper this natural ventilation process. A more practical way of approaching this problem might be to have a single bin on a farm completely sealed and airtight. The infested grain can be transferred to this bin for disinfestation using controlled atmospheres.

6.4 Comparison of Efficiency of CO_2 Retention in Pilot and Farm Bins

6.4.1 Concentration Time (ct) Product

In a CA treatment insects are killed when they progressively sorb CO_2 due to their respiratory action over a period of time or are suffocated by the absence of O_2 when > 99% N_2 is present. The lethal dosage is a function of the concentration of CO_2 gas in a high CO_2 atmosphere or O_2 gas in a high N_2 atmosphere in the intergranular air and the period of exposure (if the minimum required concentration is maintained). In fumigation trials with chemical fumigants the dosage is represented by the product of the fumigant concentration and time of exposure (Calderon and Carmi 1973, Wilson et al. 1980). In my thesis I have used the concentration time product (hereafter referred as ct-product) to estimate and compare the efficiency of CO_2 retention ($\eta_{retention}$) among various experiments in pilot and farm bins. The ct-product was calculated as:

$$ct\text{-}product = \frac{C_w^{ts+1} + C_w^{ts}}{2} \cdot [(ts+1)-(ts)] \qquad (6.2)$$

where:

C_w^{ts+1} = weighted-volume average CO_2 concentration at the sampling time ts+1 (%)

C_w^{ts} = weighted-volume average CO_2 concentration at the sampling time ts (%).

The weighted-volume average CO_2 concentrations for the pilot and farm bin experiments were calculated using the procedure given in section 6.3.

In various pilot- and farm-bin experiments the mass of dry ice used, the grain and air volumes or the empty space volumes as in farm Bin 3 (hereafter referred as domain volumes), and the duration of the experiment were different. To compare various experiments the number of domain volumes of CO_2 used, NDV of CO_2, was estimated as :

$$NDV\ of\ CO_2 = \frac{Volume\ of\ CO_2 Used}{Domain\ volume} \qquad (6.3)$$

Now using the ratio of the cumulative ct-product to the number of domain volumes of CO_2 used, the $\eta_{retention}$ was estimated as :

$$\eta_{retention} = \frac{Cumulative\ ct\ product\ x\ 100\%}{NDV\ CO_2\ x\ t\ x\ C_{th}} \qquad (6.4)$$

where:

t = duration of the experiment (h),

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

6.4.2 Pilot-Bin Experiments

The pertinent values calculated using the above procedure are given in Table 6.1. Among the pilot-bin experiments, higher $\eta_{retention}$ was observed in wheat bulks with covered grain surfaces. For example in Bin 1 with an open grain surface the $\eta_{retention}$ was 43.4% compared to 54.6% when the grain surface was covered (Table 6.1), further supporting that covering the grain surface improves the retention of CO_2 in the grain bulk. In none of the pilot-bin experiments the $\eta_{retention}$ was more than 55%. The low values of $\eta_{retention}$ in the pilot bins could be because of the following reasons.

(i) At 21 h after the introduction of dry ice a certain amount of CO_2 gas remained in the dry ice box (which will become available to replenish the CO_2 gas in the grain bulk). For example, in the dry ice box of Bin 1 with an open grain surface 19.8 g of dry ice, which is about 11% of the total input, remained in the box at 21 h.

(ii) In an uncovered grain bulk the CO_2 gas escaped through the top grain surface to the surrounding atmosphere .

(iii) In both the covered and the uncovered grain bulks the wheat contained in the bins sorbed a certain amount of CO_2 gas. Cofie-Agblor et al. (1992) estimated that at 100% concentration the amount of CO_2 gas sorbed by wheat ranges from 0.18 g/kg to 0.42 g/kg at a moisture content of 18% and at temperatures ranging from 0 to 30°C. Linearly extrapolating these figures for a CO_2 concentration of 10%, in Bin 1 with 180 g dry ice input and covered grain surface the amount of CO_2 gas sorbed could be 62 g or 0.036 g/kg of wheat. When treating a large grain bulk with CO_2 gas, allowances should be made for the sorption of CO_2 gas by the grain.

(iv) Even in sealed bins (5 min pressure decay time from 500 to 250 Pa), a gas exchange rate of 4 to 7% d^{-1} is unavoidable (Banks 1983). It is possible that in the pilot bins during the 21 h experiment, some amount of CO_2 gas would have been lost to the atmosphere.

Table 6.1. Comparison of $\eta_{retention}$ in pilot- and farm-bin experiments.

Experiment	Mass of Dry Ice	Cumulative ct-product	Ratio of Cumulative ct-product to NDV of CO_2*	$\eta_{retention}$ (%)
Pilot-Bin Experiments**				
Bin 1 open grain surface	180 g	98.0	2121.2	43.4
Bin 1 open grain surface refilled after each test)	180 g	96.8	2095.3	42.9
Bin 1 covered grain surface	180 g	119.6	2665.1	54.6
Bin 1 open grain surface	540 g	298.3	2136.0	43.7
Bin 2 open grain surface	370 g	200.6	2138.5	43.8
Bin 2 covered grain surface	370 g	228.3	2444.3	50.1
Bin 2 covered grain surface	740 g	383.3	2034.3	41.7
Bin 3 open grain surface	180 g	101.7	2194.7	44.9
Bin 3 covered grain surface	180 g	114.5	2465.6	50.5
Farm-Bin Experiments**				
Experiment 1	56 kg	682.2	1361.7	12.2
Experiment 2	56 kg	827.6	1673.2	15.0
Experiment 3	162 kg	2324.8	1616.4	9.7
Experiment 4	163 kg	2947.1	2026.7	11.9
Experiment 5	55 kg	1429.0	2934.6	26.3
Experiment 6	33.8 kg	918.3	3061.7	27.4
Experiment 7	56 kg	518.6	864.6	7.8
Experiment 8	56 kg	572.9	959.6	8.6
Experiment 9	56 kg	987.8	1617.7	33.7
Experiment 10	56 kg	1149.2	1910.2	39.8
Experiment 11	56 kg	1238.4	2064.5	43.0
Experiment 12	252 kg	4964.0	2190.1	3.9

* NDV CO_2 - number of domain volumes of CO_2

** Pilot- and farm-bin experiments are described in Tables 5.1 and 5.2, respectively.

Increasing the amount of dry ice did not increase the $\eta_{retention}$. For example in Bin 1 with an uncovered grain surface, both the 540 g and 180 g dry ice tests resulted in nearly the same $\eta_{retention}$. On the other hand, in Bin 2 with a covered grain surface, 740 g dry ice resulted in a reduced $\eta_{retention}$. A probable reason for this could be that the sorption of CO_2 by the wheat would have increased with increased dry ice input (the wheat contained in Bin 2 can adsorb a maximum of 694 g of CO_2 gas at an CO_2 initial concentration of 100%).

6.4.3 Farm-Bin Experiments

A remarkable decrease in the $\eta_{retention}$ in the farm bins was observed compared to the pilot bins. The uncontrollable loss of CO_2 gas through various leaks in the bin wall and the bin wall to the floor joints probably reduced the $\eta_{retention}$ in the farm bins. As with the pilot bins, increasing the amount of dry ice did not cause any increase in $\eta_{retention}$ in the farm bins (Experiments 3 and 4 in Table 6.1). The probable reason for this could be that in addition to increased sorption of CO_2 gas by the wheat with increased dry ice input, the rate of loss through the bin wall might have also increased. In a non-airtight bin it may not be possible to achieve any further increase in the CO_2 concentration than that observed in these experiments, unless some rigorous sealing is done. The fully perforated floor bin had the least $\eta_{retention}$ because of the leaks through both the bin wall and the plenum chamber. The maximum $\eta_{retention}$ was obtained in Experiment 5 (dry ice introduced on the grain surface) and in Experiment 6 (dry ice introduced through a 10-cm-diameter perforated vertical tube near the central axis). The introduction of dry ice through the vertical tube near the centre of the grain bulk was not considered as a feasible method because of the practical difficulties mentioned earlier. Among all the combinations tried an obvious choice to create reasonable CO_2 concentrations in the grain bulks stored in non-airtight bins would be to introduce the dry ice on top of the grain surface and cover it with a PVC sheet.

In an empty bin with a concrete floor the $\eta_{retention}$ was very high compared with the wheat filled bins. This might be because: (i) the $\eta_{retention}$ in wheat filled bins was reduced due to the sorption of CO_2 gas; (ii) in farm Bin 1 with a circular duct, and in farm Bin 2 with a fully perforated floor, there are additional unsealable leaks at points where the bin wall and the duct or fully perforated floor joins. On a farm an ideal bin choice for CA treatment would be a bin with no ducts or perforated floors. In an empty bin excluding the concrete floor by spreading a polyvinylidene chloride sheet resulted in an increased $\eta_{retention}$ (nearly 10% increase). The $\eta_{retention}$ in the insect experiment was only about 4%. Prolonged duration of the experiment and addition of large quantities of dry ice caused large quantities of CO_2 gas loss to the atmosphere. Therefore, for a cost effective CA treatment, in addition to covering the grain surface, it will be essential to seal the bin to avoid easy escape of CO_2 gas.

6.5 Bioassay

Based on the results of the farm-bin experiments (Section 6.2), it was decided to use 28 kg of dry ice (14 kg on the grain surface underneath the covering sheet and 14 kg through the circular duct on the floor), to attempt to create lethal concentrations of CO_2 to study the mortality of rusty grain beetle adults put in cages. A considerable loss of CO_2 through the leaks in the bin was observed. To replenish the lost CO_2 from the wheat bulk additional 28 kg of dry ice at each time were introduced at 24, 48, 72, 96, 152, 168, 192, and 216 h. The average grain temperature in the test bin was 18.9±3.0°C and the average grain temperature in the control bin was 18.3±2.0°C, during the whole duration of the experiment.

In the experiments on insect mortality the weighted-volume average CO_2 concentration in the bin for the whole grain mass never increased beyond 30% (Fig. 6.21). The CO_2 concentrations were measured every 24 h, just before the introduction of the next batch of dry ice. In the first few hours after the introduction of the dry ice the CO_2 concentrations in the bulk were usually high and then started declining after that (Figs. 6.18 and 6.19). It can be safely concluded that the CO_2 concentrations

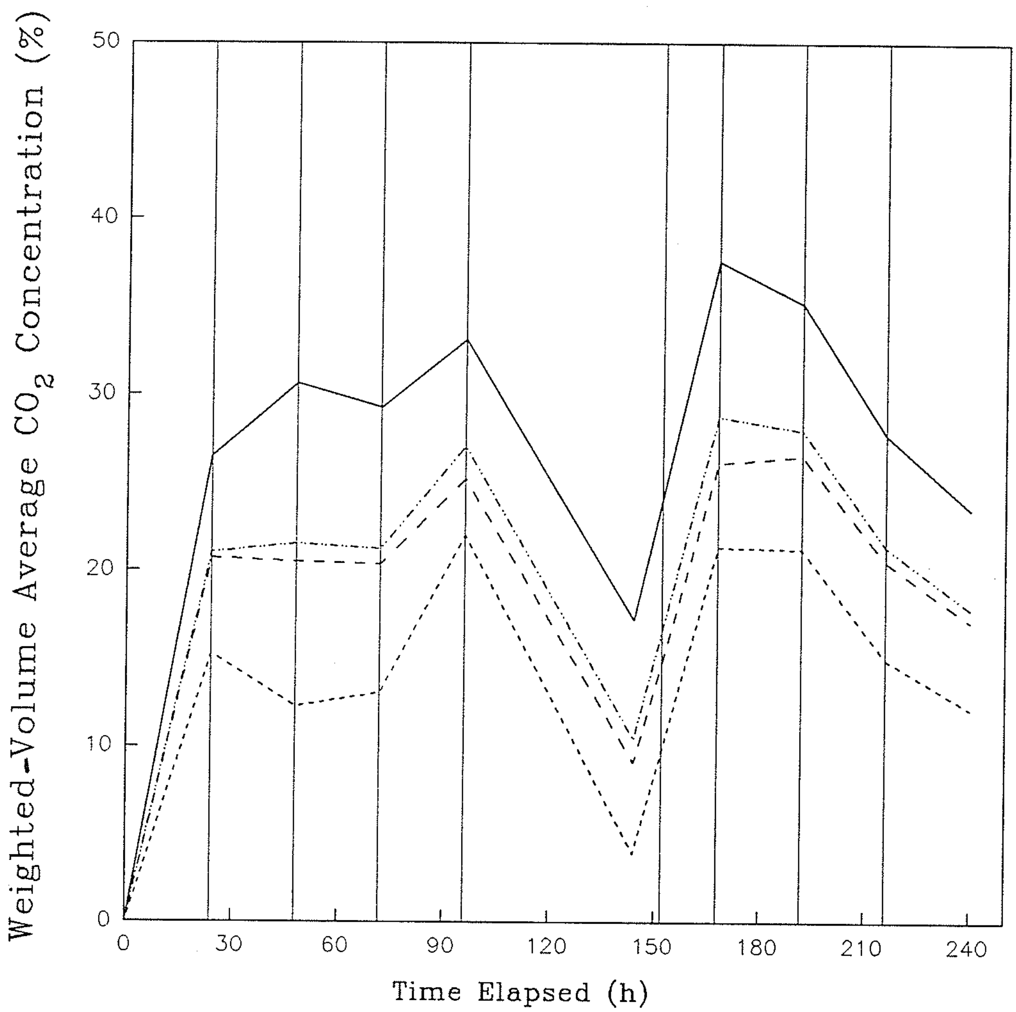

Fig. 6.21. Change in weighted volume average CO_2 concentrations with time in the insect bin. (vertical solid lines indicate the time at which dry ice was added)

(—— 0.55; - - - 1.30; ······ 2.05 m from the floor and ·-·-·- average for the whole bin) in the test bin might have been higher between the sampling times than those observed at 24 h after the introduction of dry ice. In the control bin, on the other hand, the CO_2 concentrations were very low (Appendix E).

Forty-two insect samples (of 50 insects each) were removed every 48 h from the test and the control bins separately. In the laboratory the insects were allowed to potentially recover at a temperature of 25±2°C for 48 to 72 h and counted. The mortality of insects was calculated as:

$$Mortality\ (\%) = \frac{Number\ of\ dead\ insects}{Total\ No.\ of\ insects} \times 100 \tag{6.6}$$

The mortality of insects in the test bin increased with an increase in exposure time (Fig. 6.22). As expected, the mortality was maximum at level 1 (0.55 m from the floor), because of the high CO_2 concentration in that region. At the end of 10 d, the average mortality at level 1 was 90.7%. Excluding the sampling point 1, (Fig 5.4) where the mortality was only 10%, the average mortality at the rest of the sampling locations at level 1 was 97% after 10 d of exposure. The low mortality at sampling point 1 was because of the high rate of CO_2 leakage through the bin wall near that sampling location. The aeration duct was inserted through the bin wall near this sampling point and the thermocouple wires exited through a hole made in the bin wall near this location. Even though the joints between the bin wall and the duct and the hole through which the thermocouple wires exited were carefully sealed using silicon sealant, uncontrollable leaks might have existed in these locations causing high CO_2 loss near that region. For example at 192 h the CO_2 concentration at sampling point 1 at level 1 was 14.32% compared to the average CO_2 concentration of 38.37% in the rest of the sampling locations at level 1. This might have resulted in low mortality at sampling point 1. At level 3 where the CO_2 concentrations were lower than at levels 1 or 2 (Appendix E), the average mortality at the end of 10 d exposure period was only 32.5%.

Rameshbabu et al. (1991), in a laboratory study, observed 99% mortality of rusty grain beetle

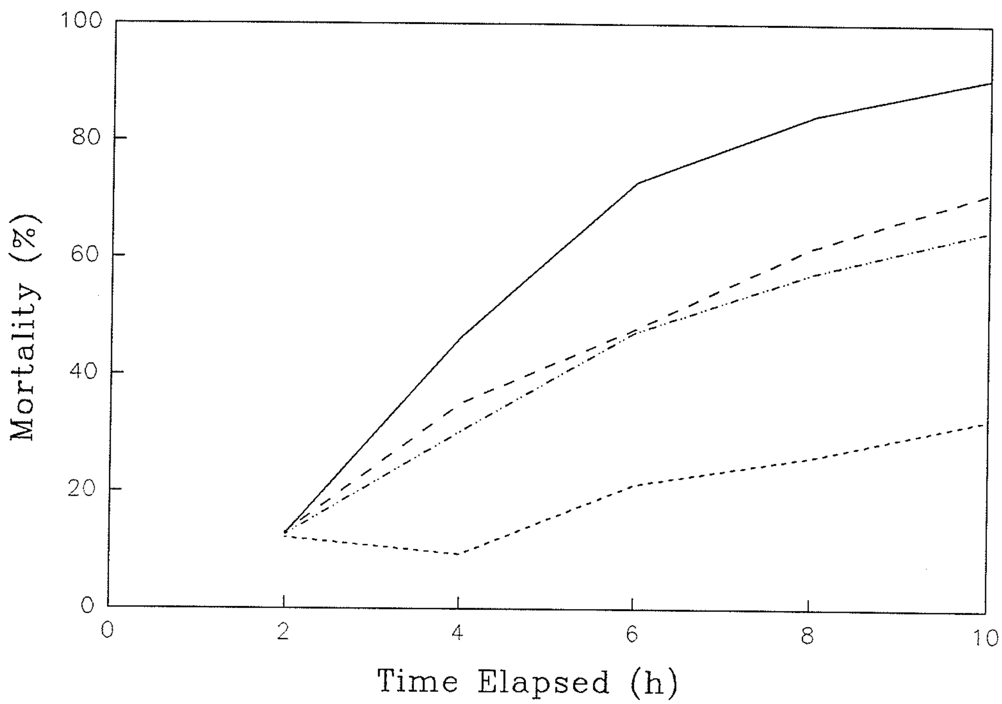

Fig. 6.22. Mortality of rusty grain beetle adults at various levels under the elevated CO_2 concentrations in a wheat bulk.

(—— 0.55; ---- 1.30; and ······ 2.05 m from the floor and -·-·-· average for the whole bin) adults at high CO_2 concentrations (80-91.7%) and at a temperature of 20°C after 4 d of exposure. In a non-airtight bin, due to the loss of CO_2 to the atmosphere, and due to the layering of CO_2 in the bottom portions of the grain bulk, it was not be practical to create or maintain such high CO_2 levels. Based on a pilot-scale study in airtight bins containing 322 kg of wheat, White et al. (1990) found that rusty grain beetle adults can be completely controlled in 4-6 wk at 25±3°C, when CO_2 levels were about 20% and O_2 levels were between 5 and 10%. At declining (20 to 9%) CO_2 levels and at declining temperatures from 21 to 7°C, 99.6% of rusty grain beetle adults were killed in 12 wk of exposure. White and Jayas (1992) observed that insects and mites in wheat and barley bulks can be completely controlled at 34% CO_2 , 15% O_2, and at 18 to 10°C or at 29% CO_2, 3% O_2, and at 25 to 20°C in 2 wk of exposure.

Thus, to achieve complete control of rusty grain beetle adults, either high CO_2 concentrations (>70%) should be maintained for short periods of time (up to 4 d), or low CO_2 concentrations (20 to 40%) should be maintained for 4-6 wk. In both cases the minimum required CO_2 concentration should be maintained at all locations in the bulk. Based on the CO_2 distribution tests it is obvious that CO_2 concentrations of >70% can not be created or maintained in the existing bolted metal bins. When dry ice was introduced on the surface of the bulk, covered with a polyvinylidene chloride sheet, and replenished every 24 h, CO_2 concentrations of 15 to 30% were observed in top layers (Experiment 5). If the exposure period was extended up to 4-6 wk, better control of rusty grain beetles in the top levels of the test bin would have occurred. This can be further supported with the observed linear relationship between the mortality (%) and the ct-product (Fig. 6.23). Further experiments are required to confirm this.

The cost of phosphine fumigation in Canada is Can. $ 1.20 per t of grain (White and Jayas 1993) and in the US it is Can. $ 0.40 per t of grain (Reed et al. 1990). In the insect experiment a total of 252 kg of dry ice was used. The cost of treatment was Can. $1.30 per t of wheat (calculated based

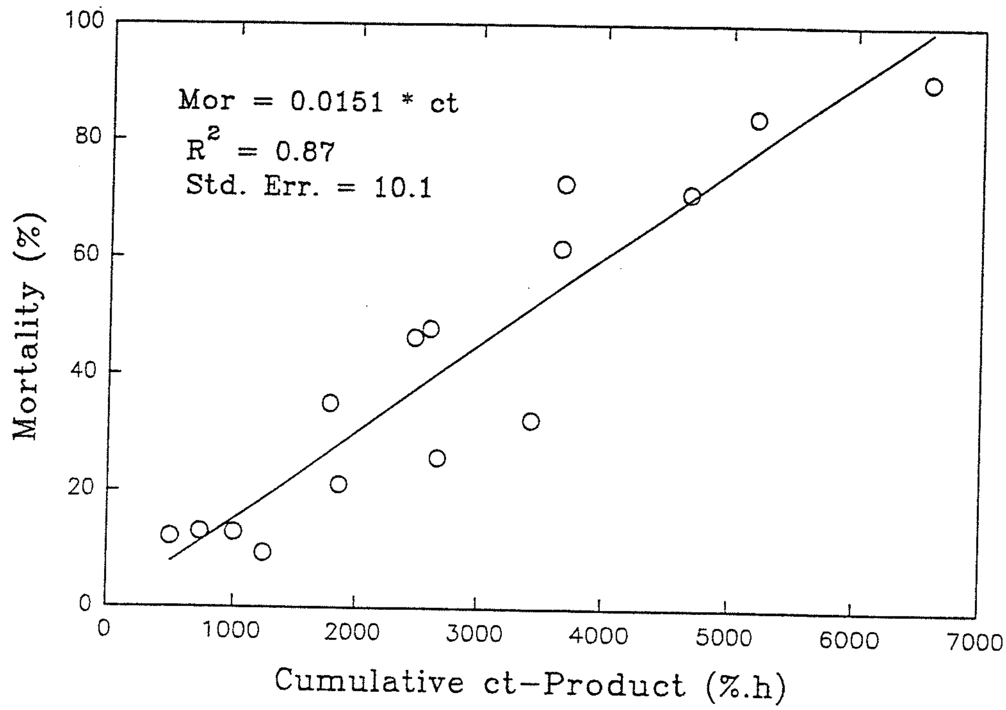

Fig. 6.23. Increase in mortality of rusty grain beetle adults with cumulative ct-product.

(○ Data Points; and —— Regression Line) on a price of \$0.25 per kg of dry ice), which is comparable to the cost of phosphine fumigation in Canada. But, to obtain 100% mortality of the rusty grain beetle adults the treatment would have to be continued for 4-6 wk, which would increase the cost of treatment. In this experiment, the dry ice was replenished every 24 h at the rate of 28 kg each time. As already discussed in Section 6.4, increasing the amount of dry ice or increasing the frequency of application did not cause any increase in $\eta_{retention}$. It is possible that the CO_2 levels observed in the test bin might have been achieved even with lesser amounts of CO_2 input after the first purging with large amounts of dry ice. The replenishment rate should be estimated based on the rate of CO_2 loss from the bin. Also the bins could be sealed to a better level so that the rate of CO_2 loss can be minimized. Further data on the CO_2 loss from the bin and the effect of sealing the bin, without affecting the natural ventilation process, on the CO_2 retention are required. The mortality of insects in the top layers of the bulk with increased exposure periods should be studied to confirm the effectiveness of low CO_2 levels in that region.

In spite of all these imperfections, the CO_2 treatment might be effective in controlling natural infestations of rusty grain beetle adults as they typically move to the bottom of the grain mass (White and Loschiavo 1986), where the CO_2 levels were the highest. Further research on the control of natural infestations of rusty grain beetle adults, an economically important insect pest of Canada, could provide results for the successful application of CO_2 treatment in bolted metal bins.

6.6 Simulation of CO_2 Distribution in Wheat Bulks

6.6.1 Boundary Conditions for Simulation in Pilot-Bins

A FORTRAN program was written to solve the unsteady state diffusion problem (eq. 4.21). For simulating the distribution of CO_2 in the grain bulk, half of the grain bulk (along section A-A of Figs. 5.1, 5.2, and 5.3) was discretized into linear elements with 445 nodes for Bin 1, 430 nodes for Bin 2 and 390 nodes for Bin 3. The measured CO_2 concentrations near the floor opening (sampling point

5 of Bin 1, the average of sampling locations 5, 9, and 10 of Bin 2, and the sampling location 1 of Bin 3) were specified for the nodes lying inside or on the boundary of the floor opening. To include this boundary condition in the program, the measured CO_2 concentrations at these locations were fitted to an equation of the form:

$$\% \; CO_2 = a \, e^{-b.t} \tag{6.6}$$

using procedure NLIN of SAS (SAS 1982). A typical plot of the measured CO_2 data at sampling location 1 of Bin 3 and the values predicted by eq. 6.6 are shown in Fig. 6.24. Similar plots were obtained for other test combinations also.

For tests with uncovered top grain surfaces, the measured CO_2 concentrations near the surface of the grain were specified at the nodes lying on this boundary, and when the grain surface was covered with a plastic sheet, this boundary was assumed impermeable to flow of CO_2 ($\partial c/\partial n = 0$). The bin wall and the bin floor, excluding the floor opening were assumed impermeable to the flow of CO_2 gas. A diffusion coefficient of 4.15 mm^2/s for red spring wheat at 12% mc (Singh et al. 1985) was used in the simulations. It was assumed that the diffusion coefficient was independent of the direction of diffusion (Singh et al. 1984), and of concentration (Cunningham and Williams 1980). Initially the sorption and production of CO_2 by the wheat were assumed to be negligible (q=0).

6.6.2 Simulation Results

The simulations were run with the assigned boundary conditions and the initial concentration at every node in the grid set equal to the atmospheric CO_2 concentration (0.03%). The predicted CO_2 concentrations were much lower than the measured concentrations at every sampling point and at all times. The mean relative percent error of prediction (e) was calculated as:

$$e = \frac{1}{n} \sum \frac{|M_i - P_i|}{M_i} \, x \, 100 \tag{6.7}$$

where;

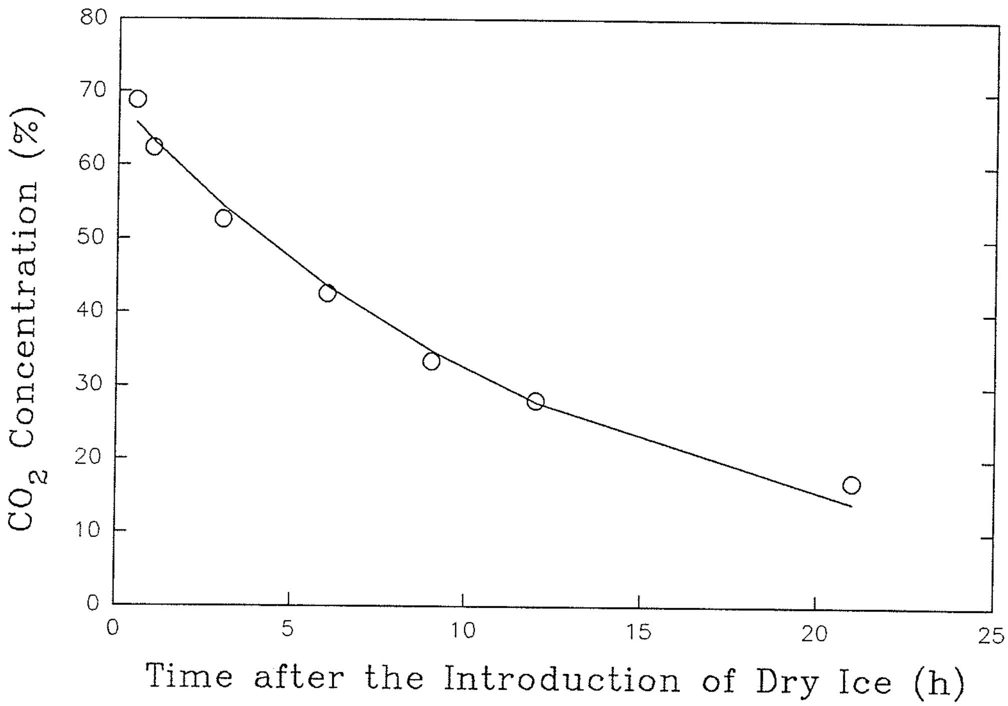

Fig. 6.24. Measured CO_2 concentrations and predicted concentrations using eq. 6.6 at sampling point 1 in replicate 1 of Bin 3 with 180 g dry ice and open grain surface.

(—— Predicted by eq. 6.6; ○ Measured Values)

M_i = measured CO_2 concentration at sampling point i

P_i = predicted CO_2 concentration at sampling point i

n = number of data points.

The e value for replicate 1 of Bin 1 with an uncovered top grain surface ranged from 70.75% at 3 h to 30.88% at 21 h. Similar high e values were observed for other test combinations.

The governing partial differential equation and the associated boundary conditions (eqs. 4.1 to 4.4), on which the model was based, assume that the mechanism of transport is only by diffusion (concentration difference of CO_2). In the experiments, I placed 180 to 740 g of dry ice in well sealed metal boxes under the floor openings. As mentioned in Section 6.1. when this dry ice sublimated into CO_2 gas, due to the increase in volume, a pressure must have developed inside the box which would have caused a mass movement of CO_2 through the grain bulk. This might have caused such large percentage errors in prediction.

It was observed that dry ice pellets, when exposed to room temperature, took about 45 min to 1 h to sublimate totally. Assuming that all the pressure generated by the sublimation process is dissipated in the first 1 h, it was decided to use the measured CO_2 data at 1 h as the initial condition for the simulations.

Using the measured CO_2 concentrations at 1 h after the introduction of dry ice, the CO_2 concentration at every node in the grid was calculated by linear interpolation. Using this interpolated data as the initial condition, CO_2 distribution was simulated at 3, 6, 9, 12 and 21 h after the introduction of dry ice, for all the test combinations. The e values ranged from 5.9% at 21 h in Bin 1 with 180 g of dry ice and grain surface open to 55.1% at 21 h in Bin 2 with 740 g of dry ice and the grain surface covered (Table 6.2). The high e values could be because of the following reasons :

1. The diffusion coefficients (D_x, D_y and D_z) used in the simulations were 4.15 mm²/s (Henderson and Oxley 1944, Singh et al. 1984), and it was assumed that the diffusion coefficient was

Table 6.2. Mean relative percent errors between measured and predicted CO_2 concentrations for all the tests in pilot bins. Measured CO_2 concentrations at 1 h was linearly interpolated and taken as the initial concentration.

Bin	Grain Surface	Mass of Dry Ice (g)	Replicate	Mean Relative Percent Error*				
				3 h	6 h	9 h	12 h	21 h
Bin 1	Open	180	1	22.49	23.15	15.65	11.06	5.87
			2	19.90	21.90	15.69	17.54	16.02
			3	20.25	27.58	23.20	20.01	16.01
			4#	20.85	25.57	15.15	14.34	12.31
	Covered		1	15.31	29.44	39.06	37.94	38.07
			2	15.67	18.93	30.45	30.95	28.28
			3	12.48	24.06	32.69	33.73	32.44
			4#	12.34	23.83	34.48	34.50	32.44
		540	1	17.63	16.70	15.93	32.35	37.04
			2	26.11	27.20	21.50	19.16	36.57
			3	18.32	22.00	19.13	30.83	36.99
			4#	17.00	20.76	19.31	27.78	43.43
Bin 2	Open	370	1	17.71	16.87		33.41	39.10
			2	25.65	28.85		11.38	14.31
			3	15.36	10.56		13.31	18.56
			4#	18.55	8.74		13.74	22.39
	Covered		1	18.17	17.16		11.84	17.38
			2	13.84	10.01		10.82	14.05
			3	18.43	15.01		14.45	18.30
			4	16.91	15.83		10.62	16.40
		740	1	13.07	14.04		29.52	49.88
			2	11.52	17.05		34.50	55.05
			3	15.49	12.97		19.44	43.93
			4	10.34	13.78		13.78	47.30
Bin 3	Open	180	1	31.77	34.43	27.08	21.86	12.21
			2	26.44	30.56	20.97	18.17	9.88
			3	34.77	35.02	28.60	27.60	19.54
			4#	31.18	33.24	24.25	21.50	12.19
	Covered		1	32.86	37.37	37.23	30.36	16.94
			2	30.13	35.20	34.77	29.22	17.94
			3	30.17	34.36	38.04	30.35	19.34
			4#	29.87	35.17	36.47	29.95	17.51

$$* \text{ Mean Relative Percent Error}(\%) = \frac{1}{n} \sum \frac{|\text{Measured} - \text{Predicted}|}{\text{Measured}} \times 100$$

The measured data for the three replicates were averaged and compared with the simulation results

n number of data points (25 in Bin 1, 50 in Bin 2, and 45 in Bin 3) direction independent. As discussed in Section 6.1., the airflow resistance of grains is higher in the vertical direction than in the horizontal direction because of the kernel orientation and different airflow paths in horizontal and vertical directions. It is possible that the diffusion coefficient may also depend on the gravity of CO_2 movement. But, Singh et al. (1984) concluded that the diffusion coefficient is direction independent. In their experiments, however, they filled grain in the diffusion coefficient apparatus in its vertical position and tilted it to the horizontal position for determining the diffusion coefficient in the horizontal direction. In this way, the diffusion paths for both the vertical and the horizontal directions were identical although the direction of the force of gravity was changed. In practical situations, when a farm bin is filled with wheat the oblate shaped wheat kernels lie with their major axes horizontal, thus possibly providing less resistance to diffusion in the horizontal direction than in the vertical direction.

2. To use the 1 h measured data as the initial condition in the simulations, I linearly interpolated the limited measured data to every point in the finite element mesh. The CO_2 distribution at 1 h may not be varying linearly between nodes, and might have caused errors in prediction.

Ideally, the simulation should start from time 0 with the initial condition of atmospheric CO_2 concentration everywhere in the domain. To do this either a model of forced convective mass transport (bulk CO_2 movement under pressure gradients) must be included in the diffusion model or the apparent flow coefficient of CO_2 through wheat bulks must be estimated. I determined the apparent flow coefficient of CO_2 through wheat by physically simulating the pilot-bin experiments in a laboratory apparatus (Section 5.3). In the following paragraphs, I will explain the procedure I followed for estimating the apparent flow coefficient of CO_2 through wheat bulks.

6.7 Calculation of Apparent Flow Coefficient of CO_2 Through Wheat Bulks

The apparent flow coefficient of CO_2 through wheat bulks was calculated assuming that at all times the conditions approximate a steady state condition, i.e. the concentration gradient in the grain column and the diffusion flux at any instant are those that would be found if the concentration in the inlet end was maintained at the instantaneous measured value. This assumption is similar to that made by Cowie and Watts (1971) for calculating the diffusion of methane and chloromethane in air and that made by Singh et al. (1984) for calculating the diffusion coefficient of CO_2 through wheat bulks. The apparent flow coefficient was calculated using the following equation :

$$D_{app} = \frac{Q_m \bullet \Delta x}{A \bullet \Delta c} \tag{6.8}$$

where:

D_{app} = apparent flow coefficient of CO_2 through wheat bulk ($m^2\ s^{-1}$)

Q_m = mass flow rate of CO_2 through wheat ($g\ s^{-1}$)

A = cross sectional area of the grain column (m^2)

Δc = concentration difference between the inlet end of the grain column and a corresponding sampling point along the grain column ($g\ m^{-3}$)

Δx = distance between the inlet end of the grain column and the sampling point at which Δc was calculated (m)

The mass flow rate Q_m was calculated for two different time periods in the duration of whole experiment as Q_{m1} and Q_{m2}; where Q_{m1} is the mass flow rate during the time period up to which the dry ice sublimated into CO_2 gas and Q_{m2} is the mass flow rate during the time period after which the dry ice sublimated into CO_2 gas and until the end of the experiment (8 h). The mass of CO_2 gas in the apparatus, after all the dry ice had sublimated into the CO_2 gas, was estimated using the measured concentrations in the gas chamber and in the grain column. Subtracting this mass from the mass of dry ice introduced in the gas chamber and dividing by the time difference gave the value of Q_{m1}. The difference in the mass of dry ice in the apparatus after all the dry ice sublimated and that of the amount at 8 h (calculated using the measured CO_2 concentrations) was divided by the time difference to get the value of Q_{m2}.

At any given sampling time the value of $\Delta x/\Delta c$ was estimated between the inlet end of the grain column to each of the five sampling points along the grain column (Fig. 5.8), and D_{app} estimated for each of these values. The average of these five D_{app} values was taken as the D_{app} for that sampling time. Similarly, the D_{app} values were calculated for all the sampling times. The D_{app} decreased with time from 0 to 8 h. The log transformed values of D_{app} were linearly related to time as:

$$\ln(D_{app}) = A + B \ln(t) \tag{6.9}$$

where:

t = time (h)

A and B = product dependent constants

The GLM procedure of SAS (SAS 1982) was used to estimate the constants A and B for various experiments (Table 6.3).

6.7.1 Effect of Temperature

The D_{app} values increased with an increase in temperature from -10 to 30°C. Bailey (1959) observed an increase in the diffusion rate of O_2 through wheat with an increase in temperature in the range of 1.7 to 42°C. Singh et al. (1984) also observed an increase in the diffusion rate of CO_2 through grain bulks with an increase in temperature in the temperature range of -10 to 30°C. They both observed a quadratic relationship between the diffusion rate of gases through grain bulks and the temperature. In this study, I observed a linear increase in D_{app} and the temperature in the range of -10 to 30°C. According to Jost (1960), true diffusion (the results of Bailey (1959) and Singh et al. (1984))

Table 6.3. Empirical constants A and B (in eq. 6.9) at various temperatures, wheat moisture contents, and with different amounts of dry ice

	A	B	R^2
Temperature (°C)			
-10	7.526	-0.614	0.891
0	9.067	-0.761	0.923
10	9.838	-0.835	0.935
20	10.566	-0.935	0.892
30	11.426	-0.941	0.863
Grain Moisture Content (%)			
11	9.273	-0.780	0.927
12.3	10.566	-0.935	0.892
14	7.855	-0.640	0.851
16.5	10.203	-0.872	0.917
18.5	9.214	-0.761	0.907
Amount of Dry Ice (g)			
30	11.268	-1.015	0.879
40	10.566	-0.935	0.892
50	12.437	-1.137	0.923
60	13.172	-1.202	0.887
80	16.509	-1.553	0.825
120	21.533	-1.995	0.829
Horizontal Direction*	12.237	-1.039	0.853

* The grain column was filled in the same way as by Singh et al. (1984). The experiment for the horizontal direction was conducted with wheat at a moisture content of 12.3%, and at a temperature of 20°C. Mass of dry ice used for this experiment was 40 g.

generally shows a comparatively strong dependence on temperature while the effect of temperature during bulk flow of gases through capillaries is rather small. The relationship between the constants A and B, separately, to the temperature were:

$$A = -16.6455 + 0.093 \times T \qquad R^2 = 0.974 \text{ and S.E.} = 0.27 \tag{6.10}$$

$$B = 1.5273 - 0.00828 \times T \qquad R^2 = 0.927 \text{ and S.E.} = 0.04 \tag{6.11}$$

where:

T = temperature (K), S.E. = standard error of y estimate

6.7.2 Effect of Moisture Content

No definite pattern of increase or decrease in the D_{app} values was observed with an increase in the moisture content of the wheat. Both the empirical constants A and B randomly varied with an increase in moisture content from 11 to 18% (Table 6.3). The in situ porosity increased from 42% at 11% moisture content to 47.3% at 18% moisture content. However this increased pore space did not cause an increase in the D_{app} values. The mass displacement of CO_2 created by the dry ice sublimation process would have been so large that the effect of increased porosity at higher moisture contents was reduced.

6.7.3 Effect of the Amount of Dry Ice

As expected, the D_{app} values increased with an increase in the mass of dry ice introduced. Increasing the mass of dry ice proportionately increased the volume of CO_2 gas produced by the sublimation process. The increased volume of CO_2 gas caused an increase in pressure in the gas chamber thus increasing the mass displacement of CO_2 through the wheat bulk. Even though the constants A and B increased linearly with an increase in the mass of dry ice, such a relationship may not be useful in a mathematical model to predict the CO_2 distribution in grain bulks. This is because the mass of dry ice used in the experiments for determining the D_{app} will be different from the amount of dry ice that would be used in a farm bin. The pressure drop across the grain column created by the various amounts of dry ice, if all of it were sublimated at once, was found to be more realistic. The pressure drop across the grain column was estimated using the following equation:

$$\frac{P}{L} = \frac{m}{v}\frac{RT}{L} \tag{6.12}$$

where:

P = the pressure created by the dry ice if all the dry ice introduced in the gas chamber sublimated at once (kPa)

L = length of the grain column (m)

m = mass of dry ice introduced (kg)

R = individual gas constant (0.1889 kJ kg^{-1} K^{-1})

T = temperature (K)

v = volume of the CO_2 box (m^3).

The relationship between the constants A and B, separately, with the pressure drop across the grain column created by various amounts of dry ice introduced in the gas chamber were of the form :

A = 6.3683 + 0.0482 x (P/L) R^2 = 0.970; S.E. = 0.79 (6.13)

B = -0.5448 - 0.00465 x (P/L) R^2 = 0.967; S.E. = 0.08 (6.14)

6.8 Prediction of CO_2 Distribution in Wheat Bulks Using D_{app} Values

The diffusion program was modified to predict the CO_2 distribution in wheat bulks using D_{app} values during the initial time periods after the introduction of dry ice and using the diffusion coefficient values afterwards. The D_{app} values were calculated using the eq. 6.9. The empirical constants A and B were estimated using eqs. 6.13 and 6.14, respectively, for the expected pressure drop across the wheat bulk. The empirical constants A and B in eqs. 6.13 and 6.14 were for a temperature of 20°C. The average wheat bulk temperatures were different in various experiments (Table A.10). The D_{app} values at the actual wheat bulk temperatures were estimated by linearly interpolating using eq. 6.9, 6.10, and 6.11. The ratio of the D_{app} values calculated using eq. 6.9 in the horizontal and vertical directions had a relationship of the form :

$$(6.15) \qquad \frac{D_{app}H}{D_{app}V} = 4.011 - 0.212 \cdot \ln(t)$$

where:

$D_{app}H$ = apparent flow coefficient of CO_2 through wheat bulk in the horizontal direction ($mm^2\ s^{-1}$)

$D_{app}V$ = apparent flow coefficient of CO_2 through wheat bulk in the vertical direction ($mm^2\ s^{-1}$)

Using eq. 6.15 and the D_{app} values in the vertical direction, the D_{app} values in the horizontal direction were calculated. The D_{app} values thus calculated were used in the simulations for the first 3 h after the introduction of the dry ice. After this arbitrarily chosen time period, assuming all the pressure created by the dry ice sublimation is dissipated and that the movement of CO_2 through wheat bulk is purely due to the concentration gradient, a diffusion coefficient of 4.15 $mm^2\ s^{-1}$ was used (Henderson and Oxley 1944, Singh et al. 1985).

The e values were calculated using eq. 6.7 (Table 6.4). At sampling times 6 h and afterwards, the predicted CO_2 concentrations were close to the measured values in all the three bins with 180 or 370 g dry ice. In most of the experiments, and in particular in Bin 1 with 540 g dry ice and open grain surface, the e values were lower in the first four levels above the floor than in all the five levels (shown as 4 L and 5 L, respectively, in Table 6.4). This might be due to the low values of measured concentrations at level 5 which is near the grain surface. Also, a small depression in the grain surface

Table 6.4. Mean relative percent errors between the measured and predicted CO_2 concentrations for all tests in pilot bins. Values of D_{app} were used in the first 3 h of simulation and the diffusion coefficient was used afterwards.

Bin	Grain Surface	Mass of Dry Ice (g)	Replicate	Mean Relative Percent Error*											
				1 h	3 h	6 h		9 h		12 h		21 h		24 h	
						5 L*	4 L**	5 L	4 L	5 L	4 L	5 L	4 L	5 L	4 L
Bin 1	Open	180	1	34.95	20.47		6.30	8.86	8.09	7.41	5.85	9.92	4.48		
			2	35.06	16.00		9.41	9.16	9.52	9.28	8.95	8.07	4.34		
			3	34.95	13.31		6.76	9.40	6.61	10.40	8.03	17.19	6.55		
			4#	34.05	12.96		7.17	9.80	7.25	10.35	8.18	18.20	7.73		
	Covered		1	54.42	25.25		14.36			16.00	11.02	10.78	9.85		
			2	28.82	32.50		13.69			13.01	8.58	10.80	9.04		
			3	34.90	31.23		12.22			15.06	9.84	9.42	7.91		
			4#	38.61	29.89		12.29			14.43	9.59	9.98	8.54		
		540	1	103.40	63.81	34.20	16.95	44.16	17.54	53.20	17.05	52.62	23.07		
			2	104.17	59.62	43.92	16.74	39.93	10.03	40.55	7.61	57.73	16.40		
			3	109.82	48.07	25.86	13.78	21.21	9.40	22.38	13.23	21.15	13.15		
			4#	105.56	56.16	32.92	15.37	30.70	10.30	30.84	10.31	36.85	17.26		
Bin 2	Open	370	1	20.83	28.84		10.44			6.80	10.61	21.20	22.58		
			2	23.52	21.76		9.07			8.00	8.85	22.10	27.20		
			3	19.91	10.23		19.28			9.78	15.26	10.50	9.79		
			4#	18.61	13.33		11.09			5.08	8.60	17.56	17.45		
	Covered		1	27.75	15.13		21.51			12.76	17.91	6.30	8.40		
			2	30.91	15.84		21.83			14.72	19.94	6.63	8.70		
			3	22.88	14.64		10.26			7.30	9.24	9.66	8.67		
			4#	21.65	12.26		11.09			7.77	10.67	7.13	6.76		
		740	1	97.11	112.99	121.98	70.47			95.52	69.10	101.81	80.18	101.08	80.20
			2	118.40	165.16	156.91	93.00			116.28	88.25	124.27	100.73	128.57	103.69
			3	113.26	101.41	102.46	55.83			84.70	60.02	92.78	73.51	95.50	74.65
			4#	105.25	120.90	123.65	70.97			96.06	70.02	103.30	81.67	104.70	82.80

Bin	Grain Surface	Mass of Dry Ice (g)	Replicate	Mean Relative Percent Error*											
				1 h	3 h	6 h		9 h		12 h		21 h		24 h	
						5 L*	4 L**	5 L	4 L	5 L	4 L	5 L	4 L	5 L	4 L
Bin 3	Open	180	1	127.21	47.89		26.62	21.81	21.12	17.79	17.83	10.88	10.84		
			2	102.58	49.84		22.84	16.37	17.88	14.32	15.38	9.32	9.80		
			3	158.72	54.77		29.59	25.76	22.45	21.96	18.01	18.31	12.55		
			4#	150.64	61.34		32.26	18.97	20.96	16.33	16.79	13.64	13.82		
	Covered		1	93.21	55.66		34.72	25.70	26.52	16.74	17.59	12.03	11.30		
			2	188.50	49.39		25.55	17.11	17.22	13.50	13.31	7.72	7.35		
			3	144.12	65.29		36.28	21.52	21.57	13.82	13.80	9.67	9.87		
			4#	127.38	54.83		29.87	20.39	21.03	14.18	14.52	8.80	8.50		

$$* \text{ Mean Relative Percent Error(\%)} = \frac{1}{n} \sum \frac{|\text{Measured} - \text{Predicted}|}{\text{Measured}} \times 100$$

The measured data for the three replicates were averaged and compared with the simulation results

n number of data points (25 in Bin 1, 50 in Bin 2, and 45 in Bin 3)

* the mean relative percent errors were calculated for all 5 levels

** the mean relative percent errors were calculated for first 4 levels

would cause a large difference in the measured CO_2 concentrations at level 5, as this sampling level is only 0.05 m from the surface.

During the initial time periods after the introduction of the dry ice (sampling times 1 h and 3 h), the e values were very high (Table 6.4). At these sampling times the predicted CO_2 concentrations in the vertical direction were higher than the measured concentrations. For example, in replicate 1 of Bin 1 with 180 g dry ice and open grain surface the e value at level 2 was 53.15% and that at level 1 was only 16.74%. Similar high e values in the vertical direction were observed in the other two bins. The reason for this can not be explained now.

The e values were very high in Bin 2 with 740 g dry ice and covered grain surface (Table 6.4). At all sampling times the predicted CO_2 concentrations were much higher than the observed values. The observed values were low probably due to the sorption of CO_2 by the wheat. Based on this hypothesis, I decided to include the sorption of CO_2 by the wheat in the model. In the following paragraphs I will explain the procedure I followed to include the sorption of CO_2, and the subsequent simulation results.

6.8.1 Estimation of Sorption of CO_2 by the Wheat

Cofie-Agblor et al. (1992) measured the sorption of CO_2 by wheat at various moisture contents (12, 14, 16, and 18%) and at various temperatures (0, 10, 20, and 30°C). They measured the sorption of CO_2 by wheat using an initial intergranular CO_2 concentration of 100%. Other than the work by Cofie-Agblor et al. (1992) I could not find any other elaborate study on the sorption of CO_2 by wheat. So I decided to extrapolate linearly their data to estimate the sorption at lower concentrations. Based on a study on the characteristics of CO_2 sorption by several grains, Yamamoto and Mitsuda (1980) concluded that the sorption of CO_2 by grains is completely reversed when the grain is allowed to stand in still air. The sorption and desorption curves were symmetric to the time axis indicating that the sorption and desorption are two opposite and dynamic phenomena. If the CO_2 concentration at any time is lowered from the original CO_2 concentration it is essential to account for the desorption of CO_2 by the grain. The sorption or desorption of CO_2 by wheat in mathematical terms is the sink or source term (q) in the governing partial differential equation (eq. 4.1). The value of q for each element in the domain was estimated using the following equation:

$$q^{(e)} = (-1)^i \cdot \left(\frac{C_n^{(e)} + C_{n-1}^{(e)}}{2}\right) \frac{SCO_2 \ \rho_w}{\rho_{CO_2} \ \Phi \ 86400} \tag{6.16}$$

where:

$q^{(e)}$	=	sorption or desorption of CO_2 by wheat (g m^{-3} s^{-1})
SCO_2	=	rate of sorption of CO_2 by wheat, linearly extrapolated from data of Cofie-Agblor et al. (1992) (g kg^{-1} day^{-1})
ρ_w	=	bulk density of wheat (kg m^{-3})
ρ_{CO2}	=	density of CO_2 gas (g m^{-3})
$C_n^{(e)}$	=	average predicted CO_2 concentration of element e at the present time step (g m^{-3})
$C_{n-1}^{(e)}$	=	average predicted CO_2 concentration of element e at the previous time step (g m^{-3})
Φ	=	porosity of wheat
i	=	1 when $C_{n-1}^{(e)} > C_n^{(e)}$
i	=	2 when $C_{n-1}^{(e)} < C_n^{(e)}$

6.8.2 Simulation Results

Table 6.5 shows the e values at various sampling times in all the three bins. In Bins 1 and 3 with 180 g of dry ice and with an open or covered grain surface, the inclusion of sorption of CO_2 by

Table 6.5. Mean relative percent errors between the measured and the predicted CO_2 concentrations for all the tests in pilot bins, when the sorption of CO_2 by the wheat was included in the model.

Bin	Grain Surface	Mass of Dry Ice (g)	Replicate	Mean Relative Percent Error* 1 h	3 h	6 h 5 L'	6 h 4 L''	9 h 5 L	9 h 4 L	12 h 5 L	12 h 4 L	21 h 5 L	21 h 4 L	24 h 5 L	24 h 4 L
Bin 1	Open	180	1	34.71	18.66		7.73	13.56	12.22	11.78	11.46	8.32	4.89		
			2	31.62	14.68		11.97	13.57	13.46	13.99	13.77	9.13	7.89		
			3	34.77	12.54		9.04	11.21	10.25	13.11	13.40	11.95	4.74		
			4#	32.91	14.09		9.49	11.78	11.95	12.61	12.89	7.11	4.89		
	Covered		1	54.16	22.90		14.24			19.07	12.82	14.66	10.73		
			2	28.63	29.87		10.75			16.35	10.57	15.40	10.99		
			3	34.70	28.60		12.03			19.31	13.13	15.12	11.10		
			4#	38.40	27.32		11.57			17.96	11.90	14.70	10.53		
		540	1	103.14	62.10	32.00	15.72	41.07	15.75	50.43	15.63	50.86	21.81		
			2	103.92	58.20	42.04	16.11	38.03	9.49	39.23	7.43	56.34	15.52		
			3	109.54	46.59	24.19	13.14	19.49	8.96	19.60	11.42	19.41	11.70		
			4#	105.29	54.62	30.95	14.45	28.31	9.13	28.56	9.07	35.30	16.07		
Bin 2	Open	370	1	21.20	14.94		11.08			11.84	7.04	14.86	13.57		
			2	21.64	15.94		13.28			10.15	9.34	10.08	7.62		
			3	20.25	10.69		22.12			20.35	14.57	7.13	4.60		
			4#	18.95	12.71		13.57			12.69	8.25	8.94	9.38		
	Covered		1	26.55	12.18		19.44			19.57	14.57	12.77	9.21		
			2	21.96	11.41		19.80			21.42	16.32	13.42	9.98		
			3	23.98	18.04		10.08			10.04	7.80	10.00	9.11		
			4#	21.63	10.97		15.59			16.81	12.37	11.75	8.90		
		740	1	96.64	108.61	111.25	63.37			79.70	58.22	78.98	64.15	76.70	62.84
			2	117.85	159.46	143.43	83.68			96.04	72.63	94.64	77.89	95.68	78.31
			3	112.29	95.46	89.76	46.63			65.61	45.94	66.88	54.43	67.68	54.46
			4#	105.09	116.96	113.15	63.91			80.30	59.08	80.24	65.41	79.81	65.18
Bin 3	Open	180	1	126.62	46.44		25.85	22.36	21.13	20.04	19.58	12.94	11.68		
			2	102.10	47.88		23.21	17.08	17.28	15.72	16.15	10.29	8.93		
			3	158.03	52.89		26.98	23.14	21.64	20.58	18.63	14.76	11.82		
			4#	125.83	48.01		24.67	18.47	19.84	16.92	17.90	10.41	10.53		

Table 6.5 continued....

Bin	Grain Surface	Mass of Dry Ice (g)	Replicate	Mean Relative Percent Error*											
				1 h	3 h	6 h		9 h		12 h		21 h		24 h	
						5 L*	4 L**	5 L	4 L	5 L	4 L	5 L	4 L	5 L	4 L
	Covered		1	92.87	53.95		32.54	24.79	25.84	18.83	19.58	14.49	13.42		
			2	187.68	47.28		23.76	15.41	17.02	15.39	15.53	13.87	12.74		
			3	143.48	62.87		32.07	19.01	20.09	13.90	13.82	12.34	11.44		
			4#	126.79	52.74		27.25	19.08	20.53	15.81	16.04	12.80	11.87		

$$* \text{ Mean Relative Percent error}(\%) = \frac{1}{n} \sum \frac{|\text{Measured} - \text{Predicted}|}{\text{Measured}} \times 100$$

\# the measured data for the three replicates were averaged and compared with the simulation results

n number of data points (25 in Bin 1, 50 in Bin 2, and 45 in Bin 3)

* the mean relative percent errors were calculated for all 5 levels

** the mean relative percent errors were calculated for first 4 levels

the wheat slightly increased the accuracy of prediction in the first few hours after the introduction of dry ice (sampling times 1 and 3 h), and reduced the accuracy of prediction later on. At 21 h after the introduction of dry ice, for example, in Bin 1 with covered grain surface the predicted concentrations with q > 0 were lower than the predicted concentrations with q = 0. It is possible that at low CO_2 concentrations (180 g dry ice will create a CO_2 concentration of approximately 10% in the intergranular space of Bins 1 and 3), the rate of sorption may be lower than the values obtained by linearly extrapolating the CO_2 sorption rate at 100% concentration.

In Bin 1 with 540 g of dry ice, and in Bin 2 with 370 or 740 g of dry ice, the accuracy of prediction was increased at all sampling times indicating that including the sorption of CO_2 by wheat is essential for accurate model predictions. The e values with 370 g of dry ice in Bin 2 were around 10% at 21 h after the introduction of dry ice. But with 540 g of dry ice in Bin 1 and 740 g dry ice in Bin 2, the e values were high even after the inclusion of the sorption and desorption in the model. As mentioned earlier, linear extrapolation of sorption data at 100% initial CO_2 concentration might not be the correct way to estimate sorption at lower concentrations. Further experimental data on the rate of sorption of CO_2 by wheat at lower initial concentrations are needed.

To demonstrate the importance of including the sorption of CO_2 by wheat on the accuracy of model prediction, I simulated the CO_2 concentrations using various amounts of sorption rates (0 to 100% of actual sorption rate in steps of 10%). The simulated CO_2 concentrations were compared with the measured values of the average of three replicates of the 740 g dry ice experiment in Bin 2 with covered grain surface. Table 6.6 shows the e values at various sampling times with various q values. The accuracy of prediction at 24 h was the best (an e value of 6.54%) with 60% of actual q and was reduced with further increase in the sorption rate. At 70% and 100% of actual sorption rate the predicted CO_2 concentrations were close to the measured values at 21 and 12 h, respectively.

Of the total amount of CO_2 sorbed by grains in 24 h, 50 to 60% was sorbed in the first 4 to 6 h (Yamamoto and Mitsuda 1980). Similar observation was made by Cofie-Agblor et al. (1992) on the sorption of CO_2 by wheat. Furthermore Cofie-Agblor et al. (1992) observed that nearly 80% of the total amount of CO_2 sorbed by wheat occurred in the first 12 h. From Table 6.6 it can be seen that the e value was the minimum at 12 h with 100% of the actual sorption rate. It may be possible that with lower concentrations the sorption of CO_2 by wheat might be at its maximum (100% of actual sorption rate). Thus, using a high sorption rate in the initial few hours and a low sorption rate afterwards might give accurate model predictions. Further experimental evidence is required before such an approach is taken in the model.

Table 6.6. Mean relative percent errors between the predicted CO_2 concentrations and the average of the measured concentrations with 740 g of dry ice in Bin 2 with covered grain surface, with various sorption rates. The actual sorption rate was estimated from Cofie-Agblor et al. (1992).

Sorption Rate (% of actual q)	Mean Relative Percent Error*									
	1 h	3 h	6 h		12 h		21 h		24 h	
			5 L*	4 L**	5 L	4 L	5 L	4 L	5 L	4 L
10	105.07	118.67	117.46	67.49	87.16	63.68	88.92	70.22	88.48	69.69
20	104.52	115.91	110.71	63.69	77.90	57.10	74.25	58.54	71.97	56.37
30	103.97	113.16	103.95	59.89	68.65	50.53	59.58	46.86	55.47	43.05
40	103.42	110.42	97.25	56.13	59.47	44.00	45.06	35.32	39.09	29.83
50	102.87	107.65	90.44	52.30	50.14	37.37	30.48	23.81	22.70	16.71
60	102.32	104.88	83.68	48.52	40.81	30.74	15.91	12.30	6.54	3.88
70	101.77	102.10	76.97	44.82	31.49	24.11	4.26	3.37	11.13	10.64
80	101.23	99.43	70.53	41.28	22.52	17.73	11.71	13.84	26.54	23.02
90	100.68	96.66	63.88	37.64	13.29	11.22	28.17	22.91	42.83	36.01
100	100.13	93.88	57.27	34.07	6.77	5.94	42.58	34.21	59.19	49.10

* the mean relative percent errors were calculated for all 5 levels
** the mean relative percent errors were calculated for first 4 levels

7. CONCLUSIONS

Based on the results of this study the following conclusions can be drawn:

1. In the pilot bins, irrespective of the shape and location of floor opening, the CO_2 concentrations were uniform along the horizontal cross sections in the top 2/3 height of the grain bulk but were lower than the CO_2 concentrations in the bottom portions.
2. In the farm bins, irrespective of the point of application of dry ice (on the grain surface, in the aeration duct, or near the central axis of the grain bulk), the CO_2 concentrations were higher in the bottom portions of the bulk than in the top portions. For example, in farm Bin 1 when dry ice was introduced on the grain surface, at 48 h after the introduction of dry ice, the CO_2 concentrations were about 20% higher at the bottom level compared to the top level.
3. Introducing the dry ice on the grain surface gave higher CO_2 concentrations in the top portions of the bulk than when the dry ice was introduced in the aeration duct. For example, at 48 h after the introduction of dry ice, the average CO_2 concentrations at the top level was 4.0% when dry ice was introduced in the aeration duct compared to 11.9% when dry ice was introduced on the grain surface. In non-airtight bins the dry ice can be introduced on the grain surface to create high CO_2 concentrations in the top portions of the bulk.
4. In the pilot-bins the efficiency of retention ($\eta_{retention}$) was higher when the grain surface was covered with PVC sheets. The maximum observed $\eta_{retention}$ was only 54.6%. During CA treatment of wheat, allowances must be given for the sorption of CO_2 gas by the grain.
5. The $\eta_{retention}$ was low in all the farm-bin experiments. The maximum $\eta_{retention}$ was achieved when dry ice was introduced on the grain surface (26.3%) or near the central axis of the grain bulk (27.4%), and the grain surface was covered with a PVC sheet.
6. The $\eta_{retention}$ in the empty bin with a concrete floor was higher (43%) than that in wheat filled

bins with provision for aeration (27.4%). A bin with no aeration duct or perforated floor would be the best choice for application of CA treatment in non-airtight bins and the grain surface should be covered with a PVC sheet.

7. Progressively sealing different portions of the grain bin resulted in increased $\eta_{retention}$ (about 10%). Sealing a farm bin would be essential for better retention of CO_2 gas in the grain bulk.

8. The mortality of rusty grain beetle adults was higher in the bottom portions of the bulk (about 90%) than in the top portions (about 30%). During CA treatment of infested grain bulks the top portions of the grain bulk should be checked for insect mortality before terminating the treatment.

9. A pure diffusion model did not predict the CO_2 concentrations in the grain bulk accurately when dry ice was used as a source of CO_2 gas. The model predictions were improved when an apparent flow coefficient values were used instead of pure diffusion. A model of forced convective mass transport in the initial time periods and a pure diffusion model might predict the CO_2 concentrations in the pilot bins with reasonable accuracy.

8. SUGGESTIONS FOR FUTURE RESEARCH

Carbon dioxide distribution and retention were studied in wheat-filled bins with an aeration duct or fully perforated floor. Based on the results from the CO_2 retention tests in an empty bin with a concrete floor, I hypothesize that the CO_2 retention in a bin with no aeration duct or perforated floor would be better than in a bin with aeration systems. Experiments should be conducted to determine the CO_2 retention in wheat-filled bins with no aeration duct or perforated floor. The $\eta_{retention}$ was the best when dry ice was introduced through a perforated tube near the central axis of the grain bulk and allowed to flow horizontally towards the leaky bin walls. This method of application was not studied in detail because most existing farm bins do not have aeration ducts near the central axis of the bin. However, newer aeration systems (such as the one designed by the Grain Guard, Lethbridge, AB), have aeration ducts near the centre of the bins that allow the air to flow horizontally. Experiments should be conducted in bolted metal bins with these types of aeration systems to determine the CO_2 retention.

The $\eta_{retention}$ was generally low in bolted metal bins. Experiments should be conducted in welded hopper-bottom bins, which are more airtight than bolted-metal bins, to determine the retention of CO_2. Although high CO_2 concentrations were observed when the dry ice pellets were introduced directly on the grain surface, the CO_2 also tends to disappear quickly because of bin leakage. Experiments must be conducted to determine the CO_2 retention by releasing the CO_2 slowly into the grain bulk. This can be accomplished by placing blocks of dry ice into an insulated box.

The mortality of rusty grain beetle adults in cages was higher in the bottom portions of the grain bulk where the CO_2 concentrations were usually higher. Rusty grain beetle adults have a tendency to move towards the bottom of the grain bulk. Further research on the control of natural infestations of rusty grain beetle adults could provide results for the successful application of CO_2 treatment in bolted-metal bins.

For accurately predicting the CO_2 concentrations using mathematical models, data on the sorption of CO_2 at various initial concentrations and the model of CO_2 gas loss from the grain bin are essential and should be studied in the future.

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APPENDICES

APPENDIX A

Experimental data on CO_2 distribution in 1.42-m-diameter bins (pilot Bins 1, 2 and 3) containing wheat to a depth of 1.37 m.

Table A.1: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m, with a 0.3-m-diameter perforated floor opening near the centre. The grain surface was open. Mass of dry ice introduced was 180 g (Pilot 1).

Time Since Start	Level	Replicate	Sampling Locations 1	2	3	4	5	6	7	8	9	10	11
1 h	2	1	1.67	2.48	3.13	3.72	4.16	3.24	2.76	1.95	3.11	3.69	3.71
		2	2.63	2.72	3.59	3.78	4.06	3.76	2.43	3.20	3.41	3.87	3.68
		3	2.53	2.70	3.52	3.96	4.20	3.20	2.09	1.92	3.49	4.14	2.48
		Mean	2.28	2.63	3.41	3.82	4.14	3.40	2.43	2.36	3.34	3.90	3.29
		SD	0.53	0.13	0.25	0.12	0.07	0.31	0.34	0.73	0.20	0.23	0.70
		CV	23.18	5.06	7.26	3.27	1.74	9.19	13.81	31.00	6.00	5.81	21.33
	1	1	5.35	10.59	19.24	37.75	44.19	17.84	5.45	6.07	17.28	20.18	8.23
		2	7.43	12.37	21.52	40.10	46.15	17.93	7.14	7.37	18.21	19.70	8.69
		3	6.92	11.40	20.10	38.53	44.85	17.66	6.69	6.97	17.89	19.83	8.61
		Mean	6.57	11.45	20.29	38.79	45.06	17.81	6.43	6.80	17.79	19.90	8.51
		SD	1.08	0.89	1.15	1.20	1.00	0.14	0.88	0.67	0.47	0.25	0.25
		CV	16.51	7.78	5.68	3.09	2.21	0.77	13.62	9.79	2.66	1.25	2.89
3 h	3	1	1.29	1.69	1.81	2.02	2.05	1.91	1.43	1.45	1.76	1.98	1.91
		2	1.69	1.83	2.09	2.29	2.26	2.13	1.53	1.58	2.02	2.21	1.72
		3	1.65	1.89	2.23	2.99	2.74	2.20	1.56	1.55	2.12	2.36	1.68
		Mean	1.54	1.80	2.04	2.43	2.35	2.08	1.51	1.53	1.97	2.18	1.77
		SD	0.22	0.10	0.21	0.50	0.35	0.15	0.07	0.07	0.19	0.19	0.12
		CV	14.27	5.69	10.47	20.57	15.05	7.28	4.52	4.46	9.45	8.77	6.94
	2	1	4.97	5.64	6.66	7.24	7.40	6.39	4.09	5.49	6.06	7.02	5.71
		2	6.19	6.38	7.17	7.40	7.30	6.67	5.36	5.34	6.77	7.27	5.88
		3	5.54	6.25	7.33	7.55	7.68	6.86	5.17	4.98	6.49	6.79	5.50
		Mean	5.57	6.09	7.05	7.40	7.46	6.64	4.87	5.27	6.44	7.03	5.70
		SD	0.61	0.40	0.35	0.16	0.20	0.24	0.69	0.26	0.36	0.24	0.19
		CV	10.97	6.49	4.96	2.10	2.64	3.56	14.06	4.97	5.55	3.42	3.34
	1	1	8.91	11.23	17.64	32.75	39.32	15.52	8.00	7.55	15.34	18.90	9.62
		2	9.83	12.38	18.85	35.15	41.66	16.36	8.93	9.00	16.88	18.93	10.33
		3	9.15	11.66	18.48	33.70	41.06	16.98	9.06	8.66	15.83	17.21	10.03
		Mean	9.30	11.76	18.32	33.87	40.68	16.29	8.66	8.40	16.02	18.35	9.99
		SD	0.48	0.58	0.62	1.21	1.22	0.73	0.58	0.76	0.79	0.98	0.36
		CV	5.13	4.94	3.38	3.57	2.99	4.50	6.67	9.02	4.91	5.37	3.57
6 h	4	1	1.29	1.27	1.23	1.26	1.14	1.10	1.18	1.31	1.19	1.20	1.28
		2	1.26	1.37	1.46	1.60	1.51	1.34	1.17	1.23	1.45	1.46	1.24
		3	1.23	1.31	1.36	1.47	1.43	1.24	1.16	1.19	1.31	1.47	1.26
		Mean	1.26	1.32	1.35	1.44	1.36	1.23	1.17	1.24	1.32	1.38	1.26
		SD	0.03	0.05	0.12	0.17	0.19	0.12	0.01	0.06	0.13	0.15	0.02
		CV	2.38	3.82	8.54	11.89	14.31	9.83	0.85	4.91	9.88	11.12	1.59
	3	1	3.43	3.42	3.57	3.74	3.53	3.52	3.17	3.25	3.46	3.52	3.36
		2	3.46	3.69	3.97	4.24	3.94	3.70	3.16	3.36	3.84	3.90	3.42
		3	3.44	3.50	3.82	4.12	3.86	3.73	3.16	3.23	3.70	3.88	3.33
		Mean	3.44	3.54	3.79	4.03	3.78	3.65	3.16	3.28	3.67	3.77	3.37
		SD	0.02	0.14	0.20	0.26	0.22	0.11	0.01	0.07	0.19	0.21	0.05
		CV	0.44	3.92	5.34	6.47	5.75	3.11	0.18	2.13	5.24	5.68	1.36

Table A.1. continued ....

	2	1	7.06	7.36	8.31	9.09	8.83	7.29	6.68	6.49	7.85	8.33	6.87
		2	7.72	7.92	8.73	9.12	8.72	7.61	6.99	6.92	8.15	8.53	7.27
		3	7.33	7.60	8.47	9.01	8.91	7.55	6.76	6.57	8.04	8.42	6.96
		Mean	7.37	7.63	8.50	9.07	8.82	7.48	6.81	6.66	8.01	8.43	7.03
		SD	0.33	0.28	0.21	0.06	0.10	0.17	0.16	0.23	0.15	0.10	0.21
		CV	4.50	3.68	2.49	0.63	1.08	2.27	2.36	3.43	1.89	1.19	2.98
	1	1	9.76	11.33	16.15	27.82	32.66	13.72	8.85	8.71	14.35	15.93	9.95
		2	9.49	11.76	16.29	27.53	32.44	13.92	9.47	9.47	14.84	15.97	10.48
		3	9.60	11.46	15.77	26.31	31.93	13.41	8.93	9.12	14.16	15.52	9.64
		Mean	9.62	11.52	16.07	27.22	32.34	13.68	9.08	9.10	14.45	15.81	10.02
		SD	0.14	0.22	0.27	0.80	0.37	0.26	0.34	0.38	0.35	0.25	0.42
		CV	1.41	1.91	1.67	2.94	1.16	1.88	3.71	4.18	2.43	1.58	4.24
9 h	5	1	0.33	0.31	0.29	0.28	0.27	0.34	0.35	0.22	0.28	0.27	0.32
		2	0.42	0.30	0.30	0.27	0.27	0.27	0.24	0.22	0.27	0.27	0.31
		3	0.20	0.21	0.22	0.23	0.22	0.19	0.17	0.22	0.33	0.71	0.29
		Mean	0.32	0.27	0.27	0.26	0.25	0.27	0.25	0.22	0.29	0.42	0.31
		SD	0.11	0.06	0.04	0.03	0.03	0.08	0.09	0.00	0.03	0.25	0.02
		CV	34.93	20.15	16.14	10.18	11.40	28.15	35.82	0.00	10.96	60.97	4.98
	4	1	2.20	1.95	1.85	1.91	1.66	1.68	1.87	1.90	1.82	1.73	1.84
		2	1.92	1.99	2.02	2.19	2.08	1.87	1.94	1.97	2.03	2.07	2.04
		3	1.88	1.92	1.93	1.93	1.88	1.79	1.51	1.70	1.92	1.89	1.76
		Mean	2.00	1.95	1.93	2.01	1.87	1.78	1.77	1.86	1.92	1.90	1.88
		SD	0.17	0.04	0.09	0.16	0.21	0.10	0.23	0.14	0.11	0.17	0.14
		CV	8.72	1.80	4.40	7.77	11.21	5.36	13.01	7.55	5.46	8.97	7.67
	3	1	3.99	4.37	4.50	4.78	4.46	4.29	4.07	4.22	4.38	4.20	4.14
		2	4.09	4.44	4.74	4.90	4.35	4.44	3.91	4.21	4.64	4.63	4.44
		3	4.13	4.38	4.68	4.68	4.38	4.23	3.69	4.09	4.59	4.57	4.03
		Mean	4.07	4.40	4.64	4.79	4.40	4.32	3.89	4.17	4.54	4.47	4.20
		SD	0.07	0.04	0.12	0.11	0.06	0.11	0.19	0.07	0.14	0.23	0.21
		CV	1.77	0.86	2.69	2.30	1.29	2.50	4.90	1.73	3.04	5.21	5.05
	2	1	7.76	7.88	8.61	9.21	9.15	7.78	7.24	7.15	7.76	8.14	6.84
		2	7.73	8.01	8.56	9.17	8.47	7.58	7.32	7.15	8.25	8.28	7.49
		3	7.32	7.71	8.37	8.58	8.41	7.00	6.27	6.84	8.06	8.30	6.98
		Mean	7.60	7.87	8.51	8.99	8.68	7.45	6.94	7.05	8.02	8.24	7.10
		SD	0.25	0.15	0.13	0.35	0.41	0.41	0.58	0.18	0.25	0.09	0.34
		CV	3.23	1.91	1.49	3.93	4.74	5.44	8.42	2.54	3.08	1.06	4.82
	1	1	9.81	10.91	13.97	22.83	26.44	12.15	8.87	8.91	12.41	13.73	9.07
		2	9.23	10.71	13.58	21.32	23.55	11.21	8.45	8.42	12.63	13.43	9.16
		3	9.28	10.44	13.54	19.57	22.73	11.68	8.42	8.75	12.01	12.59	8.91
		Mean	9.44	10.69	13.70	21.24	24.24	11.68	8.58	8.69	12.35	13.25	9.05
		SD	0.32	0.24	0.24	1.63	1.95	0.47	0.25	0.25	0.31	0.59	0.13
		CV	3.40	2.21	1.73	7.68	8.04	4.02	2.93	2.87	2.55	4.46	1.40
12 h	5	1	0.39	0.33	0.28	0.30	0.25	0.28	0.29	0.53	0.29	0.26	0.37
		2	0.34	0.32	0.35	0.32	0.30	0.32	0.28	0.23	0.45	1.00	0.34
		3	0.31	0.31	0.32	0.27	0.23	0.22	0.23	0.20	0.21	0.26	0.33
		Mean	0.35	0.32	0.32	0.30	0.26	0.27	0.27	0.32	0.32	0.51	0.35
		SD	0.04	0.01	0.04	0.03	0.04	0.05	0.03	0.18	0.12	0.43	0.02
		CV	11.66	3.12	11.09	8.48	13.87	18.41	12.05	57.03	38.59	84.32	6.00

Table A.1. continued ....

	4	1	2.36	2.27	2.14	2.18	2.08	2.01	2.27	2.26	2.11	1.99	2.22
		2	2.17	2.41	2.47	2.61	2.40	2.23	2.05	2.12	2.19	2.30	2.10
		3	2.35	2.30	2.29	2.45	2.21	2.06	2.13	2.24	2.25	2.28	2.28
		Mean	2.29	2.33	2.30	2.41	2.23	2.10	2.15	2.21	2.18	2.19	2.20
		SD	0.11	0.07	0.17	0.22	0.16	0.12	0.11	0.08	0.07	0.17	0.09
		CV	4.66	3.17	7.18	9.01	7.22	5.49	5.18	3.43	3.22	7.92	4.17
	3	1	4.72	4.69	4.80	4.99	4.75	4.64	4.24	4.60	4.61	4.55	4.52
		2	4.45	4.99	5.19	5.43	4.93	4.60	4.36	4.53	4.77	4.99	4.45
		3	4.70	4.83	5.13	5.38	4.77	4.63	4.29	4.57	4.92	4.98	4.62
		Mean	4.62	4.84	5.04	5.27	4.82	4.62	4.30	4.57	4.77	4.84	4.53
		SD	0.15	0.15	0.21	0.24	0.10	0.02	0.06	0.04	0.16	0.25	0.09
		CV	3.25	3.10	4.17	4.57	2.05	0.45	1.40	0.77	3.25	5.19	1.89
	2	1	7.60	7.64	8.31	8.92	8.94	7.57	7.10	6.84	7.94	7.88	6.87
		2	7.24	8.06	8.64	8.98	8.27	7.47	6.85	7.27	7.80	7.92	7.15
		3	7.73	7.78	8.57	9.09	8.56	7.11	6.94	7.09	7.96	8.17	7.13
		Mean	7.52	7.83	8.51	9.00	8.59	7.38	6.96	7.07	7.90	7.99	7.05
		SD	0.25	0.21	0.17	0.09	0.34	0.24	0.13	0.22	0.09	0.16	0.16
		CV	3.37	2.73	2.04	0.96	3.91	3.28	1.82	3.06	1.10	1.97	2.22
	1	1	8.93	9.88	12.02	18.52	21.60	10.76	8.41	8.51	11.15	11.45	8.59
		2	8.82	10.05	12.28	17.84	20.47	10.45	8.32	9.01	11.03	11.53	9.56
		3	9.92	9.96	12.04	18.19	19.34	10.15	8.24	8.49	10.84	11.60	8.89
		Mean	9.22	9.96	12.11	18.18	20.47	10.45	8.32	8.67	11.01	11.53	9.01
		SD	0.61	0.09	0.14	0.34	1.13	0.31	0.09	0.29	0.16	0.08	0.50
		CV	6.57	0.85	1.19	1.87	5.52	2.92	1.02	3.40	1.42	0.65	5.51
21 h	5	1	0.41	0.35	0.28	0.25	0.23	0.31	0.48	0.23	0.37	0.31	0.52
		2	0.25	0.32	0.32	0.29	0.35	0.28	0.25	0.21	0.54	0.49	0.35
		3	0.24	0.30	0.28	0.24	0.25	0.22	0.18	0.16	0.22	0.19	0.24
		Mean	0.30	0.32	0.29	0.26	0.28	0.27	0.30	0.20	0.38	0.33	0.37
		SD	0.10	0.03	0.02	0.03	0.06	0.05	0.16	0.04	0.16	0.15	0.14
		CV	31.80	7.78	7.87	10.18	23.24	16.97	51.74	18.03	42.51	45.76	38.13
	4	1	2.50	2.39	2.26	2.26	2.11	2.12	2.37	2.31	2.22	2.19	2.49
		2	2.32	2.45	2.51	2.49	2.68	2.36	2.19	2.25	2.51	2.61	2.29
		3	2.29	2.34	2.34	2.45	2.51	2.29	2.23	2.28	2.39	2.40	2.35
		Mean	2.37	2.39	2.37	2.40	2.43	2.26	2.26	2.28	2.37	2.40	2.38
		SD	0.11	0.06	0.13	0.12	0.29	0.12	0.09	0.03	0.15	0.21	0.10
		CV	4.79	2.30	5.39	5.12	12.03	5.47	4.18	1.32	6.14	8.75	4.32
	3	1	4.30	4.56	4.58	4.69	4.32	4.35	4.12	4.28	4.44	4.48	4.34
		2	4.48	4.63	5.00	5.10	3.86	4.57	4.01	4.35	4.58	4.43	4.22
		3	4.01	4.16	4.46	4.59	4.70	4.46	3.99	4.07	4.40	4.48	4.09
		Mean	4.26	4.45	4.68	4.79	4.29	4.46	4.04	4.23	4.47	4.46	4.22
		SD	0.24	0.25	0.28	0.27	0.42	0.11	0.07	0.15	0.09	0.03	0.13
		CV	5.56	5.70	6.06	5.64	9.80	2.47	1.73	3.44	2.11	0.65	2.97

Table A.1. continued ....

2	1	6.15	6.18	6.85	6.86	6.93	6.04	5.89	5.82	6.37	6.48	6.04
	2	6.29	6.47	6.92	7.25	6.85	5.77	5.68	6.13	6.57	6.47	6.01
	3	5.66	5.90	6.00	6.47	6.83	5.88	5.48	5.68	6.20	6.22	5.67
	Mean	6.03	6.18	6.59	6.86	6.87	5.90	5.68	5.88	6.38	6.39	5.91
	SD	0.33	0.29	0.51	0.39	0.05	0.14	0.21	0.23	0.19	0.15	0.21
	CV	5.48	4.61	7.77	5.69	0.77	2.30	3.61	3.92	2.90	2.31	3.48
1	1	6.89	7.48	8.41	11.23	11.87	7.25	5.97	6.76	7.84	7.94	6.98
	2	7.08	7.64	8.42	11.03	12.30	7.27	6.69	7.09	8.01	7.69	6.94
	3	6.16	6.38	7.32	9.67	11.64	6.84	6.02	6.15	7.25	7.46	6.29
	Mean	6.71	7.17	8.05	10.64	11.94	7.12	6.23	6.67	7.70	7.70	6.74
	SD	0.49	0.69	0.63	0.85	0.34	0.24	0.40	0.48	0.40	0.24	0.39
	CV	7.24	9.57	7.85	7.98	2.81	3.41	6.46	7.15	5.18	3.12	5.75

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table.A.2: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m, with a 0.3-m-diameter perforated floor opening near the centre. Bin was emptied and refilled after each replicate. The grain surface was open. Mass of dry ice introduced was 180 g (Pilot 2).

Time Since Start	Level	Replicate	Sampling Locations 1	2	3	4	5	6	7	8	9	10	11
1 h	2	1	3.22	3.24	3.16	3.06	2.84	2.51	2.01	2.70	2.98	2.69	2.56
		2	2.14	2.83	3.02	3.22	3.41	2.94	2.19	2.49	3.15	3.37	2.70
		3	1.96	2.96	3.22	3.56	3.92	2.62	1.59	1.85	2.97	3.64	2.32
		Mean	2.44	3.01	3.13	3.28	3.39	2.69	1.93	2.35	3.03	3.23	2.53
		SD	0.68	0.21	0.10	0.26	0.54	0.22	0.31	0.44	0.10	0.49	0.19
		CV	27.93	6.96	3.28	7.78	15.94	8.30	15.95	18.87	3.33	15.14	7.61
	1	1	10.49	13.62	20.36	37.76	40.57	16.01	8.47	10.62	17.62	18.05	9.19
		2	11.37	14.17	20.73	38.48	48.74	17.58	8.78	10.01	20.13	20.51	11.08
		3	9.71	15.04	22.29	29.18	39.54	17.32	7.98	1.68	17.56	21.12	9.61
		Mean	10.52	14.28	21.13	35.14	42.95	16.97	8.41	7.44	18.44	19.89	9.96
		SD	0.83	0.72	1.02	5.17	5.04	0.84	0.40	4.99	1.47	1.63	0.99
		CV	7.89	5.02	4.85	14.72	11.74	4.96	4.80	67.16	7.96	8.17	9.96
3 h	3	1	1.81	2.19	1.97	1.87	1.78	1.70	1.60	2.11	2.20	1.78	1.68
		2	1.53	1.91	1.92	2.08	1.91	2.08	1.68	1.77	1.94	1.98	1.68
		3	1.48	1.95	2.65	2.56	2.13	2.09	2.07	1.65	2.23	2.42	1.52
		Mean	1.61	2.02	2.18	2.17	1.94	1.96	1.78	1.84	2.12	2.06	1.63
		SD	0.18	0.15	0.41	0.35	0.18	0.22	0.25	0.24	0.16	0.33	0.09
		CV	11.07	7.51	18.71	16.30	9.12	11.36	14.10	12.94	7.51	15.89	5.68
	2	1	6.79	6.66	6.93	6.61	6.22	6.03	5.31	6.54	6.55	5.99	6.00
		2	5.50	5.97	5.91	6.09	6.63	5.38	5.41	5.53	6.45	6.18	5.63
		3	5.89	6.83	7.37	7.52	7.45	5.83	5.23	5.99	6.93	7.06	5.69
		Mean	6.06	6.49	6.74	6.74	6.77	5.75	5.32	6.02	6.64	6.41	5.77
		SD	0.66	0.46	0.75	0.72	0.63	0.33	0.09	0.51	0.25	0.57	0.20
		CV	10.92	7.02	11.12	10.74	9.26	5.79	1.70	8.40	3.81	8.91	3.44
	1	1	10.82	12.54	18.15	31.31	38.55	16.20	9.18	10.44	17.21	18.31	9.15
		2	8.91	10.74	15.26	28.90	34.08	13.21	8.75	8.79	15.63	16.24	9.00
		3	10.45	12.25	19.72	28.42	30.80	12.44	9.25	9.68	17.79	17.72	9.69
		Mean	10.06	11.84	17.71	29.54	34.48	13.95	9.06	9.64	16.88	17.42	9.28
		SD	1.01	0.97	2.26	1.55	3.89	1.99	0.27	0.83	1.12	1.07	0.36
		CV	10.07	8.16	12.77	5.24	11.28	14.24	2.99	8.57	6.62	6.12	3.91
6 h	4	1	1.34	1.49	1.48	1.58	1.18	1.10	1.05	1.15	1.20	1.17	1.20
		2	1.36	1.48	1.65	1.66	1.54	1.45	1.22	1.33	1.66	1.54	1.18
		3	1.22	1.46	1.71	1.86	1.80	1.40	1.02	1.20	1.68	1.64	1.20
		Mean	1.31	1.48	1.61	1.70	1.51	1.32	1.10	1.23	1.51	1.45	1.19
		SD	0.08	0.02	0.12	0.14	0.31	0.19	0.11	0.09	0.27	0.25	0.01
		CV	5.79	1.03	7.39	8.48	20.66	14.38	9.84	7.57	17.94	17.08	0.97
	3	1	3.49	4.08	3.71	3.78	2.94	2.99	2.90	3.10	3.34	3.21	3.20
		2	3.43	3.78	3.97	3.86	3.70	3.82	3.53	3.60	3.91	4.10	3.67
		3	3.47	3.73	4.11	4.87	4.10	4.20	3.48	3.60	3.52	4.20	3.76
		Mean	3.46	3.86	3.93	4.17	3.58	3.67	3.30	3.43	3.59	3.84	3.54
		SD	0.03	0.19	0.20	0.61	0.59	0.62	0.35	0.29	0.29	0.55	0.30
		CV	0.88	4.90	5.16	14.57	16.46	16.86	10.60	8.41	8.12	14.21	8.49

Table A.2. continued ....

	2	1	8.03	7.98	8.37	18.14	17.15	6.17	6.31	7.15	7.48	6.86	6.87
		2	7.25	7.35	7.32	7.82	8.03	7.28	7.07	7.21	8.13	8.12	7.50
		3	7.80	8.18	9.04	9.94	9.28	7.96	7.12	7.94	8.76	9.56	7.66
		Mean	7.69	7.84	8.24	11.97	11.49	7.14	6.83	7.43	8.12	8.18	7.34
		SD	0.40	0.43	0.87	5.45	4.94	0.90	0.45	0.44	0.64	1.35	0.42
		CV	5.21	5.53	10.52	45.55	43.04	12.66	6.64	5.92	7.88	16.52	5.69
	1	1	11.14	11.74	15.50	25.01	25.92	11.63	8.21	9.70	13.70	15.25	9.70
		2	9.77	10.67	14.51	24.36	31.41	11.75	9.55	9.79	14.17	14.91	10.29
		3	10.65	11.05	16.73	24.60	27.70	13.38	10.23	10.53	15.35	16.58	10.93
		Mean	10.52	11.15	15.58	24.66	28.34	12.25	9.33	10.01	14.41	15.58	10.31
		SD	0.69	0.54	1.11	0.33	2.80	0.98	1.03	0.46	0.85	0.88	0.62
		CV	6.60	4.86	7.14	1.33	9.88	7.98	11.02	4.55	5.90	5.66	5.97
9 h	5	1	0.34	0.35	0.38	0.31	0.32	0.31	0.28	0.29	0.28	0.32	0.28
		2	0.29	0.23	0.52	0.24	0.24	0.30	0.17	0.21	0.24	0.15	0.15
		3	0.25	0.26	0.29	0.39	0.37	0.40	0.19	0.23	0.22	0.29	0.17
		Mean	0.29	0.28	0.40	0.31	0.31	0.34	0.21	0.24	0.25	0.25	0.20
		SD	0.05	0.06	0.12	0.08	0.07	0.06	0.06	0.04	0.03	0.09	0.07
		CV	15.37	22.30	29.22	23.95	21.15	16.36	27.47	17.11	12.39	35.82	35.00
	4	1	1.91	2.10	2.13	2.54	2.03	1.94	1.92	2.02	2.10	2.00	2.00
		2	1.80	1.86	2.04	2.14	1.93	1.95	1.60	1.79	2.01	1.81	1.53
		3	1.94	2.18	2.48	2.69	2.81	2.42	1.91	1.95	2.53	2.78	1.85
		Mean	1.88	2.05	2.22	2.46	2.26	2.10	1.81	1.92	2.21	2.20	1.79
		SD	0.07	0.17	0.23	0.28	0.48	0.27	0.18	0.12	0.28	0.51	0.24
		CV	3.91	8.14	10.49	11.57	21.35	13.04	10.05	6.14	12.56	23.40	13.39
	3	1	4.19	4.46	4.50	4.45	4.54	4.41	4.35	4.23	4.53	4.59	4.35
		2	4.05	4.50	4.67	4.69	3.98	4.22	3.90	3.64	4.37	4.13	3.69
		3	4.09	4.65	5.26	5.45	5.68	5.27	4.41	4.66	5.30	5.37	4.51
		Mean	4.11	4.54	4.81	4.86	4.73	4.63	4.22	4.18	4.73	4.70	4.18
		SD	0.07	0.10	0.40	0.52	0.87	0.56	0.28	0.51	0.50	0.63	0.43
		CV	1.75	2.21	8.29	10.73	18.30	12.08	6.61	12.26	10.50	13.35	10.39
	2	1	7.79	7.67	7.56	7.59	8.08	7.20	7.39	7.41	7.63	7.93	7.64
		2	7.57	7.53	7.80	7.81	8.12	7.34	6.86	6.80	7.54	7.14	6.37
		3	8.27	8.16	8.65	9.61	9.91	9.50	7.69	8.43	9.17	9.32	7.95
		Mean	7.88	7.79	8.00	8.34	8.70	8.01	7.31	7.55	8.11	8.13	7.32
		SD	0.36	0.33	0.57	1.11	1.05	1.29	0.42	0.82	0.92	1.10	0.84
		CV	4.54	4.25	7.16	13.29	12.01	16.09	5.75	10.91	11.29	13.58	11.44
	1	1	9.16	10.26	12.22	17.43	22.45	11.63	9.15	9.51	12.67	12.63	9.37
		2	9.39	10.24	13.63	20.56	22.13	10.73	8.73	10.16	11.41	11.60	8.31
		3	9.89	10.56	13.00	18.17	22.08	11.40	10.37	9.63	13.07	13.29	10.17
		Mean	9.48	10.35	12.95	18.72	22.22	11.25	9.42	9.77	12.38	12.51	9.28
		SD	0.37	0.18	0.71	1.64	0.20	0.47	0.85	0.35	0.87	0.85	0.93
		CV	3.94	1.73	5.45	8.74	0.90	4.16	9.05	3.54	7.00	6.81	10.05
12 h	5	1	0.40	0.39	0.39	0.35	0.36	0.35	0.34	0.36	0.32	0.36	0.54
		2	0.25	0.28	0.27	0.25	0.29	0.36	0.21	0.22	0.25	0.18	0.18
		3	0.29	0.31	0.29	0.33	0.42	0.48	0.27	0.33	0.26	0.34	0.53
		Mean	0.31	0.33	0.32	0.31	0.36	0.40	0.27	0.30	0.28	0.29	0.42
		SD	0.08	0.06	0.06	0.05	0.07	0.07	0.07	0.07	0.04	0.10	0.21
		CV	24.79	17.41	20.30	17.07	18.24	18.24	23.80	24.30	13.68	33.63	49.20

Table A.2. continued ....

	4	1	2.44	2.43	2.50	2.41	2.43	2.35	2.36	2.39	2.51	2.46	2.31
		2	2.34	2.43	2.38	2.41	2.29	2.33	2.10	2.26	2.44	2.11	1.73
		3	2.38	2.62	3.00	5.16	3.24	2.80	2.39	2.37	2.98	2.96	2.29
		Mean	2.39	2.49	2.63	3.33	2.65	2.49	2.28	2.34	2.64	2.51	2.11
		SD	0.05	0.11	0.33	1.59	0.51	0.27	0.16	0.07	0.29	0.43	0.33
		CV	2.11	4.40	12.52	47.73	19.33	10.66	6.98	2.99	11.11	17.02	15.60
	3	1	4.52	4.86	5.08	4.94	4.75	4.88	4.78	4.85	4.92	4.87	4.63
		2	4.64	5.27	5.06	5.00	4.50	4.63	4.13	4.08	4.42	4.36	3.98
		3	4.65	5.23	5.89	6.09	5.70	5.77	4.97	4.98	5.69	5.81	5.00
		Mean	4.60	5.12	5.34	5.34	4.98	5.09	4.63	4.64	5.01	5.01	4.54
		SD	0.07	0.23	0.47	0.65	0.63	0.60	0.44	0.49	0.64	0.74	0.52
		CV	1.57	4.42	8.86	12.11	12.70	11.76	9.52	10.49	12.77	14.67	11.38
	2	1	7.74	7.26	7.36	7.76	8.13	7.32	7.10	7.41	7.47	7.86	7.42
		2	7.30	8.53	7.64	7.90	7.66	7.13	6.94	6.66	6.98	7.22	7.53
		3	7.99	8.27	8.72	9.45	10.08	9.16	7.88	7.90	8.71	9.21	7.86
		Mean	7.68	8.02	7.91	8.37	8.62	7.87	7.31	7.32	7.72	8.10	7.60
		SD	0.35	0.67	0.72	0.94	1.28	1.12	0.50	0.62	0.89	1.02	0.23
		CV	4.55	8.37	9.08	11.21	14.88	14.25	6.88	8.53	11.55	12.55	3.01
	1	1	8.47	9.43	10.78	15.26	19.62	9.79	8.40	8.87	11.03	10.79	9.12
		2	9.23	10.38	11.77	17.71	20.20	10.17	8.65	8.14	10.62	10.06	7.69
		3	9.37	9.86	11.61	15.76	19.94	10.80	9.07	9.14	11.70	11.85	9.56
		Mean	9.02	9.89	11.39	16.24	19.92	10.25	8.71	8.72	11.12	10.90	8.79
		SD	0.48	0.48	0.53	1.29	0.29	0.51	0.34	0.52	0.55	0.90	0.98
		CV	5.37	4.81	4.67	7.97	1.46	4.98	3.89	5.93	4.90	8.26	11.12
21 h	5	1	0.41	0.43	0.41	0.31	0.36	0.35	0.34	0.35	0.33	0.38	0.34
		2	0.26	0.31	0.34	0.32	0.48	0.37	0.24	0.26	0.34	0.27	0.21
		3	0.31	0.32	0.28	0.31	0.43	0.53	0.25	0.29	0.27	0.36	0.18
		Mean	0.33	0.35	0.34	0.31	0.42	0.42	0.28	0.30	0.31	0.34	0.24
		SD	0.08	0.07	0.07	0.01	0.06	0.10	0.06	0.05	0.04	0.06	0.09
		CV	23.38	18.84	18.95	1.84	14.24	23.68	19.91	15.28	12.08	17.40	34.95
	4	1	2.50	2.55	2.61	2.49	2.44	2.39	2.46	2.50	2.57	2.53	2.56
		2	2.32	2.63	2.86	2.89	3.01	2.77	2.24	2.38	2.97	2.85	2.19
		3	2.42	2.67	3.00	3.22	3.19	2.86	2.36	2.45	2.91	2.97	2.28
		Mean	2.41	2.62	2.82	2.87	2.88	2.67	2.35	2.44	2.82	2.78	2.34
		SD	0.09	0.06	0.20	0.37	0.39	0.25	0.11	0.06	0.22	0.23	0.19
		CV	3.74	2.34	7.00	12.75	13.59	9.33	4.68	2.47	7.66	8.17	8.23
	3	1	3.78	4.56	4.63	4.50	4.35	4.42	4.43	4.41	4.53	4.61	4.50
		2	4.13	4.52	4.97	4.86	4.70	4.85	4.18	4.33	4.90	4.96	4.29
		3	4.40	4.86	5.35	5.57	5.22	5.22	4.53	4.52	5.24	5.05	4.51
		Mean	4.10	4.65	4.98	4.98	4.76	4.83	4.38	4.42	4.89	4.87	4.43
		SD	0.31	0.19	0.36	0.54	0.44	0.40	0.18	0.10	0.36	0.23	0.12
		CV	7.58	4.00	7.23	10.94	9.20	8.29	4.12	2.16	7.26	4.77	2.80

Table A.2. continued ....

2	1	6.16	6.22	6.24	6.33	6.62	6.06	6.00	6.00	6.29	6.54	6.37
	2	6.08	6.16	6.12	6.77	7.02	6.19	6.07	6.09	6.43	6.83	6.22
	3	6.67	6.93	6.74	7.61	7.89	6.69	6.36	6.60	6.60	7.15	6.12
	Mean	6.30	6.44	6.37	6.90	7.18	6.31	6.14	6.23	6.44	6.84	6.24
	SD	0.32	0.43	0.33	0.65	0.65	0.33	0.19	0.32	0.16	0.31	0.13
	CV	5.08	6.65	5.16	9.42	9.05	5.27	3.11	5.19	2.41	4.46	2.02
1	1	6.56	6.94	7.58	9.47	11.04	7.23	6.80	6.67	6.96	7.82	6.67
	2	6.34	6.93	7.57	9.35	11.72	7.72	6.15	6.41	7.83	7.96	6.91
	3	7.18	7.65	8.51	10.44	11.99	8.40	7.45	7.13	8.08	8.16	6.69
	Mean	6.69	7.17	7.89	9.75	11.58	7.78	6.80	6.74	7.62	7.98	6.76
	SD	0.44	0.41	0.54	0.60	0.49	0.59	0.65	0.36	0.59	0.17	0.13
	CV	6.51	5.76	6.85	6.13	4.23	7.55	9.56	5.41	7.71	2.14	1.97

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.3: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with a 0.3-m-diameter perforated floor opening near the centre. The grain surface was covered with a PVC sheet. Mass of dry ice introduced was 180 g (Pilot 3).

Time Since Start	Level	Replicate	Sampling Locations 1	2	3	4	5	6	7	8	9	10	11
1 h	2	1	2.50	2.22	2.68	2.82	3.37	3.16	2.55	2.77	2.91	2.54	2.67
		2	3.09	2.66	3.13	3.86	4.62	3.95	4.22	3.41	3.75	3.24	3.60
		3	2.99	2.56	3.16	3.52	4.11	3.72	3.83	2.97	3.19	3.27	3.75
		Mean	2.86	2.48	2.99	3.40	4.03	3.61	3.53	3.05	3.28	3.02	3.34
		SD	0.32	0.23	0.27	0.53	0.63	0.41	0.87	0.33	0.43	0.41	0.59
		CV	11.04	9.30	8.99	15.60	15.58	11.26	24.73	10.73	13.03	13.69	17.52
	1	1	10.28	14.89	23.05	43.83	56.76	23.82	12.13	10.16	21.67	23.86	11.84
		2	9.43	12.48	20.46	41.41	58.25	22.66	10.48	9.60	19.58	20.01	10.88
		3	9.31	12.66	20.09	42.83	57.40	22.82	10.93	9.36	19.40	18.25	10.11
		Mean	9.67	13.34	21.20	42.69	57.47	23.10	11.18	9.71	20.22	20.71	10.94
		SD	0.53	1.34	1.61	1.22	0.75	0.63	0.85	0.41	1.26	2.87	0.87
		CV	5.47	10.06	7.61	2.85	1.30	2.72	7.63	4.23	6.24	13.86	7.92
3 h	3	1	2.16	2.10	1.71	1.43	1.52	1.90	2.59	2.33	1.82	1.90	1.81
		2	1.96	1.78	1.66	1.59	1.60	1.78	2.23	2.09	1.70	1.71	2.15
		3	2.02	2.03	1.57	1.48	1.56	1.74	2.49	2.19	1.68	1.72	2.54
		Mean	2.05	1.97	1.65	1.50	1.56	1.81	2.44	2.20	1.73	1.78	2.17
		SD	0.10	0.17	0.07	0.08	0.04	0.08	0.19	0.12	0.08	0.11	0.37
		CV	5.01	8.54	4.31	5.46	2.56	4.61	7.63	5.47	4.37	6.02	16.86
	2	1	6.98	6.62	6.87	7.03	7.32	7.49	7.93	6.88	7.01	7.00	7.49
		2	6.39	6.28	6.40	7.10	6.39	7.27	7.30	6.68	6.83	6.70	6.74
		3	6.44	6.15	6.44	6.83	7.07	6.89	6.88	6.40	6.40	6.09	6.69
		Mean	6.60	6.35	6.57	6.99	6.93	7.22	7.37	6.65	6.75	6.60	6.97
		SD	0.33	0.24	0.26	0.14	0.48	0.30	0.53	0.24	0.31	0.46	0.45
		CV	4.95	3.82	3.97	2.01	6.95	4.21	7.17	3.62	4.65	7.03	6.43
	1	1	10.65	12.50	18.15	35.85	49.73	20.08	11.88	10.65	18.33	19.52	11.17
		2	9.95	11.70	17.05	33.48	50.12	19.83	10.91	10.03	17.70	19.52	11.42
		3	9.37	11.45	17.79	36.38	47.74	19.61	11.10	10.15	16.94	18.25	11.18
		Mean	9.99	11.88	17.66	35.24	49.20	19.84	11.30	10.28	17.66	19.10	11.26
		SD	0.64	0.55	0.56	1.54	1.28	0.24	0.51	0.33	0.70	0.73	0.14
		CV	6.42	4.62	3.18	4.38	2.59	1.19	4.55	3.20	3.94	3.84	1.26
6 h	4	1	1.83	1.74	1.48	1.35	1.10	1.39	2.02	1.89	1.47	1.45	1.93
		2	1.56	1.43	1.24	1.06	1.19	1.18	1.77	1.53	1.17	1.43	1.80
		3	1.90	1.80	1.50	1.30	1.27	1.51	2.11	2.06	1.55	1.53	2.01
		Mean	1.76	1.66	1.41	1.24	1.19	1.36	1.97	1.83	1.40	1.47	1.91
		SD	0.18	0.20	0.14	0.16	0.09	0.17	0.18	0.27	0.20	0.05	0.11
		CV	10.18	11.99	10.29	12.54	7.17	12.28	8.96	14.81	14.34	3.60	5.54
	3	1	4.25	4.23	3.75	3.42	3.42	3.81	4.72	4.52	3.87	3.77	4.57
		2	3.62	3.74	3.48	3.45	3.48	3.69	4.14	4.02	3.56	3.75	4.37
		3	3.90	4.78	3.74	3.66	3.56	3.82	4.70	4.40	3.67	3.90	4.72
		Mean	3.92	4.25	3.66	3.51	3.49	3.77	4.52	4.31	3.70	3.81	4.55
		SD	0.32	0.52	0.15	0.13	0.07	0.07	0.33	0.26	0.16	0.08	0.18
		CV	8.05	12.24	4.19	3.73	2.01	1.92	7.28	6.05	4.25	2.14	3.86

Table A.3. continued ....

	2	1	8.77	8.52	8.61	8.64	9.02	9.13	9.39	8.61	8.89	8.84	9.22
		2	7.98	7.47	7.75	9.12	9.19	9.02	8.56	8.54	8.48	8.30	8.54
		3	8.80	8.31	8.70	9.44	9.55	8.97	9.13	8.16	8.75	8.29	8.72
		Mean	8.52	8.10	8.35	9.07	9.25	9.04	9.03	8.44	8.71	8.48	8.83
		SD	0.47	0.56	0.52	0.40	0.27	0.08	0.42	0.24	0.21	0.31	0.35
		CV	5.46	6.86	6.28	4.44	2.92	0.91	4.70	2.87	2.39	3.71	3.99
	1	1	11.05	12.68	16.50	29.51	38.72	17.26	12.24	11.63	16.37	17.22	11.82
		2	9.57	11.54	14.59	28.54	36.39	16.14	10.86	11.04	14.87	15.85	11.01
		3	10.37	12.21	15.73	28.75	38.53	16.69	11.49	11.00	15.62	16.57	11.77
		Mean	10.33	12.14	15.61	28.93	37.88	16.70	11.53	11.22	15.62	16.55	11.53
		SD	0.74	0.57	0.96	0.51	1.29	0.56	0.69	0.35	0.75	0.69	0.45
		CV	7.17	4.72	6.16	1.76	3.42	3.35	5.99	3.14	4.80	4.14	3.94
12 h	5	1	2.75	2.74	2.69	2.69	2.57	2.77	2.78	2.83	2.73	2.74	2.55
		2	2.52	2.64	2.57	2.51	2.49	2.55	2.69	2.45	2.45	2.62	3.07
		3	2.39	2.79	2.85	2.76	2.75	2.72	2.60	3.24	2.84	2.69	2.86
		Mean	2.55	2.72	2.70	2.65	2.60	2.68	2.69	2.84	2.67	2.68	2.83
		SD	0.18	0.08	0.14	0.13	0.13	0.12	0.09	0.40	0.20	0.06	0.26
		CV	7.14	2.80	5.20	4.86	5.12	4.30	3.35	13.91	7.52	2.25	9.25
	4	1	3.92	3.81	3.52	3.28	3.15	3.49	4.24	4.11	3.56	3.62	4.10
		2	3.78	3.64	3.39	3.25	3.20	3.36	3.91	3.77	3.35	3.46	3.92
		3	3.94	4.00	3.74	3.52	3.34	4.19	4.13	4.09	3.72	3.67	3.94
		Mean	3.88	3.82	3.55	3.35	3.23	3.68	4.09	3.99	3.54	3.58	3.99
		SD	0.09	0.18	0.18	0.15	0.10	0.45	0.17	0.19	0.19	0.11	0.10
		CV	2.25	4.72	4.98	4.42	3.05	12.13	4.10	4.78	5.24	3.06	2.47
	3	1	6.15	5.98	5.56	5.24	5.23	5.70	6.52	6.36	5.65	5.65	6.48
		2	5.87	5.91	5.65	5.51	5.41	5.66	6.33	6.11	5.62	5.67	6.31
		3	5.90	6.38	6.59	6.05	5.59	5.71	6.41	6.21	5.87	6.04	6.21
		Mean	5.97	6.09	5.93	5.60	5.41	5.69	6.42	6.23	5.71	5.79	6.33
		SD	0.15	0.25	0.57	0.41	0.18	0.03	0.10	0.13	0.14	0.22	0.14
		CV	2.57	4.16	9.61	7.36	3.33	0.46	1.49	2.02	2.39	3.80	2.16
	2	1	9.04	8.93	9.07	9.26	9.31	9.26	9.56	9.06	9.11	9.06	9.25
		2	9.14	8.87	9.14	9.64	9.94	9.31	9.23	9.00	8.98	9.17	9.13
		3	8.91	9.12	9.32	9.88	10.00	9.48	8.91	9.06	9.38	9.53	9.04
		Mean	9.03	8.97	9.18	9.59	9.75	9.35	9.23	9.04	9.16	9.25	9.14
		SD	0.12	0.13	0.13	0.31	0.38	0.12	0.33	0.03	0.20	0.25	0.11
		CV	1.28	1.45	1.41	3.26	3.92	1.23	3.52	0.38	2.23	2.66	1.15
	1	1	10.45	10.87	12.69	18.96	24.61	13.10	10.81	10.56	12.58	13.02	10.79
		2	10.49	11.02	12.36	20.24	26.13	13.26	10.93	10.64	12.53	13.07	10.89
		3	10.25	10.92	13.10	19.46	25.78	13.28	11.05	10.90	13.40	12.90	10.77
		Mean	10.40	10.94	12.72	19.55	25.51	13.21	10.93	10.70	12.84	13.00	10.82
		SD	0.13	0.08	0.37	0.65	0.80	0.10	0.12	0.18	0.49	0.09	0.06
		CV	1.24	0.70	2.92	3.30	3.12	0.75	1.10	1.66	3.81	0.67	0.59
21 h	5	1	4.11	4.51	4.58	4.45	4.41	4.60	4.42	4.62	4.24	4.38	3.98
		2	4.50	4.74	4.67	4.61	4.61	4.64	4.67	4.57	4.58	4.90	5.00
		3	3.99	4.60	4.71	4.55	4.53	4.71	4.74	4.57	4.40	4.55	4.14
		Mean	4.20	4.62	4.65	4.54	4.52	4.65	4.61	4.59	4.41	4.61	4.37
		SD	0.27	0.12	0.07	0.08	0.10	0.06	0.17	0.03	0.17	0.27	0.55
		CV	6.35	2.51	1.43	1.78	2.23	1.20	3.65	0.63	3.86	5.75	12.54

Table A.3. continued ....

4	1	5.42	5.36	5.18	4.99	4.85	5.13	5.60	5.48	5.19	5.12	5.51
	2	5.50	5.42	5.26	5.15	5.11	5.25	5.66	5.51	5.22	5.29	5.69
	3	5.50	5.59	5.54	5.44	5.27	5.39	5.42	5.49	5.50	5.48	5.60
	Mean	5.47	5.46	5.33	5.19	5.08	5.26	5.56	5.49	5.30	5.30	5.60
	SD	0.05	0.12	0.19	0.23	0.21	0.13	0.12	0.02	0.17	0.18	0.09
	CV	0.84	2.19	3.55	4.39	4.18	2.48	2.25	0.28	3.22	3.40	1.61
3	1	6.30	6.66	6.39	5.99	6.04	6.35	6.75	6.84	6.33	6.35	6.60
	2	6.88	6.67	6.54	6.45	6.33	6.43	6.93	6.89	6.46	6.47	6.89
	3	6.22	6.91	6.90	6.76	6.50	6.62	6.69	6.83	6.96	6.50	6.67
	Mean	6.47	6.75	6.61	6.40	6.29	6.47	6.79	6.85	6.58	6.44	6.72
	SD	0.36	0.14	0.26	0.39	0.23	0.14	0.12	0.03	0.33	0.08	0.15
	CV	5.57	2.10	3.97	6.05	3.70	2.14	1.84	0.47	5.05	1.23	2.25
2	1	8.06	7.83	8.11	7.92	8.16	8.06	7.90	8.06	7.72	7.93	8.02
	2	8.11	8.06	8.18	8.67	8.60	8.29	8.28	8.15	8.20	8.22	8.30
	3	8.06	8.40	8.65	8.70	9.15	8.71	8.33	8.21	8.48	8.66	8.44
	Mean	8.08	8.10	8.31	8.43	8.64	8.35	8.17	8.14	8.13	8.27	8.25
	SD	0.03	0.29	0.29	0.44	0.50	0.33	0.24	0.08	0.38	0.37	0.21
	CV	0.36	3.54	3.53	5.24	5.74	3.95	2.88	0.93	4.73	4.44	2.59
1	1	8.61	8.93	9.55	12.12	14.66	9.50	8.81	8.71	9.39	9.66	8.80
	2	8.86	8.97	9.55	12.28	14.99	9.71	8.98	8.86	9.60	9.63	9.02
	3	8.57	9.20	10.03	12.90	15.60	10.16	9.20	8.91	9.91	10.00	9.02
	Mean	8.68	9.03	9.71	12.43	15.08	9.79	9.00	8.83	9.63	9.76	8.95
	SD	0.16	0.15	0.28	0.41	0.48	0.34	0.20	0.10	0.26	0.21	0.13
	CV	1.81	1.61	2.85	3.31	3.16	3.44	2.17	1.18	2.72	2.10	1.42

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.4: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m, with a rectangular perforated floor opening. The grain surface was open. Mass of dry ice introduced was 370 g (Pilot 4).

Time Since Start	Level	Replicate	Sampling Locations 1	2	3	4	5	6	7	8	9	10	11	12	13
1 h	2	1	6.15	8.16	6.16	7.32	8.58	7.24	7.55	8.52	8.33	10.03	11.17	9.28	9.40
		2	6.65	6.56	7.18	6.57	7.62	7.83	7.64	8.52	8.75	7.28	7.12	7.38	6.91
		3	4.97	4.48	5.55	6.56	7.25	6.47	6.16	6.39	6.55	7.70	8.58	6.86	7.51
		Mean	5.92	6.40	6.30	6.82	7.82	7.18	7.12	7.81	7.88	8.34	8.96	7.84	7.94
		SD	0.86	1.85	0.82	0.44	0.69	0.68	0.83	1.23	1.17	1.48	2.05	1.27	1.30
		CV	14.56	28.83	13.08	6.40	8.78	9.50	11.66	15.75	14.83	17.77	22.90	16.25	16.37
	1	1	18.63	24.99	36.80	35.73	57.35	34.06	18.62	37.49	58.27	56.26	42.40	37.11	28.68
		2	20.62	24.64	32.95	34.47	61.44	36.37	21.37	41.85	61.79	65.68	39.11	38.37	25.22
		3	15.52	25.49	31.60	34.92	56.94	33.92	17.19	35.39	56.23	54.97	39.74	38.11	25.77
		Mean	18.26	25.04	33.78	35.04	58.58	34.78	19.06	38.24	58.76	58.97	40.42	37.86	26.56
		SD	2.57	0.43	2.70	0.64	2.49	1.38	2.12	3.30	2.81	5.85	1.75	0.67	1.86
		CV	14.08	1.71	7.99	1.82	4.25	3.96	11.15	8.62	4.79	9.91	4.32	1.76	7.00
3 h	3	1	3.86	3.90	5.84	3.74	5.80	3.81	4.75	3.84	3.42	4.83	5.39	4.64	5.38
		2	3.95	4.02	4.35	4.61	4.54	5.05	4.31	3.81	4.18	4.15	4.01	4.27	4.01
		3	3.77	3.94	4.34	4.27	4.72	4.42	4.86	3.87	4.18	4.41	4.55	4.50	5.01
		Mean	3.86	3.95	4.84	4.21	5.02	4.43	4.64	3.84	3.93	4.46	4.65	4.47	4.80
		SD	0.09	0.06	0.86	0.44	0.68	0.62	0.29	0.03	0.44	0.34	0.70	0.19	0.71
		CV	2.33	1.55	17.82	10.42	13.58	14.01	6.27	0.78	11.17	7.69	14.96	4.18	14.77
	2	1	14.91	13.31	15.60	18.29	16.59	15.68	14.35	15.89	15.66	12.28	19.57	15.60	16.90
		2	15.20	15.47	16.45	15.21	15.24	15.82	14.02	15.46	15.34	15.58	15.66	15.84	15.92
		3	14.62	13.72	14.76	14.76	15.11	15.46	14.69	14.55	14.97	16.71	14.80	14.29	15.24
		Mean	14.91	14.17	15.60	16.09	15.65	15.65	14.35	15.30	15.32	14.86	16.68	15.24	16.02
		SD	0.29	1.15	0.85	1.92	0.82	0.18	0.34	0.68	0.35	2.30	2.54	0.83	0.83
		CV	1.95	8.10	5.42	11.94	5.24	1.16	2.33	4.47	2.25	15.49	15.24	5.47	5.21
	1	1	22.07	26.23	31.82	32.06	49.06	31.82	22.87	32.05	47.95	45.80	35.17	31.26	28.85
		2	20.76	25.74	34.11	32.55	45.91	34.49	25.42	38.62	53.80	52.34	37.91	35.58	28.73
		3	23.39	25.77	28.34	32.15	47.40	30.86	22.14	17.83	45.03	45.35	33.07	32.08	26.65
		Mean	22.07	25.91	31.42	32.25	47.46	32.39	23.48	29.50	48.93	47.83	35.38	32.97	28.08
		SD	1.32	0.27	2.91	0.26	1.58	1.88	1.72	10.63	4.47	3.91	2.43	2.29	1.24
		CV	5.96	1.06	9.25	0.81	3.32	5.81	7.34	36.02	9.13	8.18	6.86	6.96	4.41
6 h	4	1	3.67	3.17	2.64	2.43	2.49	2.44	3.16	3.54	2.81	3.17	4.07	2.76	3.36
		2	2.16	3.11	2.99	3.63	3.73	3.38	2.84	2.72	3.43	3.15	2.71	3.33	2.86
		3	3.33	3.23	3.20	3.20	3.24	3.20	3.35	3.08	3.01	3.26	3.30	3.38	3.30
		Mean	3.05	3.17	2.94	3.09	3.15	3.01	3.12	3.11	3.08	3.19	3.36	3.16	3.17
		SD	0.79	0.06	0.28	0.61	0.62	0.50	0.26	0.41	0.32	0.06	0.68	0.34	0.27
		CV	25.94	1.89	9.61	19.70	19.81	16.59	8.27	13.20	10.26	1.83	20.30	10.91	8.60
	3	1	9.53	8.40	7.92	7.86	7.82	7.59	8.12	10.35	8.14	8.39	8.61	8.53	10.67
		2	8.95	8.74	7.44	9.02	8.19	9.16	8.25	8.42	8.79	8.29	8.15	8.53	7.82
		3	8.68	8.54	8.51	8.75	7.68	8.62	8.64	8.07	8.19	8.52	8.87	8.96	8.72
		Mean	9.05	8.56	7.96	8.54	7.90	8.46	8.34	8.95	8.37	8.40	8.54	8.67	9.07
		SD	0.43	0.17	0.54	0.61	0.26	0.80	0.27	1.23	0.36	0.12	0.36	0.25	1.46
		CV	4.80	2.00	6.74	7.10	3.34	9.43	3.25	13.72	4.32	1.37	4.27	2.86	16.06

Table A.4. continued ....

	2	1	18.15	18.90	16.46	17.84	18.20	17.40	17.78	19.65	19.34	16.56	21.14	17.82	17.21
		2	16.70	18.57	18.18	19.71	17.98	18.76	17.75	17.53	19.39	18.19	18.24	18.75	18.83
		3	17.89	17.66	18.19	17.87	17.24	18.29	18.54	18.10	18.53	18.41	18.27	17.53	17.64
		Mean	17.58	18.38	17.61	18.47	17.81	18.15	18.02	18.43	19.09	17.72	19.22	18.03	17.89
		SD	0.77	0.64	1.00	1.07	0.50	0.69	0.45	1.10	0.48	1.01	1.67	0.64	0.84
		CV	4.40	3.49	5.66	5.80	2.82	3.81	2.48	5.95	2.53	5.70	8.67	3.53	4.69
	1	1	22.67	24.82	28.22	29.93	36.69	26.50	20.45	27.67	38.26	37.49	28.72	21.94	21.06
		2	23.68	24.58	26.75	28.61	39.61	29.00	24.70	32.18	39.72	42.14	33.22	28.78	26.78
		3	22.25	24.27	26.61	28.51	37.40	25.38	22.12	27.57	38.00	36.79	30.57	28.29	24.54
		Mean	22.87	24.56	27.19	29.02	37.90	26.96	22.42	29.14	38.66	38.81	30.84	26.34	24.13
		SD	0.74	0.28	0.89	0.79	1.52	1.85	2.14	2.63	0.93	2.91	2.26	3.82	2.88
		CV	3.21	1.12	3.28	2.73	4.02	6.87	9.55	9.04	2.40	7.49	7.33	14.49	11.95
12 h	5	1	0.87	0.80	0.62	0.65	0.54	0.74	1.24	1.00	0.92	0.76	1.76	0.79	1.52
		2	0.52	0.59	0.56	0.64	0.76	0.67	0.64	0.72	0.98	0.95	0.62	0.69	0.58
		3	0.96	0.73	0.73	0.81	0.79	0.84	1.06	1.02	0.75	0.95	1.37	0.98	1.10
		Mean	0.78	0.71	0.64	0.70	0.70	0.75	0.98	0.91	0.88	0.89	1.25	0.82	1.07
		SD	0.23	0.11	0.09	0.10	0.14	0.09	0.31	0.17	0.12	0.11	0.58	0.15	0.47
		CV	29.67	15.13	13.54	13.63	19.59	11.39	31.42	18.36	13.51	12.37	46.35	17.96	44.15
	4	1	5.61	5.17	4.59	4.29	4.28	4.42	5.40	5.61	4.80	5.32	5.73	4.71	5.73
		2	5.06	5.12	4.93	5.72	5.68	5.12	4.15	5.19	5.66	5.17	4.66	5.47	4.78
		3	5.31	5.17	5.16	5.18	5.27	5.07	4.93	4.92	4.91	5.16	5.33	5.05	5.34
		Mean	5.33	5.15	4.89	5.06	5.08	4.87	4.83	5.24	5.12	5.22	5.24	5.08	5.28
		SD	0.28	0.03	0.29	0.72	0.72	0.39	0.63	0.35	0.47	0.09	0.54	0.38	0.48
		CV	5.17	0.56	5.86	14.26	14.18	8.02	13.08	6.64	9.13	1.72	10.32	7.50	9.04
	3	1	10.99	10.52	9.66	10.01	9.67	9.51	10.79	10.57	9.64	10.62	11.09	10.53	10.78
		2	11.30	11.07	10.29	10.82	9.87	11.30	10.10	9.92	10.98	11.11	10.44	10.46	10.15
		3	10.84	10.44	10.46	10.38	10.19	10.17	10.66	10.38	10.21	9.99	10.26	10.68	10.55
		Mean	11.04	10.68	10.14	10.40	9.91	10.33	10.52	10.29	10.28	10.57	10.60	10.56	10.49
		SD	0.23	0.34	0.42	0.41	0.26	0.91	0.37	0.33	0.67	0.56	0.44	0.11	0.32
		CV	2.12	3.21	4.16	3.90	2.65	8.77	3.49	3.25	6.54	5.31	4.12	1.06	3.04
	2	1	16.46	16.14	16.42	16.89	16.96	16.74	16.13	16.50	17.53	16.57	17.21	15.91	15.86
		2	15.35	14.34	16.84	16.09	17.03	16.33	16.78	17.68	18.03	17.86	17.56	17.61	17.45
		3	16.42	16.32	17.08	21.65	17.59	16.71	16.45	17.09	17.00	16.81	17.21	15.68	16.48
		Mean	16.08	15.60	16.78	18.21	17.19	16.59	16.45	17.09	17.52	17.08	17.33	16.40	16.60
		SD	0.63	1.09	0.33	3.01	0.35	0.23	0.33	0.59	0.52	0.69	0.20	1.05	0.80
		CV	3.92	7.02	1.99	16.51	2.01	1.38	1.98	3.45	2.94	4.02	1.17	6.43	4.83
	1	1	19.02	19.76	20.72	21.96	26.79	21.35	19.06	23.07	26.35	26.78	22.86	21.31	19.83
		2	20.47	21.91	19.43	22.27	27.91	23.53	20.49	23.41	27.23	28.01	24.31	23.34	20.71
		3	19.85	20.54	21.10	22.40	26.76	21.05	18.99	22.95	26.19	25.70	22.56	20.73	19.88
		Mean	19.78	20.74	20.42	22.21	27.15	21.98	19.51	23.14	26.59	26.83	23.24	21.79	20.14
		SD	0.73	1.09	0.88	0.23	0.66	1.35	0.85	0.24	0.56	1.16	0.94	1.37	0.49
		CV	3.68	5.25	4.29	1.02	2.41	6.16	4.34	1.03	2.11	4.31	4.03	6.29	2.45
21 h	5	1	0.66	0.71	0.55	0.53	0.47	0.65	0.85	0.90	0.78	0.76	1.22	0.76	0.97
		2	0.54	0.60	0.51	0.62	0.64	0.71	0.59	0.56	0.74	0.61	0.53	0.64	0.55
		3	0.81	0.71	0.69	0.77	0.85	0.81	0.90	0.99	0.77	0.76	0.89	0.81	0.86
		Mean	0.67	0.67	0.58	0.64	0.65	0.72	0.78	0.82	0.76	0.71	0.88	0.74	0.79
		SD	0.14	0.06	0.09	0.12	0.19	0.08	0.17	0.23	0.02	0.09	0.35	0.09	0.22
		CV	20.19	9.43	16.20	18.94	29.14	11.17	21.34	27.77	2.73	12.20	39.22	11.86	27.45

Table A.4. continued ....

4	1	5.11	4.87	4.52	4.13	4.03	4.45	4.90	5.24	4.68	4.72	5.24	4.49	5.29
	2	4.53	4.47	4.78	5.59	5.27	5.07	4.08	4.88	5.03	4.92	4.81	4.68	4.67
	3	5.14	4.98	4.92	4.92	4.99	4.87	4.75	4.84	4.74	4.94	4.91	4.89	4.48
	Mean	4.93	4.77	4.74	4.88	4.76	4.80	4.58	4.99	4.82	4.86	4.99	4.69	4.81
	SD	0.34	0.27	0.20	0.73	0.65	0.32	0.44	0.22	0.19	0.12	0.23	0.20	0.42
	CV	6.98	5.62	4.28	14.98	13.65	6.60	9.54	4.42	3.89	2.50	4.51	4.27	8.80
3	1	9.14	8.90	8.81	8.42	8.45	8.15	8.80	9.32	8.71	8.88	9.32	8.44	9.25
	2	9.57	9.91	8.96	9.03	9.20	9.57	9.40	9.60	8.75	9.38	9.61	9.50	9.35
	3	9.35	9.10	9.00	8.98	9.35	8.65	8.99	9.10	9.09	8.91	9.15	9.01	9.41
	Mean	9.35	9.30	8.92	8.81	9.00	8.79	9.06	9.34	8.85	9.06	9.36	8.98	9.34
	SD	0.22	0.53	0.10	0.34	0.48	0.72	0.31	0.25	0.21	0.28	0.23	0.53	0.08
	CV	2.30	5.75	1.12	3.84	5.36	8.19	3.38	2.68	2.36	3.10	2.48	5.91	0.87
2	1	12.60	11.88	12.56	12.73	12.17	12.16	11.97	12.52	13.02	12.46	12.98	11.73	12.54
	2	10.63	11.84	12.66	13.13	13.86	12.77	13.09	12.21	13.89	14.10	13.62	13.51	13.42
	3	13.16	12.59	12.92	13.12	12.68	13.08	12.27	13.24	13.14	13.32	13.43	12.58	12.91
	Mean	12.13	12.10	12.71	12.99	12.90	12.67	12.44	12.66	13.35	13.29	13.34	12.61	12.96
	SD	1.33	0.42	0.19	0.23	0.87	0.47	0.58	0.53	0.47	0.82	0.33	0.89	0.44
	CV	10.96	3.49	1.46	1.76	6.72	3.69	4.66	4.18	3.53	6.17	2.46	7.06	3.41
1	1	13.58	14.05	14.99	15.52	17.48	14.65	13.08	15.33	16.97	16.73	15.30	14.92	13.96
	2	15.07	15.74	14.18	16.02	19.14	14.41	15.03	16.72	18.68	18.35	17.33	16.81	15.37
	3	14.32	15.05	14.99	15.87	17.72	14.48	13.95	15.53	17.91	16.95	15.57	14.92	14.27
	Mean	14.32	14.95	14.72	15.80	18.11	14.51	14.02	15.86	17.85	17.34	16.07	15.55	14.53
	SD	0.75	0.85	0.47	0.26	0.90	0.12	0.98	0.75	0.86	0.88	1.10	1.09	0.74
	CV	5.20	5.69	3.18	1.62	4.95	0.85	6.97	4.74	4.80	5.07	6.86	7.02	5.10

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.5: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m, with a rectangular perforated floor opening. The grain surface was covered with a PVC sheet. Mass of dry ice introduced was 370 g (Pilot 5).

Time Since Start	Level	Replicate	Sampling Locations 1	2	3	4	5	6	7	8	9	10	11	12	13
1 h	2	1	7.58	6.90	7.11	6.91	7.22	8.21	9.15	8.05	7.02	9.59	10.82	9.72	8.60
		2	6.04	5.59	5.96	7.29	8.19	7.76	7.99	7.20	7.27	9.08	9.91	7.92	8.00
		3	6.16	5.31	5.92	6.87	7.40	7.04	7.28	7.78	7.09	8.87	10.42	8.06	9.20
		Mean	6.59	5.93	6.33	7.02	7.60	7.67	8.14	7.68	7.13	9.18	10.38	8.57	8.60
		SD	0.86	0.85	0.68	0.23	0.52	0.59	0.94	0.43	0.13	0.37	0.46	1.00	0.60
		CV	12.99	14.31	10.68	3.30	6.79	7.69	11.60	5.66	1.81	4.03	4.39	11.69	6.98
	1	1	20.43	27.85	38.04	37.72	59.26	37.23	20.95	38.52	59.92	60.78	44.30	40.20	32.00
		2	19.32	29.47	37.41	37.92	63.22	36.62	20.65	39.43	59.45	59.65	43.13	39.76	30.59
		3	19.53	26.90	37.65	37.64	60.53	36.25	20.20	32.12	59.89	60.58	41.96	38.66	30.96
		Mean	19.76	28.07	37.70	37.76	61.00	36.70	20.60	36.69	59.75	60.34	43.13	39.54	31.18
		SD	0.59	1.30	0.32	0.14	2.02	0.49	0.38	3.98	0.26	0.60	1.17	0.79	0.73
		CV	2.98	4.63	0.84	0.38	3.31	1.35	1.83	10.86	0.44	1.00	2.71	2.01	2.34
3 h	3	1	5.08	4.86	4.62	4.31	4.12	4.64	5.14	4.55	4.29	4.74	5.32	4.97	5.46
		2	4.90	4.82	4.49	4.62	4.43	4.83	5.30	4.55	4.29	4.88	5.39	5.02	5.54
		3	4.94	4.30	4.08	3.97	4.07	4.18	5.02	4.74	4.13	4.64	5.44	4.67	5.54
		Mean	4.97	4.66	4.40	4.30	4.21	4.55	5.15	4.61	4.24	4.75	5.38	4.89	5.51
		SD	0.09	0.31	0.28	0.33	0.20	0.33	0.14	0.11	0.09	0.12	0.06	0.19	0.05
		CV	1.90	6.70	6.41	7.56	4.64	7.35	2.73	2.38	2.18	2.54	1.12	3.87	0.84
	2	1	16.95	16.70	16.79	16.00	15.64	16.45	16.65	16.44	15.16	17.04	17.85	16.68	17.52
		2	16.34	16.40	16.56	16.80	16.65	16.75	16.30	16.18	15.96	17.23	18.32	17.08	17.16
		3	15.85	15.31	15.65	15.81	15.56	15.61	15.87	16.15	13.65	10.77	17.63	15.86	16.71
		Mean	16.38	16.14	16.33	16.20	15.95	16.27	16.27	16.26	14.92	15.01	17.93	16.54	17.13
		SD	0.55	0.73	0.60	0.53	0.61	0.59	0.39	0.16	1.17	3.68	0.35	0.62	0.41
		CV	3.36	4.53	3.69	3.24	3.81	3.63	2.40	0.98	7.86	24.49	1.97	3.76	2.37
	1	1	26.34	28.30	33.91	35.21	49.39	32.98	25.78	35.70	48.93	49.17	38.09	34.80	30.86
		2	25.39	28.43	33.67	34.37	51.43	33.41	24.70	36.01	51.14	51.81	38.60	35.62	30.05
		3	24.32	26.79	32.09	33.64	51.60	33.78	24.16	34.96	49.44	50.41	37.39	33.61	28.55
		Mean	25.35	27.84	33.22	34.41	50.81	33.39	24.88	35.56	49.84	50.46	38.03	34.68	29.82
		SD	1.01	0.91	0.99	0.79	1.23	0.40	0.82	0.54	1.16	1.32	0.61	1.01	1.17
		CV	3.99	3.27	2.98	2.28	2.42	1.20	3.32	1.52	2.32	2.62	1.60	2.91	3.93
6 h	4	1	3.40	3.32	3.14	3.01	3.47	3.22	3.20	3.35	3.00	3.20	3.35	3.14	3.35
		2	3.61	3.62	3.52	3.33	3.31	3.43	3.56	3.17	3.34	3.58	3.61	3.55	3.74
		3	3.66	3.27	2.82	2.67	2.69	2.87	3.50	3.48	2.93	3.25	3.93	3.35	3.80
		Mean	3.56	3.40	3.16	3.00	3.16	3.17	3.42	3.33	3.09	3.34	3.63	3.35	3.63
		SD	0.14	0.19	0.35	0.33	0.41	0.28	0.19	0.16	0.22	0.21	0.29	0.21	0.24
		CV	3.88	5.56	11.09	10.99	13.05	8.91	5.64	4.67	7.10	6.18	8.00	6.13	6.73
	3	1	8.89	8.89	8.39	8.09	7.90	8.52	9.00	8.27	8.23	8.46	8.87	8.58	9.15
		2	9.28	8.96	8.78	8.83	8.65	8.84	8.94	8.65	8.77	9.03	9.32	9.16	9.46
		3	9.10	8.25	7.96	7.82	7.26	7.96	9.30	8.87	8.01	8.27	9.38	8.25	9.39
		Mean	9.09	8.70	8.38	8.25	7.94	8.44	9.08	8.60	8.34	8.59	9.19	8.66	9.33
		SD	0.20	0.39	0.41	0.52	0.70	0.45	0.19	0.30	0.39	0.40	0.28	0.46	0.16
		CV	2.15	4.50	4.90	6.34	8.77	5.28	2.12	3.53	4.69	4.61	3.03	5.32	1.74

Table A.5. continued ....

	2	1	18.76	18.64	18.78	18.26	17.74	18.81	19.18	18.31	18.00	19.00	19.49	18.47	19.10
		2	18.74	18.50	18.75	19.40	19.12	18.20	18.36	18.63	18.70	19.96	20.00	18.80	18.85
		3	18.19	18.08	18.37	18.76	18.57	18.01	18.25	18.69	18.36	19.27	20.04	17.58	18.55
		Mean	18.56	18.41	18.63	18.81	18.48	18.34	18.60	18.54	18.35	19.41	19.84	18.28	18.83
		SD	0.32	0.29	0.23	0.57	0.69	0.42	0.51	0.20	0.35	0.50	0.31	0.63	0.28
		CV	1.74	1.58	1.23	3.04	3.76	2.28	2.73	1.10	1.91	2.55	1.55	3.45	1.46
	1	1	25.56	26.54	28.86	30.23	38.98	28.28	23.82	30.94	38.83	39.77	31.99	20.26	27.10
		2	23.90	25.13	28.81	30.63	40.37	27.36	24.09	30.10	38.82	38.58	31.64	29.42	25.65
		3	23.87	25.23	28.12	29.57	39.95	27.47	23.53	30.50	39.37	39.06	32.38	24.12	25.76
		Mean	24.44	25.63	28.60	30.14	39.77	27.70	23.81	30.51	39.01	39.14	32.00	24.60	26.17
		SD	0.97	0.79	0.41	0.54	0.71	0.50	0.28	0.42	0.31	0.60	0.37	4.60	0.81
		CV	3.96	3.07	1.45	1.78	1.79	1.81	1.18	1.38	0.81	1.53	1.16	18.69	3.08
	5	1	4.46	4.81	4.84	4.86	4.77	4.54	4.52	4.51	4.56	4.57	4.57	4.74	4.69
		2	5.18	5.32	5.08	4.30	5.09	5.19	5.12	4.24	4.32	4.94	4.84	5.07	5.07
		3	4.99	4.77	4.64	4.45	4.47	4.75	4.14	4.02	4.08	4.15	4.12	4.08	4.15
		Mean	4.88	4.97	4.85	4.54	4.78	4.83	4.59	4.26	4.32	4.55	4.51	4.63	4.64
		SD	0.37	0.31	0.22	0.29	0.31	0.33	0.49	0.25	0.24	0.40	0.36	0.50	0.46
		CV	7.65	6.17	4.54	6.39	6.49	6.87	10.76	5.77	5.56	8.68	8.06	10.89	9.97
	4	1	6.87	6.73	6.64	6.63	6.55	6.62	6.63	6.59	6.57	6.59	6.96	7.00	7.03
		2	7.38	7.41	7.09	6.94	6.97	6.90	7.20	7.09	6.95	7.25	7.42	7.04	7.47
		3	7.28	6.86	6.42	6.08	5.87	6.21	6.95	6.61	6.22	6.67	6.70	6.56	6.82
		Mean	7.18	7.00	6.72	6.55	6.46	6.58	6.93	6.76	6.58	6.84	7.03	6.87	7.11
		SD	0.27	0.36	0.34	0.44	0.56	0.35	0.29	0.28	0.37	0.36	0.36	0.27	0.33
		CV	3.77	5.16	5.08	6.65	8.59	5.28	4.12	4.19	5.55	5.27	5.19	3.88	4.67
	3	1	11.66	11.11	11.30	10.94	10.85	11.16	11.34	11.16	10.81	11.17	11.29	11.26	11.71
		2	11.90	11.75	11.39	11.45	10.07	11.19	11.90	11.53	11.28	11.31	12.18	11.62	12.08
		3	11.51	10.76	10.78	10.27	9.99	10.15	10.81	11.32	10.32	10.37	11.25	10.43	11.32
		Mean	11.69	11.21	11.16	10.89	10.30	10.83	11.35	11.34	10.80	10.95	11.57	11.10	11.70
		SD	0.20	0.50	0.33	0.59	0.48	0.59	0.55	0.19	0.48	0.51	0.53	0.61	0.38
		CV	1.68	4.48	2.95	5.44	4.61	5.46	4.80	1.64	4.44	4.63	4.54	5.50	3.25
	2	1	16.96	16.95	16.81	17.73	17.50	16.87	16.65	17.33	16.49	17.92	18.06	17.37	17.62
		2	17.36	17.32	17.21	18.06	17.39	17.17	17.20	17.70	18.31	18.11	18.71	16.95	17.83
		3	16.77	16.02	16.50	17.12	16.44	15.55	16.12	17.35	17.01	16.98	17.24	17.17	17.27
		Mean	17.03	16.76	16.84	17.64	17.11	16.53	16.66	17.46	17.27	17.67	18.00	17.16	17.57
		SD	0.30	0.67	0.36	0.48	0.58	0.86	0.54	0.21	0.94	0.61	0.74	0.21	0.28
		CV	1.77	4.00	2.11	2.70	3.41	5.21	3.24	1.19	5.43	3.42	4.09	1.22	1.61
	1	1	20.83	21.65	21.48	23.09	27.49	22.36	20.78	23.32	27.34	27.38	24.22	22.51	21.14
		2	19.76	20.20	21.97	23.14	27.25	21.21	19.59	23.16	27.90	27.55	23.20	15.71	20.90
		3	19.25	19.67	20.96	22.37	26.60	20.78	19.07	23.40	26.92	26.17	23.27	20.28	20.31
		Mean	19.95	20.51	21.47	22.87	27.11	21.45	19.81	23.29	27.39	27.03	23.56	19.50	20.78
		SD	0.81	1.03	0.51	0.43	0.46	0.82	0.88	0.12	0.49	0.75	0.57	3.47	0.43
		CV	4.04	5.00	2.35	1.88	1.70	3.81	4.42	0.52	1.80	2.78	2.42	17.78	2.06
21 h	5	1	7.16	7.54	7.97	7.92	8.04	7.78	7.79	7.82	7.82	7.85	7.34	8.06	7.55
		2	8.07	8.25	8.34	8.49	8.04	7.85	7.94	6.71	6.96	7.88	6.94	7.97	7.98
		3	7.53	7.72	7.55	7.22	7.63	7.57	6.47	6.53	6.52	7.43	7.68	7.48	8.49
		Mean	7.59	7.84	7.95	7.88	7.90	7.73	7.40	7.02	7.10	7.72	7.32	7.84	8.01
		SD	0.46	0.37	0.40	0.64	0.24	0.15	0.81	0.70	0.66	0.25	0.37	0.31	0.47
		CV	6.03	4.71	4.97	8.08	3.00	1.88	10.93	9.95	9.31	3.26	5.06	3.98	5.88

Table A.5. continued ....

4	1	9.16	9.10	9.19	8.87	8.95	9.01	8.87	9.40	9.45	9.51	9.23	9.34	9.37
	2	9.74	9.76	9.50	9.54	9.23	9.35	9.16	9.33	9.43	9.38	9.60	9.36	9.48
	3	9.37	9.15	8.63	8.48	8.07	8.45	9.20	9.27	8.60	9.02	9.38	8.90	10.84
	Mean	9.42	9.34	9.11	8.96	8.75	8.94	9.08	9.33	9.16	9.30	9.40	9.20	9.90
	SD	0.29	0.37	0.44	0.54	0.61	0.45	0.18	0.07	0.49	0.25	0.19	0.26	0.82
	CV	3.12	3.94	4.84	5.98	6.92	5.09	1.98	0.70	5.30	2.73	1.98	2.83	8.27
3	1	11.49	11.50	11.58	11.33	11.23	11.32	11.08	11.73	11.76	11.75	11.90	11.73	11.96
	2	12.23	11.87	11.91	11.88	11.89	11.70	11.95	12.06	11.55	11.78	12.13	11.71	11.99
	3	11.71	11.35	10.79	10.54	10.67	10.84	11.37	11.74	11.01	10.77	11.49	11.70	12.97
	Mean	11.81	11.57	11.43	11.25	11.26	11.29	11.47	11.84	11.44	11.43	11.84	11.71	12.31
	SD	0.38	0.27	0.58	0.67	0.61	0.43	0.44	0.19	0.39	0.57	0.32	0.02	0.57
	CV	3.22	2.31	5.04	5.99	5.42	3.82	3.86	1.58	3.38	5.03	2.74	0.13	4.67
2	1	14.18	13.73	13.74	13.97	13.84	14.12	13.95	14.66	14.21	14.98	15.06	14.65	14.61
	2	14.86	15.04	14.86	15.02	14.59	14.56	14.54	15.11	15.17	14.69	15.28	14.13	14.51
	3	14.19	13.19	13.24	13.46	13.53	12.39	13.59	14.45	14.03	14.06	14.41	14.11	13.60
	Mean	14.41	13.99	13.95	14.15	13.99	13.69	14.03	14.74	14.47	14.58	14.92	14.30	14.24
	SD	0.39	0.95	0.83	0.80	0.55	1.15	0.48	0.34	0.61	0.47	0.45	0.31	0.56
	CV	2.70	6.80	5.95	5.62	3.90	8.38	3.42	2.29	4.24	3.23	3.03	2.14	3.91
1	1	15.03	15.83	16.05	16.60	17.93	16.06	15.15	17.05	18.65	17.75	17.40	16.73	16.12
	2	15.88	16.22	15.95	17.13	18.86	16.27	15.87	17.96	19.40	18.85	17.41	16.79	16.02
	3	15.07	15.03	15.42	16.16	17.68	15.29	14.57	17.28	17.61	17.64	16.43	15.69	14.39
	Mean	15.33	15.69	15.81	16.63	18.16	15.87	15.20	17.43	18.55	18.08	17.08	16.40	15.51
	SD	0.48	0.61	0.34	0.49	0.62	0.52	0.65	0.47	0.90	0.67	0.56	0.62	0.97
	CV	3.13	3.87	2.14	2.92	3.42	3.25	4.29	2.71	4.84	3.70	3.30	3.77	6.26

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.6: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m, with a 0.3-m-diameter perforated floor opening near the wall. The grain surface was open. Mass of dry ice introduced was 180 g (Pilot 6).

Time Since Start	Level	Replicate	CO2 Sampling Locations											
			1	2	3	4	5	6	7	8	9	10	11	12
1 h	2	1	5.44	4.90	4.02	2.78	1.84	1.04	0.47	0.26	1.91	2.37	2.68	2.03
		2	6.02	5.74	4.94	4.04	2.10	1.17	0.56	0.37	2.30	2.91	3.27	2.43
		3	4.54	4.78	4.51	3.67	2.43	1.21	0.47	0.29	2.25	3.43	3.19	2.01
		Mean	5.33	5.14	4.49	3.50	2.12	1.14	0.50	0.31	2.15	2.90	3.05	2.16
		SD	0.75	0.52	0.46	0.65	0.30	0.09	0.05	0.06	0.21	0.53	0.32	0.24
		CV	13.98	10.18	10.25	18.52	13.93	7.80	10.39	18.54	9.85	18.26	10.50	10.99
	1	1	62.34	56.65	32.03	20.28	13.17	7.65	2.55	0.60	10.92	16.71	15.93	10.78
		2	62.65	58.86	32.32	20.59	12.91	7.74	2.79	0.90	11.29	17.10	16.31	11.11
		3	64.05	56.61	32.22	22.79	14.54	9.49	2.76	0.55	12.42	18.42	17.19	11.40
		Mean	63.01	57.37	32.19	21.22	13.54	8.29	2.70	0.68	11.54	17.41	16.48	11.10
		SD	0.91	1.29	0.15	1.37	0.88	1.04	0.13	0.19	0.78	0.90	0.65	0.31
		CV	1.45	2.24	0.46	6.45	6.47	12.51	4.84	27.70	6.77	5.15	3.92	2.80
3 h	3	1	1.72	1.76	1.78	1.64	1.67	1.60	1.56	1.39	1.51	1.76	1.77	1.57
		2	2.22	2.24	2.02	1.72	1.60	1.37	1.34	1.29	1.61	1.72	1.86	1.69
		3	1.61	1.93	2.02	2.11	2.31	2.08	2.04	1.65	1.76	2.05	2.17	1.80
		Mean	1.85	1.98	1.94	1.82	1.86	1.68	1.65	1.44	1.63	1.84	1.93	1.69
		SD	0.33	0.24	0.14	0.25	0.39	0.36	0.36	0.19	0.13	0.18	0.21	0.12
		CV	17.57	12.31	7.14	13.79	21.04	21.52	21.74	12.88	7.74	9.77	10.85	6.82
	2	1	8.39	7.83	7.08	6.22	5.18	4.79	4.27	3.94	5.45	6.04	6.07	5.49
		2	8.90	8.70	8.00	6.32	5.37	4.52	3.88	4.29	5.94	6.03	6.46	5.77
		3	7.18	7.61	7.18	7.27	6.71	5.71	5.11	4.29	5.65	6.65	7.10	5.97
		Mean	8.16	8.05	7.42	6.60	5.75	5.01	4.42	4.17	5.68	6.24	6.54	5.74
		SD	0.88	0.58	0.50	0.58	0.83	0.62	0.63	0.20	0.25	0.36	0.52	0.24
		CV	10.83	7.16	6.80	8.78	14.49	12.46	14.22	4.84	4.34	5.69	7.95	4.20
	1	1	52.60	46.05	25.16	15.86	11.40	8.18	6.15	5.15	10.08	13.21	12.45	9.59
		2	53.50	48.60	27.26	17.02	11.43	8.42	6.20	5.04	10.43	14.30	13.51	10.42
		3	53.39	46.76	25.74	17.88	12.86	9.83	7.15	6.24	10.45	13.59	14.24	10.54
		Mean	53.16	47.14	26.05	16.92	11.90	8.81	6.50	5.48	10.32	13.70	13.40	10.18
		SD	0.49	1.32	1.08	1.01	0.83	0.89	0.56	0.66	0.21	0.55	0.90	0.52
		CV	0.92	2.79	4.16	5.99	7.01	10.12	8.67	12.11	2.02	4.04	6.72	5.08
6 h	4	1	1.23	1.22	1.22	1.31	1.37	1.35	1.33	1.26	1.14	1.27	1.26	1.14
		2	1.48	1.44	1.39	1.29	1.42	1.24	1.18	1.30	1.24	1.28	1.27	1.27
		3	1.23	1.35	1.44	1.62	1.60	1.58	1.58	1.53	1.27	1.46	1.40	1.26
		Mean	1.31	1.34	1.35	1.41	1.46	1.39	1.36	1.36	1.22	1.34	1.31	1.22
		SD	0.14	0.11	0.12	0.19	0.12	0.17	0.20	0.15	0.07	0.11	0.08	0.07
		CV	10.99	8.27	8.54	13.15	8.27	12.48	14.82	10.69	5.59	8.00	5.96	5.91
	3	1	3.51	3.57	3.60	3.50	3.61	3.37	3.38	3.22	3.25	3.55	3.59	3.26
		2	3.45	4.22	4.02	3.44	3.40	3.32	3.29	3.25	3.53	3.63	3.67	3.49
		3	3.40	3.71	3.94	4.04	4.09	3.99	3.38	3.52	3.47	3.93	3.75	3.32
		Mean	3.45	3.83	3.85	3.66	3.70	3.56	3.35	3.33	3.42	3.70	3.67	3.36
		SD	0.06	0.34	0.22	0.33	0.35	0.37	0.05	0.17	0.15	0.20	0.08	0.12
		CV	1.59	8.92	5.79	9.03	9.56	10.48	1.55	4.96	4.31	5.41	2.18	3.55

Table A.6. continued ....

	2	1	9.90	9.57	8.88	7.84	7.06	6.56	6.16	5.81	7.18	7.59	7.61	6.81
		2	10.67	10.62	9.64	7.99	7.13	6.53	6.00	5.79	7.41	7.57	8.00	7.32
		3	8.98	9.43	8.74	8.57	7.36	6.60	6.44	5.67	6.51	7.85	8.64	6.51
		Mean	9.85	9.87	9.09	8.13	7.18	6.56	6.20	5.76	7.03	7.67	8.08	6.88
		SD	0.85	0.65	0.48	0.39	0.16	0.04	0.22	0.08	0.47	0.16	0.52	0.41
		CV	8.59	6.59	5.33	4.74	2.18	0.54	3.59	1.32	6.65	2.04	6.43	5.95
	1	1	42.52	38.16	22.14	14.38	10.98	8.78	7.69	6.98	9.95	12.38	11.91	9.86
		2	42.93	38.06	22.53	14.97	10.96	8.78	7.77	6.94	10.64	12.84	12.45	10.37
		3	40.98	36.43	20.75	15.01	11.08	8.81	7.74	7.47	10.48	12.42	11.94	9.73
		Mean	42.14	37.55	21.81	14.79	11.01	8.79	7.73	7.13	10.36	12.55	12.10	9.99
		SD	1.03	0.97	0.94	0.35	0.06	0.02	0.04	0.30	0.36	0.25	0.30	0.34
		CV	2.44	2.59	4.29	2.39	0.58	0.20	0.52	4.14	3.49	2.03	2.51	3.39
9 h	5	1	0.31	0.46	0.42	0.44	0.38	0.50	0.34	0.32	0.31	0.32	0.58	0.27
		2	0.40	0.44	0.40	0.39	0.34	0.32	0.30	0.36	0.37	0.32	0.32	0.32
		3	0.27	0.24	0.30	0.31	0.26	0.27	0.26	0.23	0.20	0.33	0.22	0.23
		Mean	0.33	0.38	0.37	0.38	0.33	0.36	0.30	0.30	0.29	0.32	0.37	0.27
		SD	0.07	0.12	0.06	0.07	0.06	0.12	0.04	0.07	0.09	0.01	0.19	0.05
		CV	20.38	32.01	17.22	17.26	18.70	33.29	13.33	21.95	29.39	1.79	49.78	16.50
	4	1	1.73	1.91	2.00	1.99	2.03	2.13	1.93	2.01	1.72	1.84	1.93	1.74
		2	2.16	2.00	1.94	1.91	1.81	1.85	1.85	1.99	1.96	1.85	1.78	1.98
		3	1.82	1.91	2.13	2.28	2.15	2.24	2.21	2.13	1.75	1.66	2.19	2.00
		Mean	1.90	1.94	2.02	2.06	2.00	2.07	2.00	2.04	1.81	1.78	1.97	1.91
		SD	0.23	0.05	0.10	0.19	0.17	0.20	0.19	0.08	0.13	0.11	0.21	0.14
		CV	11.92	2.68	4.80	9.45	8.64	9.70	9.47	3.71	7.22	6.00	10.55	7.59
	3	1	4.51	4.57	4.54	4.34	4.33	4.37	4.15	4.03	4.13	4.46	4.07	3.93
		2	5.07	4.99	4.80	4.46	4.11	4.08	3.82	3.96	4.46	4.57	4.48	4.36
		3	4.36	4.71	4.84	4.81	4.87	5.05	4.60	4.52	4.46	4.81	4.91	4.46
		Mean	4.65	4.76	4.73	4.54	4.44	4.50	4.19	4.17	4.35	4.61	4.49	4.25
		SD	0.37	0.21	0.16	0.24	0.39	0.50	0.39	0.31	0.19	0.18	0.42	0.28
		CV	8.05	4.50	3.45	5.38	8.81	11.06	9.34	7.32	4.38	3.88	9.36	6.63
	2	1	10.20	9.86	9.11	7.93	7.49	6.74	6.79	6.26	7.12	7.63	7.66	7.42
		2	10.74	10.51	9.59	7.96	7.44	6.86	6.39	6.18	7.63	8.16	8.12	7.52
		3	8.91	9.37	9.20	8.97	8.01	7.90	7.02	6.69	7.81	8.54	8.74	7.48
		Mean	9.95	9.91	9.30	8.29	7.65	7.17	6.73	6.38	7.52	8.11	8.17	7.47
		SD	0.94	0.57	0.26	0.59	0.32	0.64	0.32	0.27	0.36	0.46	0.54	0.05
		CV	9.45	5.77	2.74	7.14	4.13	8.90	4.73	4.30	4.76	5.64	6.63	0.67
	1	1	33.39	30.82	18.21	12.13	10.19	8.50	8.02	7.26	9.38	11.27	10.64	7.72
		2	33.81	31.00	18.83	13.38	9.83	8.37	7.54	7.20	10.19	11.66	11.15	9.78
		3	32.93	29.54	17.69	13.58	10.92	9.18	8.56	7.68	9.39	10.58	10.21	10.09
		Mean	33.38	30.45	18.24	13.03	10.31	8.68	8.04	7.38	9.65	11.17	10.67	9.20
		SD	0.44	0.80	0.57	0.79	0.56	0.44	0.51	0.26	0.46	0.55	0.47	1.29
		CV	1.32	2.61	3.13	6.03	5.38	5.01	6.35	3.54	4.81	4.90	4.41	14.01
12 h	5	1	0.36	0.39	0.43	0.55	0.42	0.42	0.39	0.37	0.42	0.42	0.36	0.31
		2	0.42	0.40	0.40	0.40	0.39	0.37	0.36	0.41	0.47	0.37	0.37	0.39
		3	0.30	0.25	0.30	0.32	0.30	0.33	0.34	0.35	0.30	0.29	0.25	0.25
		Mean	0.36	0.35	0.38	0.42	0.37	0.37	0.36	0.38	0.40	0.36	0.33	0.32
		SD	0.06	0.08	0.07	0.12	0.06	0.05	0.03	0.03	0.09	0.07	0.07	0.07
		CV	16.67	24.19	18.07	27.58	16.88	12.08	6.93	8.11	22.03	18.22	20.38	22.18

Table A.6. continued ....

	4	1	2.25	2.24	2.33	2.38	2.37	2.37	2.30	2.18	2.15	2.30	2.29	2.15
		2	2.57	2.44	2.27	2.23	2.17	2.17	2.19	2.35	2.33	2.28	2.20	2.39
		3	2.33	2.37	2.52	2.67	2.69	2.83	2.65	2.51	2.35	2.54	2.50	2.37
		Mean	2.38	2.35	2.37	2.43	2.41	2.46	2.38	2.35	2.28	2.37	2.33	2.30
		SD	0.17	0.10	0.13	0.22	0.26	0.34	0.24	0.17	0.11	0.14	0.15	0.13
		CV	6.99	4.32	5.50	9.22	10.88	13.78	10.09	7.03	4.84	6.10	6.61	5.78
	3	1	4.98	5.01	4.95	4.87	4.67	4.77	4.60	4.47	4.54	4.84	4.75	4.27
		2	5.58	5.32	5.18	4.91	4.65	4.53	4.45	4.80	4.53	4.90	4.84	4.78
		3	4.90	5.11	5.24	5.33	5.44	5.30	5.13	4.81	4.86	5.22	5.28	4.83
		Mean	5.15	5.15	5.12	5.04	4.92	4.87	4.73	4.69	4.64	4.99	4.96	4.63
		SD	0.37	0.16	0.15	0.25	0.45	0.39	0.36	0.19	0.19	0.20	0.28	0.31
		CV	7.21	3.07	2.99	5.06	9.16	8.10	7.56	4.12	4.04	4.10	5.72	6.70
	2	1	9.67	9.78	9.19	8.09	7.45	7.05	6.84	6.48	7.29	7.70	7.89	7.49
		2	10.28	10.14	9.44	8.34	7.40	7.06	6.79	6.54	8.00	8.06	7.94	7.72
		3	9.04	9.27	9.25	8.68	8.06	7.72	7.23	6.70	8.46	8.46	8.39	7.80
		Mean	9.66	9.73	9.29	8.37	7.64	7.28	6.95	6.57	7.92	8.07	8.07	7.67
		SD	0.62	0.44	0.13	0.30	0.37	0.38	0.24	0.11	0.59	0.38	0.28	0.16
		CV	6.42	4.49	1.40	3.54	4.81	5.28	3.46	1.73	7.45	4.71	3.41	2.10
	1	1	28.00	25.07	15.49	11.64	9.31	8.31	7.83	7.45	9.18	10.13	10.03	9.10
		2	28.39	25.28	15.94	11.47	9.33	8.33	7.72	7.42	9.15	10.67	9.67	9.42
		3	26.48	23.70	15.00	12.05	10.18	9.08	8.21	7.92	9.69	10.66	10.23	9.41
		Mean	27.62	24.68	15.48	11.72	9.61	8.57	7.92	7.60	9.34	10.49	9.98	9.31
		SD	1.01	0.86	0.47	0.30	0.50	0.44	0.26	0.28	0.30	0.31	0.28	0.18
		CV	3.65	3.48	3.04	2.54	5.17	5.12	3.25	3.69	3.25	2.95	2.84	1.95
21 h	5	1	0.43	0.45	0.46	0.49	0.48	0.48	0.45	0.43	0.45	0.43	0.42	0.37
		2	0.55	0.48	0.45	0.45	0.48	0.44	0.43	0.45	0.49	0.40	0.42	0.41
		3	0.36	0.31	0.33	0.45	0.35	0.33	0.31	0.25	0.26	0.35	0.41	0.31
		Mean	0.45	0.41	0.41	0.46	0.44	0.42	0.40	0.38	0.40	0.39	0.42	0.36
		SD	0.10	0.09	0.07	0.02	0.08	0.08	0.08	0.11	0.12	0.04	0.01	0.05
		CV	21.51	21.95	17.50	4.98	17.19	18.64	19.09	29.24	30.72	10.27	1.39	13.85
	4	1	2.55	2.67	2.58	2.55	2.76	2.78	2.43	2.44	2.46	2.51	2.48	2.38
		2	2.92	2.72	2.74	2.51	2.61	2.37	2.68	2.45	2.36	2.41	2.48	2.56
		3	2.50	2.63	2.97	2.83	2.95	2.79	2.99	2.44	2.36	2.70	2.96	2.59
		Mean	2.66	2.67	2.76	2.63	2.77	2.65	2.70	2.44	2.39	2.54	2.64	2.51
		SD	0.23	0.05	0.20	0.17	0.17	0.24	0.28	0.01	0.06	0.15	0.28	0.11
		CV	8.64	1.69	7.09	6.63	6.14	9.05	10.39	0.24	2.41	5.80	10.50	4.53
	3	1	5.03	4.95	4.84	4.71	4.75	4.59	4.51	4.37	4.41	4.71	4.68	4.48
		2	5.48	5.38	5.17	4.84	4.58	4.49	4.51	4.39	4.74	4.83	4.72	4.58
		3	4.75	4.99	5.09	5.09	5.20	5.09	4.87	4.33	4.49	4.94	5.19	4.72
		Mean	5.09	5.11	5.03	4.88	4.84	4.72	4.63	4.36	4.55	4.83	4.86	4.59
		SD	0.37	0.24	0.17	0.19	0.32	0.32	0.21	0.03	0.17	0.12	0.28	0.12
		CV	7.24	4.65	3.42	3.96	6.61	6.81	4.49	0.70	3.79	2.38	5.83	2.62

Table A.6. continued ....

2	1	8.25	8.05	7.64	6.78	6.15	6.20	6.03	5.78	6.23	6.61	6.57	6.49
	2	8.57	8.50	8.04	6.91	6.43	6.15	6.04	5.75	6.53	6.68	6.79	6.51
	3	7.35	7.76	7.70	7.20	6.91	6.58	6.29	5.82	6.39	6.88	7.16	6.08
	Mean	8.06	8.10	7.79	6.96	6.50	6.31	6.12	5.78	6.38	6.72	6.84	6.36
	SD	0.63	0.37	0.22	0.22	0.38	0.24	0.15	0.04	0.15	0.14	0.30	0.24
	CV	7.85	4.60	2.77	3.09	5.92	3.73	2.41	0.61	2.35	2.08	4.36	3.82
1	1	17.05	15.12	10.24	8.18	7.27	6.92	6.66	6.44	7.24	7.66	7.81	7.41
	2	17.23	15.55	10.68	7.79	7.40	6.72	6.64	6.41	7.37	7.81	7.45	7.52
	3	16.14	14.34	10.42	8.56	7.34	7.25	6.89	6.67	6.99	7.88	8.07	7.13
	Mean	16.81	15.00	10.45	8.18	7.34	6.96	6.73	6.51	7.20	7.78	7.78	7.35
	SD	0.58	0.61	0.22	0.39	0.07	0.27	0.14	0.14	0.19	0.11	0.31	0.20
	CV	3.48	4.09	2.12	4.71	0.89	3.84	2.06	2.19	2.68	1.44	4.00	2.73

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.7: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m, with a 0.3-m-diameter perforated floor pening near the wall. The grain surface was covered with a PVC sheet. Mass of dry ice introduced was 180 g (Pilot 7).

Time Since Start	Level	Replicate	Sampling Locations 1	2	3	4	5	6	7	8	9	10	11	12
1 h	2	1	4.55	4.45	4.07	3.65	2.85	1.73	0.79	0.44	2.47	3.17	3.40	2.60
		2	4.96	4.62	4.75	3.42	2.02	0.94	0.32	0.23	1.69	2.95	3.00	1.66
		3	4.35	5.12	4.21	3.67	2.05	1.21	0.50	0.29	2.36	3.21	3.29	2.30
		Mean	4.62	4.73	4.34	3.58	2.31	1.29	0.54	0.32	2.17	3.11	3.23	2.19
		SD	0.31	0.35	0.36	0.14	0.47	0.40	0.24	0.11	0.42	0.14	0.21	0.48
		CV	6.73	7.36	8.27	3.88	20.41	31.05	44.19	33.80	19.43	4.50	6.40	21.96
	1	1	64.84	57.32	32.00	21.08	14.59	9.53	4.01	1.19	12.44	16.39	12.86	10.70
		2	66.21	59.82	34.91	24.56	14.81	8.29	2.27	0.35	12.13	19.01	17.19	11.08
		3	66.11	57.66	33.01	18.57	14.31	8.82	3.08	0.72	11.59	17.25	15.22	11.08
		Mean	65.72	58.27	33.31	21.40	14.57	8.88	3.12	0.75	12.05	17.55	15.09	10.95
		SD	0.76	1.36	1.48	3.01	0.25	0.62	0.87	0.42	0.43	1.34	2.17	0.22
		CV	1.16	2.33	4.44	14.05	1.72	7.01	27.91	55.88	3.57	7.61	14.37	2.00
3 h	3	1	1.39	1.59	1.81	2.01	2.22	2.19	1.86	1.64	1.68	1.98	1.88	1.63
		2	2.28	2.39	2.24	2.09	1.97	1.66	1.39	1.28	1.48	2.05	2.48	1.62
		3	1.90	2.00	1.94	1.84	1.79	1.52	1.47	1.31	1.72	1.80	1.89	1.58
		Mean	1.86	1.99	2.00	1.98	1.99	1.79	1.57	1.41	1.63	1.94	2.08	1.61
		SD	0.45	0.40	0.22	0.13	0.22	0.35	0.25	0.20	0.13	0.13	0.34	0.03
		CV	24.05	20.07	11.04	6.45	10.83	19.74	15.98	14.17	7.90	6.64	16.49	1.64
	2	1	7.23	7.31	6.99	6.61	5.64	5.39	4.68	4.05	5.95	6.69	6.39	5.74
		2	8.34	8.74	8.38	7.54	6.05	4.58	4.10	3.63	5.69	6.74	6.99	5.92
		3	7.94	8.18	8.05	6.65	3.93	4.58	4.24	3.83	5.62	6.31	6.71	5.00
		Mean	7.84	8.08	7.81	6.93	5.21	4.85	4.34	3.84	5.75	6.58	6.70	5.55
		SD	0.56	0.72	0.73	0.53	1.12	0.47	0.30	0.21	0.17	0.24	0.30	0.49
		CV	7.17	8.92	9.30	7.58	21.60	9.64	6.97	5.48	3.02	3.57	4.48	8.78
	1	1	53.72	47.31	25.29	15.50	12.02	9.27	7.39	6.32	10.92	13.78	12.50	9.73
		2	55.87	46.84	27.34	18.26	12.74	5.76	6.66	5.46	11.24	12.69	13.28	10.93
		3	55.38	48.62	26.70	17.10	12.78	8.16	6.50	5.59	11.57	13.27	11.57	9.63
		Mean	54.99	47.59	26.44	16.95	12.51	7.73	6.85	5.79	11.24	13.25	12.45	10.10
		SD	1.13	0.92	1.05	1.39	0.43	1.79	0.47	0.46	0.33	0.55	0.86	0.72
		CV	2.05	1.94	3.97	8.17	3.42	23.21	6.93	8.01	2.89	4.12	6.88	7.16
6 h	4	1	1.13	1.40	1.48	1.71	1.80	1.85	1.73	1.58	1.35	1.50	1.47	1.37
		2	1.66	1.81	1.74	1.79	1.68	1.56	1.47	1.46	1.50	1.64	1.62	1.50
		3	1.55	1.61	1.65	1.75	1.67	1.57	1.54	1.62	1.66	1.56	1.69	1.66
		Mean	1.45	1.61	1.62	1.75	1.72	1.66	1.58	1.55	1.50	1.57	1.59	1.51
		SD	0.28	0.21	0.13	0.04	0.07	0.16	0.13	0.08	0.16	0.07	0.11	0.15
		CV	19.33	12.76	8.13	2.29	4.21	9.92	8.51	5.36	10.31	4.48	7.05	9.62
	3	1	3.18	3.31	3.64	4.02	4.35	4.29	3.92	3.78	3.27	3.84	3.79	3.43
		2	4.37	4.42	4.26	4.13	4.04	3.54	3.42	3.23	3.62	3.94	3.94	3.48
		3	3.89	3.90	3.89	3.78	3.09	3.03	3.38	2.85	2.99	3.74	3.38	2.79
		Mean	3.81	3.88	3.93	3.98	3.83	3.62	3.57	3.29	3.29	3.84	3.70	3.23
		SD	0.60	0.56	0.31	0.18	0.66	0.63	0.30	0.47	0.32	0.10	0.29	0.38
		CV	15.70	14.33	7.94	4.50	17.16	17.51	8.42	14.23	9.58	2.60	7.83	11.90

Table A.7. continued ....

	2	1	8.96	8.95	8.93	7.86	7.91	7.57	7.03	6.04	7.07	8.06	7.94	7.21
		2	10.28	10.55	10.31	8.68	7.59	6.93	6.35	5.87	7.89	8.49	8.48	7.57
		3	9.49	7.71	9.70	7.73	5.14	5.96	6.38	5.37	5.29	8.17	7.31	6.40
		Mean	9.58	9.07	9.65	8.09	6.88	6.82	6.59	5.76	6.75	8.24	7.91	7.06
		SD	0.66	1.42	0.69	0.52	1.52	0.81	0.38	0.35	1.33	0.22	0.59	0.60
		CV	6.94	15.70	7.17	6.37	22.03	11.89	5.83	6.05	19.69	2.71	7.40	8.49
	1	1	42.39	36.81	20.92	15.38	11.79	9.94	8.44	7.85	10.81	12.78	11.79	10.57
		2	43.36	37.99	22.65	15.67	12.10	9.76	8.09	7.02	11.60	12.71	12.46	10.72
		3	43.74	38.23	21.55	10.52	11.98	9.41	8.22	7.37	9.89	10.24	8.45	9.65
		Mean	43.16	37.68	21.71	13.86	11.96	9.70	8.25	7.41	10.77	11.91	10.90	10.31
		SD	0.70	0.76	0.88	2.89	0.16	0.27	0.18	0.42	0.86	1.45	2.15	0.58
		CV	1.61	2.02	4.03	20.88	1.31	2.78	2.14	5.62	7.95	12.15	19.71	5.62
9 h	5	1	1.34	1.43	1.70	2.05	1.95	1.79	1.89	1.69	1.51	1.53	1.71	1.43
		2	1.74	1.62	1.81	1.69	1.77	1.73	1.65	1.54	1.75	1.58	1.80	1.86
		3	1.78	1.83	1.87	1.90	1.86	1.87	1.85	1.89	1.56	1.90	1.85	1.07
		Mean	1.62	1.63	1.79	1.88	1.86	1.80	1.80	1.71	1.61	1.67	1.79	1.45
		SD	0.24	0.20	0.09	0.18	0.09	0.07	0.13	0.18	0.13	0.20	0.07	0.40
		CV	15.02	12.30	4.81	9.62	4.84	3.91	7.16	10.29	7.88	12.02	3.97	27.21
	4	1	2.22	2.06	2.57	2.90	3.03	3.16	2.83	2.76	2.13	2.50	2.42	2.08
		2	2.53	2.70	2.76	2.84	2.62	2.60	2.49	2.39	2.52	2.58	2.58	2.40
		3	2.73	2.74	2.39	2.98	2.73	2.72	2.74	2.68	2.18	2.76	2.71	2.66
		Mean	2.49	2.50	2.57	2.91	2.79	2.83	2.69	2.61	2.28	2.61	2.57	2.38
		SD	0.26	0.38	0.19	0.07	0.21	0.29	0.18	0.19	0.21	0.13	0.15	0.29
		CV	10.31	15.26	7.19	2.42	7.60	10.43	6.56	7.46	9.32	5.10	5.65	12.21
	3	1	4.37	4.33	4.72	5.13	5.27	5.03	4.50	4.47	3.25	4.92	4.77	3.85
		2	5.32	5.33	5.15	4.87	4.79	4.48	4.35	4.33	4.50	4.79	4.91	4.37
		3	4.68	4.88	4.82	4.73	5.08	4.97	4.49	4.44	4.48	4.61	5.06	4.68
		Mean	4.79	4.85	4.90	4.91	5.05	4.83	4.45	4.41	4.08	4.77	4.91	4.30
		SD	0.48	0.50	0.23	0.20	0.24	0.30	0.08	0.07	0.72	0.16	0.15	0.42
		CV	10.11	10.33	4.60	4.13	4.79	6.25	1.89	1.67	17.56	3.26	2.95	9.75
	2	1	6.87	9.00	7.09	8.26	8.18	7.93	7.16	6.18	6.18	7.41	7.88	7.69
		2	9.59	10.51	10.33	8.56	7.28	7.02	6.66	7.10	7.10	8.05	8.72	7.36
		3	9.72	8.64	8.50	8.28	6.73	7.33	7.23	6.75	6.75	8.10	8.35	7.71
		Mean	8.73	9.38	8.64	8.37	7.40	7.43	7.02	6.68	6.68	7.85	8.32	7.59
		SD	1.61	0.99	1.62	0.17	0.73	0.46	0.31	0.46	0.46	0.38	0.42	0.20
		CV	18.44	10.57	18.80	2.00	9.90	6.23	4.43	6.96	6.96	4.90	5.06	2.59
	1	1	31.63	28.91	17.58	10.46	8.99	8.09	8.30	8.36	8.36	11.19	10.87	8.79
		2	29.95	29.85	18.31	11.36	10.59	8.25	8.04	9.58	9.58	10.62	11.25	10.14
		3	30.40	27.70	18.41	13.12	11.04	9.24	8.11	8.68	8.68	11.74	9.58	9.57
		Mean	30.66	28.82	18.10	11.65	10.21	8.53	8.15	8.87	8.87	11.18	10.57	9.50
		SD	0.87	1.08	0.45	1.35	1.08	0.62	0.13	0.63	0.63	0.56	0.88	0.68
		CV	2.84	3.74	2.50	11.62	10.56	7.31	1.65	7.13	7.13	5.01	8.28	7.13
12 h	5	1	2.12	2.58	2.63	2.84	2.80	2.69	2.53	2.25	2.25	2.87	2.51	2.22
		2	2.42	2.56	2.72	2.68	2.70	2.69	2.43	2.43	1.10	2.28	2.44	2.48
		3	2.51	2.74	2.81	2.61	2.95	2.79	2.75	2.71	2.63	2.82	2.74	1.50
		Mean	2.35	2.63	2.72	2.71	2.82	2.72	2.57	2.46	1.99	2.66	2.56	2.07
		SD	0.20	0.10	0.09	0.12	0.13	0.06	0.16	0.23	0.80	0.33	0.16	0.51
		CV	8.69	3.76	3.31	4.35	4.47	2.12	6.37	9.41	39.97	12.31	6.12	24.56

Table A.7. continued ....

	4	1	2.94	3.12	3.56	3.76	3.71	3.76	3.51	3.44	3.51	3.42	3.22	3.09
		2	3.83	3.87	3.67	3.55	3.63	3.49	3.35	3.85	3.43	3.56	3.46	3.39
		3	3.53	3.68	3.79	3.74	3.78	3.86	3.69	3.36	3.60	3.67	3.38	3.40
		Mean	3.43	3.56	3.67	3.68	3.71	3.70	3.52	3.55	3.51	3.55	3.35	3.29
		SD	0.45	0.39	0.12	0.12	0.08	0.19	0.17	0.26	0.09	0.13	0.12	0.18
		CV	13.19	10.96	3.13	3.15	2.02	5.17	4.84	7.40	2.42	3.53	3.64	5.35
	3	1	5.01	5.30	5.47	5.52	5.49	5.61	5.39	5.31	5.12	5.51	5.20	4.90
		2	5.51	6.55	5.72	5.46	5.38	5.22	5.16	4.92	5.14	5.37	5.60	5.04
		3	5.84	5.65	5.71	5.54	5.61	5.40	5.05	4.98	4.85	5.34	5.43	5.46
		Mean	5.45	5.83	5.63	5.51	5.49	5.41	5.20	5.07	5.04	5.41	5.41	5.13
		SD	0.42	0.64	0.14	0.04	0.12	0.20	0.17	0.21	0.16	0.09	0.20	0.29
		CV	7.66	11.05	2.51	0.76	2.09	3.61	3.34	4.14	3.22	1.68	3.71	5.68
	2	1	9.05	9.56	8.56	8.32	8.25	7.30	7.31	7.03	7.55	8.17	8.24	7.99
		2	9.59	10.15	9.15	8.51	7.74	7.05	6.97	6.74	7.33	8.41	8.39	7.38
		3	10.11	10.03	9.50	8.16	7.07	7.06	7.45	6.44	7.05	7.18	8.22	7.70
		Mean	9.58	9.91	9.07	8.33	7.69	7.14	7.24	6.74	7.31	7.92	8.28	7.69
		SD	0.53	0.31	0.48	0.18	0.59	0.14	0.25	0.30	0.25	0.65	0.09	0.31
		CV	5.53	3.15	5.24	2.10	7.70	1.98	3.41	4.38	3.43	8.23	1.12	3.97
	1	1	26.76	23.35	15.31	9.90	9.71	8.74	7.85	8.00	8.69	10.22	9.56	9.48
		2	25.68	24.67	15.72	11.59	9.23	9.06	8.00	7.23	9.56	10.55	9.29	8.39
		3	27.33	23.82	15.68	10.05	10.08	8.59	7.71	7.09	9.68	9.81	8.79	8.42
		Mean	26.59	23.95	15.57	10.51	9.67	8.80	7.85	7.44	9.31	10.19	9.21	8.76
		SD	0.84	0.67	0.23	0.94	0.43	0.24	0.15	0.49	0.54	0.37	0.39	0.62
		CV	3.15	2.79	1.45	8.90	4.41	2.73	1.85	6.59	5.80	3.64	4.24	7.08
21 h	5	1	2.82	3.94	4.02	4.12	4.43	4.29	4.21	3.79	3.71	4.12	4.13	3.19
		2	4.20	4.39	4.59	4.51	4.33	4.38	4.13	3.94	2.02	4.22	4.52	4.42
		3	4.53	4.09	4.62	4.56	4.65	4.57	4.32	3.96	4.20	4.58	4.23	2.68
		Mean	3.85	4.14	4.41	4.40	4.47	4.41	4.22	3.90	3.31	4.31	4.29	3.43
		SD	0.91	0.23	0.34	0.24	0.16	0.14	0.10	0.09	1.14	0.24	0.20	0.89
		CV	23.56	5.53	7.67	5.48	3.66	3.24	2.26	2.38	34.55	5.62	4.72	26.08
	4	1	4.55	4.52	3.96	4.82	4.96	5.13	4.83	4.63	4.71	4.70	4.64	4.58
		2	5.05	4.98	5.11	5.12	4.95	5.04	4.84	5.00	4.67	5.01	5.13	4.99
		3	4.90	5.08	5.16	5.08	5.23	5.10	4.99	4.73	5.04	5.27	5.05	4.74
		Mean	4.83	4.86	4.74	5.01	5.05	5.09	4.89	4.79	4.81	4.99	4.94	4.77
		SD	0.26	0.30	0.68	0.16	0.16	0.05	0.09	0.19	0.20	0.29	0.26	0.21
		CV	5.31	6.15	14.31	3.25	3.15	0.90	1.83	4.00	4.22	5.71	5.32	4.33
	3	1	5.79	5.97	6.01	5.83	5.86	5.89	5.85	5.55	5.77	5.92	5.61	5.43
		2	6.88	6.18	6.60	6.42	5.96	5.28	5.72	5.58	5.96	6.40	6.24	5.91
		3	5.60	6.71	6.45	6.20	5.99	5.50	5.62	5.93	6.21	6.31	6.07	5.87
		Mean	6.09	6.29	6.35	6.15	5.94	5.56	5.73	5.69	5.98	6.21	5.97	5.74
		SD	0.69	0.38	0.31	0.30	0.07	0.31	0.12	0.21	0.22	0.26	0.33	0.27
		CV	11.34	6.07	4.83	4.85	1.15	5.56	2.01	3.72	3.69	4.11	5.46	4.64

Table A.7. continued ....

2	1	8.31	7.88	7.15	7.47	7.32	7.02	6.87	6.33	7.21	7.32	7.47	6.57
	2	9.22	8.05	8.80	7.92	6.78	7.17	6.74	6.46	6.96	7.61	7.42	7.25
	3	7.37	8.84	7.81	7.87	6.45	7.26	7.10	6.29	7.27	7.42	7.66	7.04
	Mean	8.30	8.26	7.92	7.75	6.85	7.15	6.90	6.36	7.15	7.45	7.52	6.95
	SD	0.93	0.51	0.83	0.25	0.44	0.12	0.18	0.09	0.16	0.15	0.13	0.35
	CV	11.15	6.20	10.49	3.18	6.41	1.70	2.64	1.40	2.30	1.98	1.68	5.01
1	1	16.63	14.69	10.52	8.17	8.26	7.79	7.20	7.10	7.30	8.00	7.68	7.27
	2	17.63	15.61	11.22	9.56	8.18	8.09	7.22	6.94	7.94	8.63	7.48	7.99
	3	16.65	14.67	9.44	8.66	7.06	7.53	7.06	7.12	7.50	8.24	8.47	8.25
	Mean	16.97	14.99	10.39	8.80	7.83	7.80	7.16	7.05	7.58	8.29	7.88	7.84
	SD	0.57	0.54	0.90	0.71	0.67	0.28	0.09	0.10	0.33	0.32	0.52	0.51
	CV	3.37	3.58	8.63	8.01	8.56	3.59	1.22	1.40	4.32	3.84	6.65	6.48

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.8: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with a 0.3-m-diameter perforated floor opening near the centre. The grain surface was open. Mass of dry ice introduced was 540 g (Pilot 8).

Time Since Start	Level	Replicate	1	2	3	4	5	6	7	8	9	10	11
			Sampling Locations										
1 h	3	1	3.90	4.51	4.80	5.03	5.46	5.10	4.10	3.83	4.59	5.11	4.83
		2	3.10	4.20	4.80	4.98	5.89	5.35	3.71	3.45	4.47	4.94	4.31
		3	3.62	4.10	4.35	5.14	4.86	4.76	4.10	3.70	4.58	4.34	3.98
		Mean	3.54	4.27	4.65	5.05	5.40	5.07	3.97	3.66	4.55	4.80	4.37
		SD	0.41	0.21	0.26	0.08	0.52	0.30	0.23	0.19	0.07	0.40	0.43
		CV	11.47	5.01	5.59	1.62	9.57	5.84	5.67	5.28	1.46	8.43	9.80
	2	1	35.66	37.24	38.38	37.27	35.88	35.17	34.06	33.62	35.40	35.20	32.73
		2	34.47	36.56	39.43	38.68	36.13	35.91	34.09	30.27	35.97	31.69	29.92
		3	29.24	36.54	37.35	36.79	36.63	35.78	30.38	31.35	35.34	34.20	33.17
		Mean	33.12	36.78	38.39	37.58	36.21	35.62	32.84	31.75	35.57	33.70	31.94
		SD	3.42	0.40	1.04	0.98	0.38	0.40	2.13	1.71	0.35	1.81	1.76
		CV	10.31	1.08	2.71	2.61	1.05	1.11	6.50	5.39	0.98	5.37	5.52
	1	1	66.10	78.13	84.05	83.87	81.84	70.46	66.02	66.03	76.35	71.06	67.63
		2	67.55	79.97	87.20	82.55	79.30	74.20	60.09	63.58	80.12	65.78	61.46
		3	70.72	74.56	80.20	82.35	84.24	76.48	66.56	68.25	77.54	78.20	67.34
		Mean	68.12	77.55	83.82	82.92	81.79	73.71	64.22	65.95	78.00	71.68	65.48
		SD	2.36	2.75	3.51	0.83	2.47	3.04	3.59	2.34	1.93	6.23	3.48
		CV	3.47	3.55	4.18	1.00	3.02	4.12	5.59	3.54	2.47	8.70	5.32
3 h	4	1	3.39	3.40	3.27	3.30	3.28	3.02	2.86	3.15	3.34	3.14	2.91
		2	3.30	3.50	3.52	3.46	3.39	2.94	3.01	3.00	3.41	3.36	2.90
		3	3.11	3.74	4.64	4.85	4.89	3.98	3.25	3.17	4.10	4.42	3.70
		Mean	3.27	3.55	3.81	3.87	3.85	3.31	3.04	3.11	3.62	3.64	3.17
		SD	0.14	0.17	0.73	0.85	0.90	0.58	0.20	0.09	0.42	0.68	0.46
		CV	4.38	4.93	19.15	22.03	23.34	17.47	6.47	2.99	11.61	18.80	14.48
	3	1	11.14	13.52	13.93	14.02	14.28	12.50	11.63	12.23	12.93	13.47	13.49
		2	9.88	13.84	13.84	14.62	13.92	13.63	11.53	10.93	12.96	12.11	13.12
		3	14.20	14.23	16.10	16.58	16.17	16.10	14.10	13.98	15.85	16.26	14.16
		Mean	11.74	13.86	14.62	15.07	14.79	14.08	12.42	12.38	13.91	13.95	13.59
		SD	2.22	0.36	1.28	1.34	1.21	1.84	1.46	1.53	1.68	2.12	0.53
		CV	18.92	2.56	8.75	8.88	8.17	13.08	11.72	12.36	12.06	15.17	3.88
	2	1	31.19	32.46	32.10	32.47	33.71	29.66	28.54	28.88	29.86	28.95	26.94
		2	30.82	32.50	32.11	34.74	31.59	26.17	24.64	28.20	29.40	29.59	25.36
		3	33.96	35.30	36.51	34.50	34.85	36.26	34.78	34.76	33.75	37.92	35.29
		Mean	31.99	33.42	33.57	33.90	33.38	30.70	29.32	30.61	31.00	32.15	29.20
		SD	1.72	1.63	2.54	1.25	1.65	5.12	5.11	3.61	2.39	5.00	5.34
		CV	5.36	4.87	7.58	3.68	4.96	16.69	17.44	11.78	7.71	15.56	18.28
	1	1	46.60	47.44	51.79	54.54	64.17	39.63	38.78	40.27	46.45	44.27	38.90
		2	42.27	46.39	51.89	56.14	56.27	36.08	39.64	39.91	44.36	42.78	37.24
		3	49.65	48.37	54.60	65.40	66.57	52.17	44.74	48.15	51.35	53.17	50.89
		Mean	46.17	47.40	52.76	58.69	62.34	42.63	41.05	42.78	47.39	46.74	42.34
		SD	3.71	0.99	1.59	5.86	5.39	8.45	3.22	4.66	3.59	5.62	7.45
		CV	8.03	2.09	3.02	9.99	8.65	19.83	7.85	10.89	7.57	12.02	17.59

Table A.8. continued ....

6 h	5	1	0.92	0.80	0.67	0.55	0.84	0.93	0.42	0.52	0.32	0.40	0.38
		2	0.78	0.74	0.44	0.42	0.63	0.85	0.23	0.36	0.22	0.25	0.25
		3	0.77	0.76	0.80	0.81	0.90	0.72	0.70	0.68	0.45	0.69	0.59
		Mean	0.82	0.77	0.64	0.59	0.79	0.83	0.45	0.52	0.33	0.45	0.41
		SD	0.08	0.03	0.18	0.20	0.14	0.11	0.24	0.16	0.12	0.22	0.17
		CV	10.19	3.98	28.63	33.47	17.95	12.72	52.54	30.77	34.95	50.08	42.19
	4	1	6.96	6.93	7.05	6.82	6.95	6.17	5.84	6.51	6.67	6.65	6.38
		2	7.06	7.27	7.25	7.36	6.69	6.21	5.98	6.13	6.75	6.62	6.19
		3	6.58	7.56	7.86	8.58	8.99	7.14	6.67	6.70	7.03	6.96	6.85
		Mean	6.87	7.25	7.39	7.59	7.54	6.51	6.16	6.45	6.82	6.74	6.47
		SD	0.25	0.32	0.42	0.90	1.26	0.55	0.44	0.29	0.19	0.19	0.34
		CV	3.69	4.35	5.71	11.88	16.70	8.44	7.21	4.50	2.77	2.79	5.25
	3	1	15.11	16.77	16.86	17.16	16.92	14.33	13.90	13.54	15.71	15.08	16.34
		2	13.02	17.01	17.82	17.59	14.12	12.60	14.49	15.36	15.89	14.52	15.78
		3	16.22	16.35	16.96	18.04	18.34	15.87	15.85	14.17	16.14	16.03	13.96
		Mean	14.78	16.71	17.21	17.60	16.46	14.27	14.75	14.36	15.91	15.21	15.36
		SD	1.62	0.33	0.53	0.44	2.15	1.64	1.00	0.92	0.22	0.76	1.24
		CV	10.99	2.00	3.07	2.50	13.05	11.47	6.78	6.44	1.36	5.02	8.10
	2	1	28.60	28.70	28.80	29.66	29.64	22.77	24.17	26.19	26.19	27.70	25.08
		2	27.41	28.79	29.46	30.43	27.01	26.50	22.15	24.67	27.45	25.54	22.92
		3	29.19	29.87	31.17	31.02	32.04	29.78	29.34	28.35	29.34	28.34	28.10
		Mean	28.40	29.12	29.81	30.37	29.56	26.35	25.22	26.40	27.66	27.19	25.37
		SD	0.91	0.65	1.22	0.68	2.52	3.51	3.71	1.85	1.59	1.47	2.60
		CV	3.19	2.24	4.10	2.25	8.51	13.31	14.70	7.00	5.73	5.40	10.26
	1	1	36.15	37.66	41.70	45.87	52.25	31.09	30.03	32.24	37.24	36.73	31.50
		2	34.00	37.73	41.02	44.27	49.67	29.22	30.63	31.08	37.87	35.02	28.54
		3	34.66	38.08	42.19	50.31	59.97	39.47	34.07	33.64	38.49	41.14	35.17
		Mean	34.94	37.82	41.64	46.82	53.96	33.26	31.58	32.32	37.87	37.63	31.74
		SD	1.10	0.23	0.59	3.13	5.36	5.46	2.18	1.28	0.63	3.16	3.32
		CV	3.15	0.59	1.41	6.68	9.93	16.41	6.90	3.97	1.65	8.39	10.47
9 h	5	1	0.92	0.66	0.45	0.36	0.65	0.95	0.38	0.55	0.29	0.31	0.43
		2	0.87	0.77	0.35	0.31	0.56	1.04	0.29	0.45	0.26	0.31	0.36
		3	0.80	0.81	0.79	0.87	0.92	0.54	0.57	0.76	0.72	0.60	0.71
		Mean	0.86	0.75	0.53	0.51	0.71	0.84	0.41	0.59	0.42	0.41	0.50
		SD	0.06	0.08	0.23	0.31	0.19	0.27	0.14	0.16	0.26	0.17	0.19
		CV	6.98	10.40	43.52	60.37	26.39	31.60	34.58	26.97	60.79	41.17	37.04
	4	1	7.62	7.42	7.07	7.37	6.51	6.11	6.78	6.34	6.60	6.40	6.67
		2	8.24	8.37	8.22	8.40	8.09	7.78	7.42	7.42	7.85	7.77	7.24
		3	8.11	8.97	9.54	9.75	9.97	8.32	7.96	8.32	9.54	7.97	7.76
		Mean	7.99	8.25	8.28	8.51	8.19	7.40	7.39	7.36	8.00	7.38	7.22
		SD	0.33	0.78	1.24	1.19	1.73	1.15	0.59	0.99	1.48	0.85	0.55
		CV	4.09	9.47	14.93	14.03	21.15	15.56	8.00	13.47	18.45	11.58	7.55
	3	1	12.61	14.89	15.67	14.93	13.07	13.23	13.08	10.96	13.75	13.62	15.96
		2	15.60	16.96	17.75	17.67	15.04	14.15	13.85	14.28	15.96	15.83	15.76
		3	15.63	15.22	16.68	17.17	17.10	14.38	14.78	15.79	13.15	14.90	14.10
		Mean	14.61	15.69	16.70	16.59	15.07	13.92	13.90	13.68	14.29	14.78	15.27
		SD	1.74	1.11	1.04	1.46	2.02	0.61	0.85	2.47	1.48	1.11	1.02
		CV	11.87	7.09	6.23	8.80	13.37	4.37	6.12	18.07	10.36	7.51	6.69

Table A.8. continued ....

	2	1	24.56	24.96	23.97	23.69	23.41	20.63	20.26	20.02	21.30	22.73	20.36
		2	25.89	26.00	26.41	27.11	24.37	23.54	21.98	22.40	24.60	21.98	21.22
		3	27.36	27.29	28.29	27.81	28.44	27.50	25.74	26.36	28.10	28.35	27.10
		Mean	25.94	26.08	26.22	26.20	25.41	23.89	22.66	22.93	24.67	24.35	22.89
		SD	1.40	1.17	2.17	2.20	2.67	3.45	2.80	3.20	3.40	3.48	3.67
		CV	5.40	4.47	8.26	8.41	10.51	14.43	12.37	13.97	13.79	14.30	16.02
	1	1	27.13	26.83	33.68	34.99	34.88	23.76	22.40	24.95	26.32	27.06	22.03
		2	31.17	31.96	35.61	41.07	38.78	29.27	29.89	27.21	29.31	29.98	29.93
		3	32.10	32.51	36.47	44.92	47.14	35.17	28.95	31.50	33.48	34.34	27.34
		Mean	30.13	30.43	35.25	40.33	40.27	29.40	27.08	27.89	29.70	30.46	26.43
		SD	2.64	3.13	1.43	5.01	6.26	5.71	4.08	3.33	3.60	3.66	4.03
		CV	8.77	10.29	4.05	12.41	15.56	19.41	15.07	11.93	12.11	12.03	15.24
12 h	5	1	1.02	0.63	0.35	0.24	0.55	0.87	0.44	0.58	0.24	0.28	0.38
		2	0.89	0.77	0.32	0.28	0.52	0.98	0.27	0.43	0.25	0.29	0.34
		3	0.97	0.80	0.75	1.01	0.99	0.48	0.82	0.84	0.65	0.59	0.73
		Mean	0.96	0.73	0.47	0.51	0.69	0.78	0.51	0.62	0.38	0.39	0.48
		SD	0.07	0.09	0.24	0.43	0.26	0.26	0.28	0.21	0.23	0.18	0.21
		CV	6.83	12.37	50.72	84.99	38.32	33.83	55.22	33.64	61.55	45.56	44.39
	4	1	7.88	7.54	6.85	7.21	5.99	6.08	6.81	7.07	6.46	6.37	6.80
		2	8.33	8.30	8.45	8.54	8.19	6.69	6.95	7.30	7.72	7.57	7.22
		3	7.56	7.96	7.35	7.48	7.59	6.95	8.03	7.94	6.82	6.19	7.78
		Mean	7.92	7.93	7.55	7.74	7.26	6.57	7.26	7.44	7.00	6.71	7.27
		SD	0.39	0.38	0.82	0.70	1.14	0.45	0.67	0.45	0.65	0.75	0.49
		CV	4.88	4.80	10.84	9.08	15.67	6.79	9.19	6.06	9.27	11.18	6.77
	3	1	12.07	15.20	15.11	14.53	12.85	12.79	13.70	12.03	13.24	12.61	14.92
		2	13.92	16.38	16.62	17.14	16.90	13.90	13.45	14.47	15.48	14.90	14.97
		3	12.78	13.50	16.11	16.78	15.35	15.78	14.78	13.50	14.97	15.56	14.34
		Mean	12.92	15.03	15.95	16.15	15.03	14.16	13.98	13.33	14.56	14.36	14.74
		SD	0.93	1.45	0.77	1.41	2.04	1.51	0.71	1.23	1.17	1.55	0.35
		CV	7.22	9.63	4.82	8.76	13.59	10.68	5.06	9.21	8.06	10.78	2.38
	2	1	21.42	22.29	21.04	21.46	20.40	18.72	18.79	18.36	21.19	20.59	18.12
		2	23.14	23.91	25.53	24.56	24.91	20.55	19.23	20.90	22.28	20.52	19.71
		3	22.45	21.50	22.04	22.34	21.45	23.56	23.04	21.46	21.35	22.75	19.15
		Mean	22.34	22.57	22.87	22.79	22.25	20.94	20.35	20.24	21.61	21.29	18.99
		SD	0.87	1.23	2.36	1.60	2.36	2.44	2.34	1.65	0.59	1.27	0.81
		CV	3.88	5.44	10.31	7.01	10.60	11.67	11.48	8.16	2.72	5.96	4.25
	1	1	24.06	26.79	29.11	29.90	34.22	22.56	21.33	23.07	25.82	24.08	20.43
		2	25.57	29.17	31.39	35.81	39.13	21.46	21.18	22.54	27.46	24.56	23.16
		3	26.20	27.82	30.10	30.56	35.65	27.36	27.10	25.80	29.34	28.45	26.40
		Mean	25.28	27.93	30.20	32.09	36.33	23.79	23.20	23.80	27.54	25.70	23.33
		SD	1.10	1.19	1.14	3.24	2.53	3.14	3.38	1.75	1.76	2.40	2.99
		CV	4.35	4.27	3.79	10.09	6.95	13.19	14.55	7.35	6.40	9.33	12.81

Table A.8. continued ....

21 h	5	1	0.77	0.59	0.35	0.31	0.47	0.76	0.35	0.49	0.22	0.28	0.31
		2	0.65	0.58	0.24	0.24	0.40	0.21	0.78	0.39	0.18	0.33	0.32
		3	0.75	0.80	0.79	0.91	1.02	0.72	0.72	0.68	0.49	0.56	0.56
		Mean	0.72	0.66	0.46	0.49	0.63	0.56	0.62	0.52	0.30	0.39	0.40
		SD	0.06	0.12	0.29	0.37	0.34	0.31	0.23	0.15	0.17	0.15	0.14
		CV	8.89	18.92	63.27	75.67	53.90	54.43	37.76	28.33	56.84	38.29	35.68
	4	1	6.30	6.07	5.85	5.81	5.71	5.35	5.65	5.86	5.55	5.37	5.77
		2	6.06	6.16	5.98	6.19	5.96	5.42	5.21	6.20	6.63	6.51	6.01
		3	6.35	6.45	6.80	6.96	7.14	7.60	6.46	6.22	7.41	6.98	6.51
		Mean	6.24	6.23	6.21	6.32	6.27	6.12	5.77	6.09	6.53	6.29	6.10
		SD	0.16	0.20	0.52	0.59	0.76	1.28	0.63	0.20	0.93	0.83	0.38
		CV	2.49	3.19	8.29	9.27	12.18	20.89	10.98	3.32	14.30	13.17	6.19
	3	1	10.39	11.50	11.31	11.51	11.39	10.34	10.38	10.83	10.63	9.86	11.40
		2	9.85	11.13	11.95	11.55	11.99	10.86	10.42	11.61	12.09	12.20	11.67
		3	12.27	11.87	12.16	12.53	13.29	12.78	12.15	11.54	13.40	12.54	11.98
		Mean	10.84	11.50	11.81	11.86	12.22	11.33	10.98	11.33	12.04	11.53	11.68
		SD	1.27	0.37	0.44	0.58	0.97	1.29	1.01	0.43	1.39	1.46	0.29
		CV	11.72	3.22	3.75	4.87	7.95	11.35	9.20	3.81	11.51	12.65	2.48
	2	1	15.61	15.85	15.63	15.26	16.79	14.90	14.53	14.32	14.78	14.59	13.26
		2	14.63	15.11	15.27	15.93	16.32	14.47	11.04	16.35	17.20	17.19	15.10
		3	15.99	16.71	17.84	18.07	18.36	16.81	16.39	16.38	16.34	16.46	16.15
		Mean	15.41	15.89	16.25	16.42	17.16	15.39	13.99	15.68	16.11	16.08	14.84
		SD	0.70	0.80	1.39	1.47	1.07	1.25	2.72	1.18	1.23	1.34	1.46
		CV	4.55	5.04	8.57	8.94	6.23	8.09	19.42	7.53	7.62	8.34	9.86
	1	1	17.91	18.56	19.61	21.09	25.17	16.17	14.54	16.77	17.59	16.77	15.59
		2	17.56	17.90	19.29	20.42	23.61	15.91	15.99	18.75	20.33	19.38	17.23
		3	19.38	19.39	21.97	24.15	27.89	20.60	19.60	19.49	21.64	20.49	18.79
		Mean	18.28	18.62	20.29	21.89	25.56	17.56	16.71	18.34	19.85	18.88	17.20
		SD	0.97	0.75	1.46	1.99	2.17	2.64	2.61	1.41	2.07	1.91	1.60
		CV	5.28	4.01	7.21	9.09	8.48	15.01	15.59	7.67	10.41	10.12	9.30

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.9: Measured carbon dioxide concentrations (%) at various locations in a 1.42-m-diameter bin containing wheat to a depth of 1.37 m with a rectangular perforated floor opening. The grain surface was covered with a PVC sheet. Mass of dry ice introduced was 740 g (Pilot 9).

Time Since Start	Level	Replicate	Sampling Locations 1	2	3	4	5	6	7	8	9	10	11	12	13
1 h	3	1	6.14	5.48	5.80	5.79	6.46	4.21	3.25	5.62	5.58	4.69	5.11	7.33	7.75
		2	4.70	4.10	4.44	4.46	4.04	4.82	5.21	5.06	4.70	5.56	6.28	5.98	6.71
		3	3.25	3.60	3.96	3.29	3.78	3.61	3.25	3.81	4.03	3.81	3.95	4.92	5.29
		Mean	4.70	4.39	4.73	4.51	4.76	4.21	3.90	4.83	4.77	4.69	5.11	6.08	6.58
		SD	1.45	0.97	0.95	1.25	1.48	0.61	1.13	0.93	0.78	0.88	1.17	1.21	1.23
		CV	30.77	22.16	20.16	27.71	31.05	14.36	28.99	19.19	16.30	18.67	22.78	19.88	18.76
	2	1	39.96	39.98	40.56	42.10	39.12	34.25	31.41	37.74	37.68	39.42	35.10	40.01	42.05
		2	35.84	34.13	37.02	38.22	37.45	38.79	37.59	35.92	37.21	39.42	42.69	31.95	39.15
		3	23.95	28.56	30.89	28.50	25.29	29.72	25.23	29.10	31.37	39.42	27.50	35.34	32.54
		Mean	33.25	34.22	36.16	36.27	33.95	34.25	31.41	34.25	35.42	39.42	35.10	35.77	37.91
		SD	8.31	5.71	4.89	7.01	7.55	4.53	6.18	4.55	3.52	0.00	7.60	4.05	4.87
		CV	25.00	16.69	13.53	19.31	22.23	13.24	19.68	13.30	9.92	0.00	21.64	11.31	12.86
	1	1	70.71	74.89	77.08	76.65	92.63	71.18	62.18	80.87	92.89	75.92	70.15	76.61	72.99
		2	67.26	76.88	84.90	79.10	90.69	80.30	65.41	81.13	94.42	89.08	80.56	76.54	78.74
		3	50.92	66.92	71.61	68.59	67.45	62.07	58.95	72.24	80.63	62.76	59.75	76.33	60.20
		Mean	62.96	72.90	77.86	74.78	83.59	71.18	62.18	78.08	89.31	75.92	70.15	76.49	70.64
		SD	10.57	5.27	6.68	5.50	14.01	9.11	3.23	5.06	7.56	13.16	10.40	0.15	9.49
		CV	16.79	7.23	8.58	7.35	16.76	12.80	5.19	6.48	8.46	17.33	14.83	0.19	13.43
3 h	4	1	3.91	4.32	4.31	4.22	4.26	4.14	3.77	3.43	3.91	7.54	6.26	4.33	6.28
		2	3.28	3.14	3.47	3.13	3.18	3.10	3.00	3.13	3.05	3.66	3.80	3.22	3.89
		3	3.07	3.21	3.41	3.40	3.66	3.53	2.98	2.81	3.38	5.60	3.20	3.76	3.43
		Mean	3.42	3.56	3.73	3.58	3.70	3.59	3.25	3.12	3.45	5.60	4.42	3.77	4.53
		SD	0.44	0.66	0.50	0.57	0.54	0.52	0.45	0.31	0.43	1.94	1.62	0.56	1.53
		CV	12.78	18.61	13.49	15.84	14.62	14.56	13.86	9.93	12.59	34.64	36.69	14.72	33.75
	3	1	15.01	14.55	15.00	15.81	12.32	15.07	15.63	14.23	14.23	14.29	14.76	16.75	16.67
		2	13.49	12.35	13.69	13.14	12.88	12.00	13.02	12.61	12.18	12.68	13.07	12.95	13.15
		3	11.97	13.03	13.05	13.18	13.70	13.36	11.57	11.86	9.39	13.37	12.88	14.16	13.66
		Mean	13.49	13.31	13.91	14.04	12.97	13.48	13.41	12.90	11.93	13.45	13.57	14.62	14.49
		SD	1.52	1.13	0.99	1.53	0.69	1.54	2.06	1.21	2.43	0.81	1.03	1.94	1.90
		CV	11.27	8.46	7.14	10.90	5.35	11.41	15.35	9.39	20.36	6.01	7.63	13.28	13.12
	2	1	38.85	37.13	39.89	38.13	36.98	38.49	38.20	36.03	34.90	30.67	37.67	34.91	36.80
		2	37.44	33.82	37.36	37.52	35.20	34.38	33.60	36.59	35.85	34.85	32.41	32.09	35.01
		3	35.04	33.65	34.23	36.02	36.75	35.44	34.84	33.88	35.75	32.89	36.07	37.62	36.63
		Mean	37.11	34.87	37.16	37.22	36.31	36.10	35.55	35.50	35.50	32.80	35.38	34.87	36.15
		SD	1.93	1.96	2.84	1.09	0.97	2.13	2.38	1.43	0.52	2.09	2.70	2.77	0.99
		CV	5.19	5.63	7.63	2.92	2.67	5.91	6.70	4.03	1.47	6.38	7.62	7.93	2.73
	1	1	52.58	56.63	59.47	63.56	77.40	58.44	55.95	63.33	74.99	80.33	67.30	59.23	56.98
		2	50.80	53.11	58.34	63.12	75.04	57.83	48.35	61.86	42.19	76.98	57.20	53.42	56.69
		3	51.99	56.19	62.06	61.98	74.14	57.35	50.55	61.06	78.19	75.88	58.71	61.29	58.39
		Mean	51.79	55.31	59.96	62.89	75.53	57.87	51.62	62.08	65.12	77.73	61.07	57.98	57.35
		SD	0.91	1.92	1.91	0.82	1.68	0.55	3.91	1.15	19.93	2.32	5.45	4.08	0.91
		CV	1.75	3.47	3.18	1.30	2.23	0.94	7.58	1.85	30.60	2.98	8.92	7.04	1.59

Table A.9. continued ....

6 h	5	1	2.63	4.27	4.44	4.50	4.63	4.22	3.60	3.73	3.81	4.53	4.61	4.18	3.53
		2	3.37	3.80	3.95	4.05	3.31	3.14	2.57	2.95	2.86	3.59	3.49	3.50	3.40
		3	2.48	3.13	3.70	3.51	4.01	3.44	2.65	2.44	2.62	3.78	3.15	3.77	3.58
		Mean	2.83	3.73	4.03	4.02	3.98	3.60	2.94	3.04	3.10	3.97	3.75	3.82	3.50
		SD	0.48	0.57	0.38	0.50	0.66	0.56	0.57	0.65	0.63	0.50	0.76	0.34	0.09
		CV	16.86	15.35	9.34	12.33	16.58	15.49	19.49	21.37	20.32	12.53	20.37	8.97	2.65
	4	1	8.13	8.26	8.29	8.35	8.07	8.16	7.81	7.46	7.90	8.97	8.55	8.29	8.64
		2	7.20	6.94	7.46	7.40	7.09	6.96	6.93	6.88	7.09	6.88	7.57	6.81	7.36
		3	6.73	6.92	7.27	7.30	7.12	7.14	6.31	5.69	6.83	6.73	6.71	7.29	6.63
		Mean	7.35	7.37	7.67	7.68	7.43	7.42	7.02	6.68	7.27	7.53	7.61	7.46	7.54
		SD	0.71	0.77	0.54	0.58	0.56	0.65	0.75	0.90	0.56	1.25	0.92	0.76	1.02
		CV	9.69	10.42	7.07	7.54	7.50	8.72	10.74	13.51	7.67	16.64	12.10	10.12	13.49
	3	1	19.22	18.60	18.84	18.83	17.69	16.40	19.17	17.25	17.65	18.26	17.62	19.49	19.01
		2	17.10	16.64	16.98	15.34	16.70	16.14	17.08	14.77	16.20	16.46	16.43	17.01	16.28
		3	15.95	15.96	16.50	17.28	16.58	17.00	15.52	14.93	15.95	16.26	15.16	16.09	16.09
		Mean	17.42	17.07	17.44	17.15	16.99	16.51	17.26	15.65	16.60	16.99	16.40	17.53	17.13
		SD	1.66	1.37	1.24	1.75	0.61	0.44	1.83	1.39	0.92	1.10	1.23	1.76	1.63
		CV	9.52	8.03	7.09	10.20	3.59	2.67	10.61	8.87	5.53	6.48	7.50	10.03	9.54
	2	1	36.75	35.60	35.53	36.36	33.29	36.77	35.28	34.81	33.53	33.05	34.49	33.48	37.05
		2	32.95	29.76	34.23	34.10	33.09	30.45	28.62	32.32	27.83	32.77	31.55	31.54	31.46
		3	31.88	31.75	32.83	33.53	32.46	31.85	30.81	30.53	31.87	31.88	29.72	31.01	29.97
		Mean	33.86	32.37	34.20	34.66	32.95	33.02	31.57	32.55	31.08	32.57	31.92	32.01	32.83
		SD	2.56	2.97	1.35	1.50	0.43	3.32	3.39	2.15	2.93	0.61	2.41	1.30	3.73
		CV	7.56	9.17	3.95	4.32	1.31	10.05	10.75	6.60	9.43	1.88	7.54	4.06	11.37
	1	1	47.33	48.46	52.11	55.05	61.01	49.61	45.98	54.21	59.79	65.53	53.56	52.26	49.57
		2	41.63	45.03	45.71	51.88	61.75	45.73	39.62	42.33	44.39	56.45	48.33	48.29	40.26
		3	39.07	42.52	46.73	47.68	61.05	45.72	40.55	47.08	41.67	53.63	49.79	48.05	44.60
		Mean	42.68	45.34	48.18	51.54	61.27	47.02	42.05	47.87	48.62	58.54	50.56	49.53	44.81
		SD	4.23	2.98	3.44	3.70	0.42	2.24	3.44	5.98	9.77	6.22	2.70	2.36	4.66
		CV	9.91	6.58	7.14	7.17	0.68	4.77	8.17	12.49	20.10	10.62	5.34	4.77	10.40
12 h	5	1	4.86	7.51	8.12	8.54	8.57	8.12	7.04	7.63	7.94	8.03	7.85	8.22	6.16
		2	6.63	7.20	7.92	8.12	8.11	6.60	5.20	5.47	6.23	6.50	5.89	8.30	6.56
		3	4.97	6.17	6.90	7.25	6.85	6.32	5.29	4.82	4.92	6.20	5.10	6.81	6.34
		Mean	5.49	6.96	7.65	7.97	7.84	7.01	5.84	5.97	6.36	6.91	6.28	7.78	6.35
		SD	0.99	0.70	0.65	0.66	0.89	0.97	1.04	1.47	1.51	0.98	1.42	0.84	0.20
		CV	18.07	10.08	8.56	8.26	11.35	13.81	17.75	24.63	23.80	14.20	22.55	10.78	3.15
	4	1	12.05	11.82	11.73	11.85	11.80	12.03	11.02	11.04	11.00	12.12	11.35	11.65	12.13
		2	10.32	10.79	10.78	11.23	9.85	10.43	10.42	9.83	10.85	10.65	10.30	10.91	11.15
		3	9.53	9.98	9.77	10.04	10.02	9.71	8.99	9.16	9.62	9.96	9.35	10.10	9.46
		Mean	10.63	10.86	10.76	11.04	10.56	10.72	10.14	10.01	10.49	10.91	10.33	10.89	10.91
		SD	1.29	0.92	0.98	0.92	1.08	1.19	1.04	0.95	0.76	1.10	1.00	0.78	1.35
		CV	12.12	8.49	9.11	8.33	10.23	11.07	10.28	9.52	7.22	10.11	9.68	7.12	12.38
	3	1	20.28	19.82	19.70	19.21	17.86	18.28	19.13	17.20	17.68	16.30	18.75	20.15	19.01
		2	17.64	16.55	16.32	17.38	15.89	17.18	17.04	16.33	15.52	16.10	16.50	17.44	18.17
		3	15.71	15.93	16.12	16.27	16.65	17.17	15.43	15.64	15.94	15.91	15.73	16.36	16.30
		Mean	17.88	17.43	17.38	17.62	16.80	17.54	17.20	16.39	16.38	16.10	16.99	17.98	17.83
		SD	2.29	2.09	2.01	1.48	0.99	0.64	1.86	0.78	1.15	0.20	1.57	1.95	1.39
		CV	12.83	11.99	11.57	8.43	5.91	3.64	10.79	4.77	6.99	1.21	9.23	10.86	7.78

Table A.9. continued ....

	2	1	29.77	27.30	29.86	29.56	28.59	28.81	28.53	28.75	26.36	28.52	29.12	26.74	30.93
		2	26.06	24.50	23.20	26.71	27.98	26.53	24.83	27.07	22.94	25.14	26.18	26.84	25.27
		3	24.68	24.36	23.49	25.66	24.79	23.87	24.84	24.55	25.33	25.58	25.37	25.08	22.95
		Mean	26.84	25.39	25.52	27.31	27.12	26.40	26.07	26.79	24.88	26.41	26.89	26.22	26.38
		SD	2.63	1.66	3.76	2.02	2.04	2.47	2.13	2.11	1.75	1.84	1.97	0.99	4.10
		CV	9.81	6.53	14.75	7.39	7.52	9.36	8.18	7.89	7.05	6.96	7.34	3.77	15.56
	1	1	34.48	37.25	36.40	38.54	45.13	38.37	35.80	37.94	46.34	45.54	39.03	38.69	37.87
		2	29.67	30.48	33.92	36.88	42.36	32.28	29.98	34.96	43.27	40.46	35.98	30.77	31.30
		3	30.24	30.99	32.66	33.76	40.81	32.52	30.64	33.09	40.33	40.00	34.88	32.54	29.71
		Mean	31.46	32.91	34.33	36.39	42.77	34.39	32.14	35.33	43.31	42.00	36.63	34.00	32.96
		SD	2.63	3.77	1.90	2.43	2.19	3.45	3.19	2.45	3.01	3.07	2.15	4.16	4.33
		CV	8.35	11.46	5.54	6.67	5.12	10.03	9.92	6.92	6.94	7.32	5.87	12.23	13.12
21 h	5	1	7.06	9.45	10.39	10.62	11.25	11.03	8.53	10.19	10.52	10.38	10.11	11.01	8.31
		2	7.79	9.48	10.36	10.23	9.78	9.19	6.77	7.68	7.76	8.95	9.09	8.87	8.72
		3	6.66	8.22	9.04	9.44	8.73	8.40	7.17	6.34	12.87	8.33	7.65	7.73	8.02
		Mean	7.17	9.05	9.93	10.10	9.92	9.54	7.49	8.07	10.38	9.22	8.95	9.20	8.35
		SD	0.57	0.72	0.77	0.60	1.27	1.35	0.92	1.95	2.56	1.05	1.24	1.67	0.35
		CV	7.99	7.94	7.76	5.95	12.76	14.15	12.32	24.22	24.63	11.40	13.81	18.09	4.21
	4	1	13.74	13.13	13.15	13.83	14.07	13.06	12.96	13.19	12.87	13.46	12.79	12.90	14.12
		2	11.30	12.27	11.46	11.85	11.76	10.90	11.27	11.75	12.58	12.18	10.00	11.75	11.73
		3	11.37	11.30	11.62	11.34	11.38	10.84	10.89	10.26	10.20	10.83	10.87	10.70	9.82
		Mean	12.14	12.23	12.08	12.34	12.40	11.60	11.71	11.73	11.88	12.16	11.22	11.78	11.89
		SD	1.39	0.92	0.93	1.32	1.46	1.26	1.10	1.47	1.47	1.32	1.43	1.10	2.15
		CV	11.44	7.48	7.73	10.66	11.74	10.90	9.41	12.49	12.33	10.82	12.72	9.34	18.12
	3	1	18.54	17.31	17.50	16.41	16.96	16.81	17.70	18.21	18.06	16.48	16.47	17.60	16.92
		2	15.93	15.87	16.45	16.73	15.51	15.84	16.11	16.11	15.71	15.28	15.85	17.02	15.90
		3	14.56	14.87	15.45	15.10	14.91	15.36	14.66	14.50	14.84	15.38	15.30	15.41	15.33
		Mean	16.34	16.02	16.47	16.08	15.79	16.00	16.16	16.27	16.20	15.71	15.87	16.68	16.05
		SD	2.02	1.23	1.03	0.86	1.05	0.74	1.52	1.86	1.67	0.67	0.59	1.13	0.81
		CV	12.37	7.66	6.23	5.37	6.67	4.62	9.41	11.43	10.28	4.24	3.69	6.80	5.02
	2	1	23.45	21.70	23.75	24.67	22.30	23.56	21.79	22.16	22.03	21.96	24.25	20.78	24.11
		2	20.58	17.58	20.72	20.95	22.04	20.58	20.78	21.73	18.86	20.23	18.77	21.60	20.95
		3	18.92	19.60	20.51	20.52	21.18	19.57	19.08	15.10	19.37	20.02	20.30	19.74	19.08
		Mean	20.98	19.63	21.66	22.05	21.84	21.24	20.55	19.66	20.09	20.74	21.11	20.71	21.38
		SD	2.29	2.06	1.81	2.28	0.59	2.07	1.37	3.96	1.70	1.06	2.83	0.93	2.54
		CV	10.92	10.50	8.37	10.35	2.68	9.77	6.66	20.13	8.47	5.13	13.40	4.50	11.89
	1	1	24.41	26.82	26.37	27.94	30.96	27.24	24.30	27.68	29.88	31.52	28.27	27.31	26.27
		2	22.71	23.13	24.06	24.99	29.27	23.58	21.14	22.91	28.40	27.15	24.08	23.46	23.71
		3	22.23	22.52	23.66	23.81	27.27	23.04	22.41	22.71	26.05	26.65	16.63	22.81	21.96
		Mean	23.12	24.16	24.70	25.58	29.17	24.62	22.62	24.43	28.11	28.44	22.99	24.53	23.98
		SD	1.15	2.33	1.46	2.13	1.85	2.28	1.59	2.81	1.93	2.68	5.90	2.43	2.17
		CV	4.96	9.63	5.92	8.32	6.33	9.28	7.03	11.51	6.87	9.42	25.64	9.92	9.04

Table A.9. continued ....

24 h	5	1	7.72	10.28	11.22	11.66	11.10	11.28	10.07	10.84	10.86	11.40	10.20	11.12	8.44
		2	7.90	9.29	9.82	9.33	9.59	8.55	6.93	9.10	7.57	9.92	8.83	10.51	8.54
		3	7.06	8.37	9.64	8.83	9.35	8.55	7.36	7.36	7.29	7.40	7.37	9.91	8.64
		Mean	7.56	9.31	10.23	9.94	10.01	9.46	8.12	9.10	8.57	9.57	8.80	10.51	8.54
		SD	0.44	0.96	0.86	1.51	0.95	1.58	1.70	1.74	1.99	2.02	1.42	0.61	0.10
		CV	5.85	10.26	8.46	15.20	9.47	16.66	20.97	19.12	23.16	21.13	16.08	5.75	1.17
	4	1	13.79	14.11	14.22	13.95	13.11	13.30	13.13	13.58	13.76	13.43	13.12	12.80	14.00
		2	11.82	12.25	12.49	12.08	11.22	11.25	11.44	11.85	12.48	11.56	11.76	12.00	11.65
		3	11.17	11.71	11.43	11.34	11.52	10.67	10.21	10.12	11.20	11.25	10.20	11.51	11.23
		Mean	12.26	12.69	12.71	12.46	11.95	11.74	11.59	11.85	12.48	12.08	11.69	12.10	12.29
		SD	1.36	1.26	1.41	1.35	1.02	1.38	1.47	1.73	1.28	1.18	1.46	0.65	1.49
		CV	11.13	9.92	11.08	10.80	8.50	11.77	12.65	14.60	10.26	9.76	12.50	5.38	12.14
	3	1	18.19	17.14	17.60	17.38	17.08	16.94	17.52	17.12	15.73	16.32	16.56	17.96	17.87
		2	16.35	15.27	15.63	14.44	15.65	15.47	15.38	15.47	14.98	16.37	15.71	16.27	15.28
		3	14.33	14.78	14.81	14.90	15.45	14.09	14.69	13.83	14.23	14.30	13.81	14.54	15.52
		Mean	16.29	15.73	16.01	15.57	16.06	15.50	15.86	15.47	14.98	15.66	15.36	16.26	16.22
		SD	1.93	1.25	1.43	1.58	0.89	1.43	1.48	1.64	0.75	1.18	1.41	1.71	1.43
		CV	11.85	7.92	8.95	10.15	5.54	9.20	9.30	10.63	5.01	7.54	9.17	10.52	8.82
	2	1	22.42	21.82	22.74	22.10	21.82	22.32	22.33	22.06	21.81	21.37	20.68	19.18	22.69
		2	18.85	18.03	19.70	20.74	20.37	18.93	19.48	20.49	19.78	20.43	19.59	19.86	20.07
		3	18.31	17.46	18.61	19.32	19.52	20.25	18.04	18.93	17.75	18.57	18.99	18.68	17.31
		Mean	19.86	19.10	20.35	20.72	20.57	20.50	19.95	20.49	19.78	20.12	19.75	19.24	20.02
		SD	2.23	2.37	2.14	1.39	1.16	1.71	2.18	1.57	2.03	1.42	0.86	0.59	2.69
		CV	11.25	12.41	10.52	6.71	5.65	8.34	10.94	7.64	10.26	7.08	4.34	3.08	13.44
	1	1	24.67	24.99	24.53	25.97	28.25	24.22	23.66	25.98	27.81	28.07	24.03	24.79	25.39
		2	21.76	22.18	20.95	22.76	26.26	20.49	20.59	18.23	23.63	22.73	21.46	19.71	21.21
		3	20.65	20.76	21.46	21.71	25.53	21.14	21.23	21.14	23.85	23.07	21.64	21.83	19.98
		Mean	22.36	22.64	22.31	23.48	26.68	21.95	21.83	21.78	25.10	24.62	22.38	22.11	22.19
		SD	2.08	2.15	1.94	2.22	1.41	1.99	1.62	3.91	2.35	2.99	1.43	2.55	2.84
		CV	9.28	9.51	8.68	9.45	5.28	9.08	7.42	17.97	9.37	12.14	6.41	11.54	12.78

SD = Standard Deviation
CV = Coefficient of Variation = 100.0*(SD/Mean)

Table A.10: Wheat bulk temperatures (°C) in the pilot bin experiments.

Experiment No*	Replicate 1		Replicate 2		Replicate 3		Whole Experiment	
	Mean ± SD**		Mean ± SD		Mean ± SD		Mean ± SD	
Pilot 1	24.0	0.6	27.2	0.8	26.0	0.8	25.7	1.6
Pilot 2#								
Pilot 3	16.5	2.3	17.3	2.4	17.1	2.3	17.0	2.7
Pilot 4	23.4	2.0	22.7	0.6	19.8	0.9	21.9	2.0
Pilot 5	19.7	0.7	19.5	1.8	23.2	2.1	20.7	2.3
Pilot 6	24.7	1.1	26.0	1.2	28.9	1.3	26.5	2.1
Pilot 7	26.5	0.7	27.1	1.0	28.0	0.7	27.2	1.0
Pilot 8	27.3	1.5	29.0	2.0	27.2	1.5	27.8	1.9
Pilot 9	23.5	1.2	24.7	1.3	21.9	1.6	23.2	1.7

Temperatures (°C) spans the Replicate 1 – Whole Experiment columns.

* See Table 5.1 for details of the experiment

** Standard Deviation

\# Temperatures were not recorded

APPENDIX B

Lines of constant CO_2 concentrations (%) in wheat bulks contained in 1.42-m-diameter bins. Individual plots are for the sampling times indicated at the bottom of each figure.

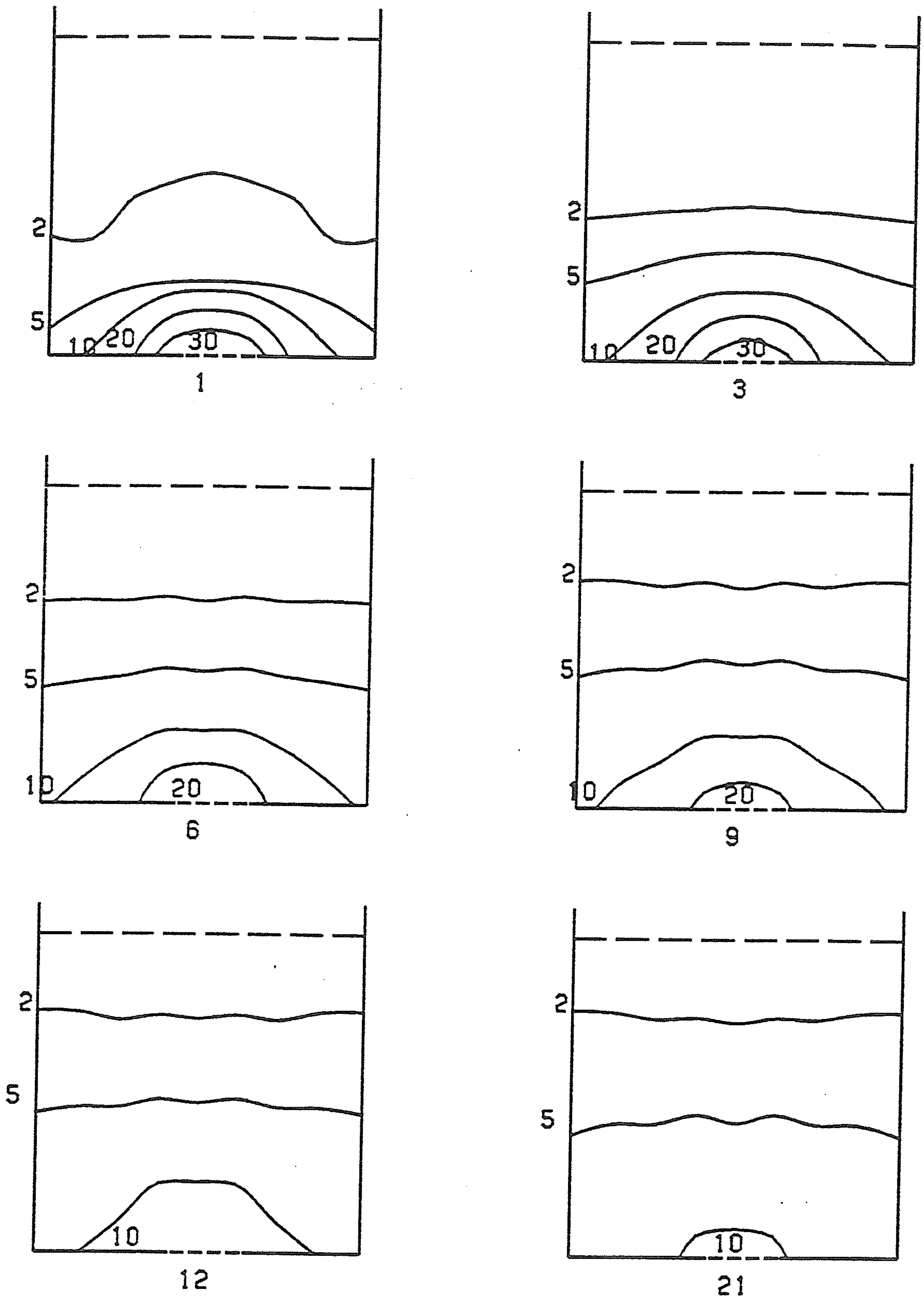

FIG.B.1. BIN 1. OPEN TOP SURFACE. 180 G DRY ICE (REP.1)

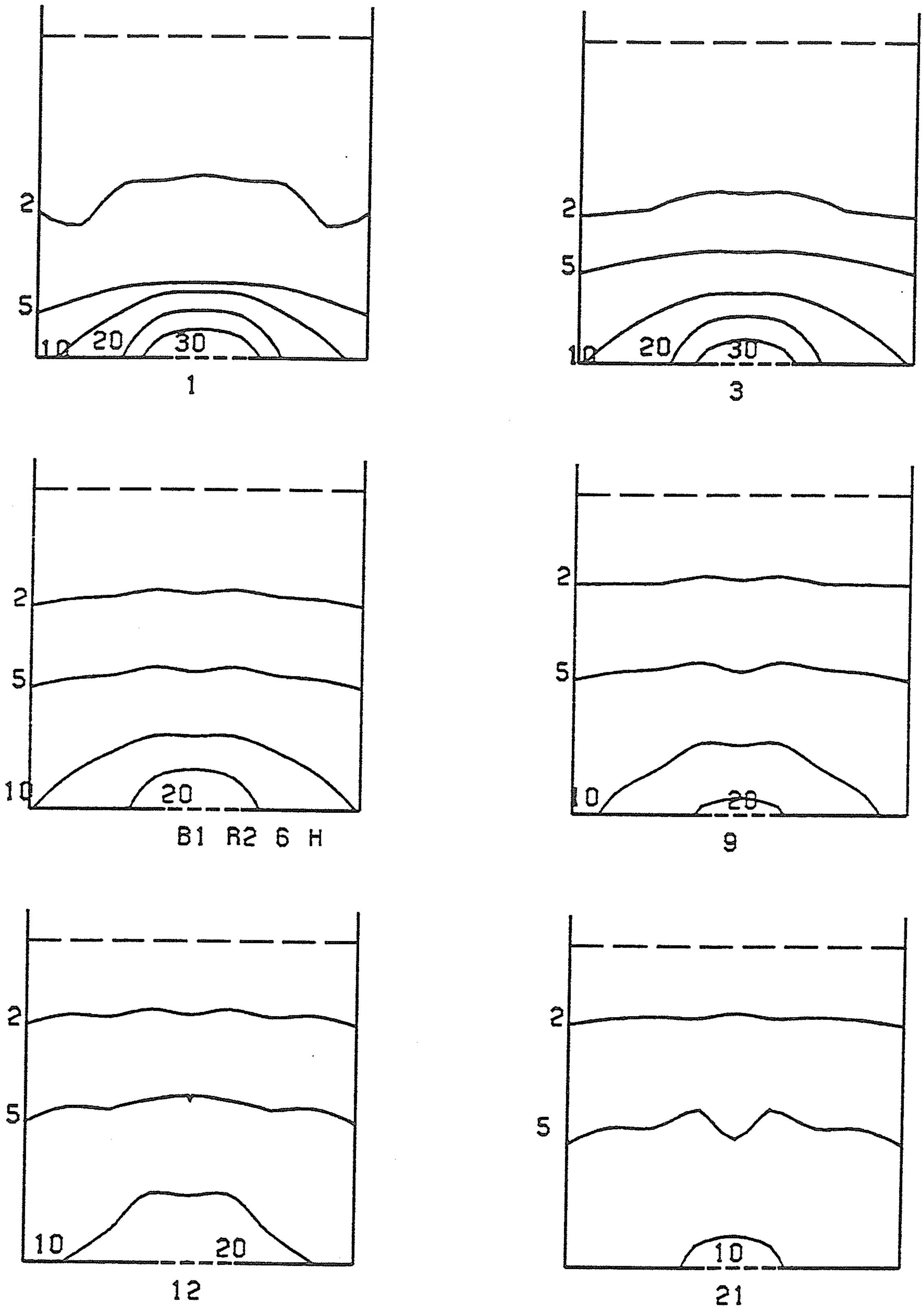

FIG.B.2. BIN 1. OPEN TOP SURFACE. 180 G DRY ICE (REP.2)

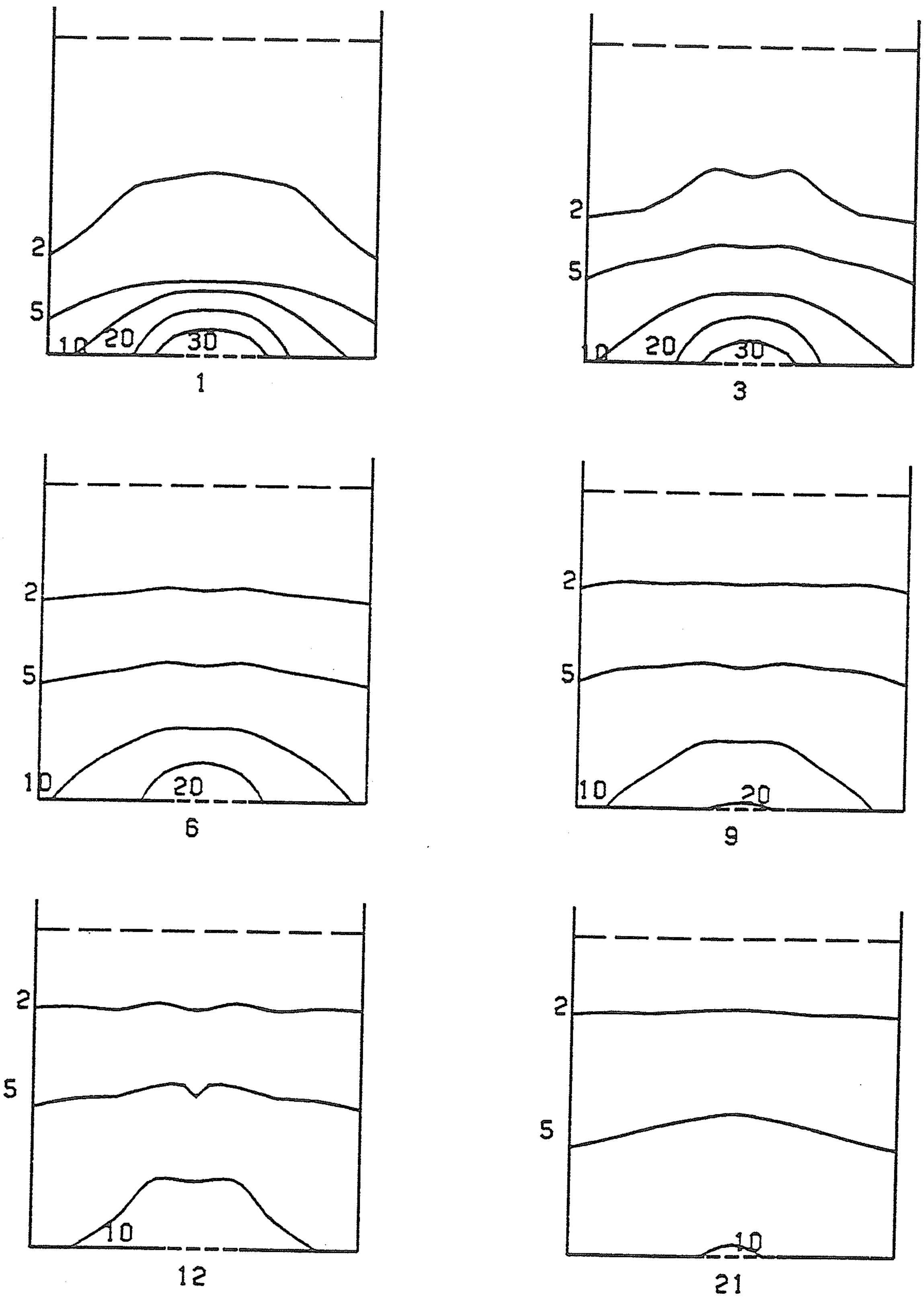

FIG.B.3. BIN 1. OPEN TOP SURFACE. 180 G DRY ICE (REP.3)

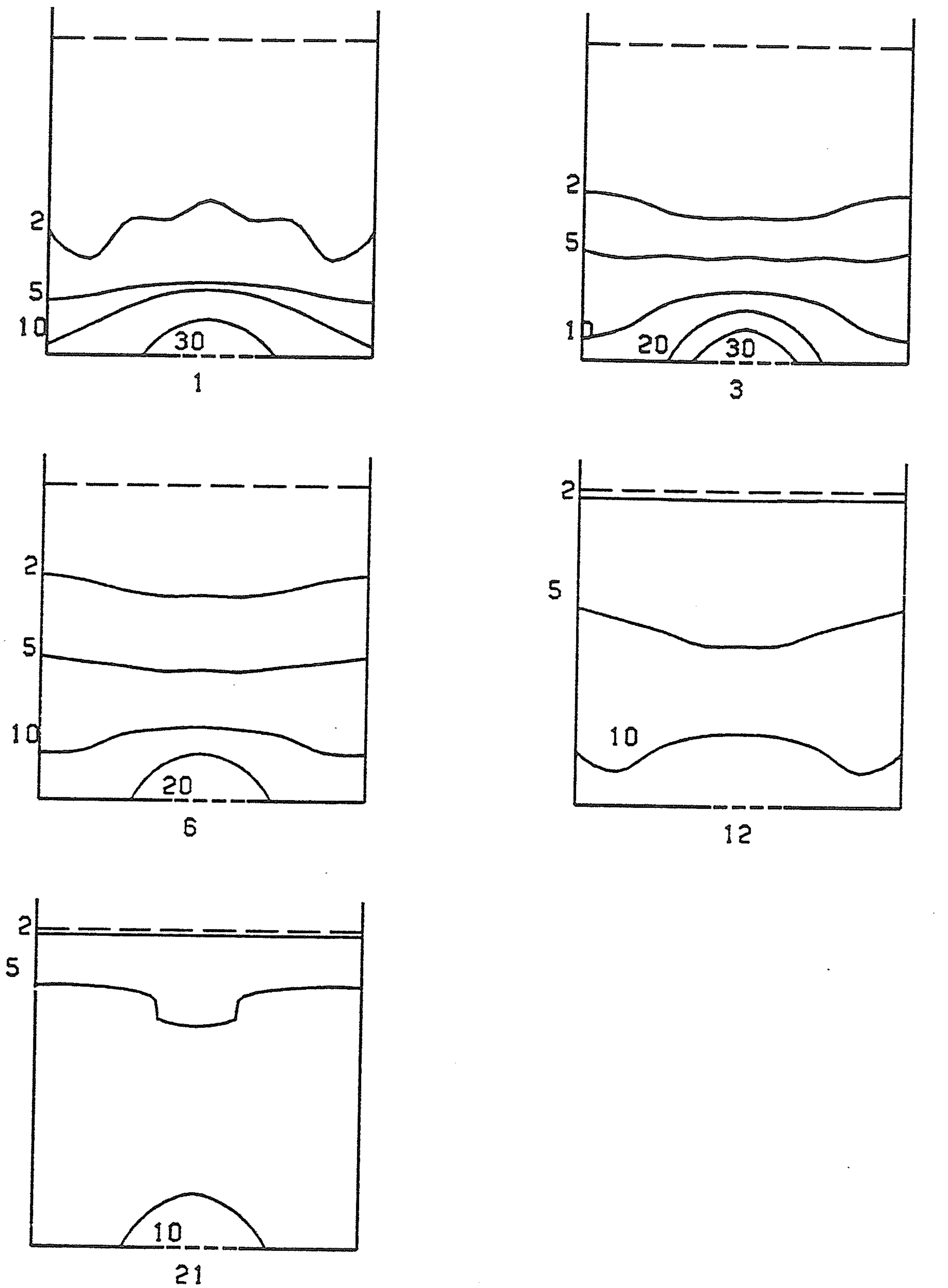

FIG.B.4. BIN 1. COVERED TOP SURFACE. 180 G DRY ICE (REP.1)

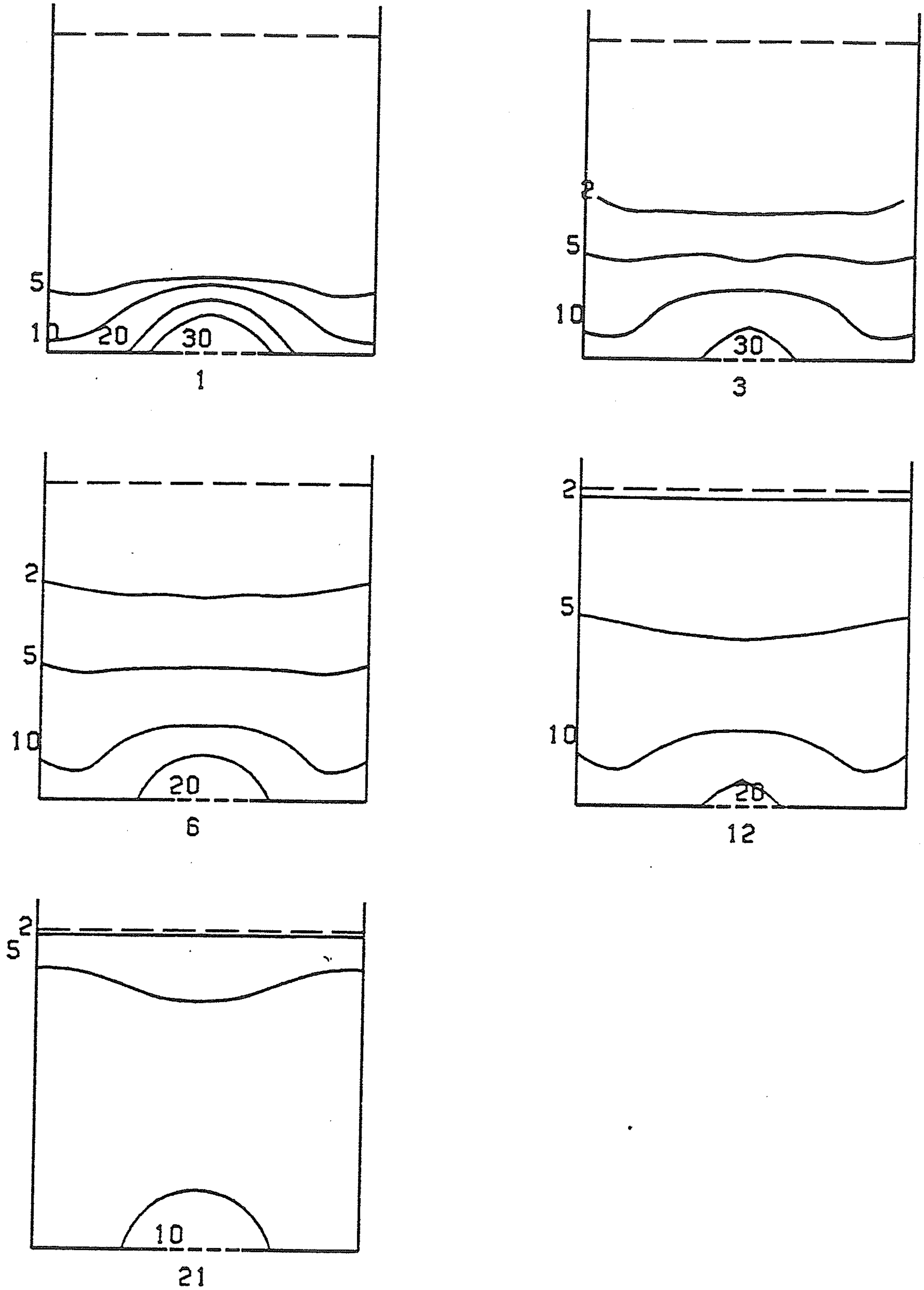

FIG.B.5. BIN 1. COVERED TOP SURFACE. 180 G DRY ICE (REP.2)

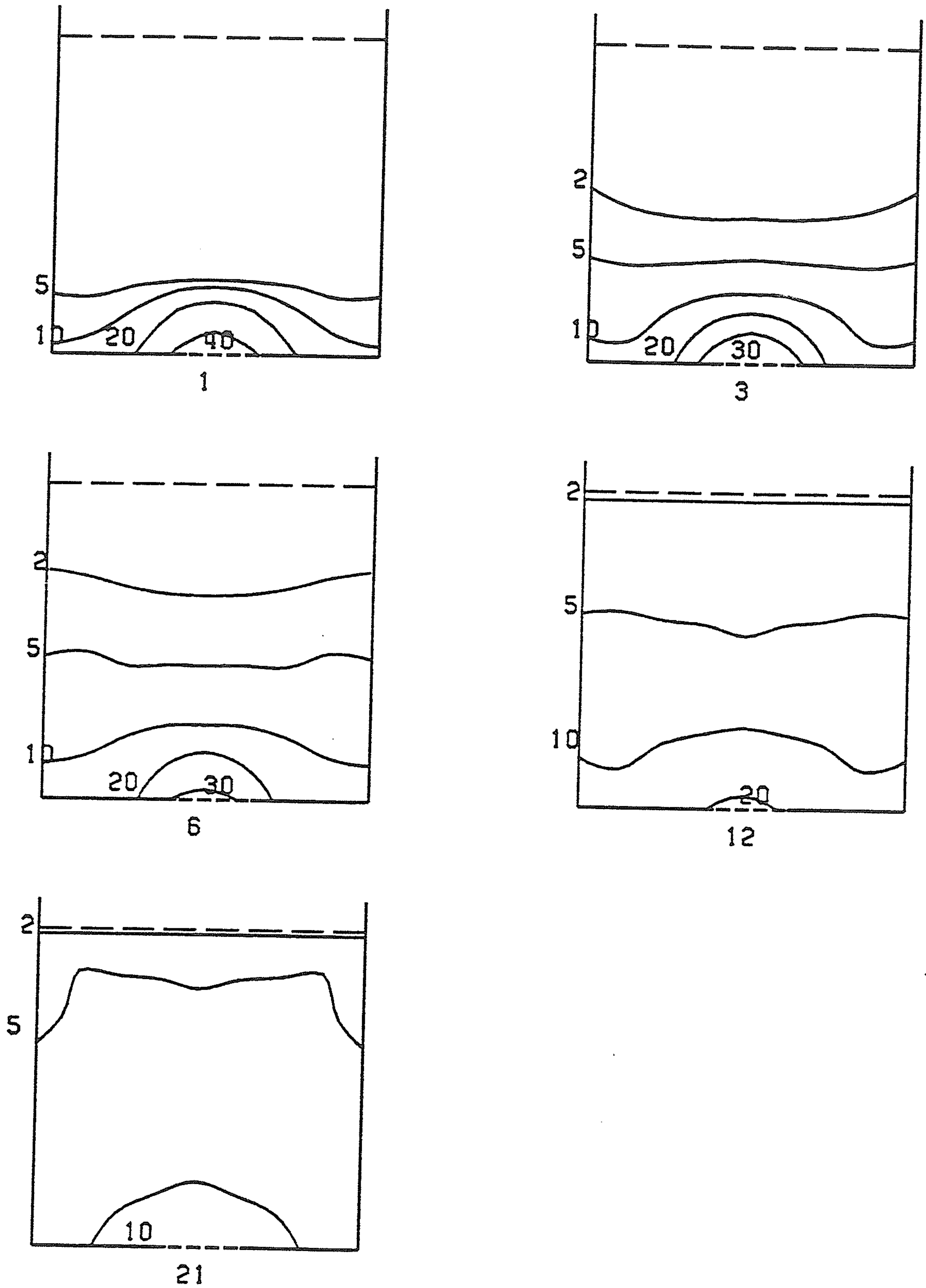

FIG.B.6. BIN 1. COVERED TOP SURFACE. 180 G DRY ICE (REP.3)

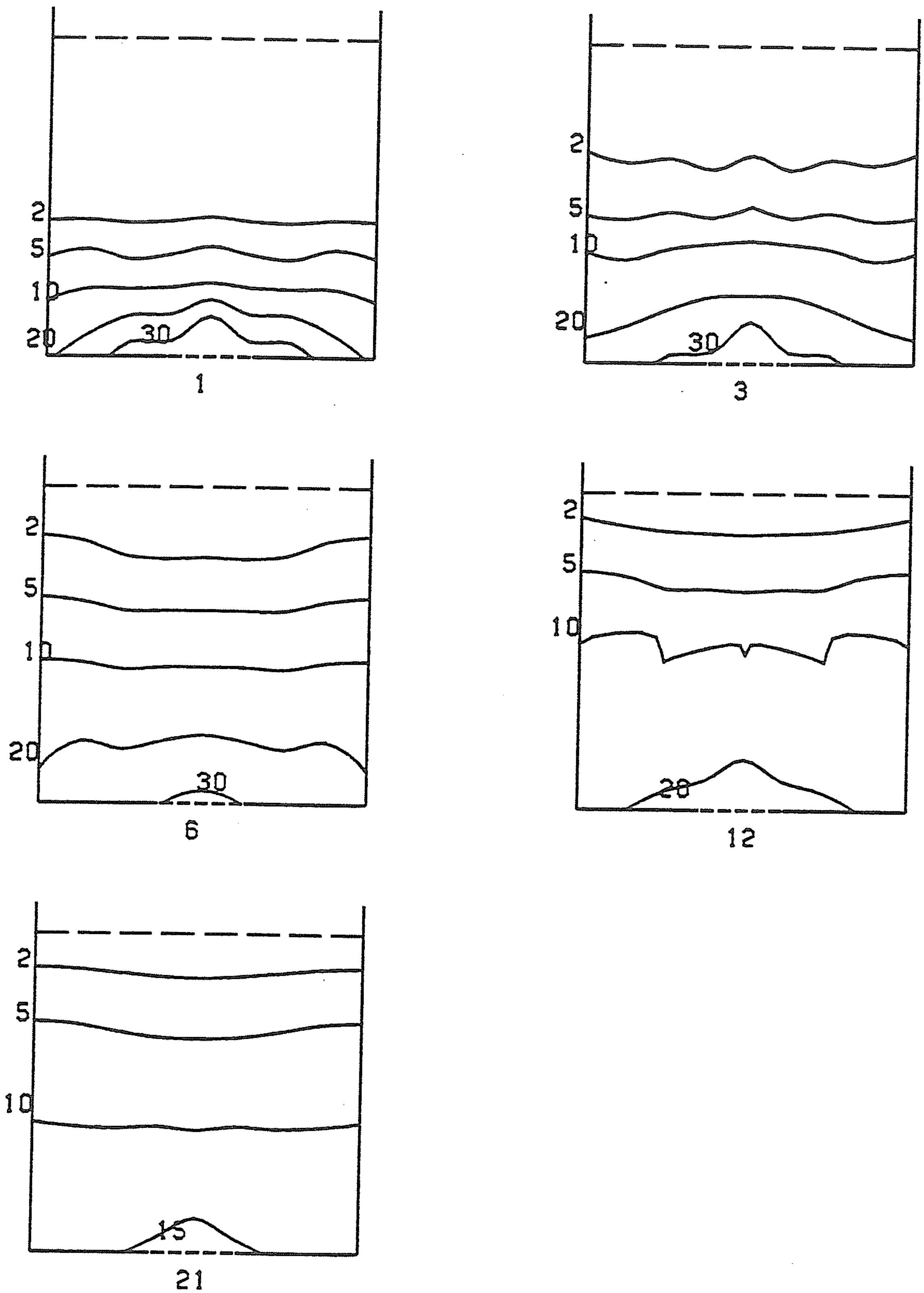

FIG.B.7. BIN 2. OPEN TOP SURFACE. 370 G DRY ICE (REP.1)
(ALONG SECTION A-A)

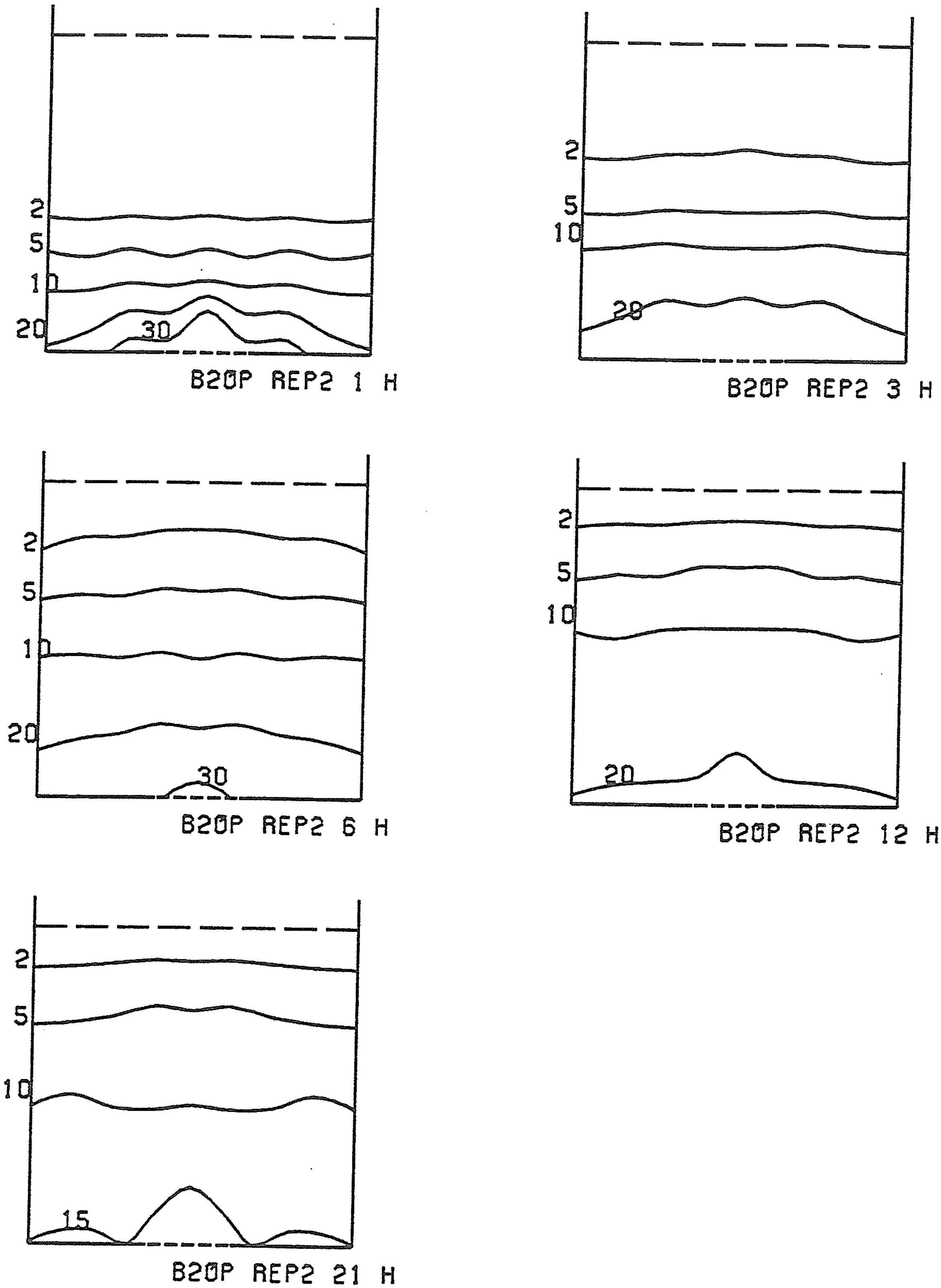

FIG.B.8. BIN 2. ØPEN TØP SURFACE. 370 G DRY ICE (REP.2)
(ALØNG SECTIØN A-A)

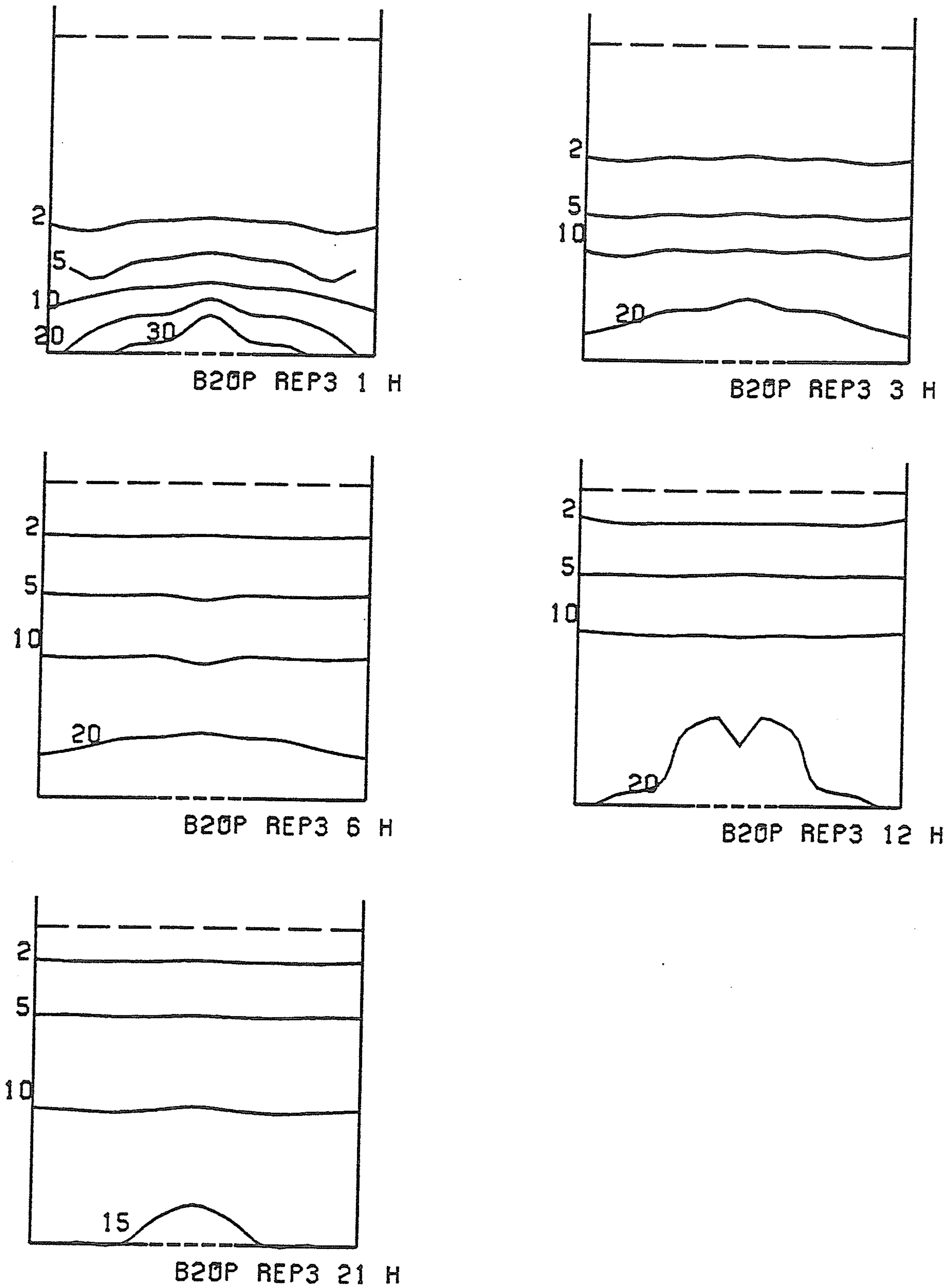

FIG.B.9. BIN 2. ØPEN TØP SURFACE. 370 G DRY ICE (REP.3)
(ALØNG SECTIØN A-A)

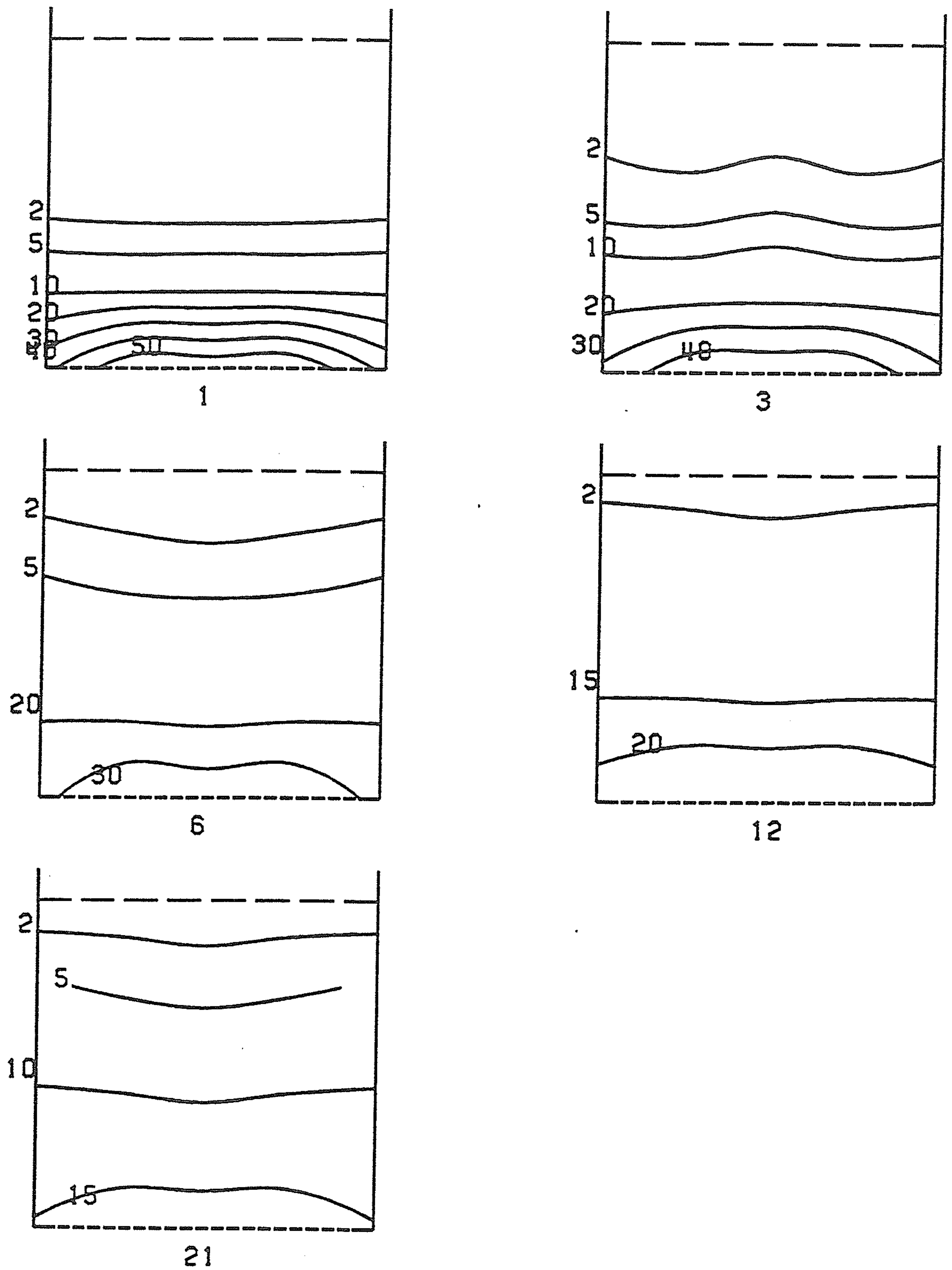

FIG.B.10. BIN 2. OPEN TOP SURFACE. 370 G DRY ICE (REP.1) (ALONG SECTION B-B)

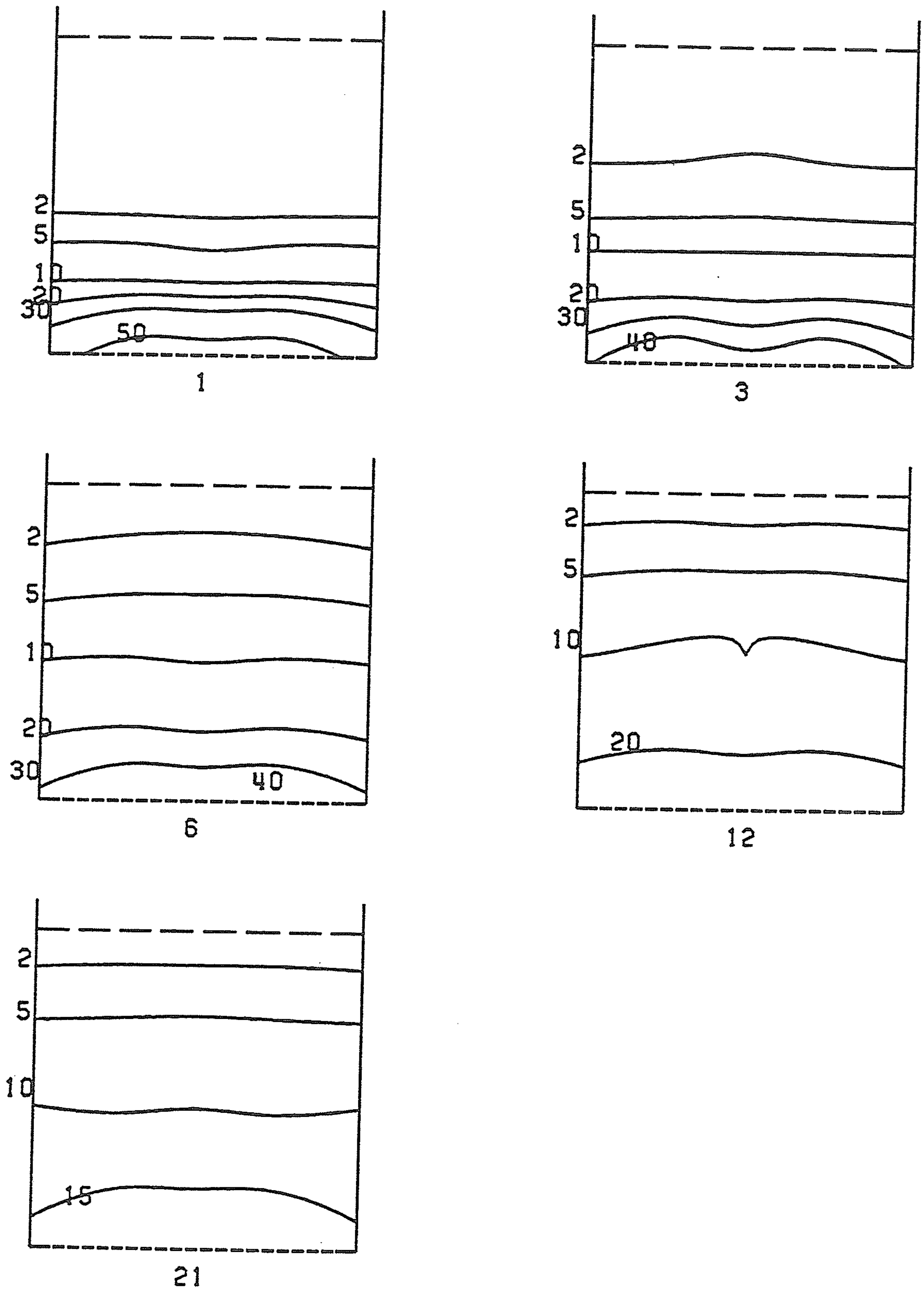

FIG.B.11. BIN 2. OPEN TOP SURFACE. 370 G DRY ICE (REP.2)
(ALONG SECTION B-B)

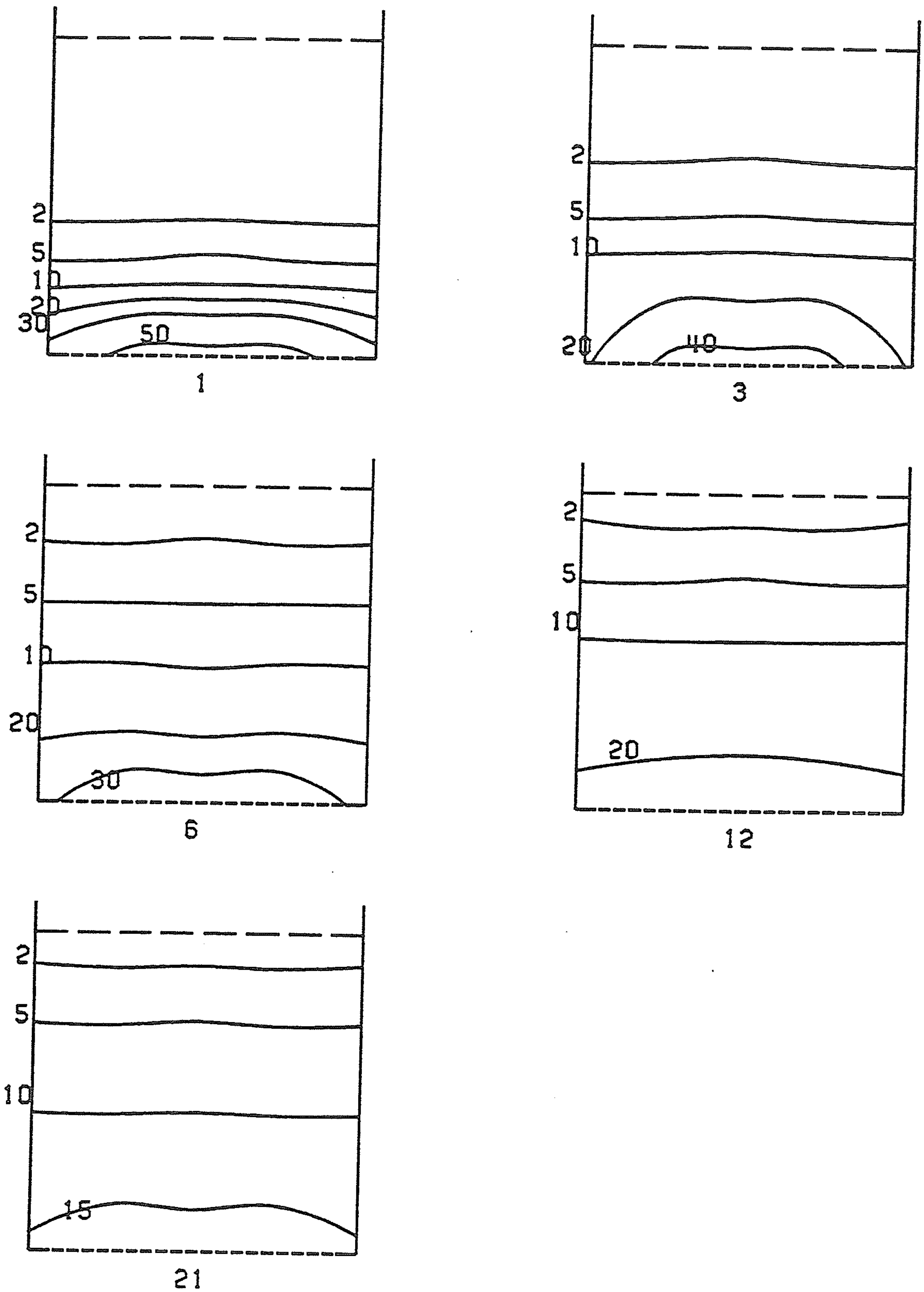

FIG.B.12. BIN 2. OPEN TOP SURFACE. 370 G DRY ICE (REP.3)
(ALONG SECTION B-B)

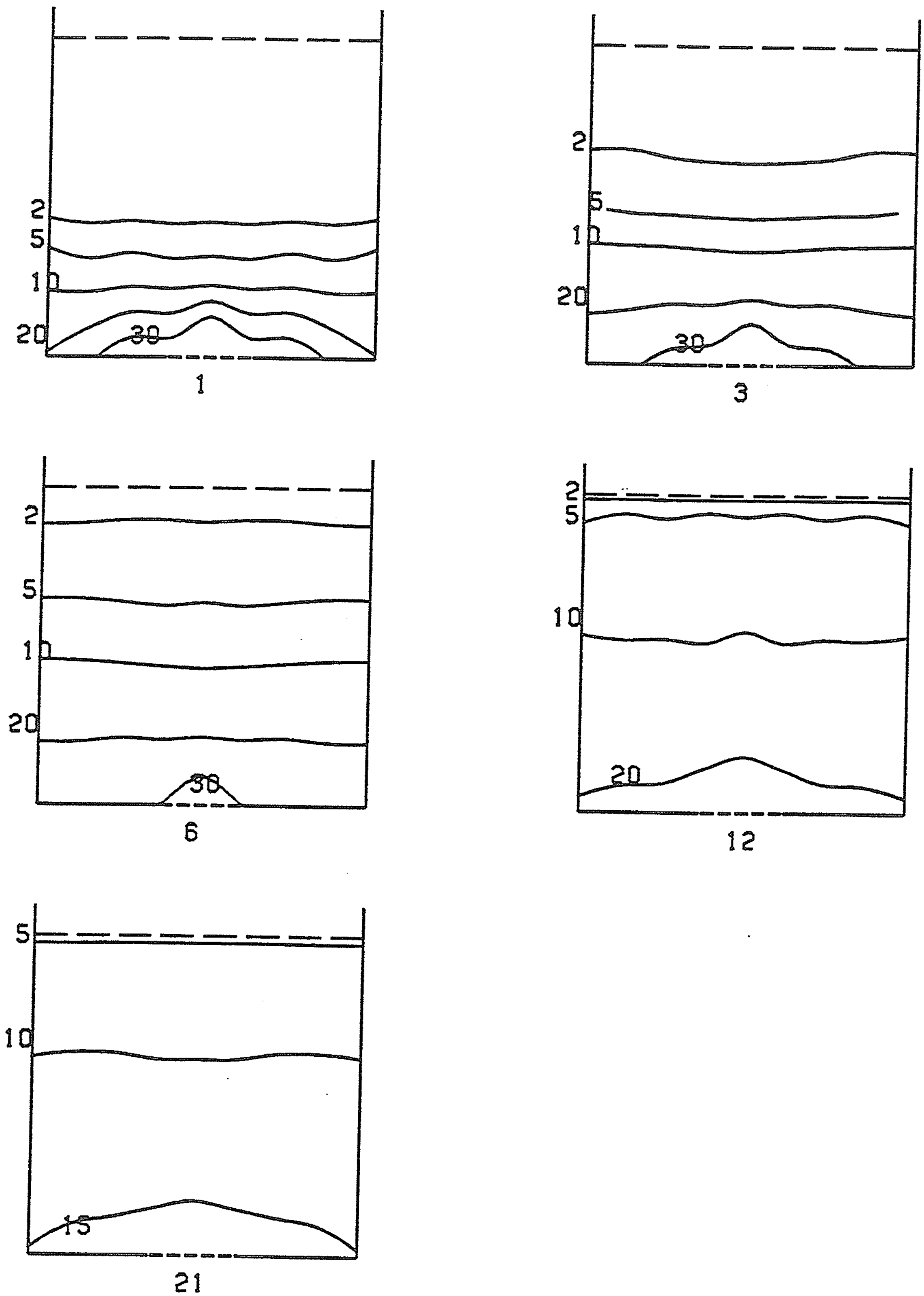

FIG.B.13. BIN 2. COVERED TOP SURFACE. 370 G DRY ICE (REP.1)
(ALONG SECTION A-A)

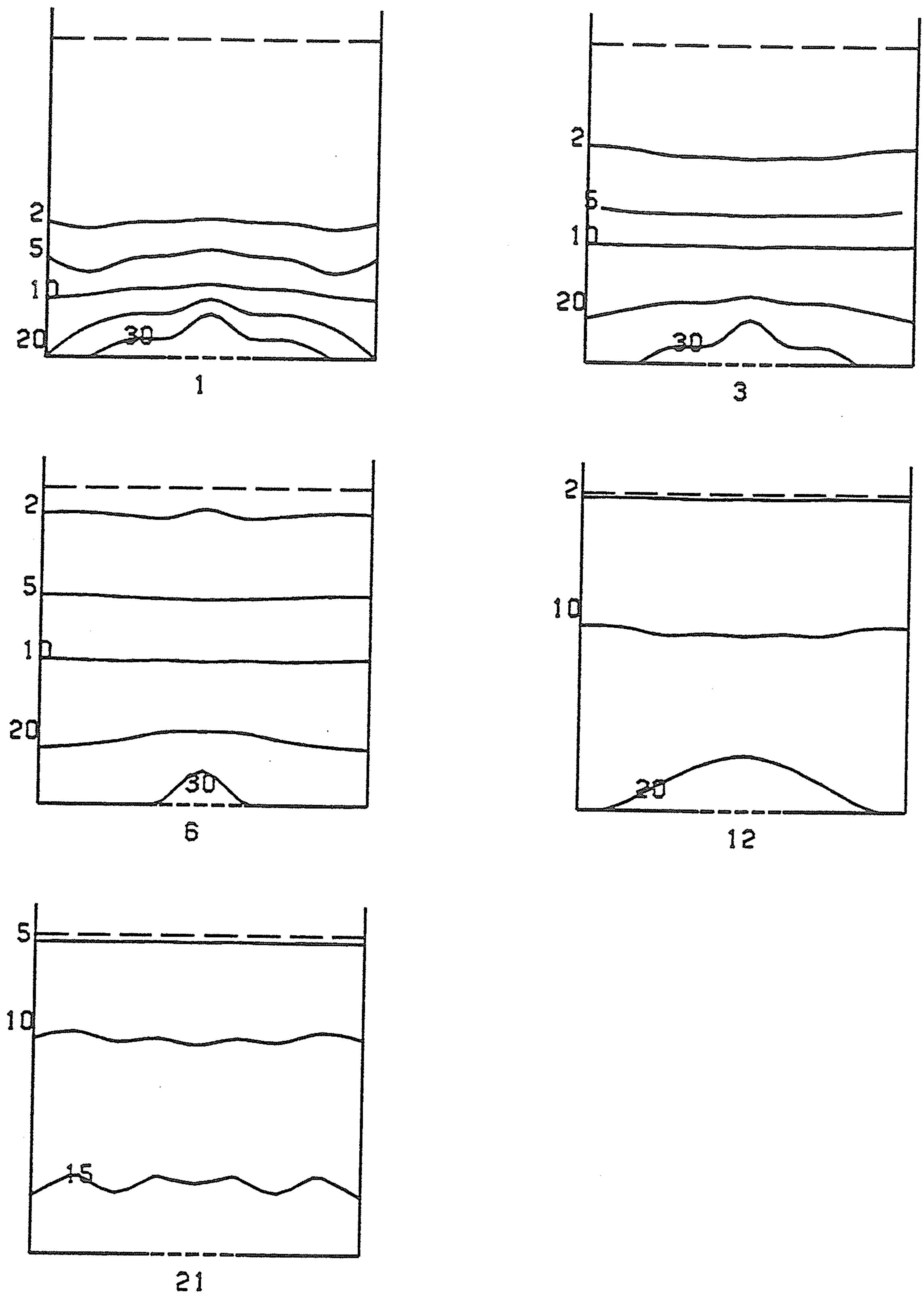

FIG.B.14. BIN 2. COVERED TOP SURFACE. 370 G DRY ICE (REP.2) (ALONG SECTION A-A)

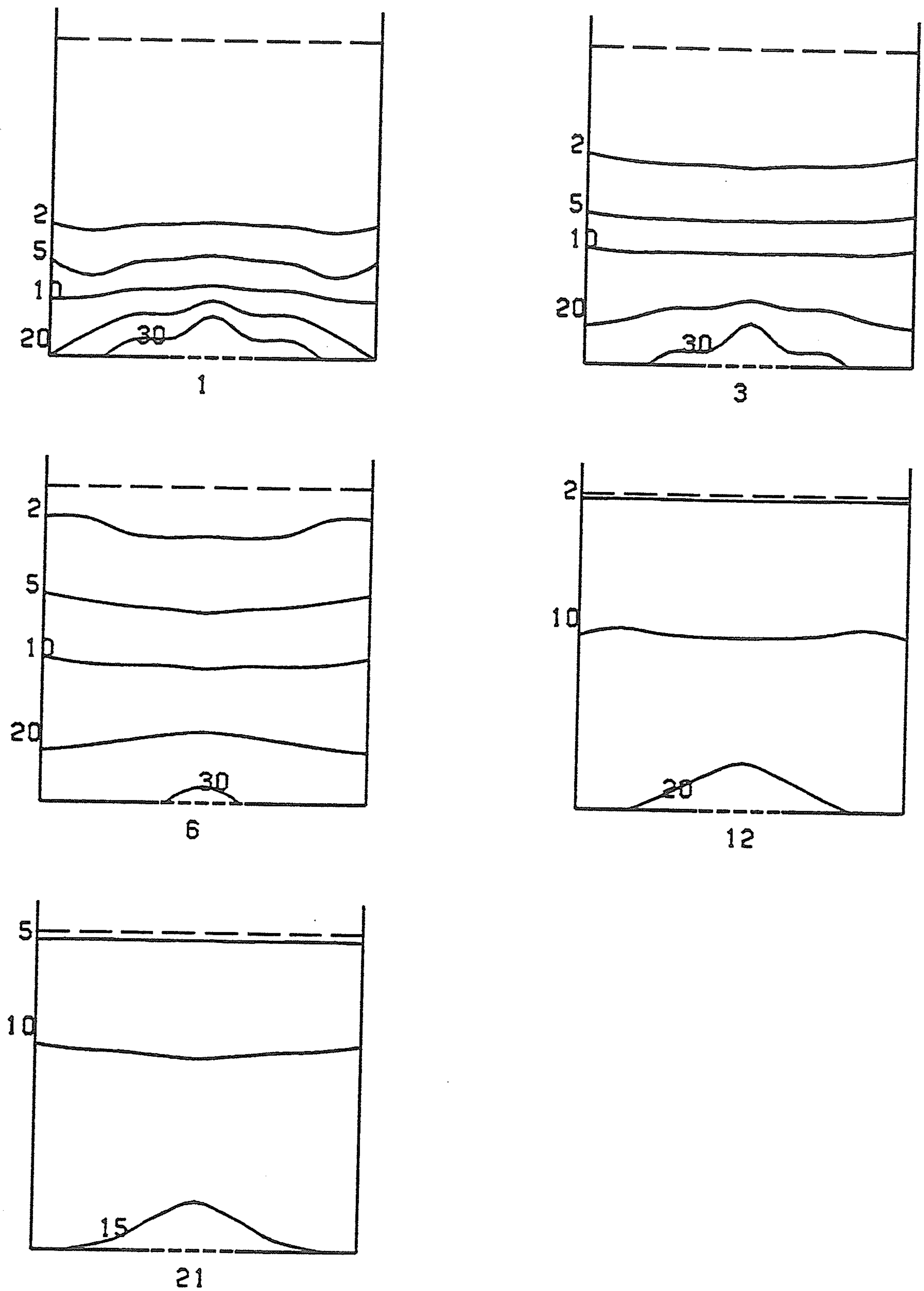

FIG.B.15. BIN 2. COVERED TOP SURFACE. 370 G DRY ICE (REP.3)
(ALONG SECTION A-A)

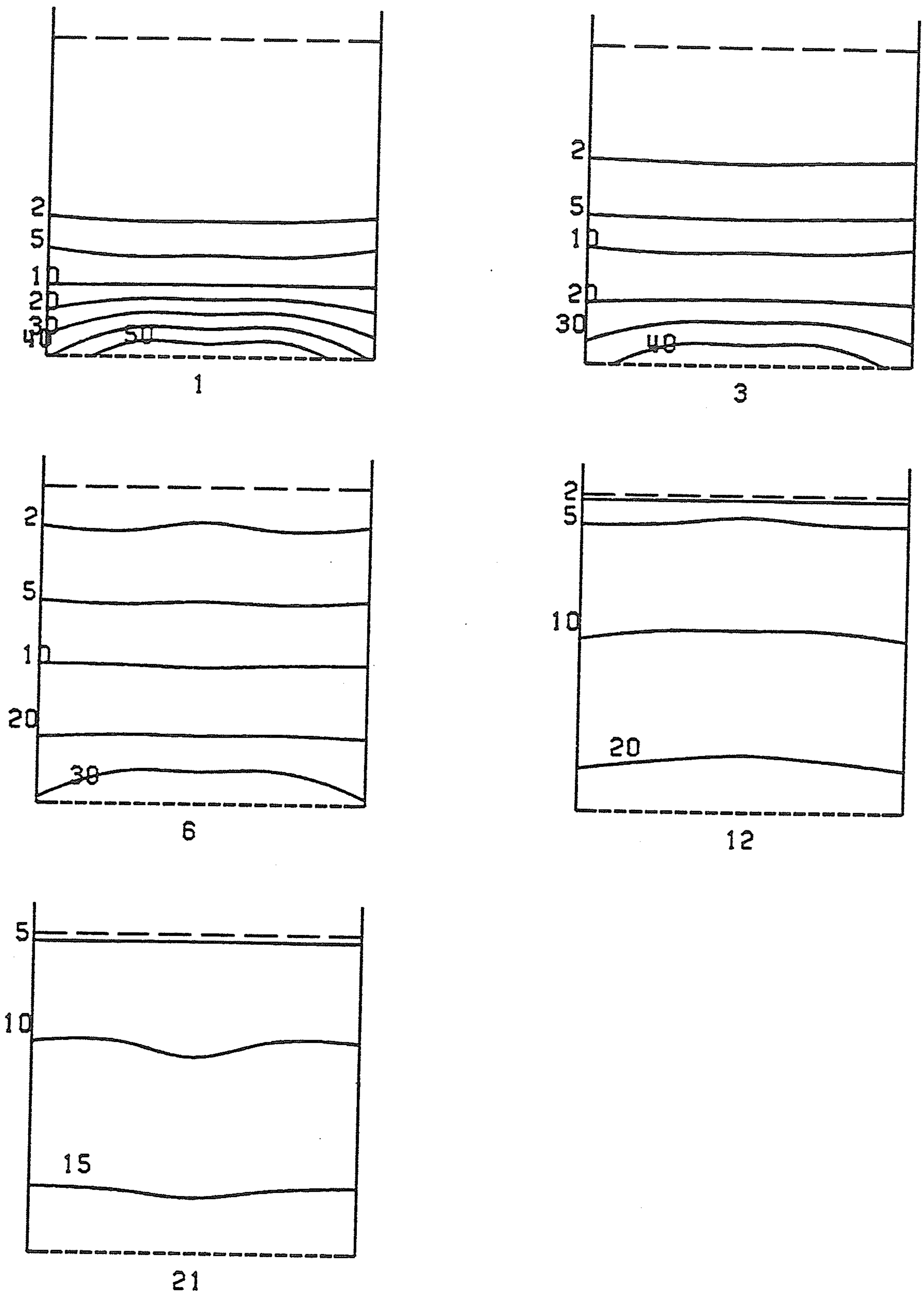

FIG.B.16. BIN 2. COVERED TOP SURFACE. 370 G DRY ICE (REP.1)
(ALONG SECTION B-B)

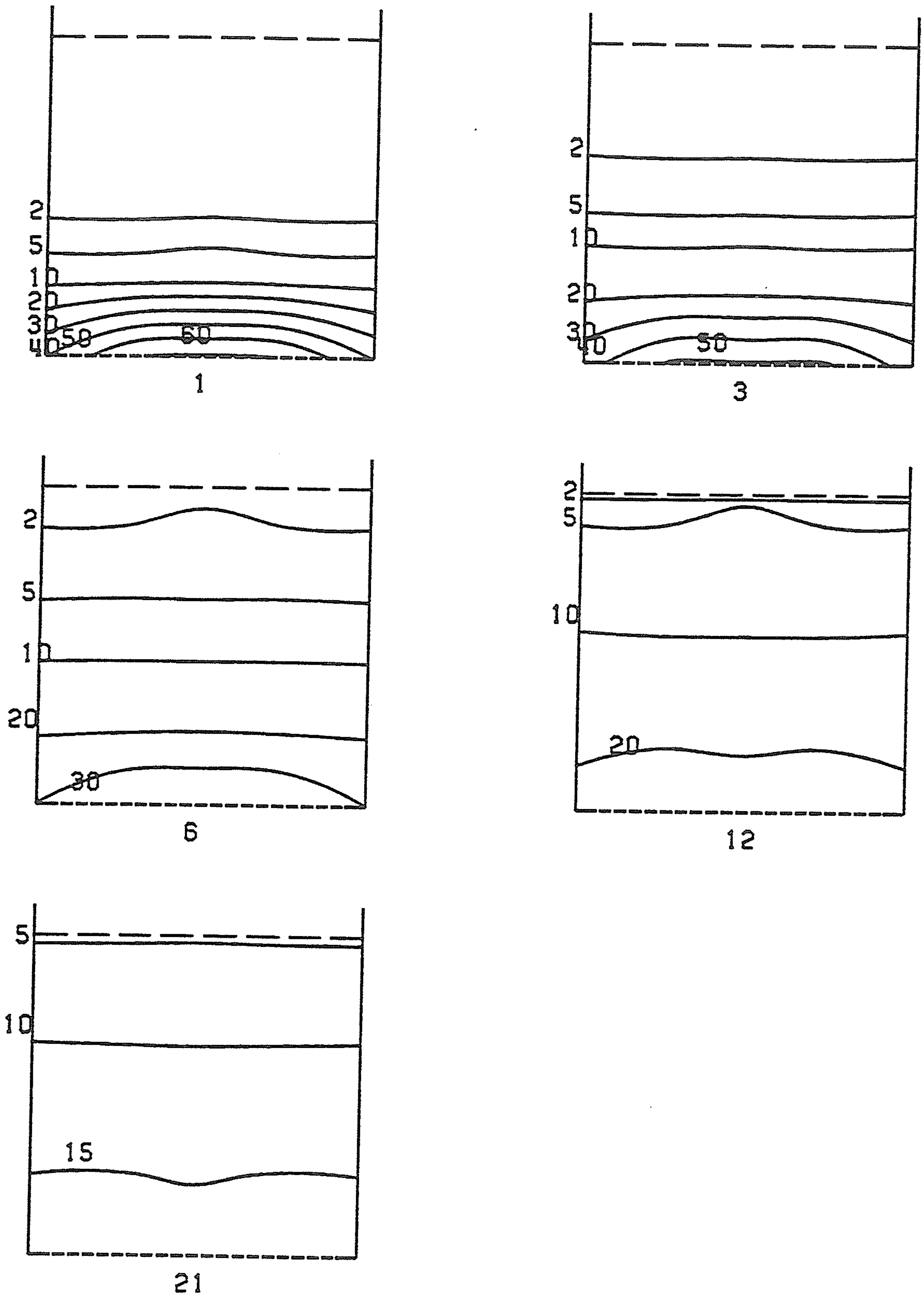

FIG.B.17. BIN 2. COVERED TOP SURFACE. 370 G DRY ICE (REP.2)
(ALONG SECTION B-B)

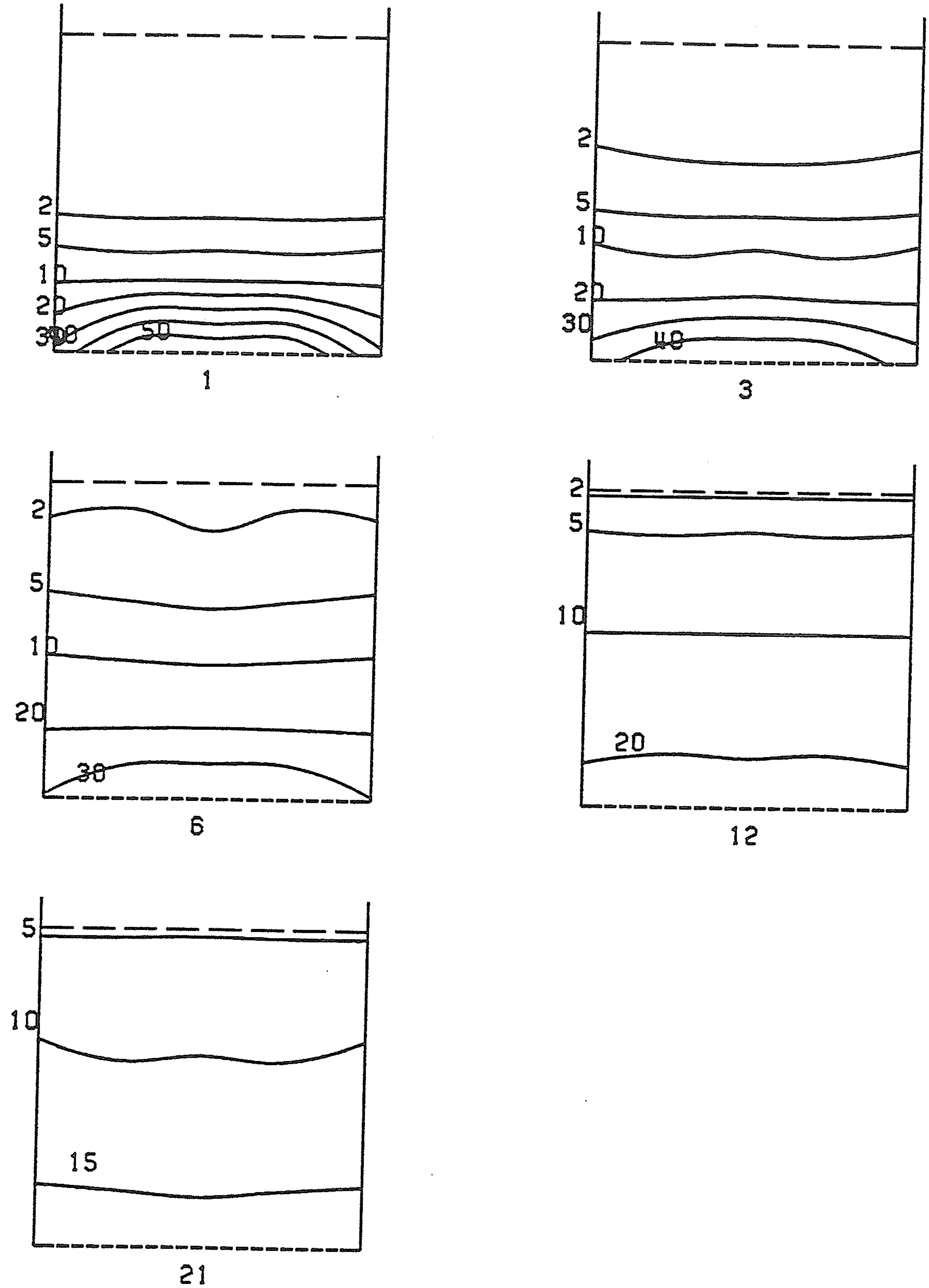

FIG.B.18. BIN 2. COVERED TOP SURFACE. 370 G DRY ICE (REP.3)
(ALONG SECTION B-B)

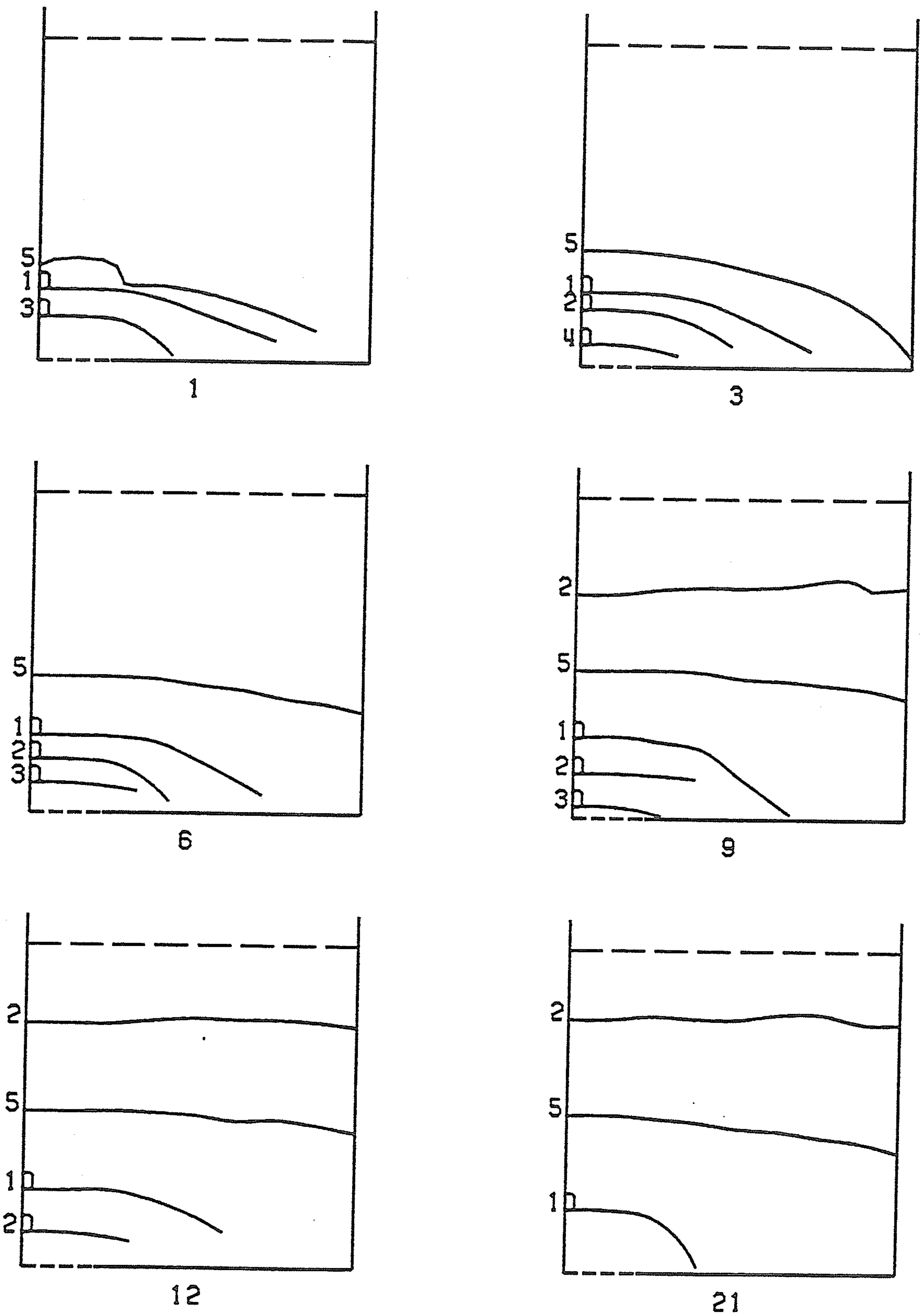

FIG.B.19. BIN 3. OPEN TOP SURFACE. 180 G DRY ICE (REP.1)
(ALONG SECTION A-A)

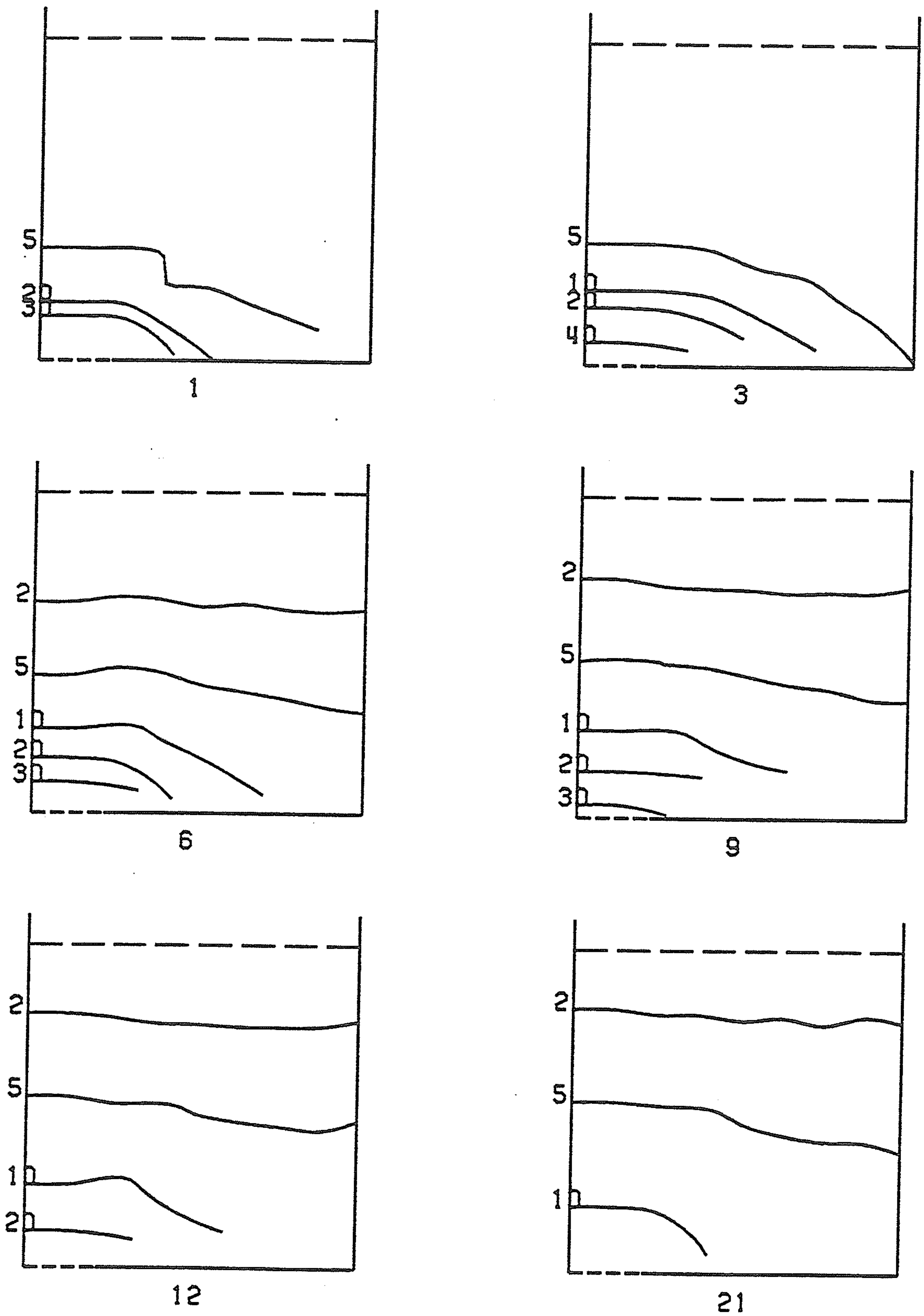

FIG.B.20. BIN 3. OPEN TOP SURFACE. 180·G DRY ICE (REP.2)
(ALONG SECTION A-A)

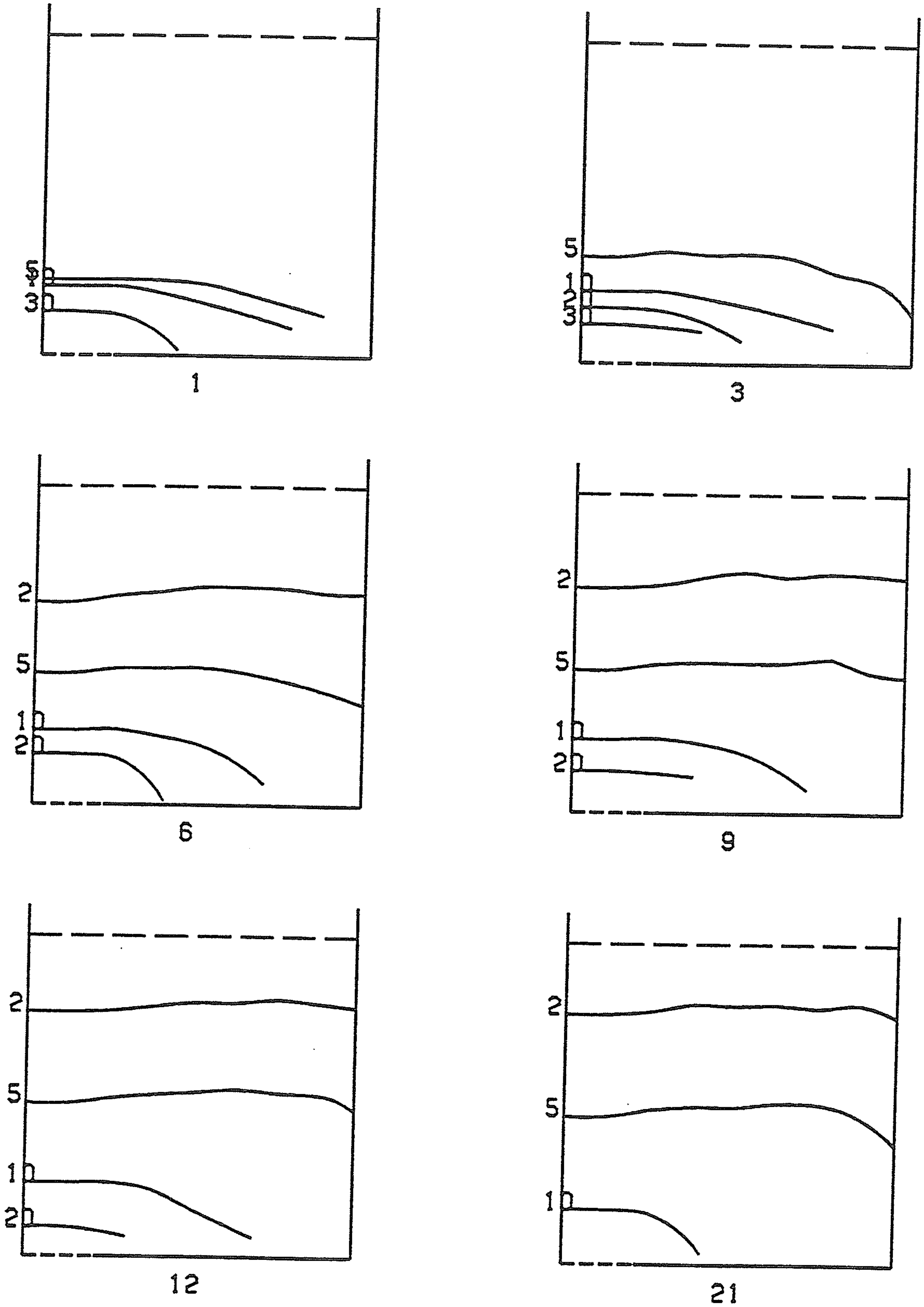

FIG.B.21. BIN 3. OPEN TOP SURFACE. 180 G DRY ICE (REP.3) (ALONG SECTION A-A)

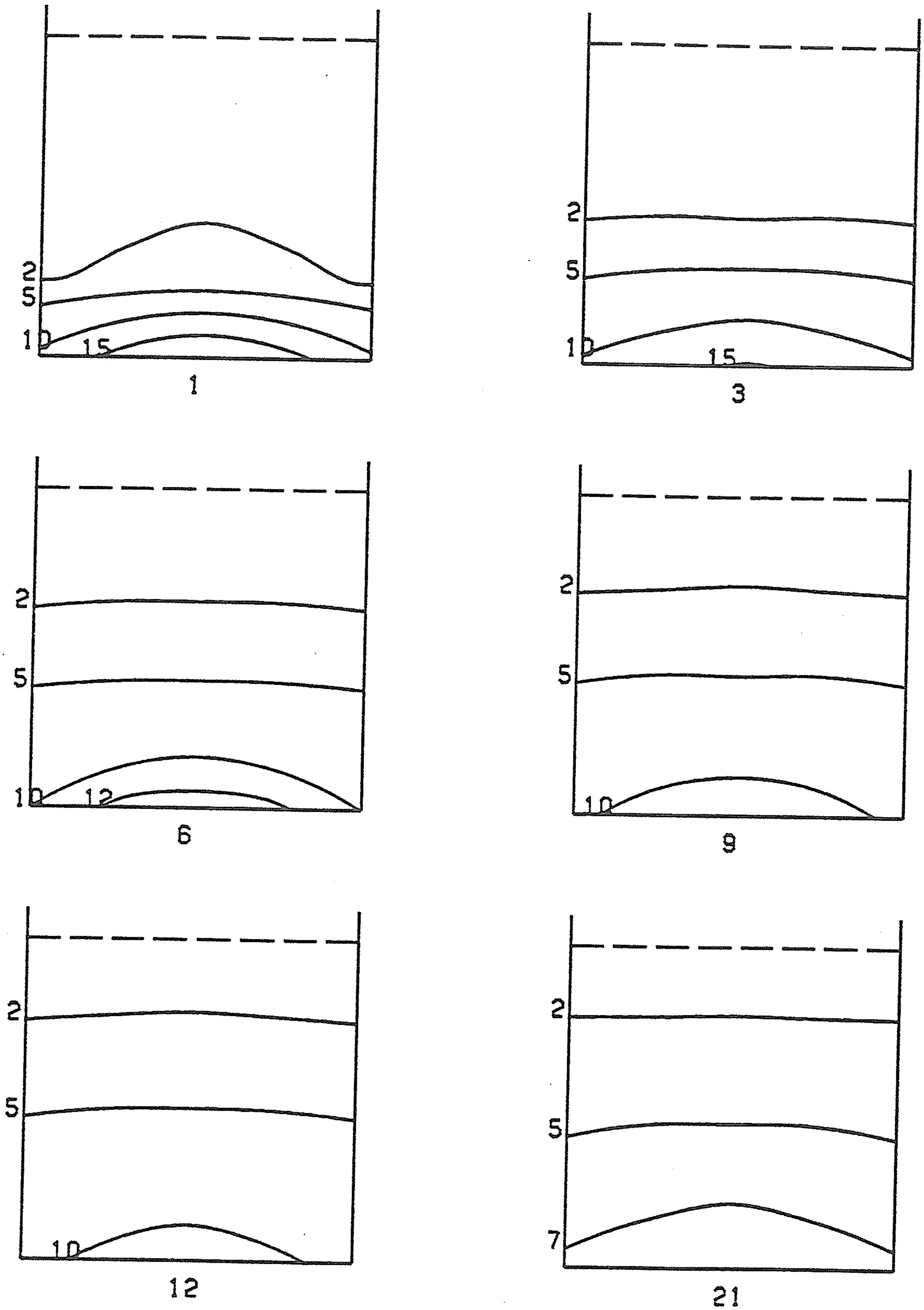

FIG.B.22. BIN 3. OPEN TOP SURFACE. 180 G DRY ICE (REP.1)
(ALONG SECTION B-B)

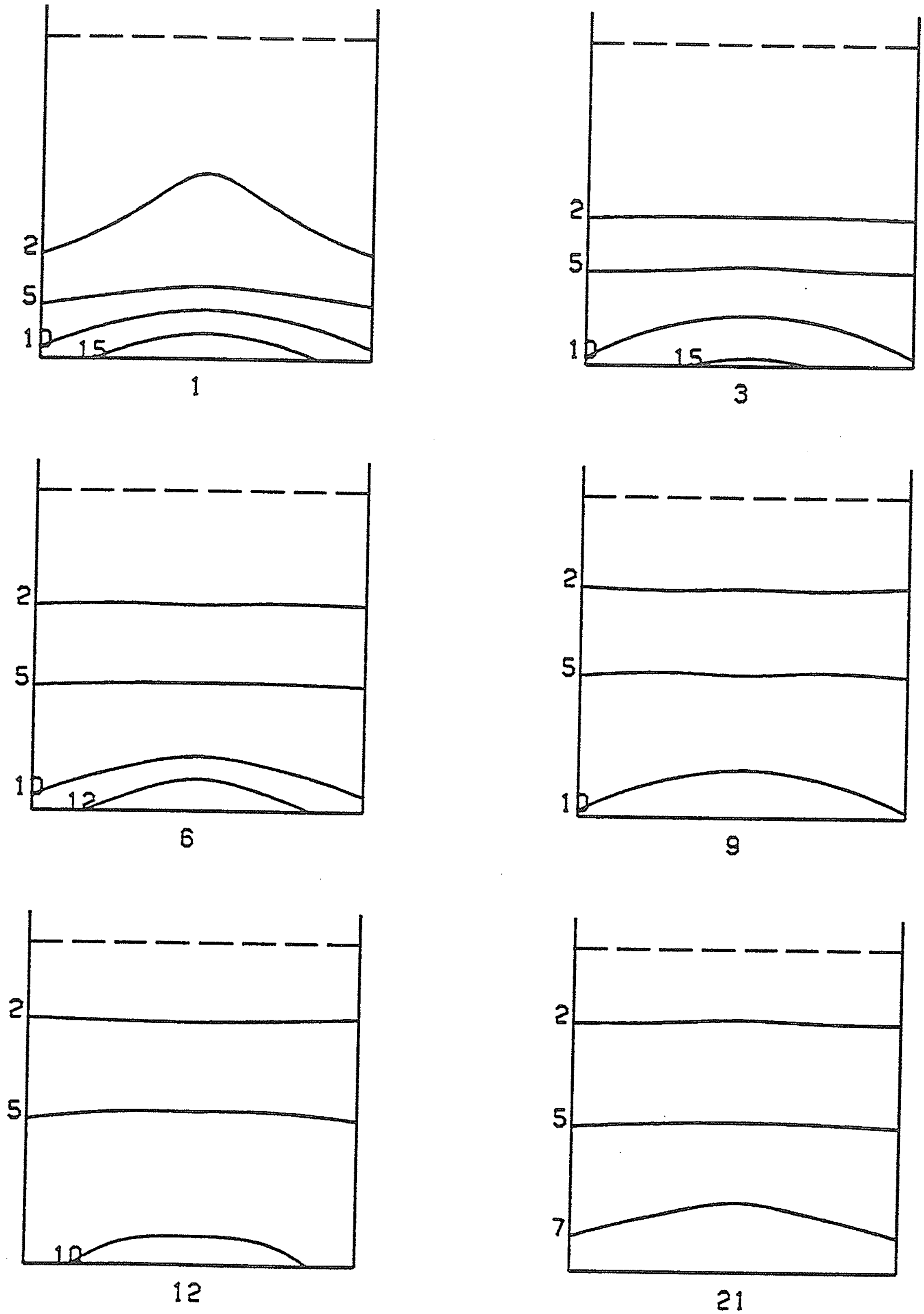

FIG.B.23. BIN 3. OPEN TOP SURFACE. 180 G DRY ICE (REP.2) (ALONG SECTION B-B)

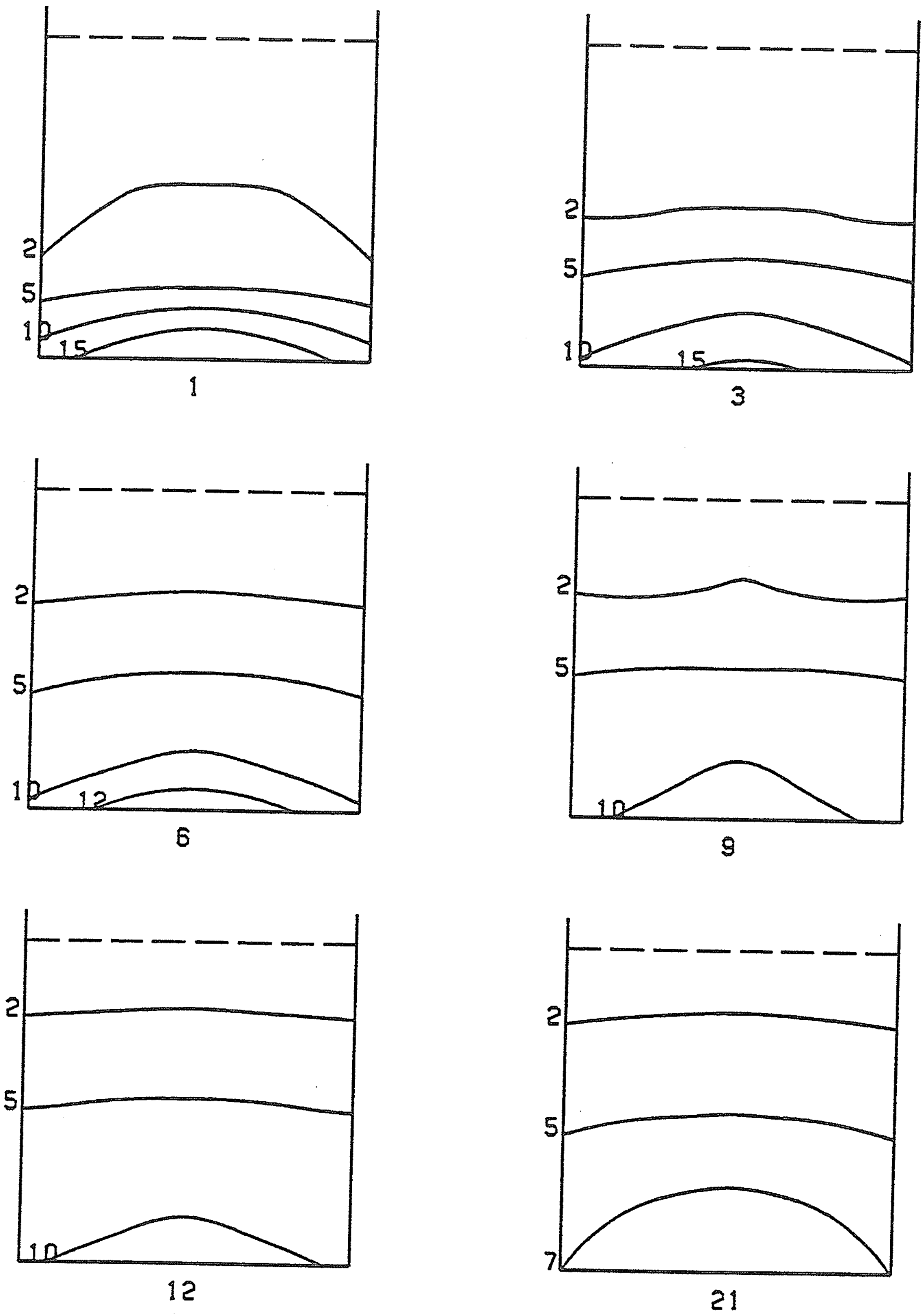

FIG.B.24. BIN 3. OPEN TOP SURFACE. 180 G DRY ICE (REP.3)
(ALONG SECTION B-B)

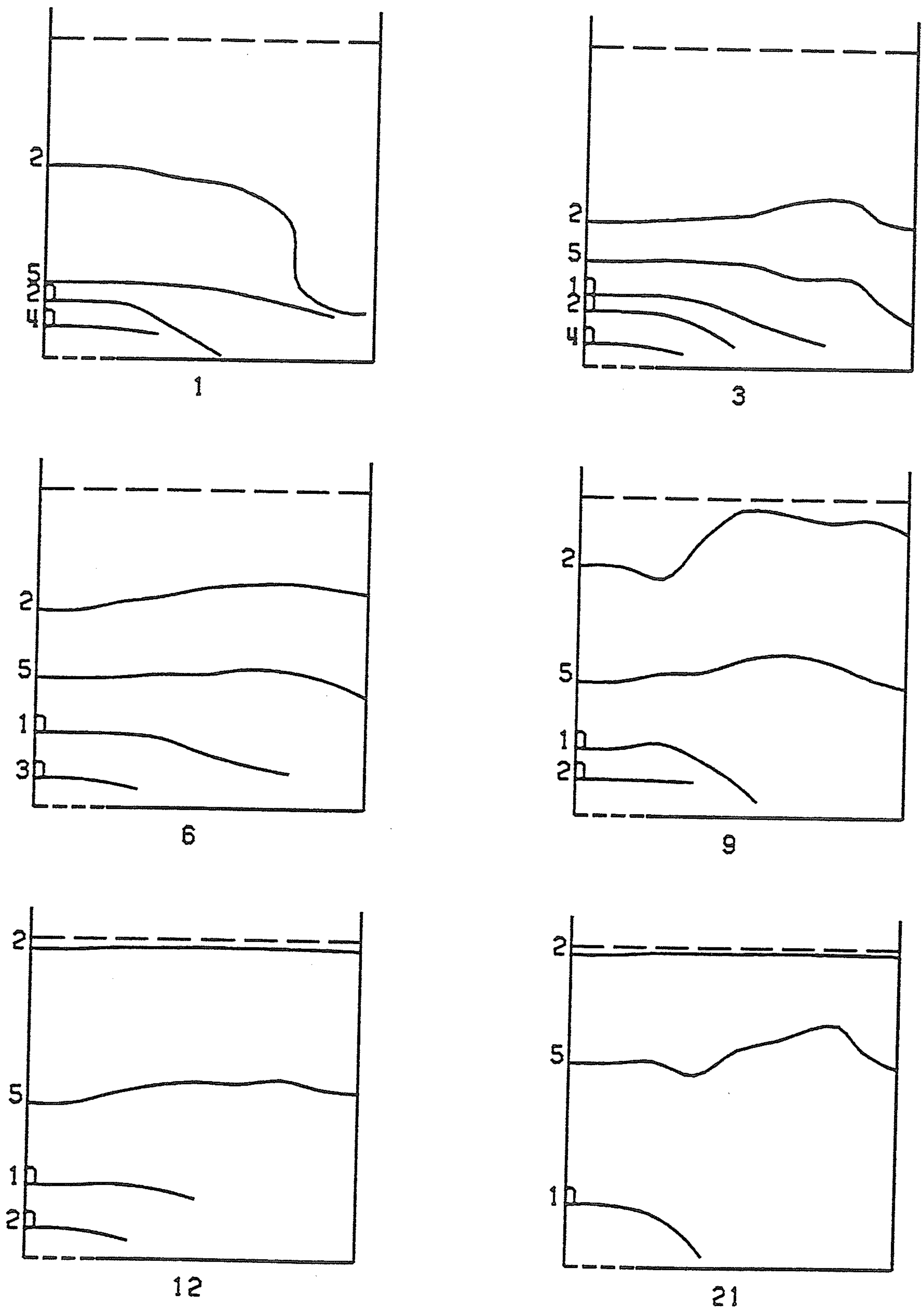

FIG.B.25. BIN 3. COVERED TOP SURFACE. 180 G DRY ICE (REP.1)
(ALONG SECTION A-A)

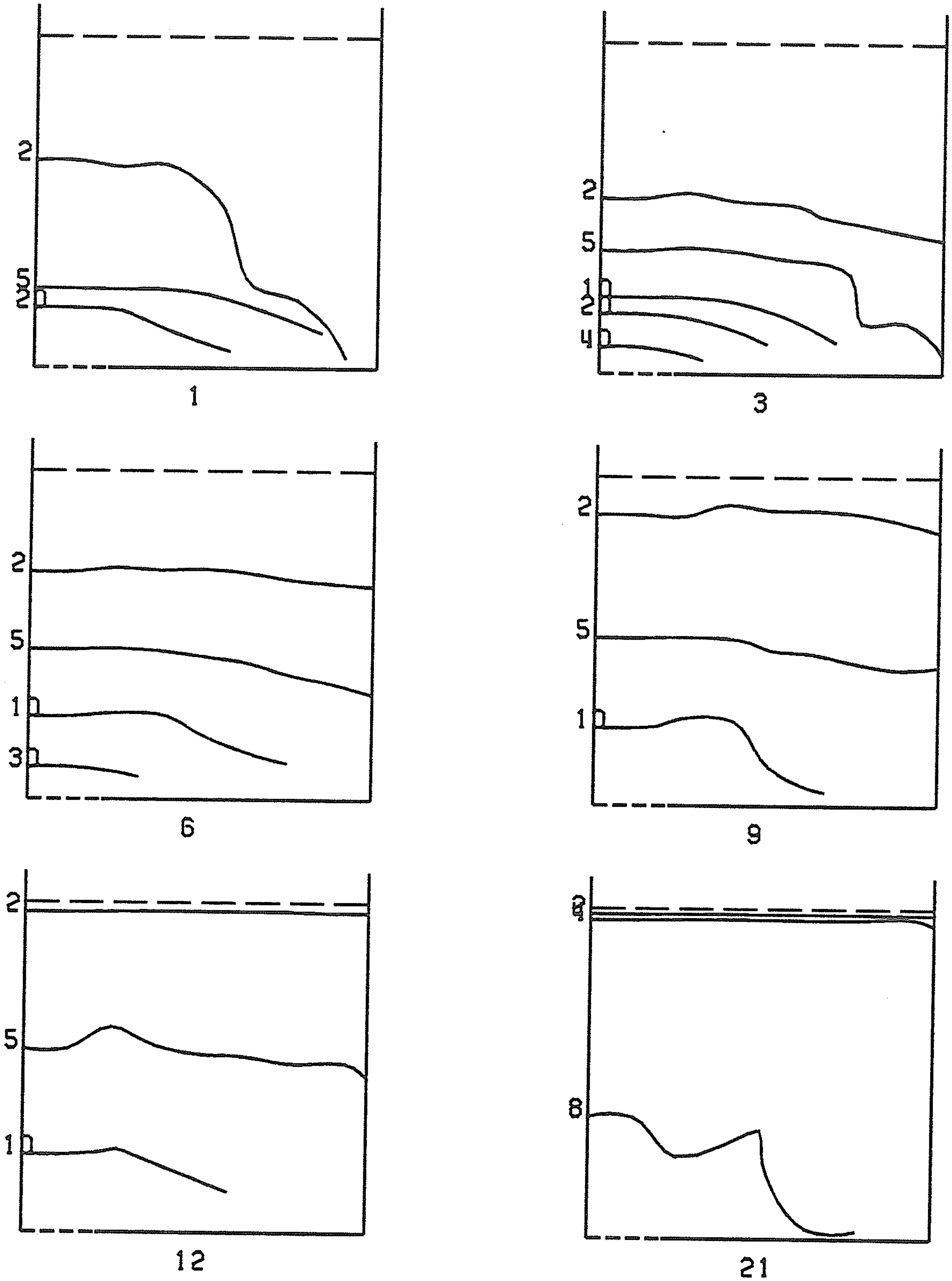

FIG.B.26. BIN 3. COVERED TOP SURFACE. 180 G DRY ICE (REP.2)
(ALONG SECTION A-A)

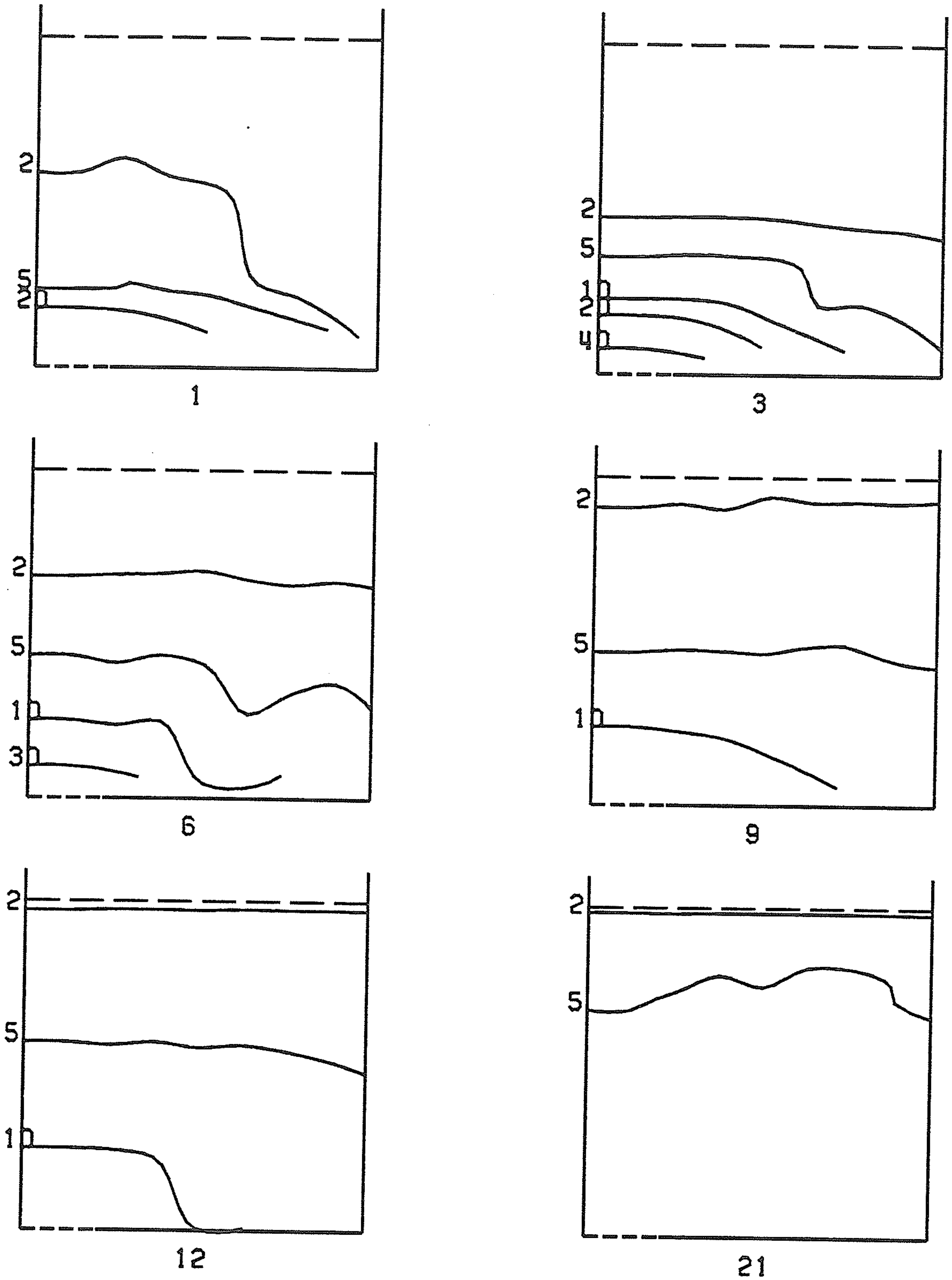

FIG.B.27. BIN 3. COVERED TOP SURFACE. 180 G DRY ICE (REP.3)
(ALONG SECTION A-A)

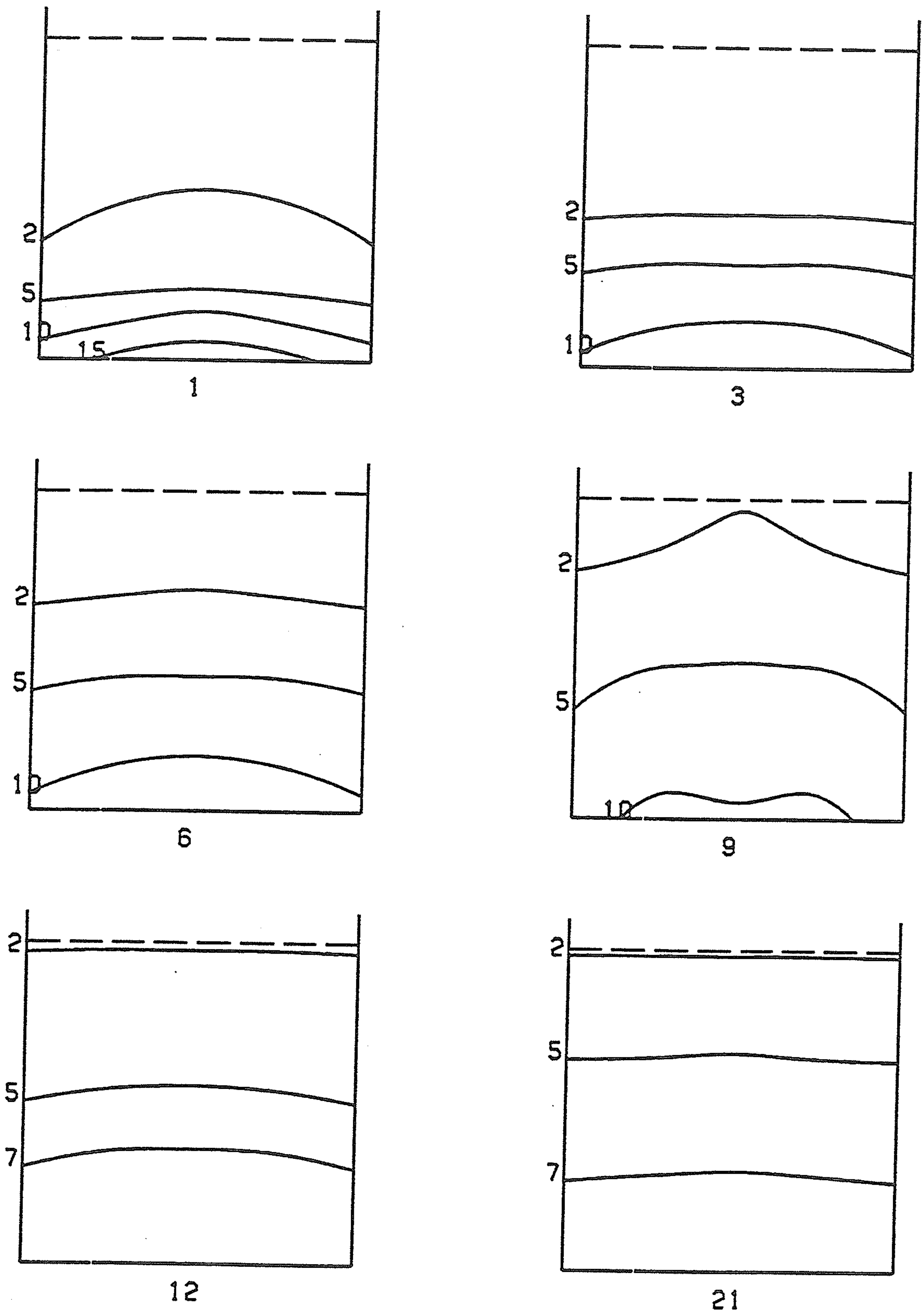

FIG.B.28. BIN 3. COVERED TOP SURFACE. 180 G DRY ICE (REP.1)
(ALONG SECTION B-B)

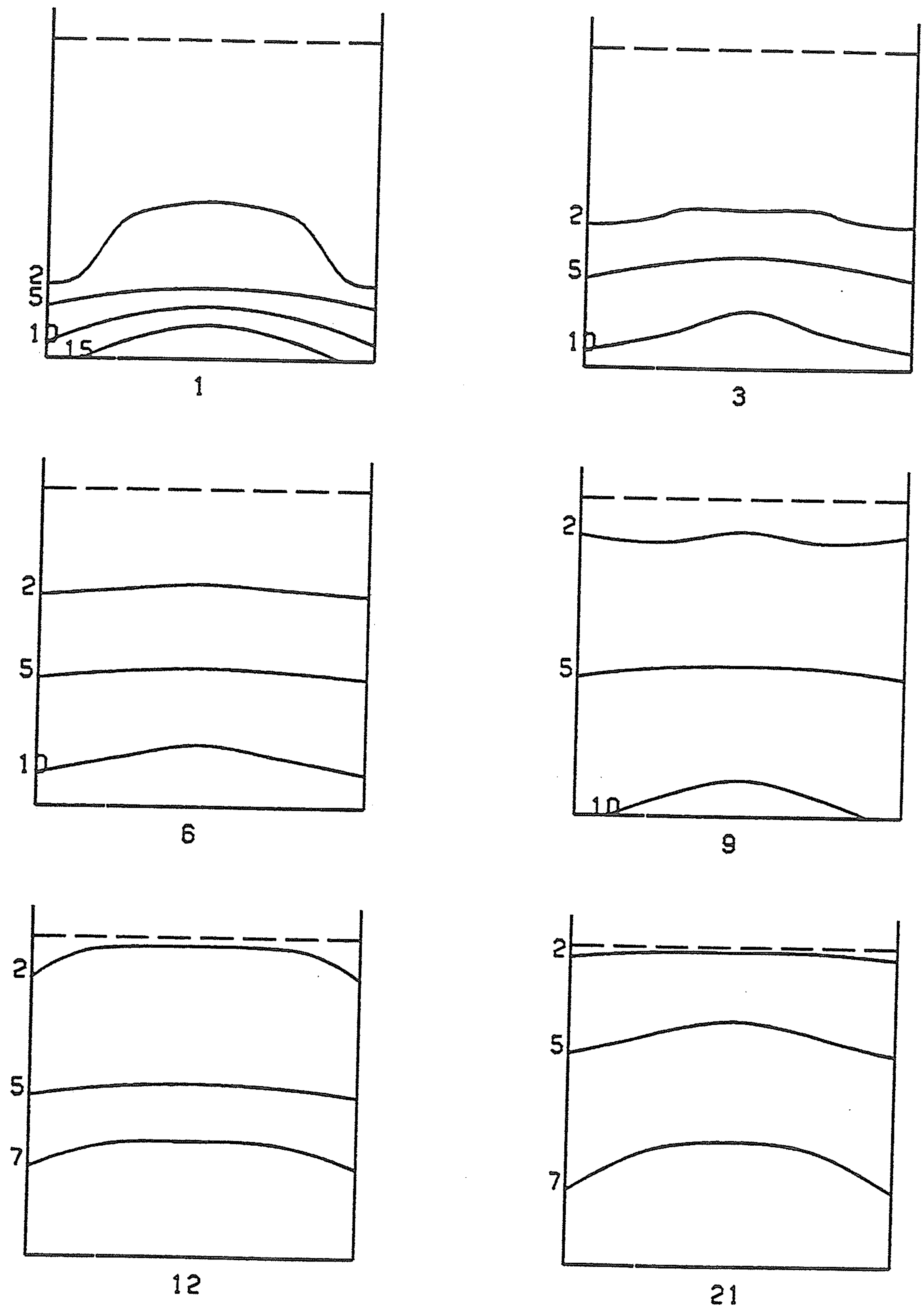

FIG.B.29. BIN 3. COVERED TOP SURFACE. 180 G DRY ICE (REP.2)
(ALONG SECTION B-B)

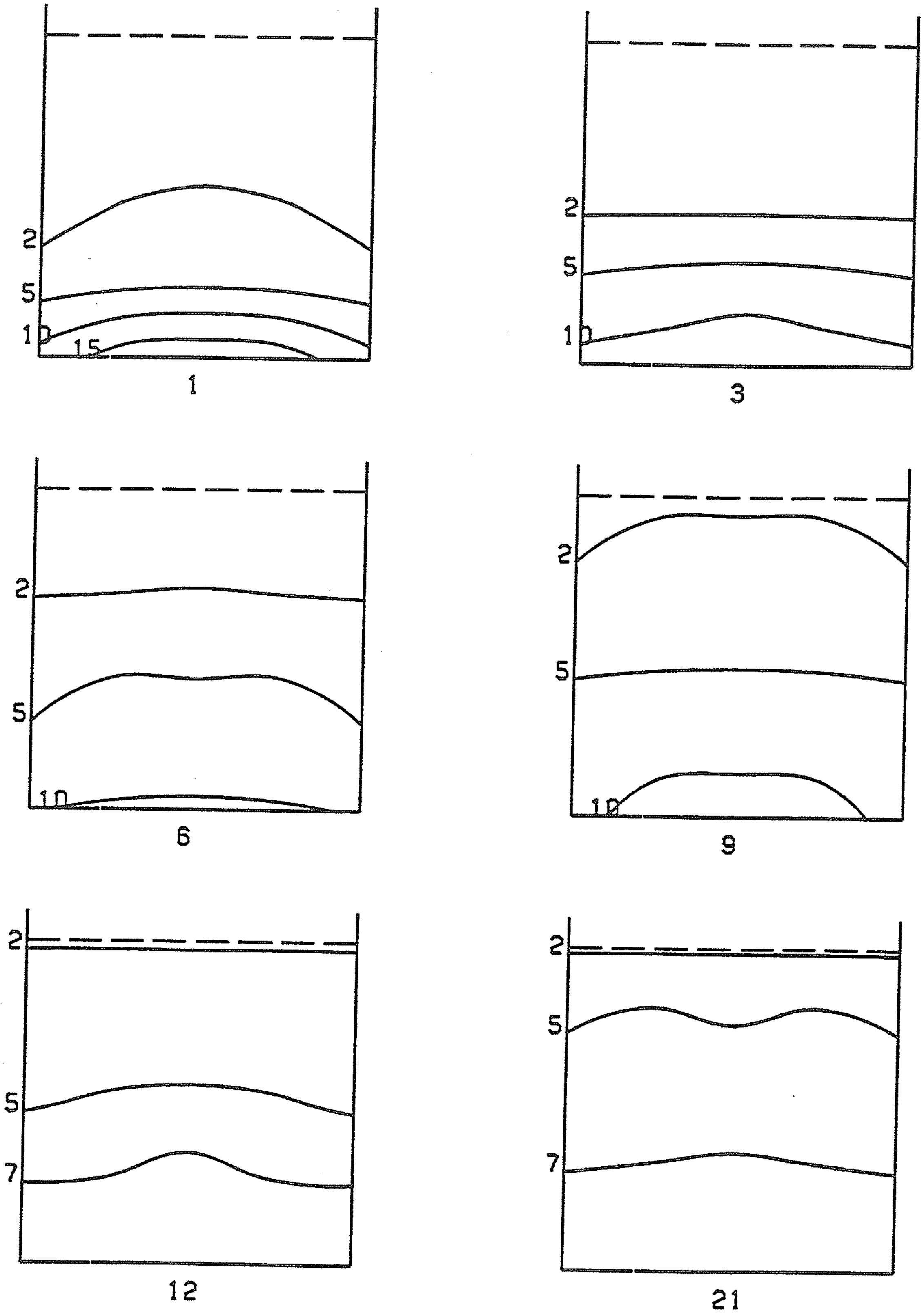

FIG.B.30. BIN 3. COVERED TOP SURFACE. 180 G DRY ICE (REP.3)
(ALONG SECTION B-B)

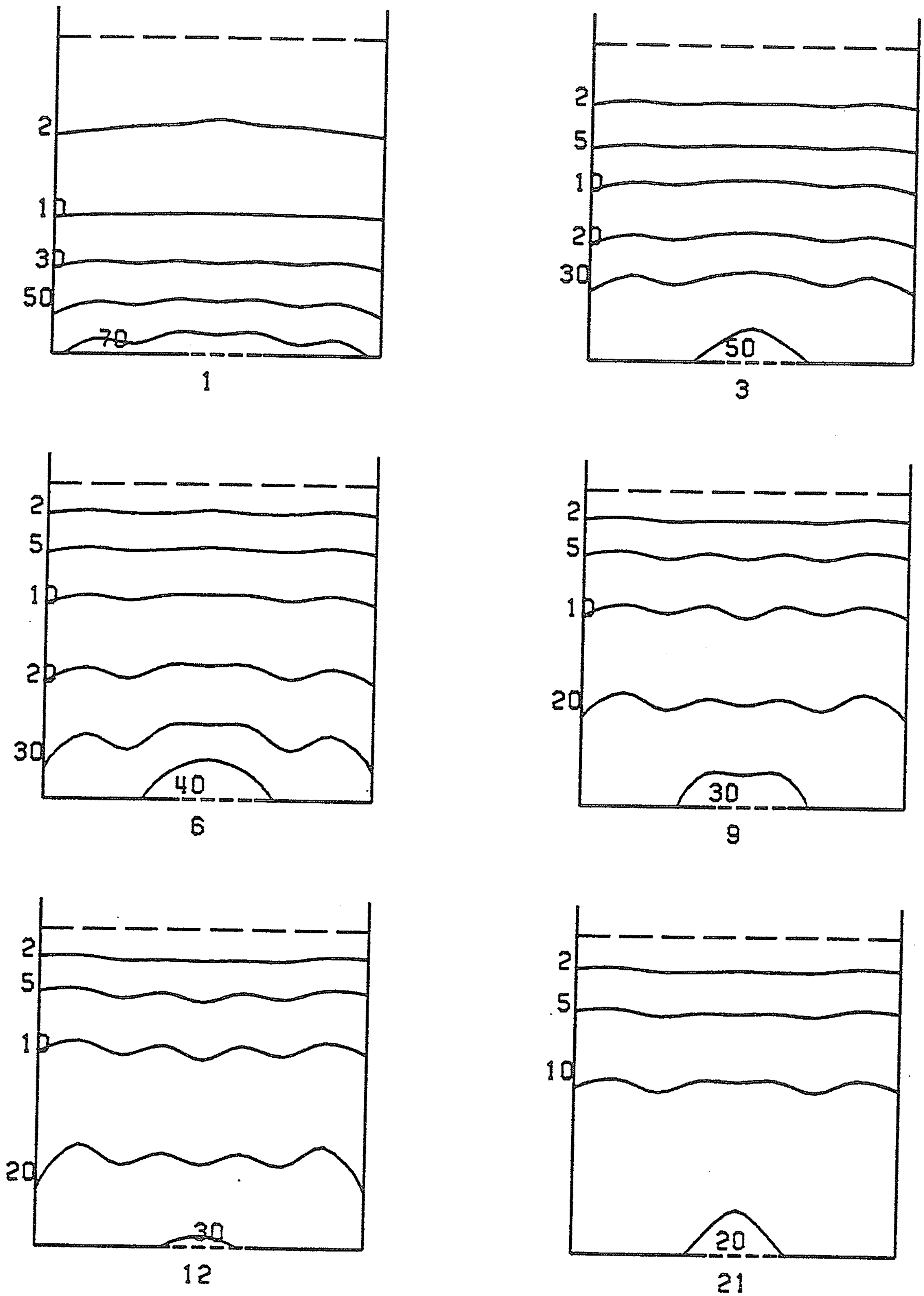

FIG.B.31. BIN 1. OPEN TOP SURFACE. 540 G DRY ICE (REP.1)

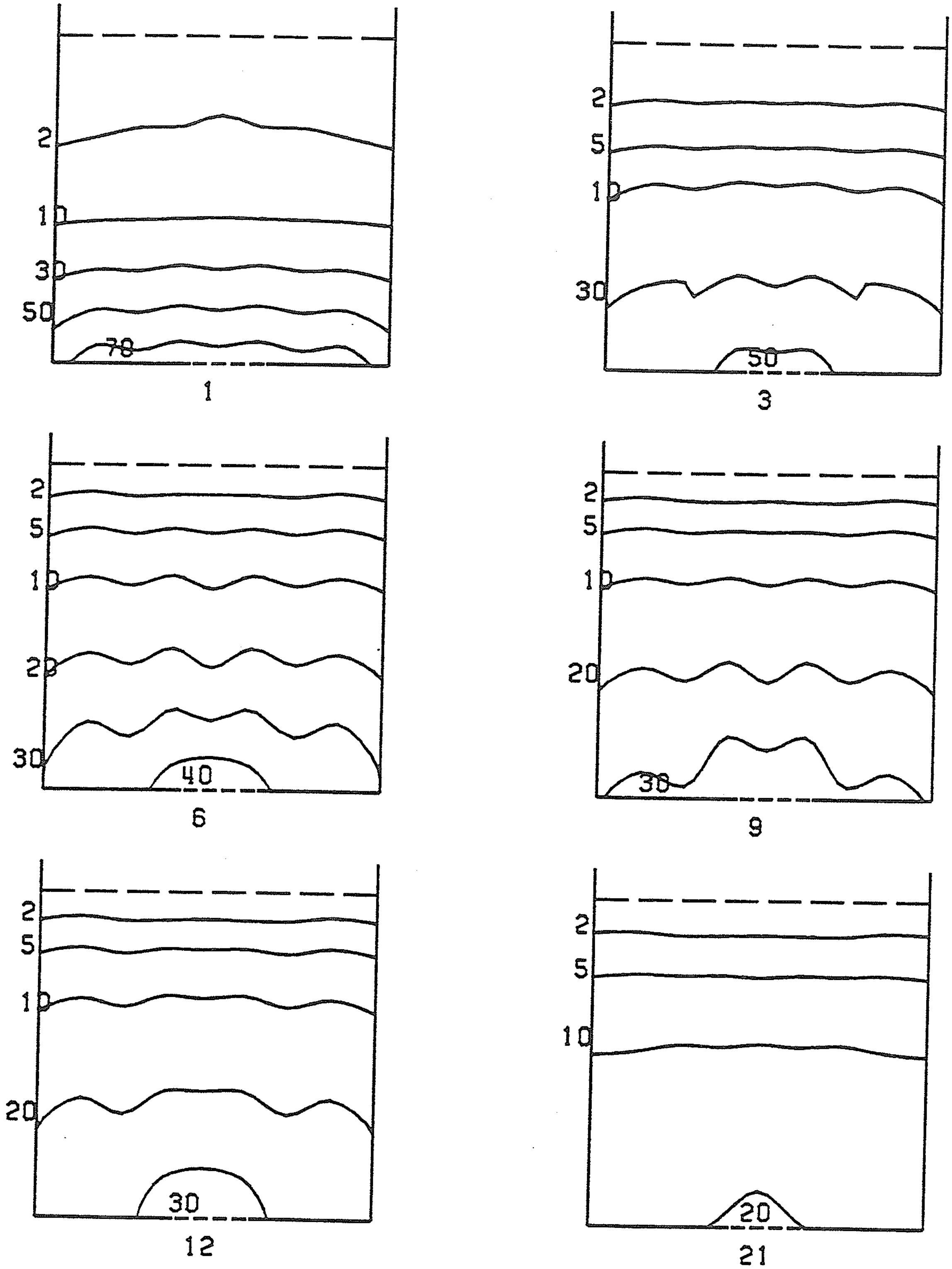

FIG.B.32. BIN 1. OPEN TOP SURFACE. 540 G DRY ICE (REP.2)

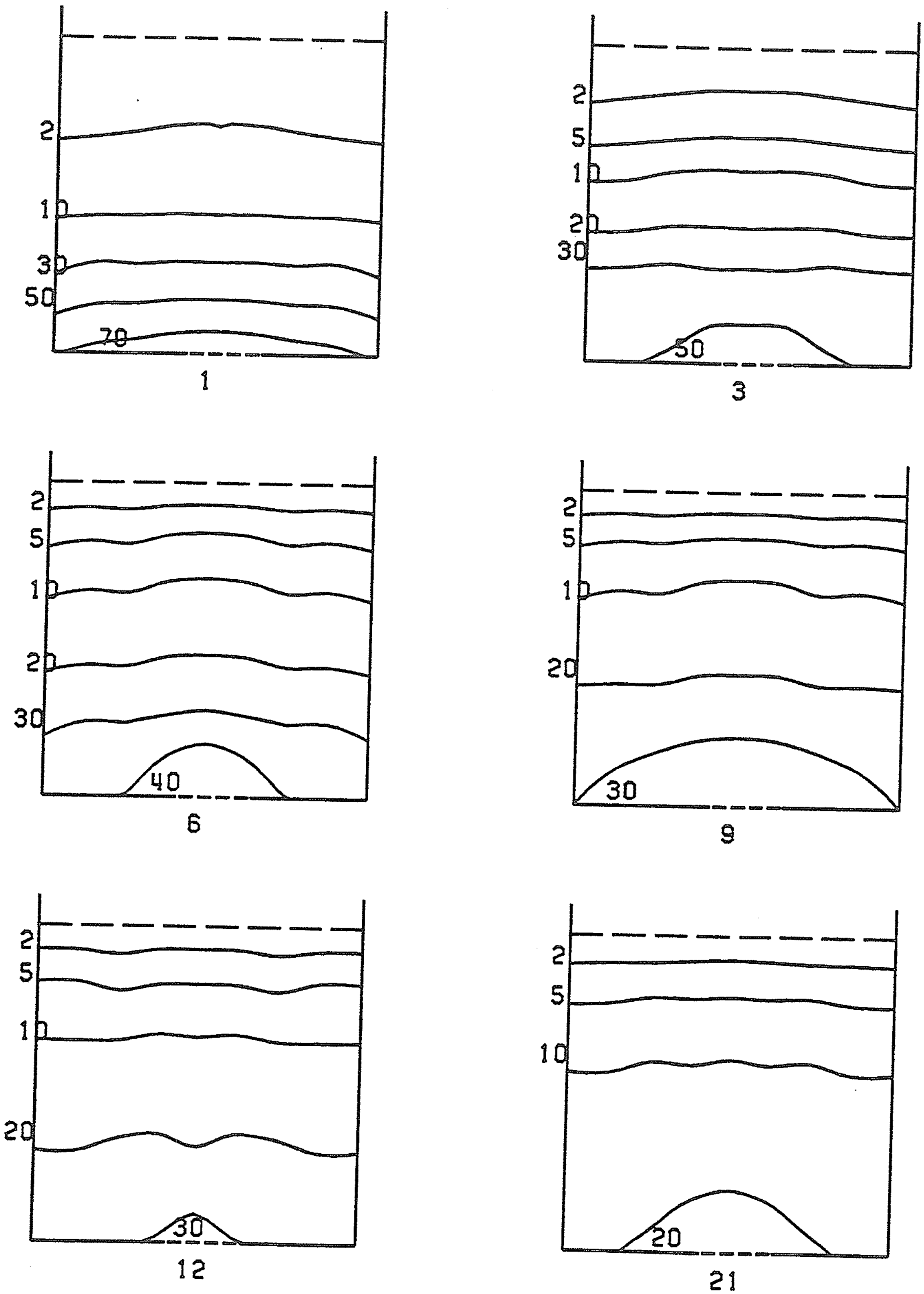

FIG.B.33. BIN 1. OPEN TOP SURFACE. 540 G DRY ICE (REP.3)

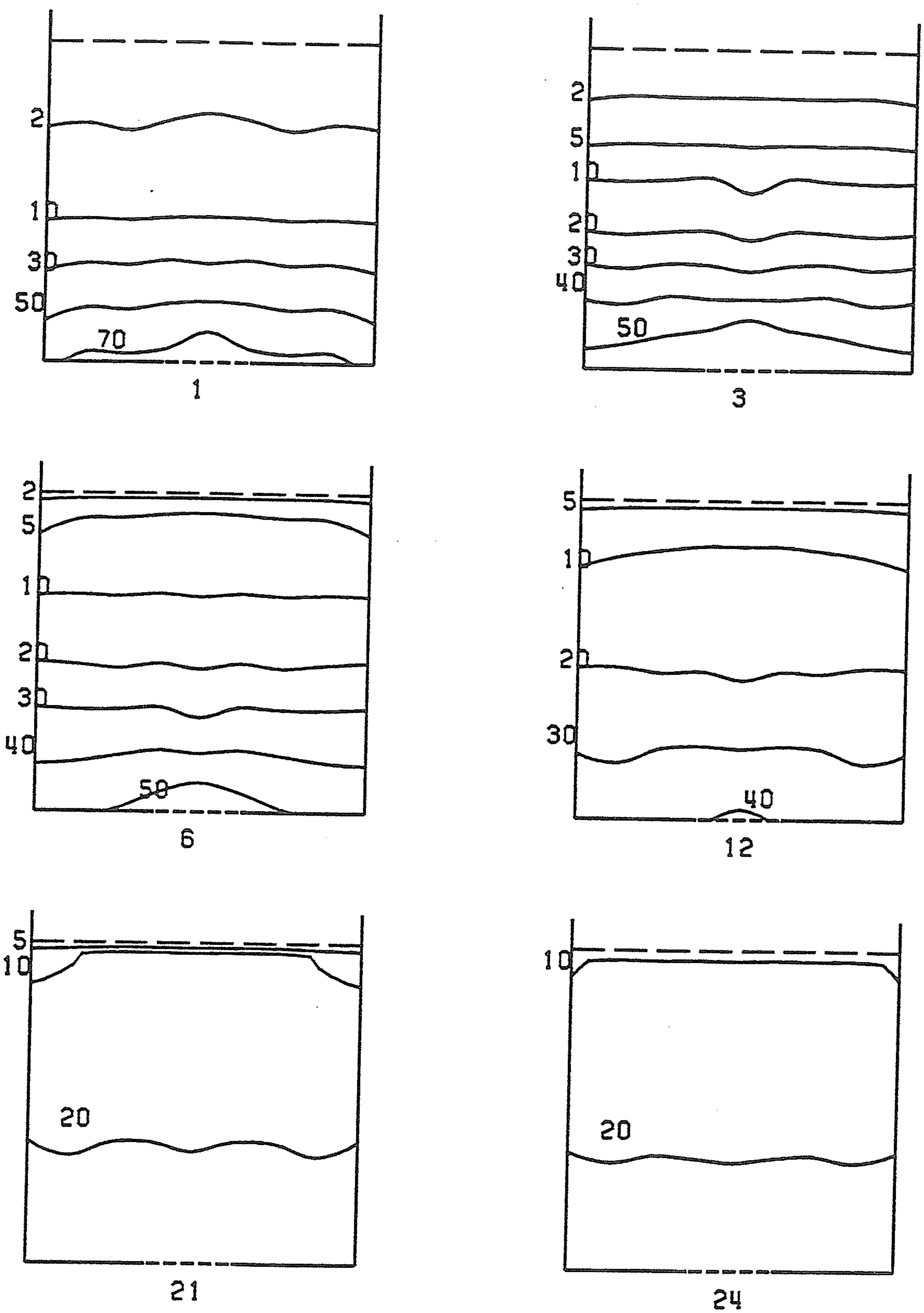

FIG.B.34. BIN 2. COVERED TOP SURFACE. 740 G DRY ICE (REP.1)
(ALONG SECTION A-A)

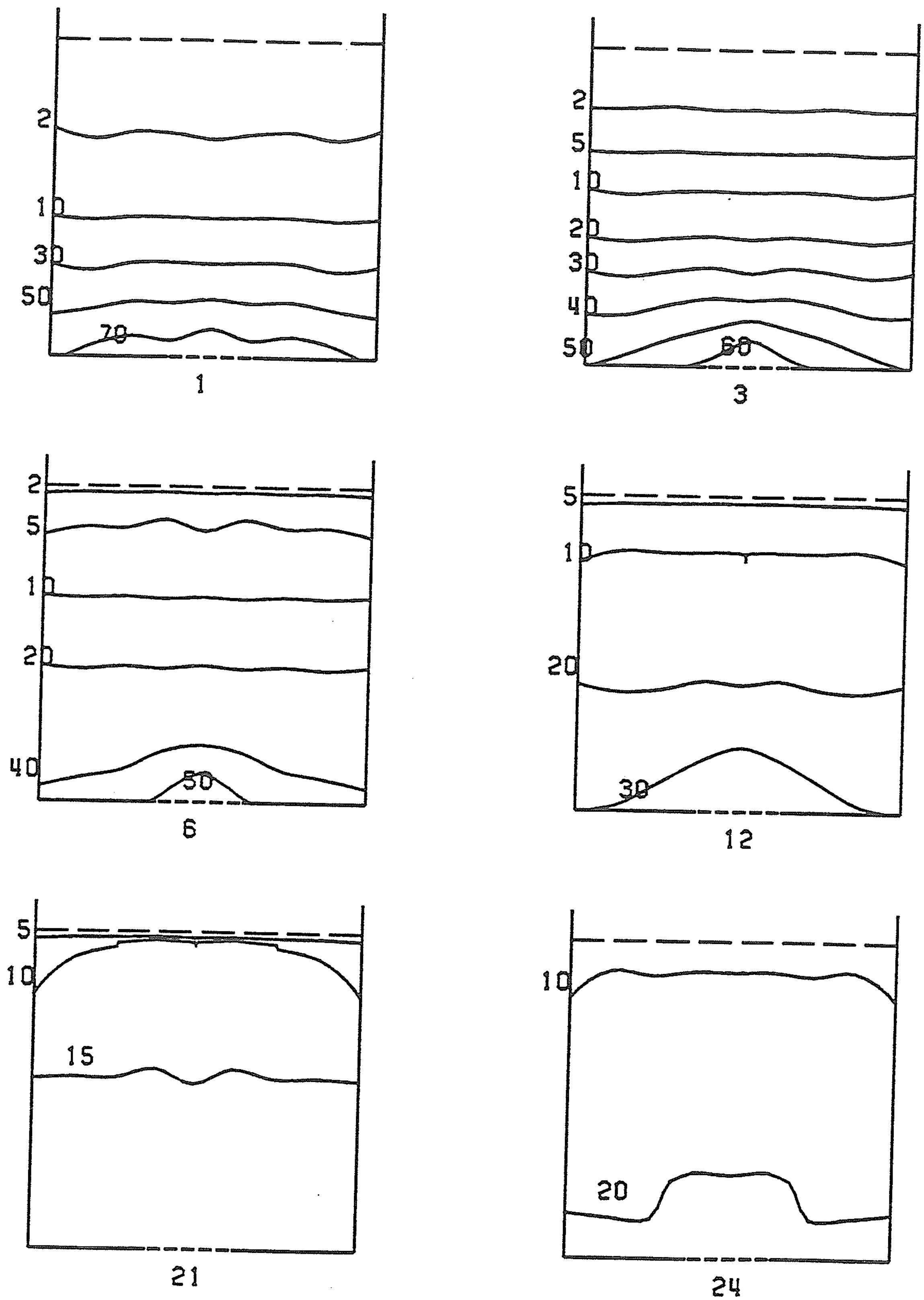

FIG.B.35. BIN 2. COVERED TOP SURFACE. 740 G DRY ICE (REP.2)
(ALONG SECTION A-A)

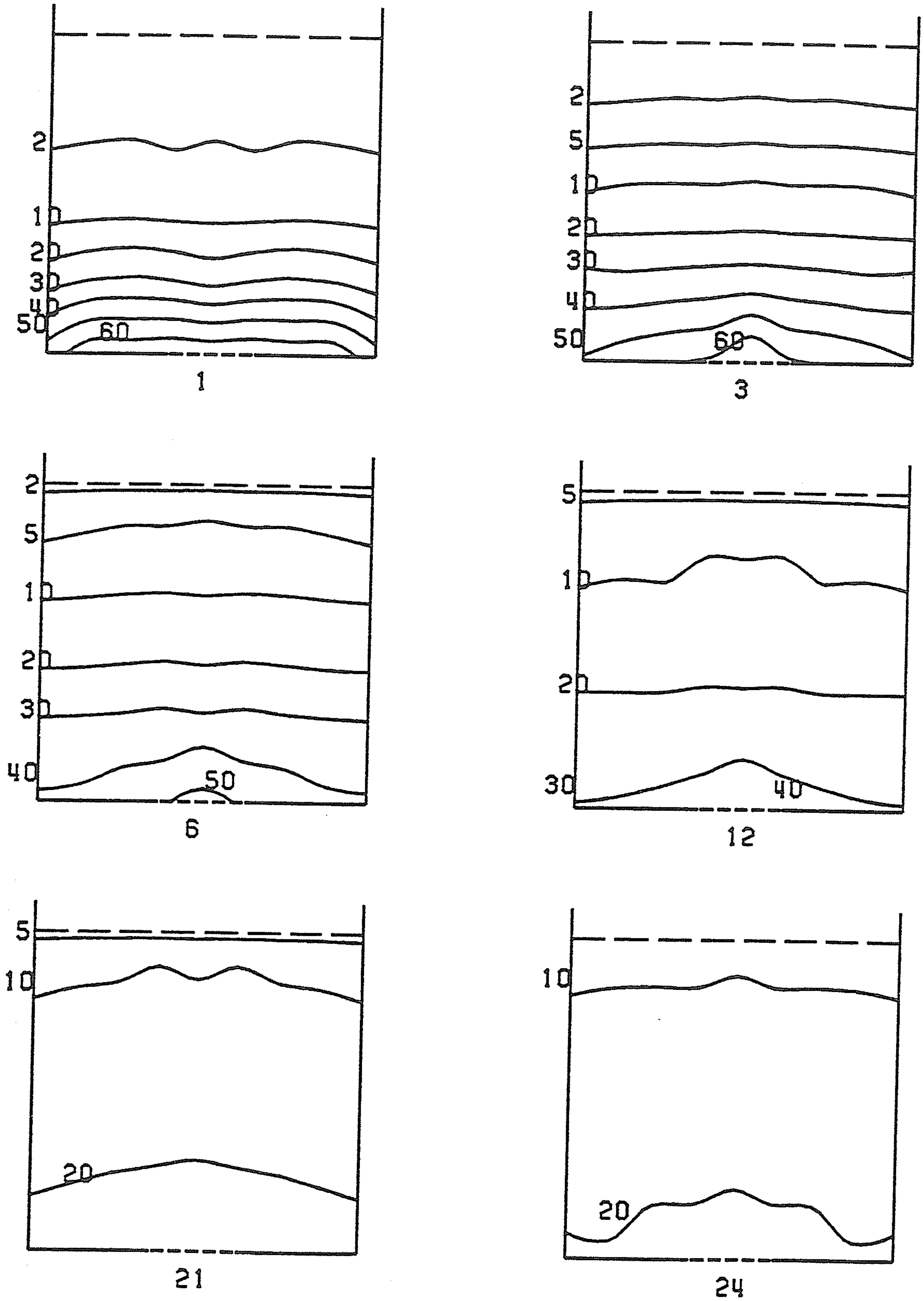

FIG.B.36. BIN 2. COVERED TOP SURFACE. 740 G DRY ICE (REP.3)
(ALONG SECTION A-A)

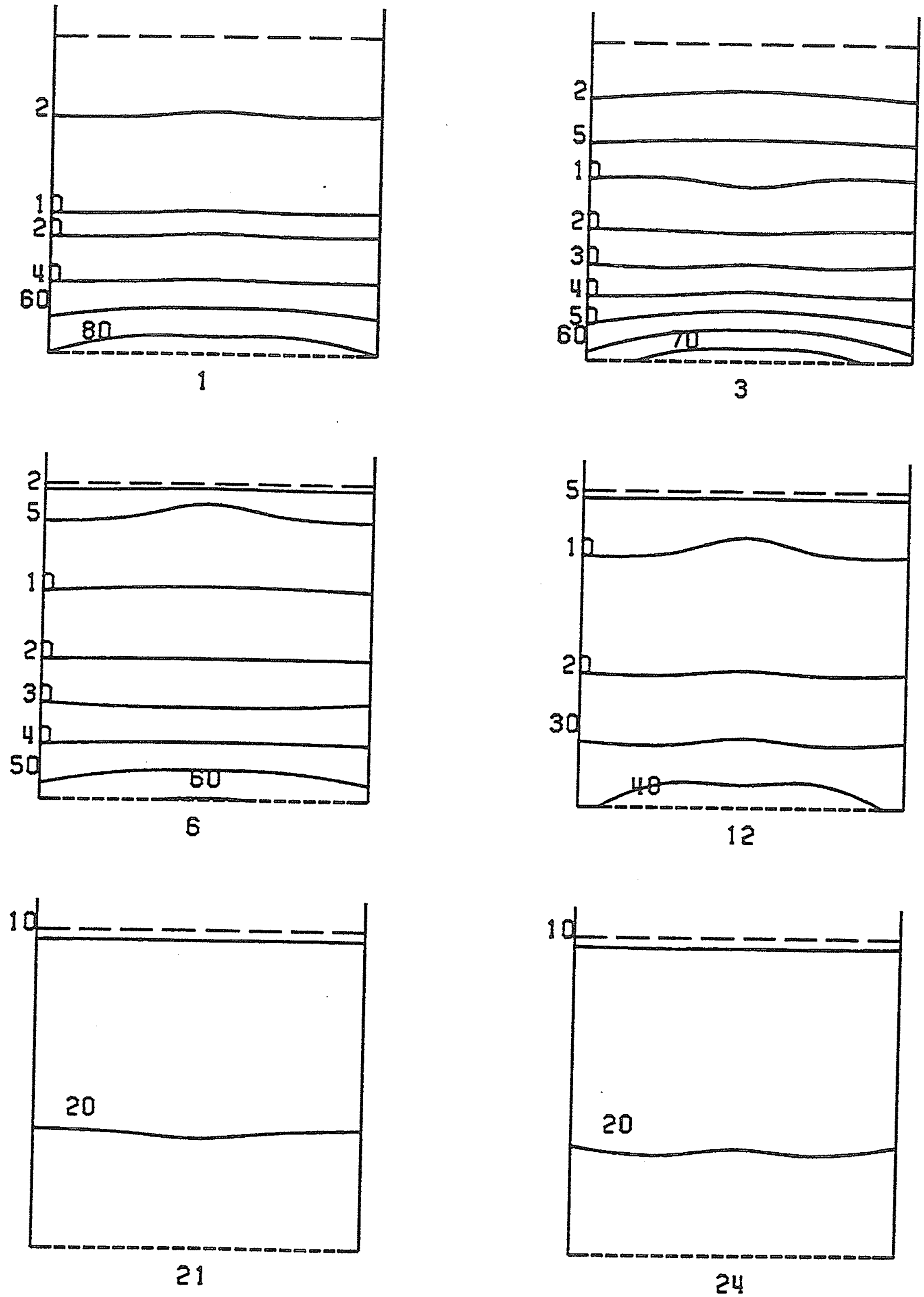

FIG.B.37. BIN 2. COVERED TOP SURFACE. 740 G DRY ICE (REP.1)
(ALONG SECTION B-B)

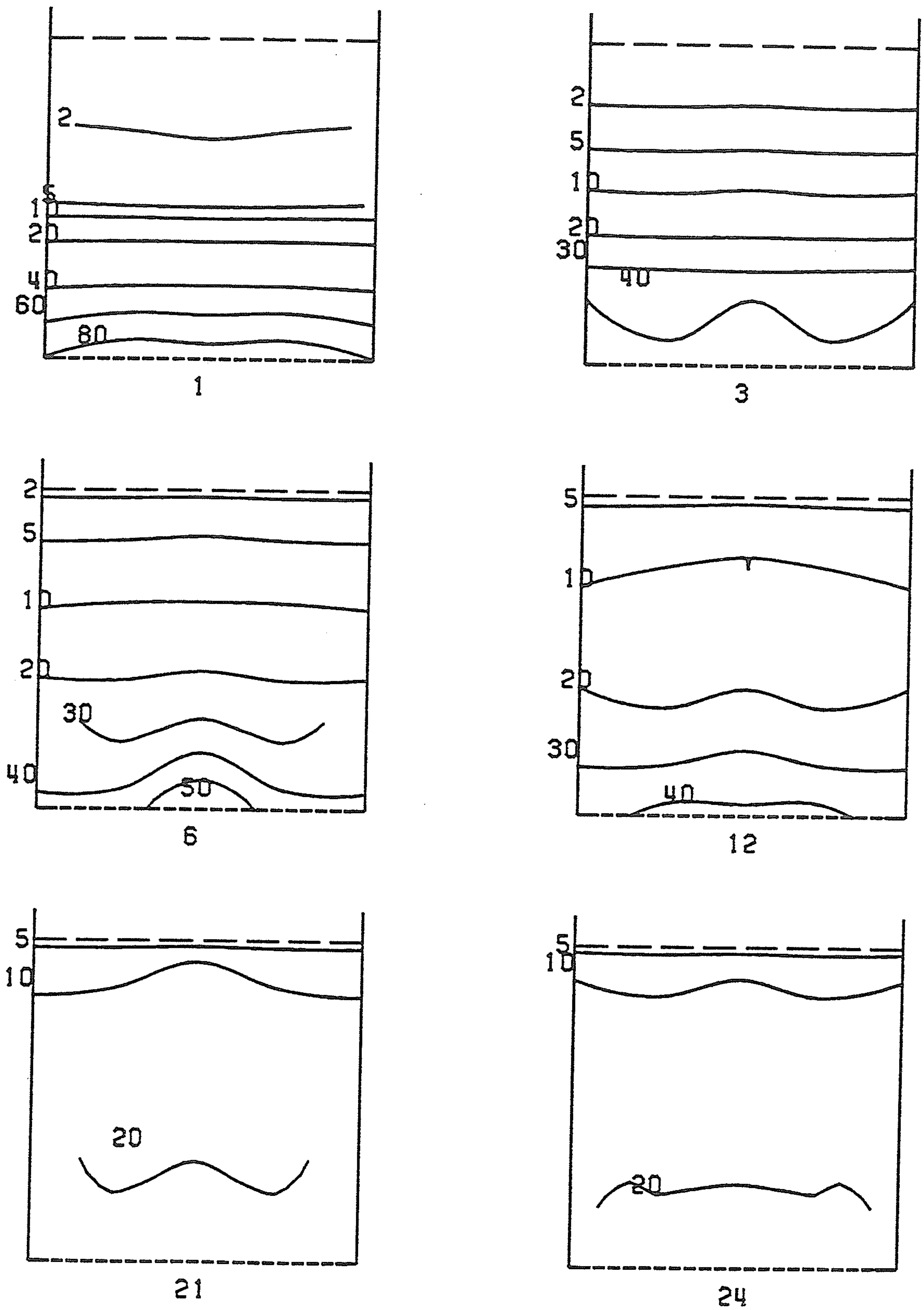

FIG.B.38. BIN 2. COVERED TOP SURFACE. 740 G DRY ICE (REP.2) (ALONG SECTION B-B)

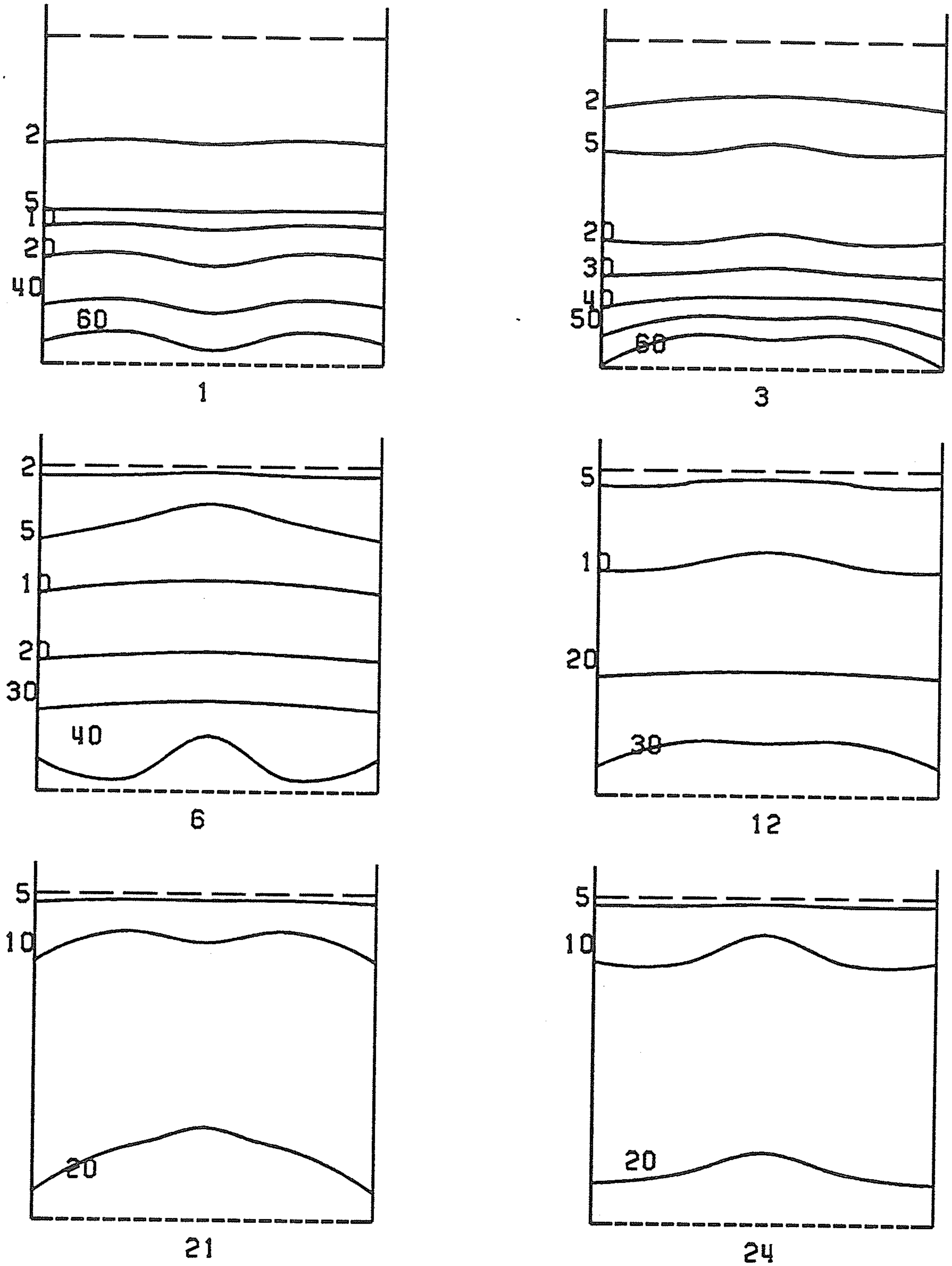

FIG.B.39. BIN 2. COVERED TOP SURFACE. 740 G DRY ICE (REP.3)
(ALONG SECTION B-B)

APPENDIX C

Experimental data on CO_2 distribution in 5.56-m-diameter bolted metal bins (farm Bins 1, 2, and 3) either empty or filled with wheat.

Table.C.1: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a circular duct on the floor. The grain surace was open. Dry ice (28 kg at 0 and 24 h) was introduced in the duct (Experiment 1).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
2 h	3	0.29	0.24	0.32	0.15	0.11	0.10	0.09	0.12	0.05	0.06	0.04	0.04	0.04
	2	2.34	3.02	2.30	1.73	1.65	1.42	1.32	1.75	1.25	1.15	0.26	0.04	0.03
	1	8.56	18.63	22.42	47.22	36.86	32.07	25.07	42.86	33.48	28.53	22.15	5.40	0.13
4 h	3	0.63	0.54	0.40	0.28	0.32	0.25	0.66	0.31	0.13	0.47	0.12	0.09	0.23
	2	4.69	5.27	5.26	5.36	0.00	5.36	4.68	5.75	5.91	5.49	5.17	3.32	4.10
	1	24.81	25.88	27.01	51.56	40.52	32.70	25.83	49.50	44.64	40.38	33.52	26.80	26.30
6 h	3	2.67	2.11	1.59	1.34	0.96	1.15	1.88	1.06	0.54	1.53	1.20	1.54	1.81
	2	5.19	11.81	10.20	7.33	8.49	7.84	8.65	7.20	9.84	9.65	8.94	8.38	6.62
	1	17.74	29.57	25.92	44.90	41.76	41.67	41.50	52.55	45.46	43.40	32.42	53.19	20.19
8 h	3	2.14	2.12	2.03	1.79	1.46	1.57	2.44	1.38	0.96	2.16	1.51	1.53	2.53
	2	10.41	12.21	12.61	12.78	10.36	10.44	9.35	9.87	8.00	8.28	11.87	10.27	11.09
	1	26.51	30.55	31.84	53.10	49.31	47.69	44.29	48.51	42.61	34.74	44.21	32.76	33.80
10 h	3	2.07	1.70	1.76	1.56	1.19	1.33	2.15	1.18	0.69	2.02	1.18	1.13	2.24
	2	9.34	9.22	10.28	10.14	8.84	8.65	8.33	7.97	8.03	7.45	9.81	8.21	9.72
	1	24.27	26.06	25.19	41.35	35.59	30.53	32.65	34.25	34.83	30.07	35.56	31.21	31.91
24 h	3	0.35	2.78	3.02	2.40	2.47	2.88	3.05	2.22	2.49	2.88	2.78	2.77	3.51
	2	0.28	0.43	5.14	3.64	4.41	6.28	6.03	5.36	4.79	4.92	5.34	4.99	5.02
	1	0.18	0.69	2.22	2.82	4.05	7.51	7.80	10.70	10.49	6.49	8.52	8.31	8.22
27 h	3	0.34	4.11	4.13	3.23	2.97	3.88	4.48	4.67	4.74	3.81	4.80	4.73	4.51
	2	1.18	3.67	11.68	11.25	10.14	10.22	10.05	10.54	12.59	11.02	9.91	8.09	7.71
	1	3.66	28.33	34.25	61.61	60.40	53.83	49.04	44.32	45.83	56.28	46.77	25.88	28.23
30 h	3	4.86	5.80	6.35	5.74	4.02	4.59	4.46	4.51	3.69	5.51	4.73	3.76	4.47
	2	6.77	19.89	20.06	19.92	15.84	16.23	15.34	14.79	16.94	16.49	17.06	13.96	14.30
	1	16.86	40.84	45.07	59.52	55.48	55.46	46.07	44.61	46.40	52.59	43.10	42.47	48.44
33 h	3	0.38	5.27	11.21	9.29	8.32	8.30	8.40	7.71	7.62	8.62	8.27	7.94	9.43
	2	0.54	2.45	22.75	25.33	26.12	27.24	24.00	23.12	25.80	23.86	23.38	21.97	20.56
	1	9.44	27.19	47.72	54.24	56.45	52.85	53.00	51.40	52.55	55.82	52.47	48.45	46.60
48 h	3	2.55	2.54	2.53	2.83	1.90	2.07	2.17	2.27	1.39	2.28	2.04	2.54	3.18
	2	3.59	7.34	7.41	8.06	7.53	7.05	7.46	7.10	5.69	6.45	7.00	6.42	6.95
	1	1.81	11.59	10.86	12.69	13.07	15.46	15.02	14.48	14.02	14.04	14.01	13.54	13.77

Table.C.2: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a circular duct on the floor. The grain surface was covered with a PVC sheet. Dry ice (28 kg at 0 and 24 h) was introduced in the duct (Experiment 2).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	0.36	0.24	0.25	0.20	0.21	0.55	1.06	1.35	0.00	0.34	0.11	0.11	0.14
	2	3.94	0.00	3.40	0.00	3.91	4.03	4.65	6.55	4.09	4.79	2.96	1.90	2.07
	1	24.25	30.04	3.30	96.81	48.53	90.21	37.09	35.11	80.76	37.81	39.52	37.41	3.23
6 h	3	2.98	2.46	2.00	1.50	1.19	1.65	3.12	2.83	1.19	1.27	2.02	1.93	3.24
	2	10.81	14.32	15.30	15.08	13.16	13.56	13.21	13.97	12.35	12.02	12.12	11.28	12.84
	1	25.51	39.25	37.83	60.72	54.30	53.81	48.34	42.35	41.29	50.97	39.68	35.39	34.50
9 h	3	0.00	9.61	8.59	6.66	5.51	6.27	7.85	7.28	5.12	6.58	6.05	6.42	0.00
	2	1.54	5.08	22.60	21.00	22.05	20.85	20.63	19.80	19.07	19.88	20.63	18.99	20.18
	1	0.00	16.50	36.30	38.95	46.02	52.25	44.35	42.37	40.26	46.10	43.74	37.94	39.38
24 h	3	2.12	7.23	4.85	0.00	5.83	0.00	6.45	7.44	5.53	6.43	5.40	5.05	4.53
	2	0.00	4.74	13.52	12.39	13.25	12.58	13.55	10.04	11.46	12.80	10.09	8.91	8.51
	1	0.63	6.46	6.30	11.48	14.62	18.89	17.56	15.57	16.62	15.02	15.14	16.42	14.74
27 h	3	4.73	7.38	8.08	8.10	7.68	8.11	9.10	7.07	8.56	8.11	7.47	6.05	5.48
	2	10.85	12.55	14.04	13.17	13.42	11.26	14.66	14.20	13.17	11.68	11.94	11.95	11.82
	1	35.49	37.33	39.01	66.83	59.12	55.07	51.38	39.83	48.88	59.95	44.86	32.08	29.62
30 h	3	6.97	7.78	8.44	8.49	8.22	8.27	9.63	7.26	8.61	8.30	7.48	7.70	7.83
	2	17.37	15.20	18.97	18.95	18.86	17.74	17.85	18.83	17.67	16.43	19.08	15.83	18.26
	1	30.92	37.62	37.30	64.80	62.21	57.73	45.54	54.52	48.84	57.68	44.64	44.36	44.17
33 h	3	9.30	9.07	9.18	9.39	7.58	8.99	9.92	7.80	8.00	8.45	8.68	9.27	10.23
	2	15.34	18.18	19.19	17.26	16.65	16.60	17.18	16.63	17.47	16.38	16.45	16.84	18.70
	1	33.49	35.64	37.17	59.40	59.68	52.13	43.58	42.58	51.64	55.67	49.63	39.33	39.76
48 h	3	3.81	4.26	4.31	3.73	3.19	4.46	4.77	3.81	3.56	3.57	3.99	5.06	0.00
	2	1.46	6.43	9.00	8.13	10.12	8.48	8.35	7.45	7.98	8.09	7.62	7.36	7.00
	1	0.48	5.52	0.00	0.00	0.00	4.99	10.11	10.24	0.00	10.96	11.08	12.11	13.07

Table.C.3: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a circular duct on the floor. The grain surface was covered with a PVC sheet. Dry ice (54 kg at 0 h, 56 kg at 25 h and 52 kg at 48 h) was introduced in the duct (Experiment 3).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	0.55	0.21	0.31	0.09	0.04	0.20	1.04	0.34	0.22	0.33	0.03	0.03	0.26
	2	4.76	6.40	6.57	0.00	0.00	0.00	6.77	6.06	2.79	4.22	4.63	4.80	5.34
	1	32.27	31.42	35.87	58.88	69.17	62.24	55.18	27.23	23.98	26.63	37.93	36.48	30.14
6 h	3	2.55	1.44	0.90	0.72	0.26	2.44	0.00	1.41	0.54	0.79	1.35	2.26	2.65
	2	9.62	8.01	8.31	7.94	11.86	10.38	8.99	8.46	8.44	8.71	9.50	9.90	8.64
	1	26.77	24.57	15.97	27.90	38.54	54.42	48.55	32.72	48.19	48.57	32.88	23.68	28.20
9 h	3	5.41	4.04	4.26	3.94	3.00	3.28	5.12	4.42	2.08	2.49	3.17	5.20	7.60
	2	14.95	15.52	15.90	16.20	13.09	13.31	14.46	11.94	11.80	12.00	13.22	13.80	13.22
	1	31.86	40.82	39.78	66.40	52.38	55.56	49.00	44.26	37.04	52.65	48.91	39.12	39.18
25 h	3	1.12	2.66	2.49	1.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	4.54	5.77	5.00	6.04	6.64	5.97	7.61	0.00	0.00	0.00	0.00	0.00	0.00
	1	5.32	9.30	7.66	12.97	14.38	12.41	9.92	0.00	0.00	0.00	0.00	0.00	0.00
27 h	3	4.38	5.10	3.13	0.41	5.62	6.67	8.66	8.83	7.57	6.12	5.46	6.81	6.94
	2	6.25	7.21	9.51	6.20	13.45	14.91	13.24	15.41	16.70	14.77	10.17	8.75	8.37
	1	27.38	27.58	29.22	40.77	72.56	66.12	54.41	47.92	58.63	66.65	31.91	15.96	13.08
30 h	3	14.00	11.64	11.70	12.24	12.94	13.41	12.03	13.39	11.17	13.07	11.53	13.12	13.45
	2	32.97	35.88	39.05	39.59	35.85	37.69	36.20	41.01	42.28	40.27	40.24	32.97	34.41
	1	79.88	67.94	66.93	76.19	72.87	80.11	73.75	81.05	81.90	89.34	64.01	60.51	67.06
33 h	3	24.45	43.40	23.89	23.81	19.11	19.64	19.43	20.62	16.09	19.94	20.52	16.44	22.18
	2	48.14	52.05	58.96	54.72	51.67	53.98	50.31	51.45	58.38	50.14	58.11	53.56	54.08
	1	77.09	79.49	76.03	90.18	86.12	82.23	78.89	78.65	75.26	77.89	80.12	75.29	72.83
48 h	3	11.52	15.84	16.45	16.57	14.04	15.84	14.01	13.78	11.72	14.06	15.27	13.24	12.22
	2	0.00	32.55	33.47	31.94	31.66	32.87	32.74	26.84	29.40	28.76	30.82	30.00	26.88
	1	19.40	47.82	58.82	63.14	66.71	63.06	54.99	58.83	57.23	61.84	60.54	53.85	54.20
51 h	3	16.64	20.96	20.53	21.91	21.88	19.29	20.35	19.19	19.96	21.64	17.09	18.03	18.83
	2	30.74	28.82	33.47	34.82	37.07	51.65	36.54	41.52	39.15	37.91	41.87	39.69	37.41
	1	57.33	63.10	59.96	75.39	64.02	78.54	71.96	70.41	72.18	69.17	69.11	62.44	58.53
54 h	3	28.15	24.51	27.64	27.76	26.77	26.82	26.77	26.12	23.68	26.03	22.57	26.29	25.67
	2	42.98	50.69	38.75	51.33	52.82	55.30	53.33	50.06	51.76	50.26	50.05	50.80	48.64
	1	58.62	59.54	72.75	72.62	84.91	79.29	81.76	79.64	82.30	88.69	75.10	74.15	69.55
57 h	3	32.03	31.39	31.26	33.93	30.74	31.32	28.32	29.34	27.71	28.11	29.52	28.91	29.03
	2	52.85	57.19	60.08	57.08	55.24	60.96	56.80	57.97	56.64	55.06	58.47	56.14	56.35
	1	79.14	74.78	73.81	86.19	86.15	85.98	83.80	82.21	83.46	84.69	81.24	77.14	77.09
72 h	3	6.74	7.82	7.15	8.46	8.16	8.21	7.14	7.14	6.83	6.02	5.72	6.77	7.20
	2	18.19	23.31	25.37	22.63	18.42	21.63	22.93	17.32	22.28	21.97	23.43	22.08	20.66
	1	32.81	39.36	40.25	51.41	44.62	56.26	52.17	46.02	53.63	45.07	44.04	48.37	50.63

Table.C.4: Measured carbon dixoide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a circular duct on the floor. The grain surface was covered with a PVC sheet. Dry ice (30 kg at 0, 12, 24, 48 and 60 h and 28 kg at 36 h) was introduced in the duct (Experiment 4).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	0.45	0.49	0.45	0.51	0.22	0.40	0.87	0.48	0.93	0.30	0.00	0.00	0.00
	2	0.00	7.60	8.93	7.31	7.30	8.69	7.78	7.38	8.99	8.63	0.00	0.00	0.00
	1	43.83	44.55	49.74	68.39	77.19	76.59	0.00	51.85	62.88	72.42	66.78	41.77	34.85
6 h	3	5.17	5.96	6.99	5.90	5.23	5.70	5.78	4.61	4.18	5.80	0.00	0.00	0.00
	2	0.00	25.81	31.52	29.70	27.77	22.26	24.41	22.51	25.10	26.23	0.00	0.00	0.00
	1	59.71	52.80	62.42	71.46	74.07	0.00	0.00	0.00	71.75	79.71	60.21	60.04	60.48
9 h	3	9.32	9.65	11.03	10.94	8.78	10.35	9.55	8.15	6.92	8.51	8.45	9.23	10.86
	2	28.29	34.89	37.91	37.06	35.97	36.71	31.96	30.85	33.47	34.18	38.21	34.19	31.48
	1	79.43	65.21	69.59	78.94	76.64	79.75	75.73	71.14	74.80	75.25	75.25	72.50	73.55
12 h	3	9.39	9.00	10.41	10.38	8.68	6.55	7.82	6.55	8.45	8.58	8.31	9.64	7.82
	2	29.17	31.02	34.36	34.80	30.58	32.34	28.44	26.29	29.13	29.78	30.39	29.47	28.27
	1	64.96	62.48	63.96	72.53	70.36	68.58	65.83	64.96	65.45	66.36	68.66	64.32	66.56
15 h	3	11.43	11.04	12.21	12.29	11.01	11.32	9.96	8.36	8.82	11.54	10.88	9.92	10.18
	2	33.76	36.61	36.28	35.01	33.88	33.77	31.56	32.14	35.28	34.91	32.47	31.76	27.35
	1	67.69	54.66	68.65	74.75	85.83	79.74	80.17	75.72	80.66	72.50	67.46	66.14	70.18
21 h	3	10.22	11.96	13.15	13.92	11.34	11.47	9.63	8.17	7.72	10.93	10.46	10.37	9.92
	2	30.78	36.45	39.66	38.52	33.23	36.58	29.77	26.52	31.90	33.82	34.92	33.49	26.86
	1	70.62	69.82	67.56	80.55	78.65	75.03	74.09	75.96	76.24	77.51	71.49	74.37	69.25
24 h	3	9.80	10.71	12.42	11.05	11.61	11.65	9.82	9.29	7.41	10.30	11.01	9.38	9.42
	2	28.41	31.51	36.45	36.40	31.61	34.73	29.82	21.56	29.24	28.86	30.07	30.66	26.23
	1	71.31	63.42	60.00	65.28	70.74	75.94	74.89	63.35	73.10	68.98	67.84	50.39	67.72
30 h	3	14.74	16.23	16.37	21.17	19.78	19.45	18.04	14.72	15.66	18.09	17.03	15.58	14.53
	2	46.74	50.53	48.56	49.07	48.73	48.96	42.68	39.95	39.76	39.46	47.95	39.29	42.10
	1	69.10	65.88	61.40	75.43	73.61	76.95	72.90	70.55	75.42	61.84	68.21	68.95	70.27
33 h	3	21.70	22.09	22.51	22.98	20.22	20.89	20.32	19.99	18.34	21.56	19.89	20.37	22.67
	2	43.09	45.46	53.92	54.87	44.60	50.16	46.25	44.55	45.41	46.64	50.79	47.95	46.99
	1	0.00	58.46	67.50	79.86	80.78	80.26	81.29	73.56	83.01	78.53	79.21	76.92	74.73
36 h	3	18.18	17.43	19.47	20.07	17.29	17.32	17.48	15.66	13.61	16.58	17.18	17.26	18.89
	2	39.58	41.21	39.59	42.29	38.28	42.00	38.16	39.64	40.09	41.74	41.06	41.14	39.07
	1	70.03	67.66	65.31	80.94	79.49	75.24	76.04	71.05	76.25	79.57	75.59	70.87	74.80
39 h	3	15.33	13.71	15.03	14.65	13.89	14.50	13.37	11.97	10.67	13.61	13.05	12.42	13.87
	2	40.05	36.35	38.63	37.39	36.34	36.97	35.25	36.03	36.91	39.96	37.17	34.31	33.95
	1	74.30	71.38	61.46	83.45	83.05	81.03	78.25	76.08	79.00	85.72	77.77	68.94	70.05
42 h	3	11.64	11.67	13.06	12.79	11.35	12.14	10.98	8.69	8.47	11.55	11.59	11.24	11.55
	2	34.00	33.70	34.49	34.70	28.58	35.76	35.77	32.32	29.55	31.37	30.17	33.54	29.20
	1	69.21	63.28	62.65	71.71	69.35	69.96	68.87	66.79	71.02	70.92	71.02	72.91	68.43
48 h	3	11.09	13.32	13.43	14.39	12.14	13.58	10.88	10.78	10.20	12.40	12.34	12.15	12.03
	2	31.78	35.31	35.42	37.22	34.87	35.76	34.85	32.88	32.11	34.84	37.64	36.15	31.30
	1	64.88	64.42	63.76	73.60	73.46	70.39	74.02	71.46	75.50	73.03	72.48	71.80	70.80
51 h	3	14.34	18.83	19.03	16.68	16.21	18.09	16.44	16.11	13.71	16.25	16.04	12.90	15.52
	2	33.30	35.36	40.97	40.74	36.20	41.04	41.87	39.66	42.09	36.10	41.71	42.83	41.12
	1	70.10	60.83	55.54	76.15	78.18	74.61	81.95	63.46	67.27	76.02	70.67	73.34	64.39
57 h	3	23.34	25.03	24.86	26.55	19.00	23.99	22.62	21.04	18.16	20.36	23.67	23.23	22.97
	2	51.03	45.66	54.23	44.89	48.74	52.56	51.77	47.88	50.95	49.17	53.33	48.96	41.17
	1	71.23	66.17	63.76	81.91	74.01	82.19	76.73	68.32	76.85	76.50	76.65	71.27	72.93
60 h	3	20.60	22.10	21.58	24.50	20.60	21.60	18.50	20.10	23.02	24.01	21.02	22.01	20.06
	2	44.86	41.43	48.97	43.37	40.03	41.89	38.76	41.23	39.81	39.08	45.54	4.77	38.82
	1	70.70	69.12	66.50	76.38	76.47	71.74	72.53	70.97	73.81	77.63	73.52	71.31	75.64

Table C.4. continued ....

70 h	3	14.82	16.43	16.72	17.14	14.44	11.86	12.61	11.79	10.67	15.38	15.03	14.32	15.18
	2	36.94	38.37	41.86	39.65	31.88	36.80	34.29	32.92	34.59	39.30	38.86	35.90	34.58
	1	62.00	63.75	63.63	74.71	71.78	73.16	74.36	68.43	68.33	72.55	76.27	70.53	73.70
73 h	3	13.58	14.50	15.44	12.91	14.50	16.04	13.93	12.16	10.65	13.01	14.24	15.38	11.64
	2	37.98	36.80	41.10	40.01	37.99	33.11	34.81	33.28	37.67	32.11	38.57	39.55	34.81
	1	64.37	63.11	57.37	69.35	64.20	61.71	72.95	68.76	64.33	62.45	66.37	69.71	68.77

Table.C.5: Measured carbon dixoide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a circular duct on the floor. The grain surface was covered with a PVC sheet. Dry ice (27 kg at 0 h and 28 kg at 24 h) was introduced on the grain surface underneath the PVC sheet (Experiment 5).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	15.97	26.45	28.97	20.92	10.57	11.65	11.28	9.99	9.85	13.53	17.30	13.66	12.48
	2	21.43	26.64	32.52	26.56	25.41	27.23	26.55	21.68	23.39	23.43	30.66	26.79	25.61
	1	31.21	34.77	35.46	45.02	59.68	40.42	26.79	31.10	33.30	34.76	36.72	36.59	36.75
6 h	3	24.02	31.29	33.44	29.98	24.34	24.02	26.48	22.71	22.83	23.96	24.71	24.66	23.15
	2	27.88	31.00	36.16	31.89	29.87	29.86	33.11	29.65	27.78	29.59	31.74	30.26	32.31
	1	34.69	36.64	40.47	35.25	34.68	35.24	35.99	34.29	32.92	35.14	36.23	35.18	36.29
9 h	3	27.34	30.74	35.48	29.53	27.25	26.31	29.55	26.40	25.64	25.96	24.79	27.96	27.13
	2	32.95	30.96	42.15	32.11	30.57	31.93	35.04	32.09	31.17	25.68	34.28	34.13	34.00
	1	35.07	40.26	43.20	40.56	36.40	35.97	34.73	33.57	33.01	35.30	34.80	35.53	35.63
24 h	3	12.79	14.08	15.20	15.01	13.47	13.99	13.08	13.21	12.35	13.53	13.47	13.91	13.84
	2	18.79	20.51	21.01	20.27	20.72	23.48	23.92	22.29	22.28	20.87	20.69	22.86	22.66
	1	25.35	24.90	27.10	27.44	24.50	28.24	28.66	28.74	28.93	26.91	27.40	29.30	28.87
27 h	3	29.52	43.28	31.96	27.67	24.12	24.44	25.41	24.96	24.71	23.48	26.27	25.85	23.60
	2	36.35	42.86	43.71	33.83	31.13	31.39	33.34	29.11	26.12	31.39	34.54	0.00	35.72
	1	45.27	53.44	45.42	43.49	48.08	46.94	43.34	35.63	42.24	43.74	47.01	17.65	0.00
33 h	3	41.66	41.68	36.04	33.54	33.76	34.18	35.56	34.79	32.65	33.13	35.36	34.59	35.99
	2	48.96	47.70	46.87	42.95	41.97	44.05	44.97	44.00	42.52	41.12	44.06	42.86	47.11
	1	52.29	52.40	49.53	47.59	47.46	47.32	47.65	44.01	46.30	46.17	47.99	48.55	48.26
48 h	3	12.72	12.63	12.16	12.84	12.17	12.22	11.18	10.62	10.61	12.05	11.87	11.50	11.69
	2	21.81	21.63	21.91	21.99	21.72	24.07	24.00	23.14	22.73	22.28	22.48	22.80	19.09
	1	30.25	27.87	30.89	31.42	30.70	31.52	34.54	33.39	34.45	29.68	30.95	31.68	33.85

Table.C.6: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a circular duct on the floor. The grain surface was covered with a PVC sheet. Dry ice (17.5 kg at 0 h and 16.3 kg at 24 h) was introduced in a 10-cm-diameter perforated tube inserted neat the centre (Experiment 6).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	1.77	3.55	4.30	4.63	4.30	4.89	2.51	1.61	3.04	3.90	4.65	4.81	1.95
	2	4.23	14.23	20.82	25.85	22.14	20.58	15.32	7.95	14.42	18.68	24.14	18.03	9.89
	1	7.77	27.86	28.46	25.56	28.03	32.08	25.92	22.40	29.49	28.80	25.69	30.66	26.76
6 h	3	5.23	15.48	15.12	15.45	16.94	15.72	12.42	9.78	13.41	15.98	13.62	14.93	7.75
	2	5.77	23.45	30.35	32.19	29.68	28.00	20.35	15.52	22.83	12.78	31.86	27.84	18.15
	1	8.20	29.74	34.94	34.11	35.73	34.88	28.07	24.37	32.94	33.08	34.93	31.01	27.70
9 h	3	5.77	14.96	17.04	15.27	15.96	17.46	12.24	10.97	15.42	15.68	14.63	13.97	7.68
	2	7.93	20.60	25.84	29.30	25.55	24.00	19.11	15.39	23.30	24.80	25.88	22.32	15.72
	1	11.81	28.13	30.57	30.43	29.72	28.95	22.87	22.51	25.05	29.21	32.88	30.29	25.37
24 h	3	9.88	17.40	18.15	17.82	17.78	18.06	15.49	12.95	15.92	14.48	17.12	16.59	11.56
	2	11.91	20.70	23.06	22.53	22.62	21.38	17.99	16.99	21.05	21.90	22.95	21.43	15.96
	1	18.84	25.33	29.33	31.37	27.24	27.96	23.58	24.91	27.52	27.13	27.62	28.44	23.48
27 h	3	16.39	18.30	20.09	20.54	20.85	20.56	18.75	17.90	19.71	20.68	17.96	17.86	15.62
	2	19.19	25.14	32.64	34.62	33.21	29.55	27.08	24.51	25.68	28.63	34.81	25.56	24.41
	1	34.15	37.32	37.46	35.10	38.26	34.26	39.82	31.75	29.77	38.22	0.00	41.37	39.58
30 h	3	12.36	16.29	18.35	19.75	17.18	18.93	17.08	14.05	17.32	17.50	0.00	12.11	11.10
	2	17.00	29.78	36.56	39.15	38.66	35.82	32.42	33.04	28.55	34.90	33.15	27.92	25.57
	1	33.00	35.99	36.91	33.06	38.84	41.33	43.31	40.03	41.56	40.74	37.92	43.07	42.00
33 h	3	7.51	9.64	11.02	9.60	9.79	9.25	7.85	6.42	7.19	9.07	5.76	6.54	3.89
	2	11.37	21.99	28.07	26.57	27.77	26.23	23.57	22.47	23.75	25.94	25.99	23.26	19.71
	1	25.62	28.61	30.30	25.14	28.88	33.94	31.78	32.30	35.10	32.41	28.08	32.22	31.59
48 h	3	9.46	12.84	13.30	13.03	12.48	13.58	8.76	9.87	11.73	12.18	11.97	13.20	9.02
	2	16.70	22.65	24.37	22.83	23.95	23.81	20.57	19.60	21.60	22.86	23.63	23.75	19.55
	1	24.35	27.17	27.31	25.90	26.61	28.33	26.87	26.86	28.52	26.30	25.86	27.73	24.64

Table.C.7: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a fully perforated floor. The grain surface was open. Dry ice (28 kg at 0 and 24 h) was introduced in the plenum (Experiment 7).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	4	0.19	0.16	0.10	0.12	0.00	0.00	0.69	0.54	0.00	0.00	0.00	0.00	0.25
	3	3.90	2.68	4.29	3.52	2.62	2.45	4.53	6.32	0.00	3.55	2.56	2.12	3.61
	2	38.26	38.03	0.00	0.00	24.80	30.96	30.39	31.82	29.84	31.80	29.30	28.15	28.90
	1	53.49	54.71	61.79	63.62	62.22	63.02	59.80	63.54	59.03	57.91	55.11	57.84	73.62
6 h	4	7.09	6.88	5.10	2.01	1.88	3.44	6.13	7.21	3.66	5.15	3.31	2.54	3.95
	3	7.79	4.51	20.28	20.20	13.71	19.93	19.90	24.08	3.63	13.26	16.81	14.75	14.75
	2	9.44	16.96	0.00	0.00	24.62	27.84	24.40	22.10	30.70	22.38	29.15	25.05	20.93
	1	11.93	14.10	23.21	20.73	44.40	27.16	16.66	21.18	26.74	18.48	24.84	25.52	20.95
9 h	4	8.40	8.52	8.15	6.00	3.92	4.67	7.94	6.76	6.04	6.24	5.39	4.37	5.30
	3	9.26	7.73	17.54	18.44	16.13	17.87	17.82	5.63	0.00	17.34	16.93	16.52	18.83
	2	9.56	16.76	0.00	0.00	22.18	23.10	19.03	10.87	20.91	19.45	21.41	21.97	18.58
	1	9.66	14.55	18.29	17.90	16.47	17.28	16.94	15.53	19.50	15.88	19.75	20.51	17.99
24 h	4	0.68	1.25	4.32	3.30	3.19	2.77	1.76	1.79	3.12	3.29	3.98	3.69	1.71
	3	0.42	3.05	3.44	2.70	5.97	3.52	1.26	0.83	0.00	2.66	2.68	3.00	1.92
	2	0.60	0.62	0.00	0.00	6.88	2.92	1.07	0.68	1.68	1.48	1.35	3.84	1.14
	1	0.41	0.56	3.19	1.09	3.48	1.92	1.26	0.66	1.02	0.96	2.40	1.97	0.91
27 h	4	0.00	0.00	0.00	1.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	4.32	1.62	7.17	6.15	6.97	5.97	6.63	10.90	1.51	9.39	5.32	5.63	6.02
	2	40.94	35.06	0.00	0.00	19.15	31.24	37.72	36.53	38.97	37.73	26.24	27.40	31.74
	1	37.21	62.01	46.26	43.64	22.98	59.15	49.64	60.38	54.28	59.21	56.64	54.25	64.37
30 h	4	3.07	3.17	2.89	2.29	2.17	2.06	4.22	3.35	2.38	2.15	1.87	1.49	1.52
	3	9.87	5.89	16.87	10.71	13.06	12.91	1.55	20.43	3.16	12.29	13.53	10.04	12.36
	2	14.98	24.66	0.00	0.00	28.38	24.94	36.12	28.43	31.81	18.23	31.05	31.65	28.61
	1	23.42	26.75	39.17	44.52	47.88	38.51	30.28	31.17	28.89	36.00	31.43	35.61	29.19
33 h	4	4.65	3.76	4.22	3.19	2.36	2.53	5.16	4.57	2.99	3.53	2.91	2.45	2.82
	3	9.08	9.80	15.64	14.31	15.05	16.55	18.51	6.02	4.51	13.91	15.24	16.47	19.87
	2	12.95	21.46	0.00	0.00	26.36	25.23	27.32	25.63	25.46	24.71	23.39	26.49	24.09
	1	11.81	20.40	22.54	20.46	24.39	22.69	23.77	24.35	24.42	25.78	24.31	28.32	22.61
48 h	4	2.78	2.83	2.98	2.43	2.02	0.00	0.00	4.25	2.36	2.45	2.23	2.31	2.18
	3	2.90	3.66	6.26	6.47	5.89	6.64	8.74	6.90	0.00	6.33	6.05	6.41	6.94
	2	2.96	6.53	0.00	0.00	7.94	8.47	7.96	7.00	9.34	8.26	9.26	9.37	8.81
	1	2.70	5.38	7.20	6.14	6.51	7.63	7.91	6.29	6.83	6.17	7.70	7.02	7.35

Table.C.8: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a fully perforated floor. The grain surface was covered with a PVC sheet. Dry ice (28 kg at 0 and 24 h) was introduced in the plenum (Experiment 8).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	4	0.85	0.27	0.15	0.04	0.23	0.22	0.72	0.00	0.00	0.00	0.00	0.00	0.00
	3	6.34	3.30	11.98	10.12	7.64	7.78	7.72	11.43	0.00	9.22	8.01	5.20	8.04
	2	22.82	34.99	0.00	0.00	33.56	37.01	31.53	33.83	37.85	35.50	35.34	32.46	34.46
	1	38.90	46.25	48.07	51.08	47.83	47.26	48.81	49.29	53.16	55.26	53.80	47.51	55.68
6 h	4	1.68	1.14	1.31	1.70	0.63	0.00	0.00	0.00	1.65	1.29	0.99	1.10	2.28
	3	5.46	5.33	9.58	9.05	8.58	9.24	8.27	12.82	0.00	10.57	9.67	9.07	9.71
	2	27.01	30.19	0.00	0.00	29.52	18.16	27.33	22.48	24.45	29.59	24.54	22.49	28.08
	1	22.76	35.20	41.09	44.74	40.19	42.14	45.83	52.06	40.25	39.23	38.37	26.63	41.18
9 h	4	2.79	1.33	1.52	1.26	1.12	1.93	3.34	2.75	1.29	1.30	1.13	1.66	2.50
	3	6.93	4.97	6.27	7.94	7.52	8.67	9.10	11.04	0.00	7.94	7.56	7.83	10.57
	2	22.13	21.51	0.00	0.00	20.25	20.90	22.36	19.76	19.62	20.72	19.26	19.92	24.87
	1	25.60	33.57	33.12	36.55	36.59	38.67	36.59	30.08	32.32	35.88	35.42	34.12	40.14
24 h	4	4.07	3.34	2.36	1.86	1.51	1.47	4.60	3.97	2.95	2.17	2.02	2.84	3.05
	3	2.49	2.41	6.51	6.40	6.68	6.93	7.40	7.30	0.00	7.02	6.88	7.19	7.89
	2	3.94	7.03	0.00	0.00	7.00	5.88	10.48	8.30	9.74	9.11	10.30	10.45	10.89
	1	3.53	6.27	8.53	8.71	21.18	9.76	8.79	9.95	8.67	8.29	8.46	9.77	8.23
27 h	4	0.00	5.82	5.52	6.40	5.79	6.33	6.69	6.16	6.92	5.37	5.72	6.14	5.21
	3	4.54	3.33	7.89	6.58	7.60	8.54	7.28	9.60	0.00	8.63	8.21	7.52	9.49
	2	19.84	30.76	0.00	0.00	19.53	21.01	20.16	15.29	23.41	20.55	20.55	21.45	19.58
	1	38.97	60.13	58.65	0.00	59.74	48.51	65.14	54.65	65.02	0.00	48.71	46.00	58.05
30 h	4	4.24	4.56	4.40	4.85	3.89	4.96	5.99	0.00	0.00	0.00	5.11	4.16	3.97
	3	3.16	4.05	7.84	8.29	7.33	7.94	7.22	0.00	0.00	0.00	7.31	7.33	8.71
	2	22.20	0.00	0.00	17.99	15.39	16.38	14.95	0.00	0.00	0.00	13.46	17.62	16.33
	1	27.31	38.89	36.06	34.41	47.29	42.00	41.09	0.00	0.00	0.00	44.42	43.55	56.12
33 h	4	3.62	2.42	3.33	3.06	2.99	4.11	5.49	4.61	2.79	2.67	2.61	3.18	4.97
	3	5.90	3.38	7.48	7.11	7.69	8.73	9.41	7.31	0.00	7.73	7.63	6.43	10.81
	2	22.37	22.05	0.00	0.00	16.54	18.38	20.23	19.15	17.40	18.49	20.62	18.88	23.17
	1	29.44	35.84	0.00	40.99	39.02	40.13	39.60	36.05	37.76	36.59	37.15	37.65	43.70
48 h	4	3.91	4.05	2.38	1.87	1.91	3.47	5.35	4.91	3.79	2.73	1.91	2.70	3.31
	3	2.22	2.15	6.80	6.41	5.94	7.68	7.56	7.23	0.00	7.20	6.69	7.60	7.44
	2	4.26	7.51	0.00	0.00	9.63	8.80	10.18	8.52	9.61	9.59	11.11	10.13	10.33
	1	3.59	6.81	9.35	9.64	10.02	9.54	8.76	8.85	9.37	9.19	9.83	9.64	8.64

Table.C.9: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter empty bin. A plastic sheet was spread and taped to the wall at a height of 2.1 m from the floor. The door joints were sealed with silicon and PVC sheet. Dry ice (28 kg at 0 and 24 h) was introduced on the concrete floor (Experiment 9).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	14.30	12.90	13.00	13.10	13.81	14.50	13.81	17.00	14.80	13.70	14.20	13.30	13.70
	2	14.07	13.09	13.65	12.72	13.43	13.44	14.89	15.69	14.89	15.29	15.28	13.97	13.15
	1	36.72	41.37	44.31	48.39	47.51	48.93	28.02	41.51	43.49	43.78	46.85	44.66	46.41
6 h	3	22.44	21.29	21.14	22.50	20.99	23.36	23.10	23.05	21.98	23.34	23.36	21.02	22.41
	2	22.42	22.23	21.42	20.14	21.88	22.30	22.65	23.08	22.50	22.79	22.32	21.96	20.98
	1	29.27	29.73	33.02	34.61	31.62	28.88	29.03	28.48	29.41	33.75	33.74	33.82	33.22
9 h	3	23.42	23.25	23.39	23.67	22.59	23.13	22.48	23.53	23.90	24.08	23.38	25.94	23.07
	2	23.59	23.63	24.19	22.35	24.30	23.68	23.80	23.59	23.61	24.16	23.51	23.59	23.76
	1	23.84	24.08	24.15	24.06	24.59	24.14	23.59	23.81	23.81	23.66	23.79	24.23	23.76
24 h	3	14.56	14.72	14.43	14.05	14.70	14.39	14.39	14.03	14.51	14.72	14.50	14.26	14.53
	2	14.53	14.83	15.05	14.32	14.84	14.77	14.26	14.59	14.49	14.66	14.70	14.36	14.87
	1	14.74	14.84	15.06	15.23	14.66	14.93	14.93	14.75	14.70	16.57	14.55	14.37	14.54
27 h	3	21.49	20.38	19.90	21.36	22.00	22.15	22.29	23.10	21.78	21.72	21.54	20.95	20.06
	2	22.15	20.85	21.04	20.46	22.21	21.51	21.05	19.44	22.18	22.46	22.16	20.98	21.75
	1	42.08	40.76	46.16	51.86	51.85	49.23	43.97	44.35	47.70	49.55	48.87	46.47	51.80
30 h	3	18.30	18.72	18.32	19.34	16.93	16.54	18.59	17.14	17.67	18.47	18.95	19.12	16.81
	2	25.20	23.34	24.21	23.99	25.31	25.12	24.61	24.21	23.62	24.85	25.12	22.91	25.60
	1	42.77	42.81	45.62	47.14	44.94	45.22	41.02	43.37	44.26	46.39	47.13	47.39	49.66
33 h	3	17.88	17.34	16.15	17.80	15.59	13.47	14.01	14.05	15.05	16.06	18.23	17.30	18.09
	2	23.21	23.34	24.70	22.85	24.02	23.42	22.01	21.68	22.90	24.61	24.15	23.86	24.72
	1	37.32	36.89	36.66	37.23	35.78	36.35	34.99	35.33	36.56	36.72	36.57	37.97	37.33
48 h	3	14.85	14.43	14.14	16.28	14.21	14.08	13.84	13.66	14.12	14.56	14.42	14.14	13.83
	2	14.52	14.03	14.70	13.81	14.34	14.35	14.58	14.76	13.85	14.61	13.99	14.05	14.81
	1	14.00	14.48	13.96	14.48	14.42	14.43	14.42	14.56	14.05	14.32	14.13	14.47	14.40

Table.C.10: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter empty bin. A plastic sheet was spread and taped to the wall at a height of 2.1 m from the floor. The door joints and bin wall to floor joints were sealed. Dry ice (28 kg at 0 and 24 h) was introduced on the concrete floor (Experiment 10).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	9.50	8.80	8.80	8.50	8.90	9.50	9.30	11.97	9.40	9.50	8.60	8.90	9.00
	2	9.73	8.85	9.16	8.33	9.12	9.30	11.99	11.08	9.93	9.70	9.43	9.47	9.68
	1	46.10	49.64	50.91	57.91	58.03	56.04	51.64	50.30	53.88	56.57	52.18	53.81	57.89
6 h	3	16.57	15.73	16.64	15.72	16.18	16.28	15.82	14.89	14.76	20.37	17.01	16.56	16.71
	2	17.08	17.31	18.92	17.76	18.99	17.70	16.78	17.21	13.67	18.63	19.83	18.40	18.50
	1	40.92	39.39	41.29	45.66	40.45	39.43	38.11	39.35	40.12	42.96	41.36	46.53	46.55
9 h	3	27.00	26.28	26.43	26.96	25.68	25.57	25.43	24.99	25.94	26.62	25.32	26.33	26.28
	2	25.88	25.97	27.07	25.63	26.49	26.29	25.30	25.88	25.63	26.35	25.81	25.91	26.26
	1	23.13	25.54	26.38	27.02	25.96	27.17	26.74	27.38	26.48	26.13	25.50	27.81	27.05
24 h	3	18.52	17.71	18.75	18.80	18.34	18.05	18.16	18.08	17.89	18.36	18.69	18.25	18.01
	2	18.22	18.49	18.96	17.89	18.65	18.12	18.01	18.39	17.73	17.56	18.59	18.35	18.72
	1	17.77	18.28	18.44	18.20	18.76	18.56	18.06	18.36	17.77	18.01	18.33	18.75	17.94
27 h	3	28.01	26.00	26.59	25.68	26.11	27.48	27.23	27.37	26.90	27.49	26.00	26.00	26.00
	2	24.90	24.34	25.30	23.16	26.68	26.36	28.10	27.74	26.50	27.02	26.82	26.19	27.01
	1	41.31	42.39	44.11	52.27	54.99	49.28	43.50	47.67	49.72	54.03	50.57	47.90	53.43
30 h	3	28.06	29.14	30.58	29.60	31.05	26.90	28.27	28.33	31.86	35.79	33.72	30.36	31.44
	2	29.36	31.07	29.98	27.75	30.76	30.44	29.48	30.92	29.01	30.06	30.24	29.62	31.06
	1	44.37	45.81	48.18	49.81	51.27	49.32	46.06	45.82	46.81	49.76	51.07	49.83	55.24
33 h	3	23.64	23.62	23.15	24.23	21.96	19.03	20.17	21.05	20.17	22.36	22.15	23.46	22.16
	2	31.17	30.65	31.46	30.46	28.30	29.62	29.37	32.33	30.10	28.50	30.10	30.73	29.90
	1	42.04	41.73	41.68	43.17	42.89	38.39	39.61	39.91	41.84	41.26	41.89	42.17	43.12
48 h	3	16.81	16.14	15.83	15.91	15.81	15.79	15.95	0.00	0.00	0.00	0.00	0.00	0.00
	2	15.88	14.32	16.99	18.76	16.84	17.59	16.95	0.00	0.00	0.00	0.00	0.00	0.00
	1	16.36	15.98	16.82	17.69	17.41	16.06	16.21	0.00	0.00	0.00	0.00	0.00	0.00

Table.C.11: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter empty bin. Two PVC sheets, one 2.1 m from the floor and one on the floor, were spread and taped to the bin wall. The door joints and bin wall to floor joints were sealed. Dry ice (28 kg at 0 and 24 h) was introduced on the floor PVC sheet (Experiment 11).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
3 h	3	4.40	3.60	3.80	4.19	4.11	3.90	4.60	4.11	4.40	4.30	3.90	3.90	3.90
	2	12.03	12.01	15.31	13.16	15.81	13.58	14.26	11.78	11.72	14.61	12.38	13.90	9.55
	1	51.32	57.58	53.72	59.87	62.63	60.68	49.83	55.08	50.74	70.28	58.40	51.59	65.99
6 h	3	8.11	8.29	5.15	8.18	8.36	8.42	6.72	8.76	8.55	8.08	8.10	8.00	7.23
	2	17.70	21.14	21.55	19.69	18.78	21.60	18.54	19.73	16.95	22.52	21.68	17.74	17.71
	1	44.22	43.34	45.43	50.32	54.66	51.71	50.10	52.06	54.95	55.62	55.47	53.93	57.27
9 h	3	8.40	9.10	8.58	9.05	8.38	7.38	8.42	8.61	8.32	9.04	9.10	9.12	8.83
	2	17.30	17.83	20.22	18.50	18.47	19.65	18.19	18.05	18.40	19.48	19.72	18.68	16.99
	1	32.04	35.52	38.21	37.88	38.71	37.33	33.53	34.57	31.40	39.11	37.40	37.39	40.30
24 h	3	10.12	16.21	17.33	16.24	15.56	17.14	16.39	17.35	17.20	17.48	17.32	17.15	16.19
	2	15.40	17.42	17.32	16.17	16.29	16.81	16.44	17.84	17.40	17.42	16.96	16.90	17.14
	1	17.28	16.84	17.23	18.45	17.38	18.17	17.30	18.33	17.80	17.23	17.63	17.58	17.91
27 h	3	22.94	21.84	24.83	24.16	23.66	24.26	24.60	24.80	24.15	24.50	23.79	23.86	24.54
	2	22.60	23.86	23.89	22.99	24.16	24.64	25.65	25.14	23.50	23.80	23.99	21.66	23.71
	1	42.77	43.21	44.74	51.81	49.59	46.18	41.50	45.67	45.30	50.54	46.85	47.28	55.23
33 h	3	30.88	32.94	34.66	34.30	33.15	29.18	31.52	29.61	32.85	33.84	34.34	31.42	34.30
	2	33.50	33.23	34.69	33.39	33.56	34.82	34.18	33.07	33.28	33.56	34.58	33.82	33.55
	1	44.60	45.68	43.83	48.11	46.92	44.38	41.88	43.69	43.52	45.92	47.59	45.43	47.57
48 h	3	18.46	20.18	19.59	20.22	20.12	19.85	20.12	17.72	18.86	20.10	20.37	19.89	19.11
	2	24.92	24.30	27.04	25.78	25.97	25.88	26.77	26.26	26.10	26.85	26.79	27.02	26.03
	1	25.88	28.49	26.25	28.23	27.78	28.81	27.72	28.55	28.20	27.85	28.06	28.10	27.04

Table.C.12: Measured carbon dioxide concentrations (%) at various locations in a 5.56-m-diameter bin containing wheat to a depth of 2.50 m, with a circular duct on the floor. The grain surface was covered with a PVC sheet. Dry ice (14 kg in the duct and 14 kg on the grain surface at 0, 24, 48, 72, 96, 150, 168, 192 and 216 h after the start) was introduced (Experiment 12).

Time Since Start	Level	Sampling Locations												
		1	2	3	4	5	6	7	8	9	10	11	12	13
24 h	3	6.05	20.03	18.76	19.81	18.64	16.13	14.76	14.95	17.53	19.00	18.33	17.58	12.97
	2	6.21	23.32	26.04	24.35	24.80	23.98	23.69	17.56	23.27	26.40	25.53	25.59	20.27
	1	8.51	27.05	29.77	30.08	29.55	32.50	29.32	28.18	31.91	33.46	31.41	31.77	26.73
48 h	3	10.71	15.19	15.76	15.96	14.82	12.49	10.57	10.35	13.84	15.25	15.63	13.64	10.20
	2	17.04	23.03	25.45	24.65	23.44	24.46	20.91	18.37	22.38	22.33	23.74	23.14	19.22
	1	26.83	31.86	33.21	34.12	34.00	34.34	29.85	30.94	34.82	34.63	36.93	36.34	32.09
72 h	3	13.45	18.83	18.82	18.42	16.00	12.38	9.69	9.61	13.92	16.38	16.89	13.95	8.60
	2	11.59	20.51	25.09	23.22	23.39	24.12	20.46	20.75	23.58	24.73	24.47	24.19	19.75
	1	20.95	28.36	28.82	33.94	31.53	33.65	30.71	30.25	35.44	37.68	34.09	35.63	28.95
96 h	3	15.59	31.54	28.84	25.82	24.50	24.28	21.37	18.96	23.89	26.50	26.55	23.79	15.00
	2	6.12	27.07	30.26	32.25	29.96	30.95	23.17	21.13	29.95	30.49	32.63	32.80	25.34
	1	17.59	33.41	37.15	36.43	37.64	38.83	31.60	33.79	40.17	39.24	39.00	38.91	33.12
144 h	3	1.91	5.03	6.56	7.29	5.20	3.71	2.75	2.28	4.01	6.23	5.89	5.30	3.85
	2	1.05	8.86	12.51	12.60	11.63	12.23	9.85	9.39	12.13	12.07	10.89	9.76	7.76
	1	1.93	15.71	19.31	22.33	19.61	19.57	18.01	19.66	23.51	22.84	20.43	21.71	17.52
168 h	3	25.89	30.56	25.31	26.33	21.79	20.10	19.18	17.76	22.63	25.03	26.24	23.26	16.60
	2	21.32	25.84	29.20	30.59	31.40	30.96	28.21	24.13	29.69	28.72	31.49	31.08	24.97
	1	25.63	33.46	38.08	39.51	38.54	41.28	38.62	38.38	45.91	42.68	41.50	42.55	37.66
192 h	3	12.26	28.84	25.64	27.91	24.44	24.63	22.74	19.45	24.99	26.88	26.21	20.75	14.12
	2	4.50	26.05	33.61	33.65	33.94	34.18	27.53	22.02	32.47	33.03	32.28	33.70	24.34
	1	14.32	34.61	36.99	39.01	39.28	38.59	32.97	35.26	43.94	43.35	40.81	41.04	34.55
216 h	3	2.11	18.85	23.04	24.97	21.51	19.91	17.21	11.88	22.18	22.11	20.48	8.16	4.52
	2	1.31	18.76	28.31	29.39	28.71	27.54	21.76	16.55	28.72	28.10	26.35	21.91	13.79
	1	0.55	27.39	32.13	34.62	33.66	34.96	25.90	31.41	38.27	37.66	33.85	32.38	23.96
240 h	3	1.63	16.45	18.03	20.06	16.78	17.29	13.23	9.89	17.32	20.18	15.68	5.81	3.65
	2	0.83	16.26	23.93	26.44	24.04	23.31	18.50	14.46	23.03	24.82	20.43	17.64	10.52
	1	0.20	21.68	27.40	27.80	28.56	30.07	23.42	26.45	31.66	32.51	29.90	28.05	20.72

APPENDIX D

Lines of constant CO_2 concentrations (%) in 5.56-m-diameter bins either empty or wheat filled. Individual plots are for the sampling times indicated at the bottom of each figure.

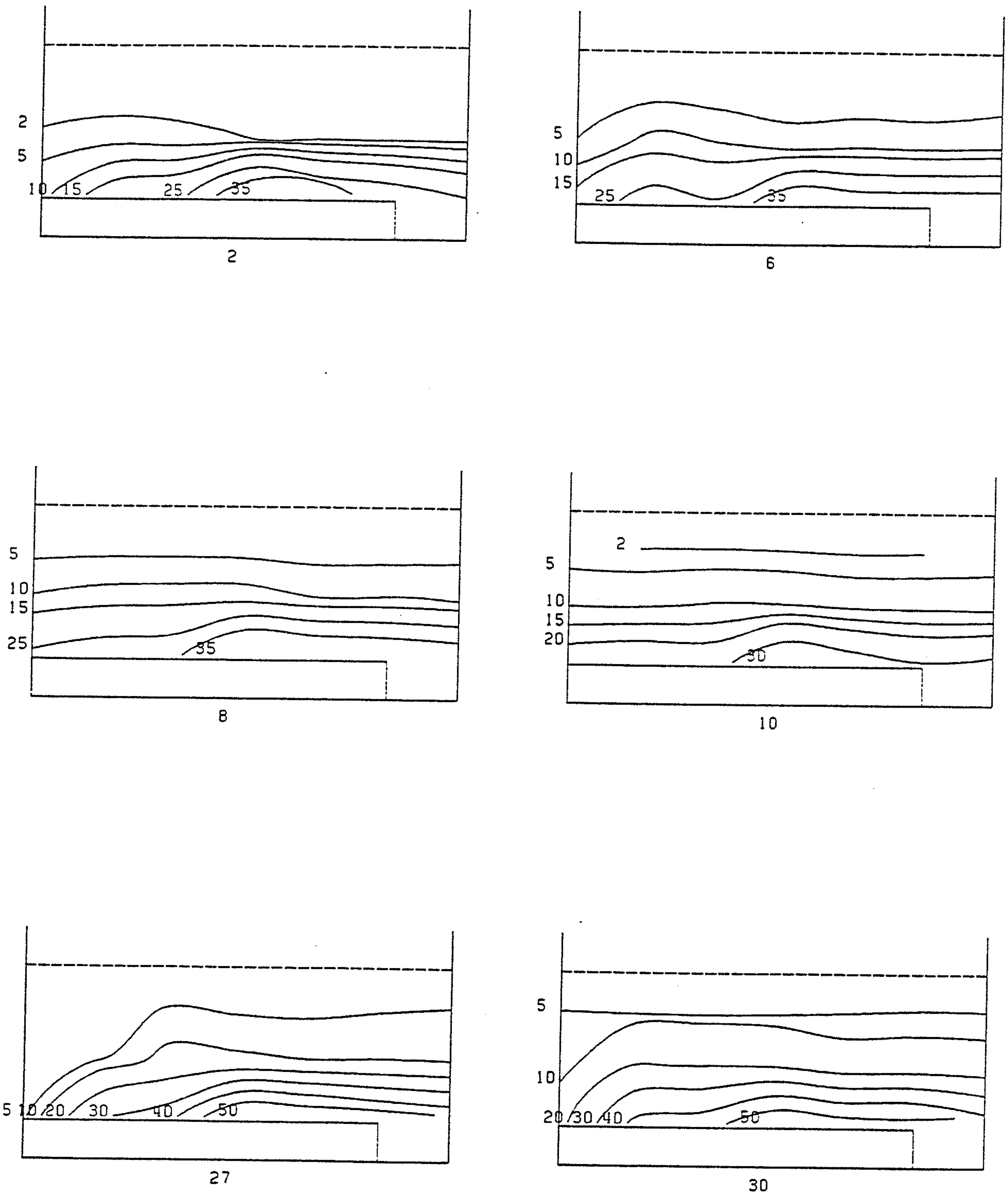

FIG.D.1. EXPERIMENT 1 (ALONG SECTION A-A)

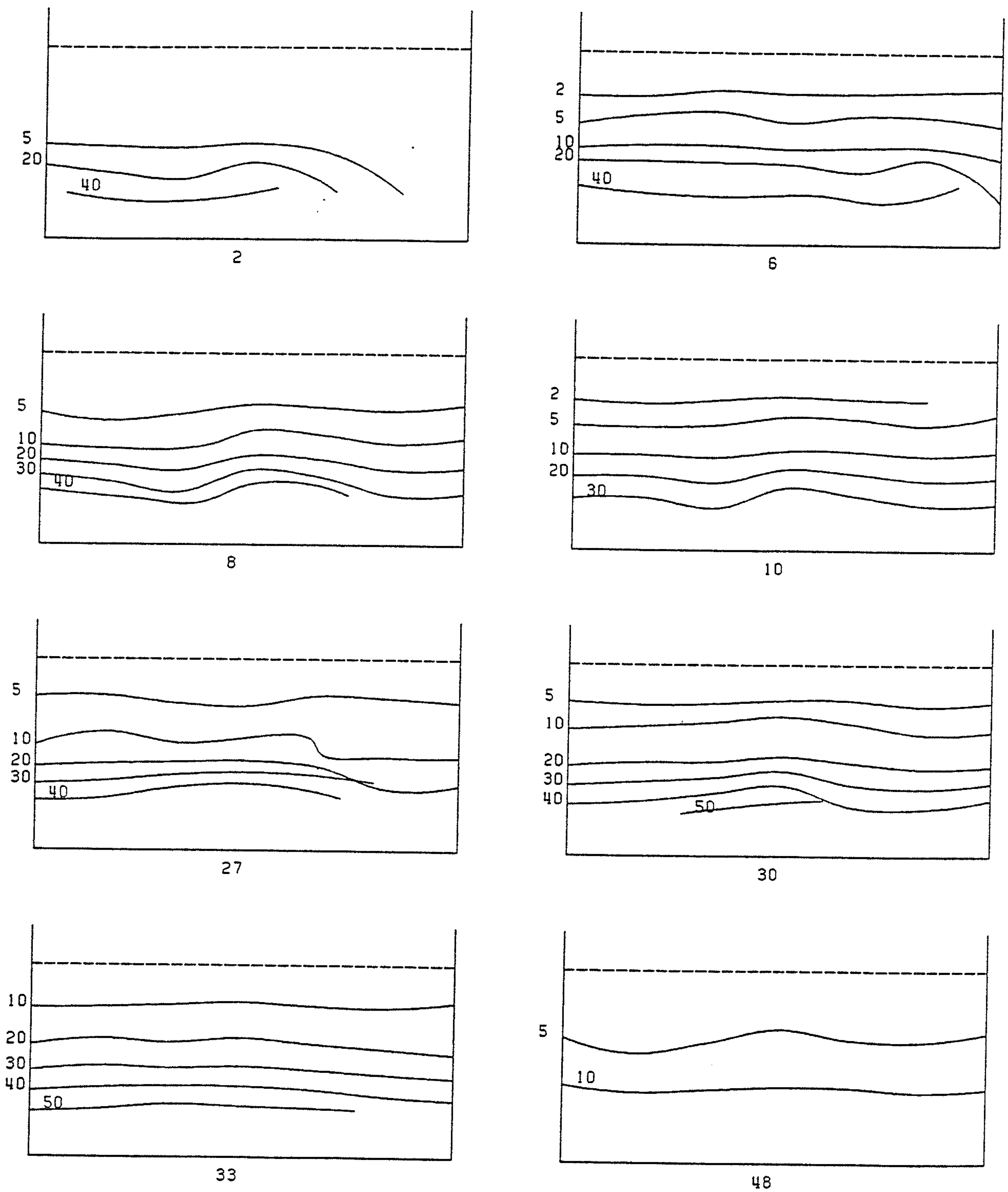

FIG.D.2. EXPERIMENT 1 (ALONG SECTION B-B)

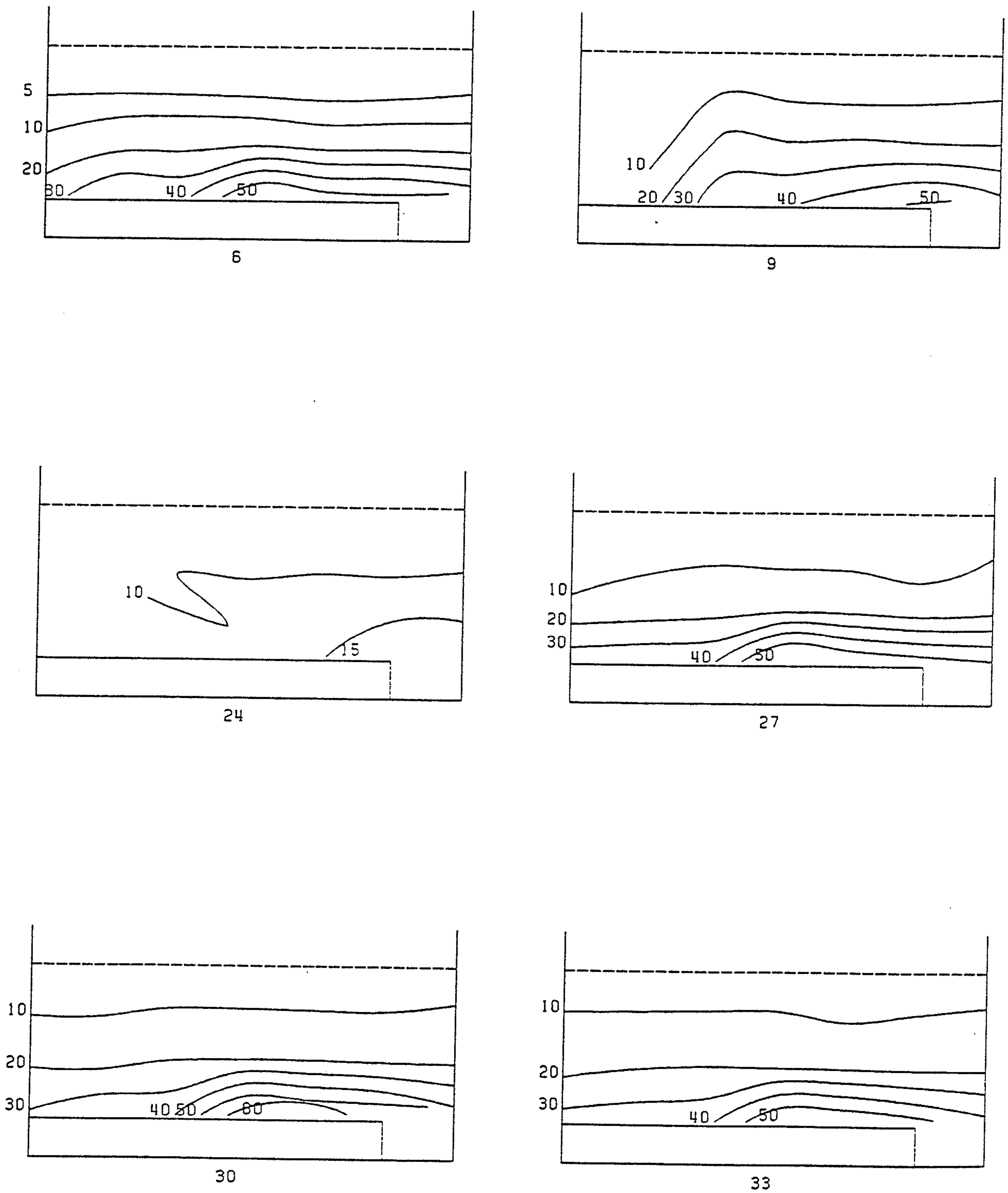

FIG.D.3. EXPERIMENT 2 (ALONG SECTION A-A)

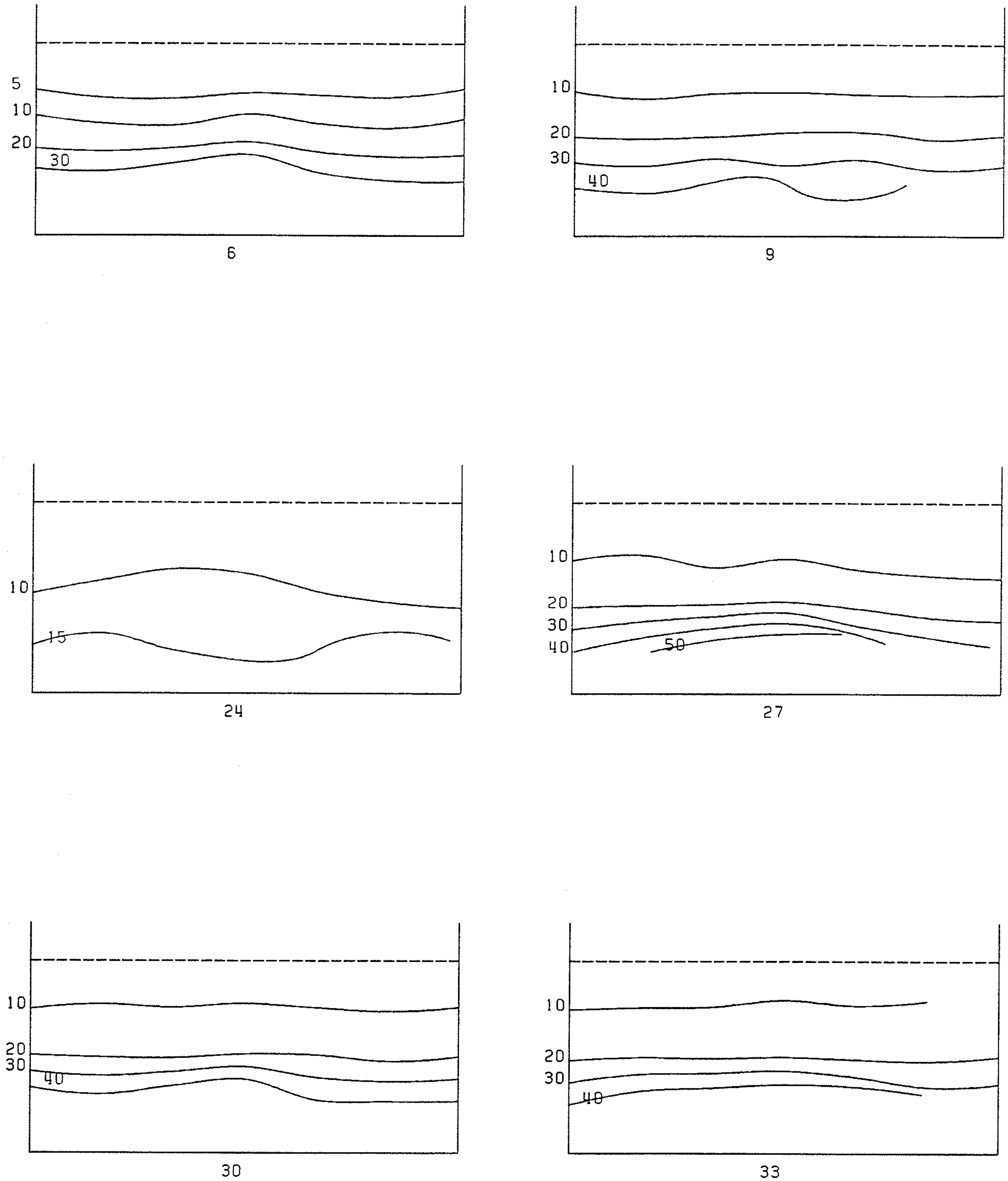

FIG.D.4. EXPERIMENT 2 (ALONG SECTION B-B)

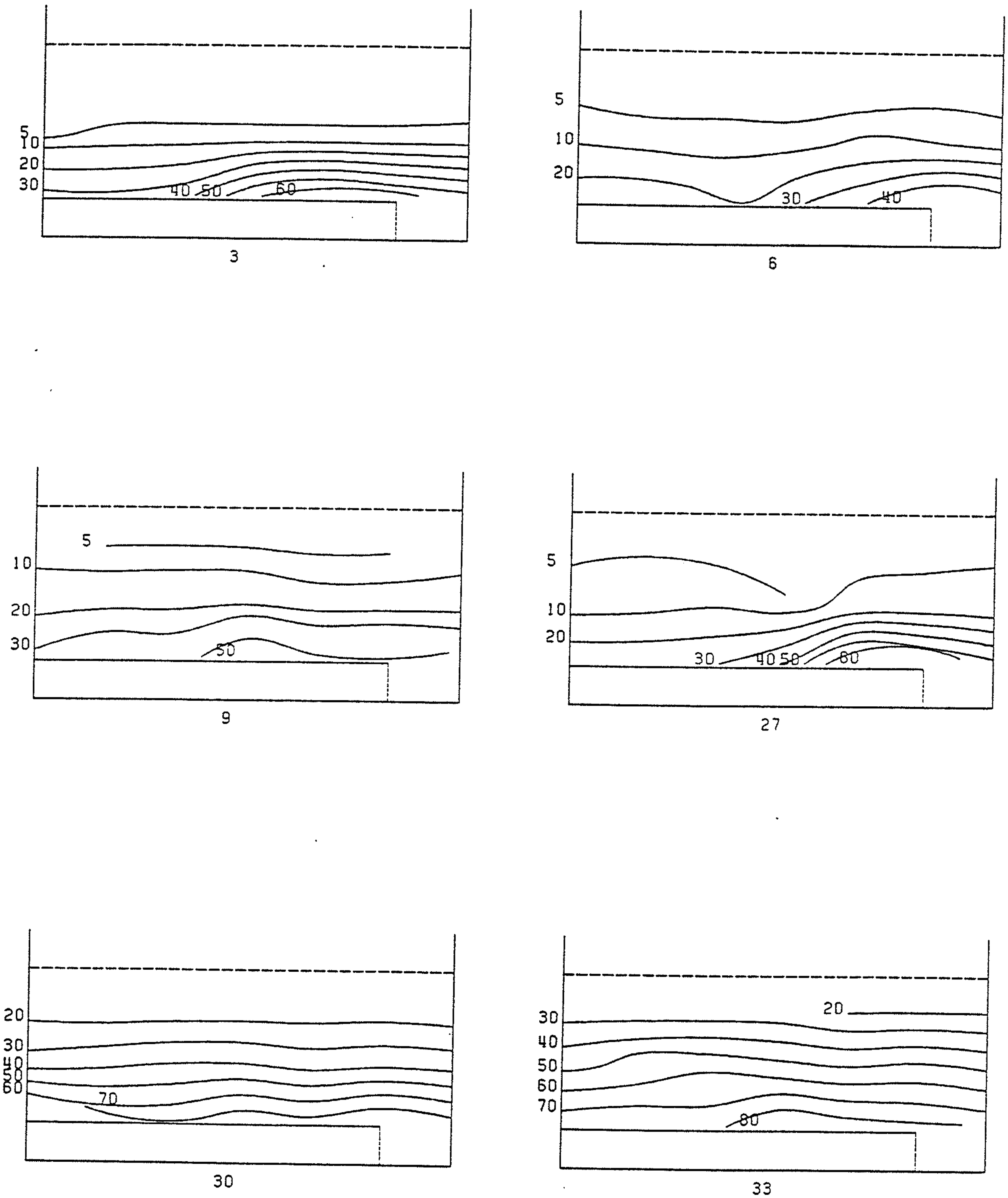

FIG.D.5. EXPERIMENT 3 (ALONG SECTION A-A)

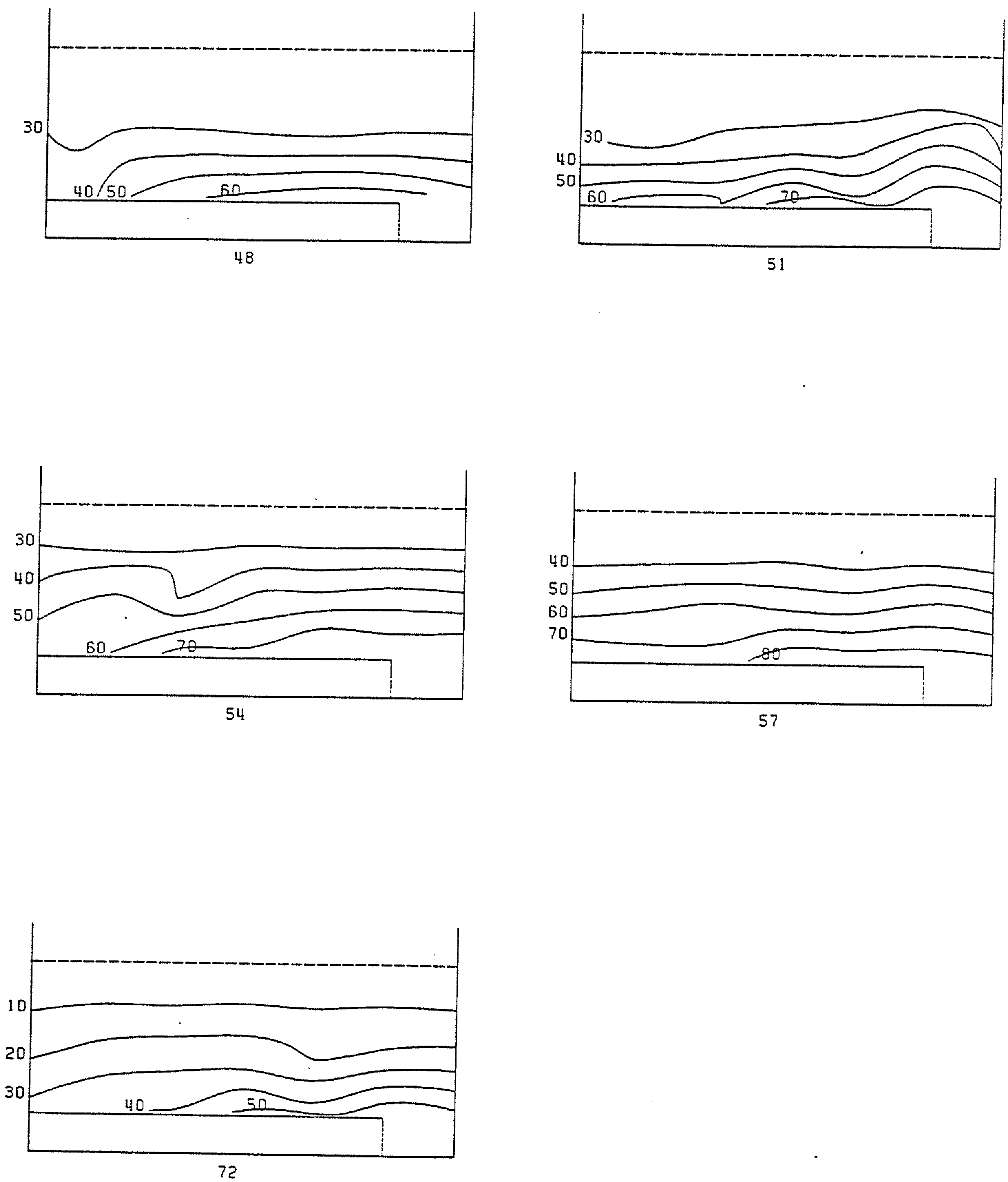

FIG.D.5 (CONTINUED). EXPERIMENT 3 (ALONG SECTION A-A)

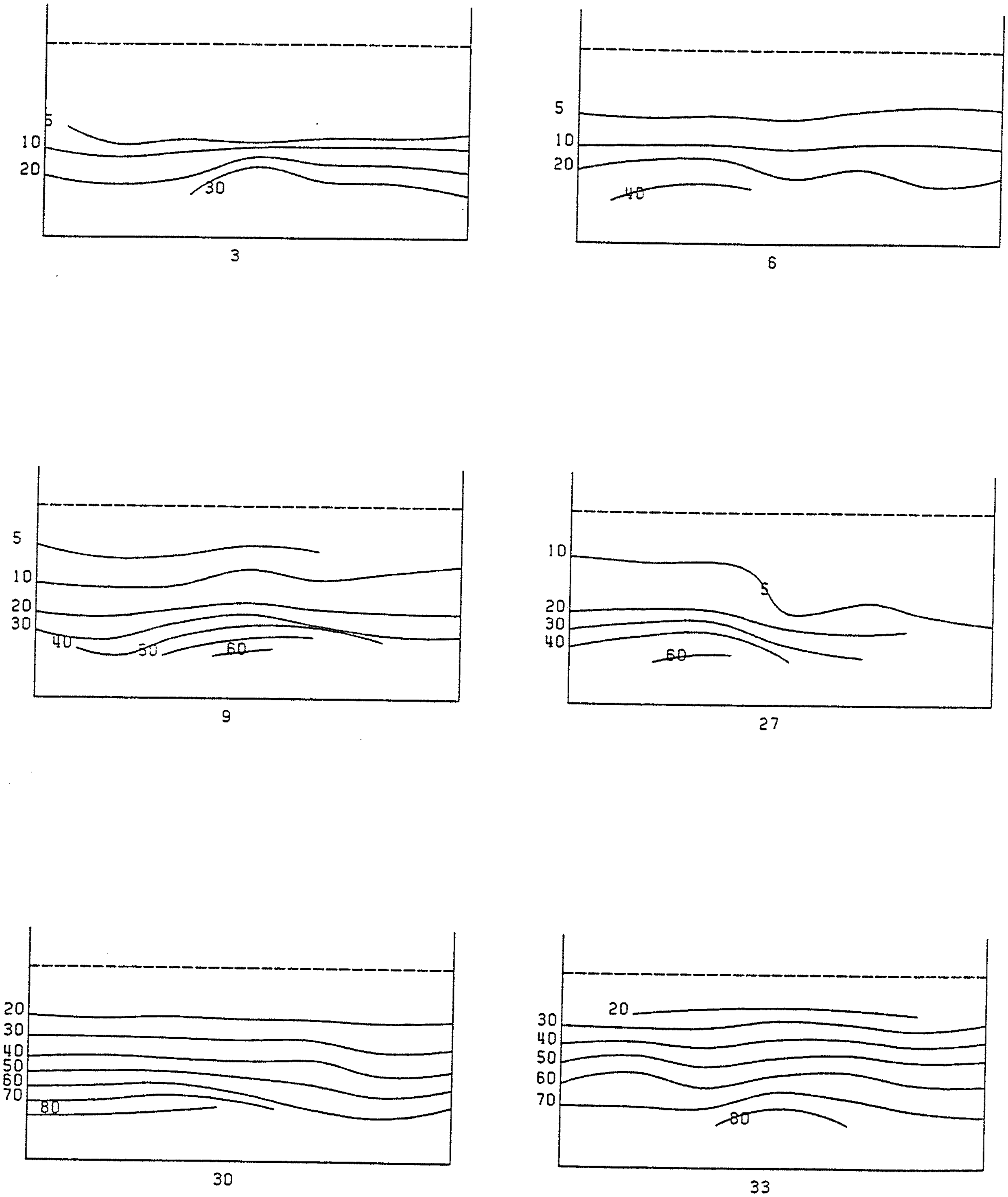

FIG.D.6. EXPERIMENT 3 (ALONG SECTION B-B)

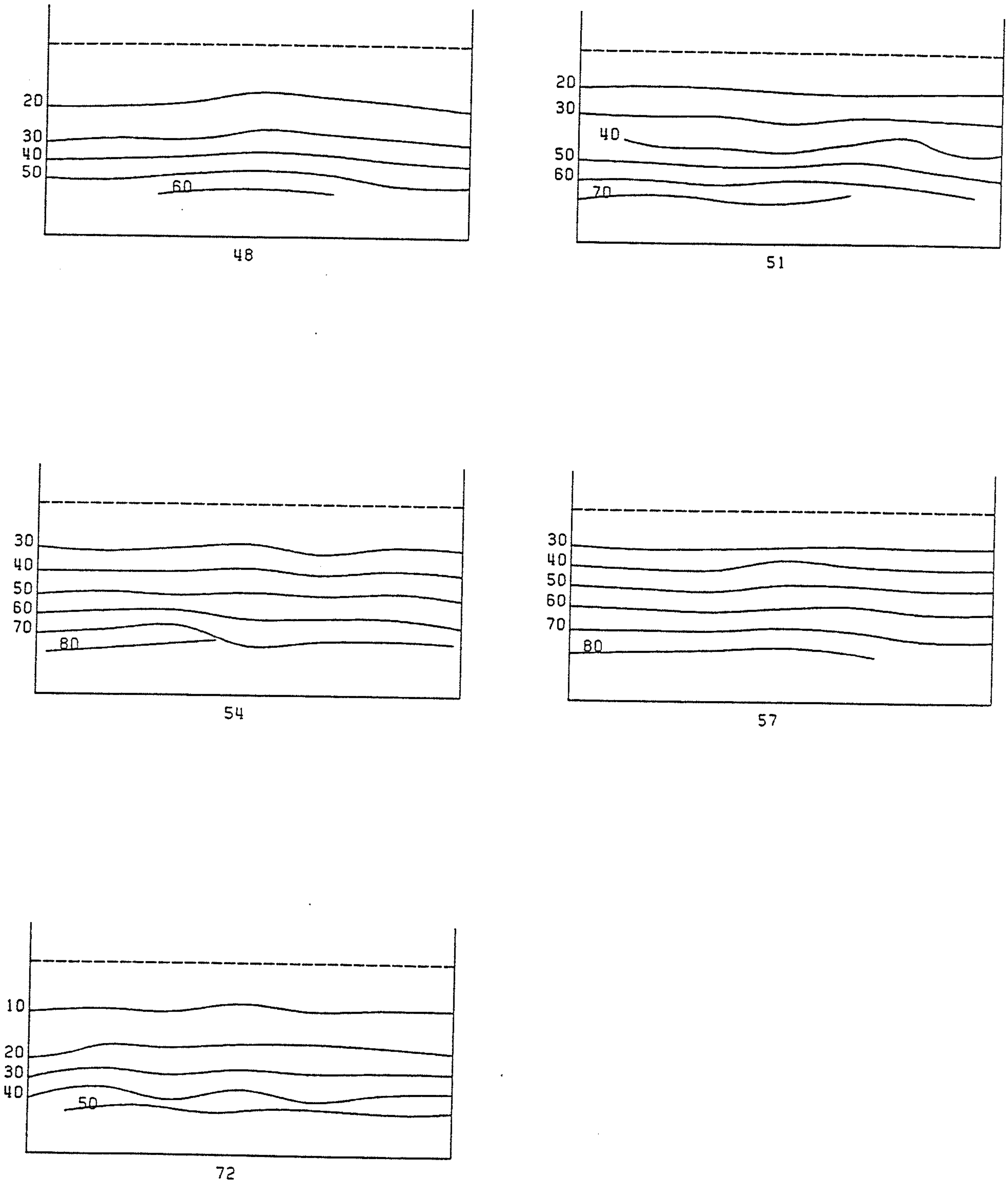

FIG.D.6 (CONTINUED). EXPERIMENT 3 (ALONG SECTION B-B)

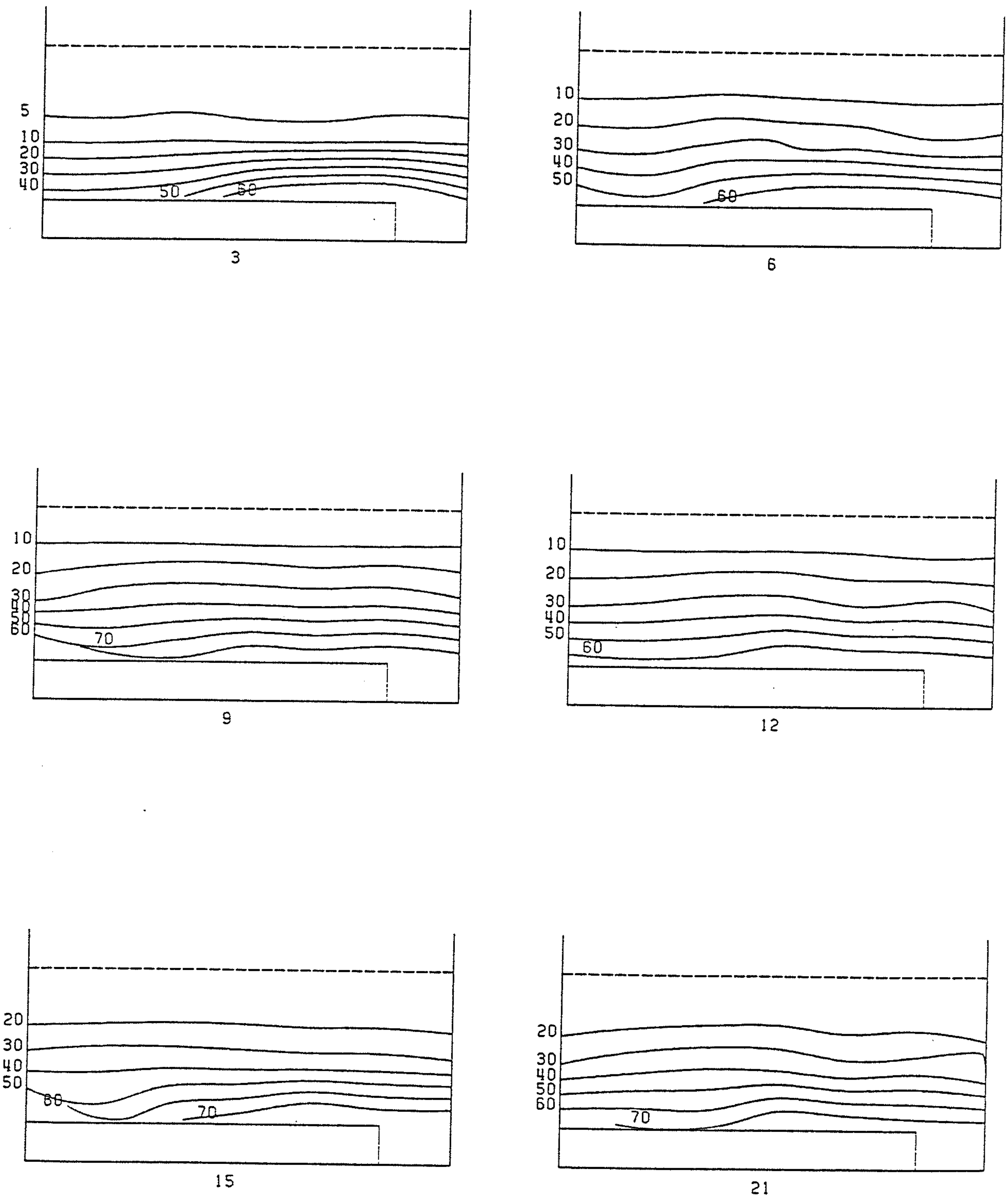

FIG.D.7. EXPERIMENT 4 (ALONG SECTION A-A)

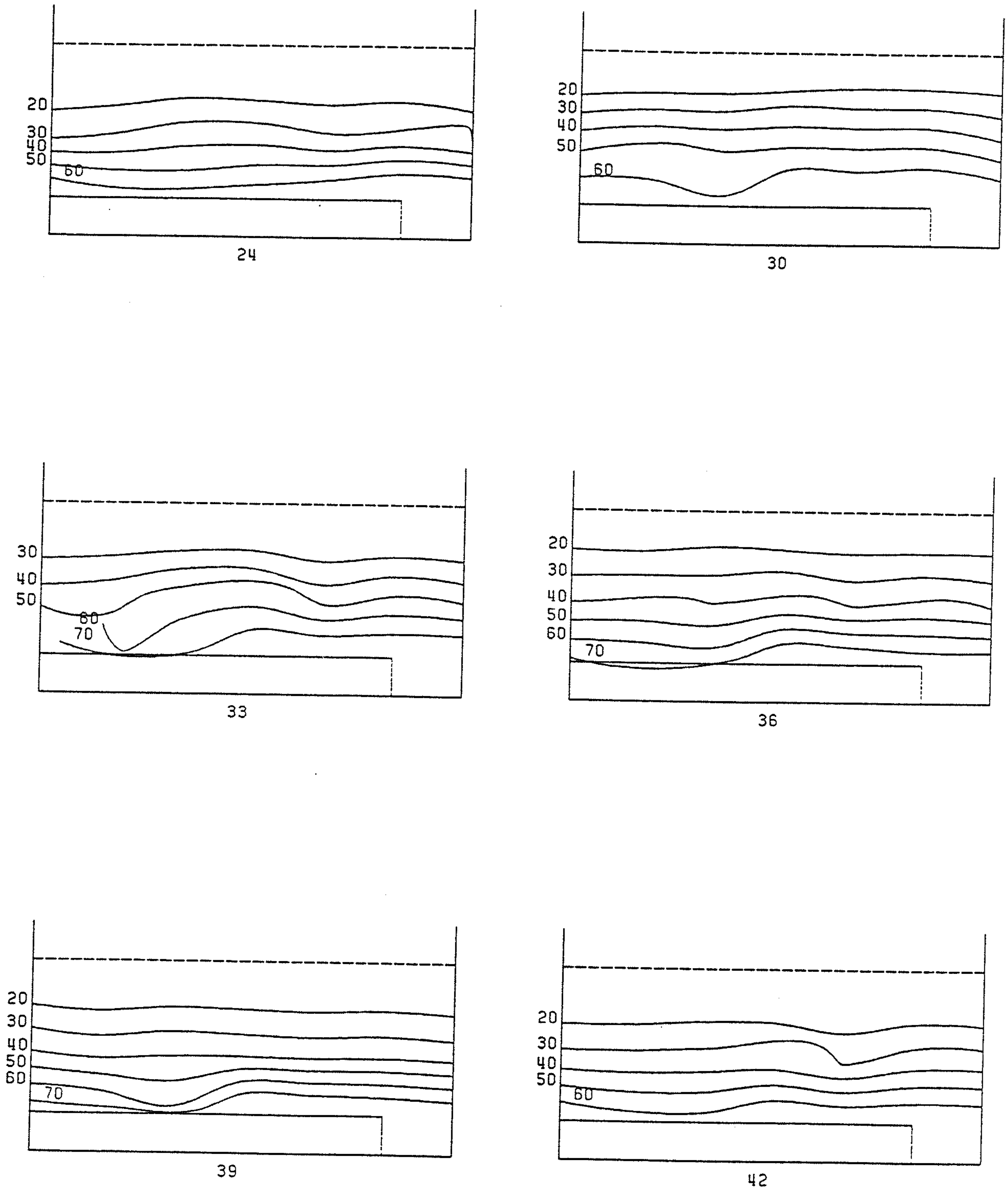

FIG.D.7 (CONTINUED). EXPERIMENT 4 (ALONG SECTION A-A)

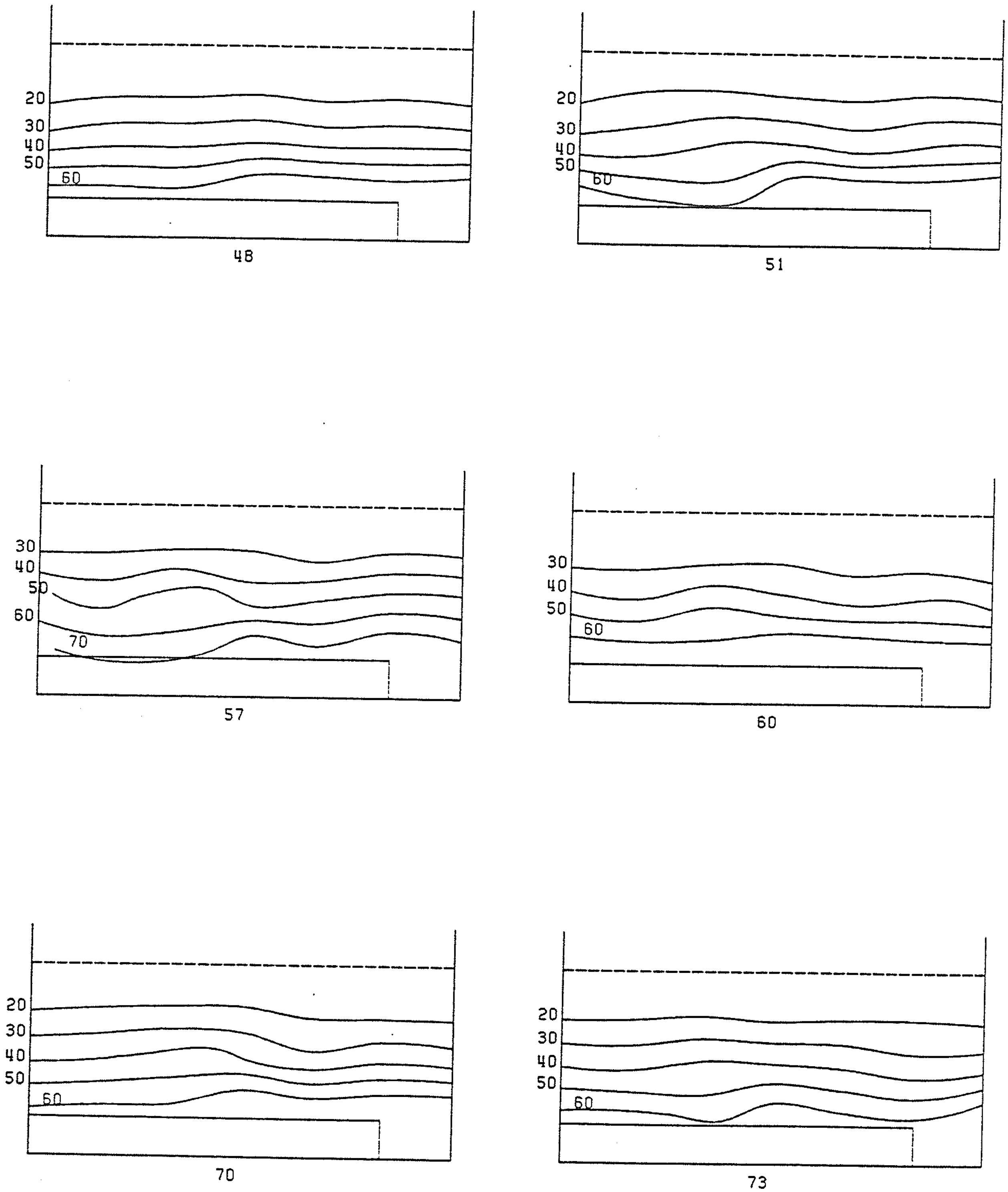

FIG.D.7 (CONTINUED). EXPERIMENT 4 (ALONG SECTION A-A)

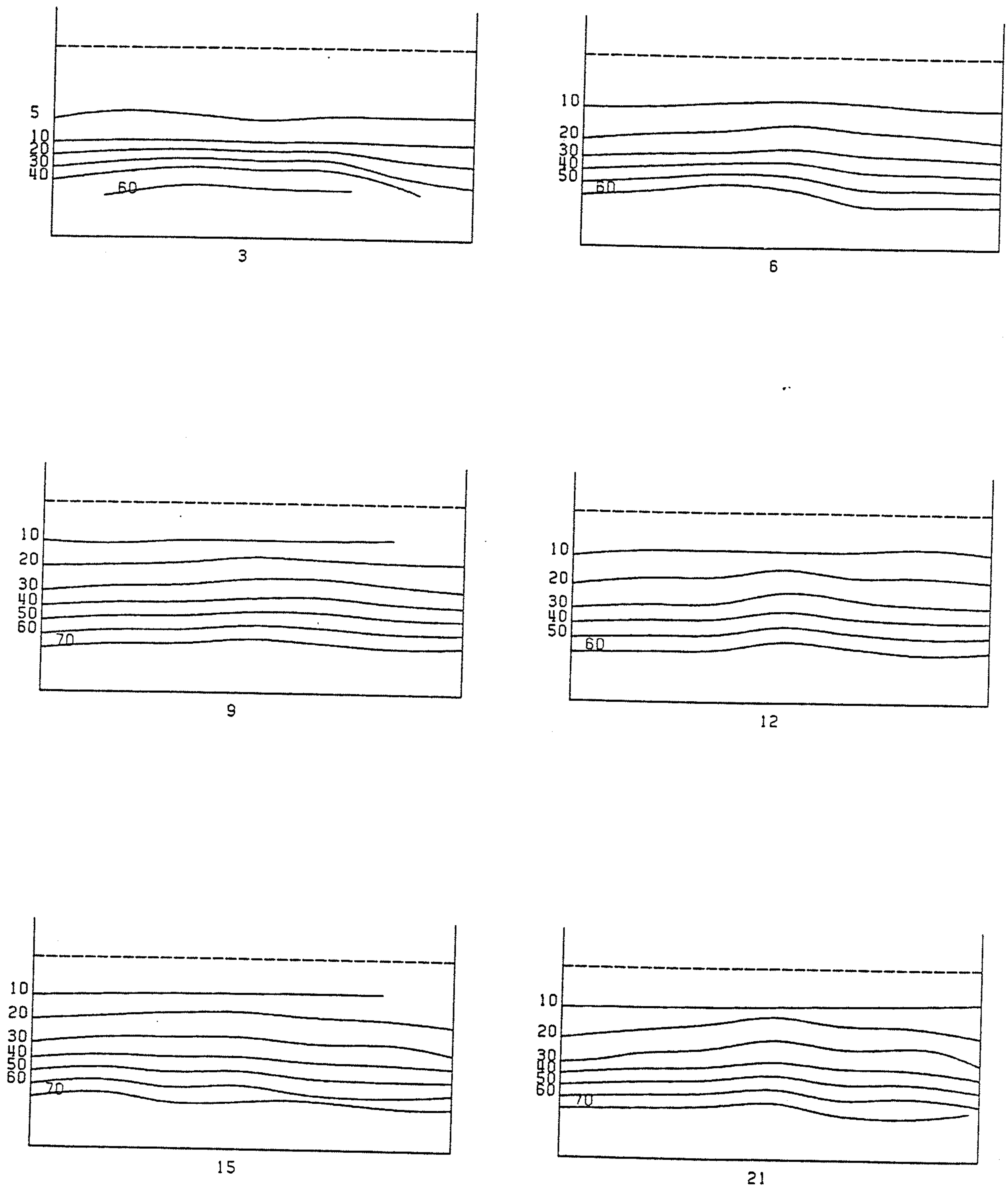

FIG.D.8. EXPERIMENT 4 (ALONG SECTION B-B)

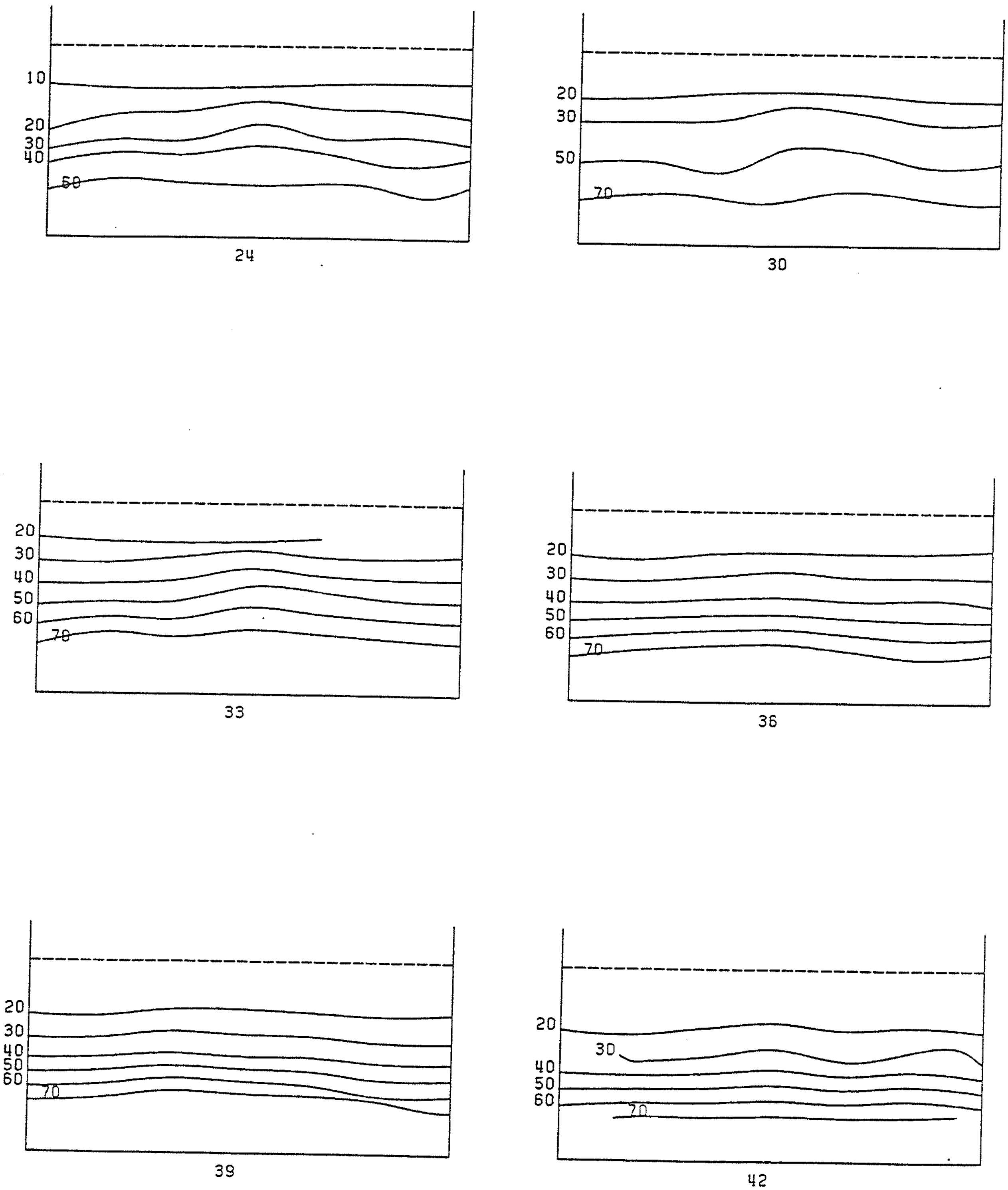

FIG.D.8. (CONTINUED). EXPERIMENT 4 (ALONG SECTION B-B)

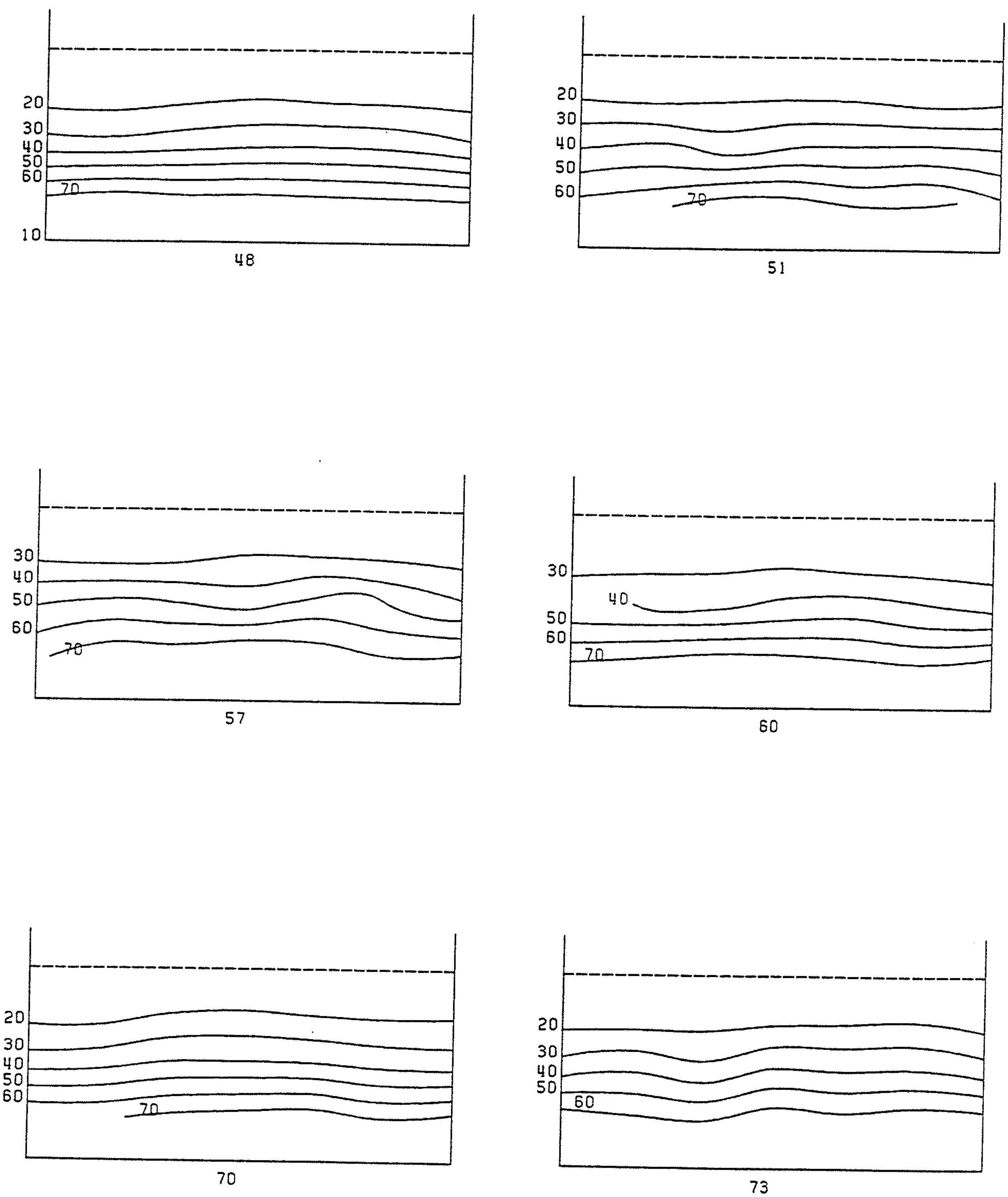

FIG.D.8. (CONTINUED). EXPERIMENT 4 (ALONG SECTION B-B)

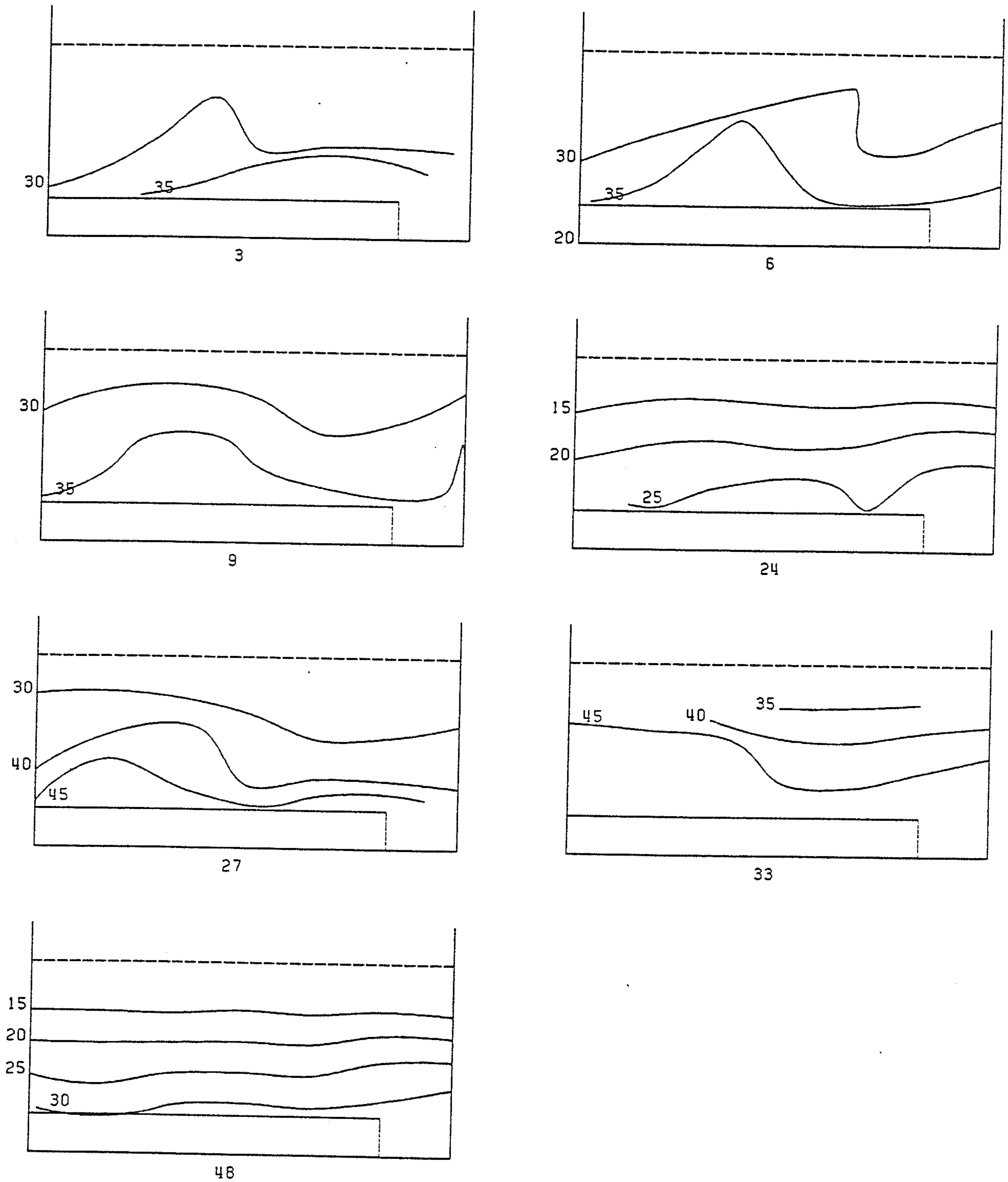

FIG.D.9. EXPERIMENT 5 (ALONG SECTION A-A)

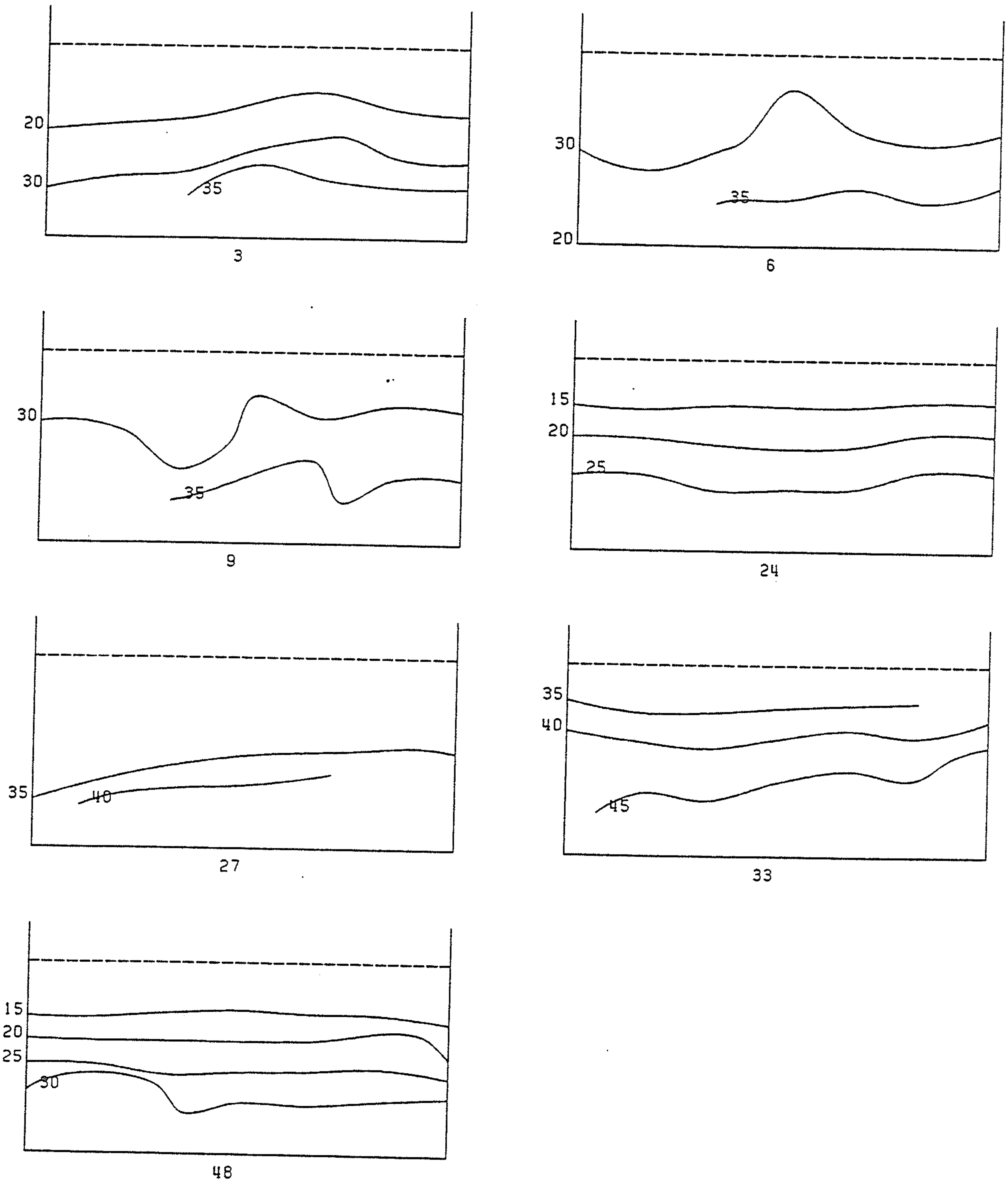

FIG.D.10. EXPERIMENT 5 (ALONG SECTION B-B)

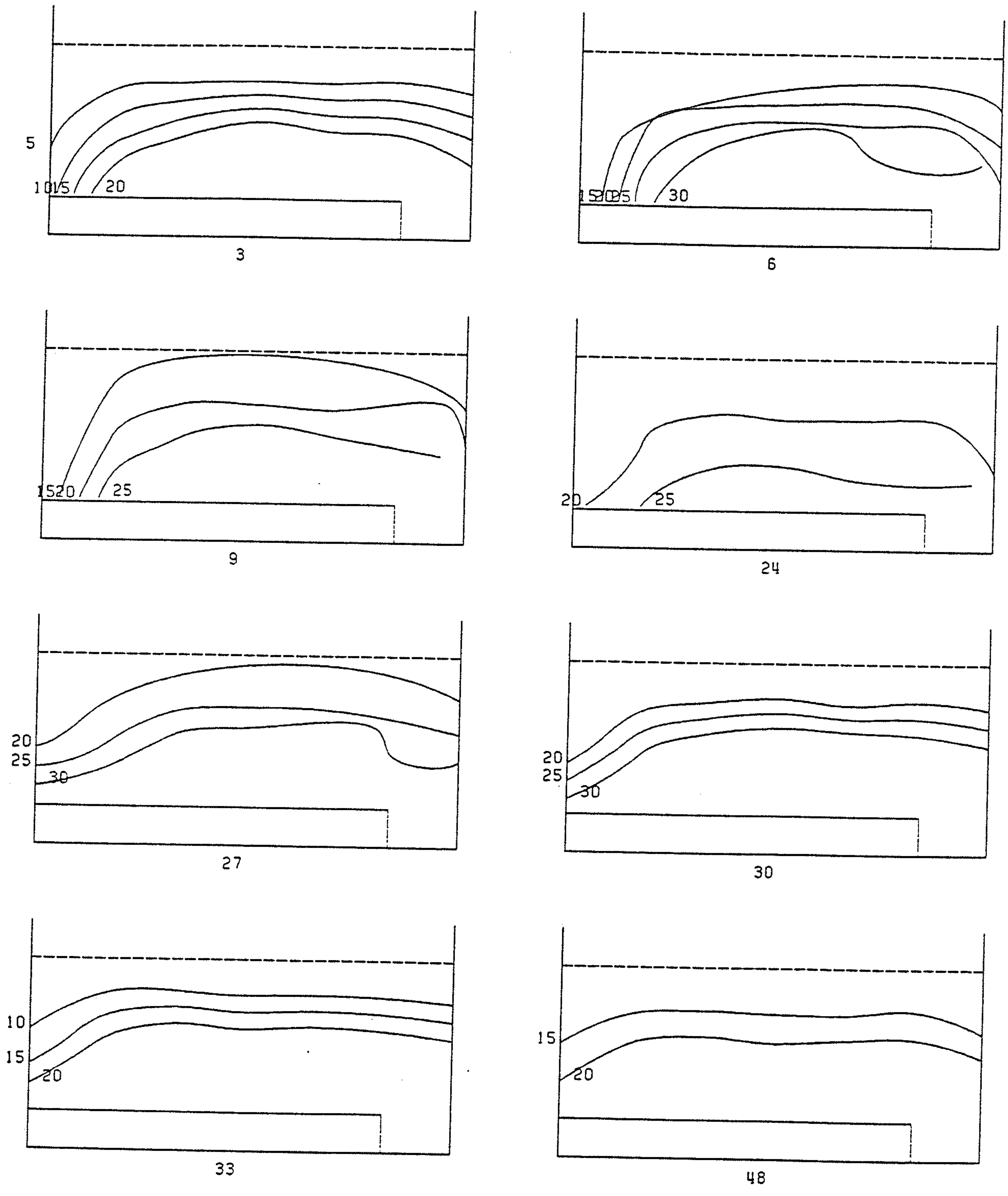

FIG. D.11. EXPERIMENT 6 (ALONG SECTION A-A)

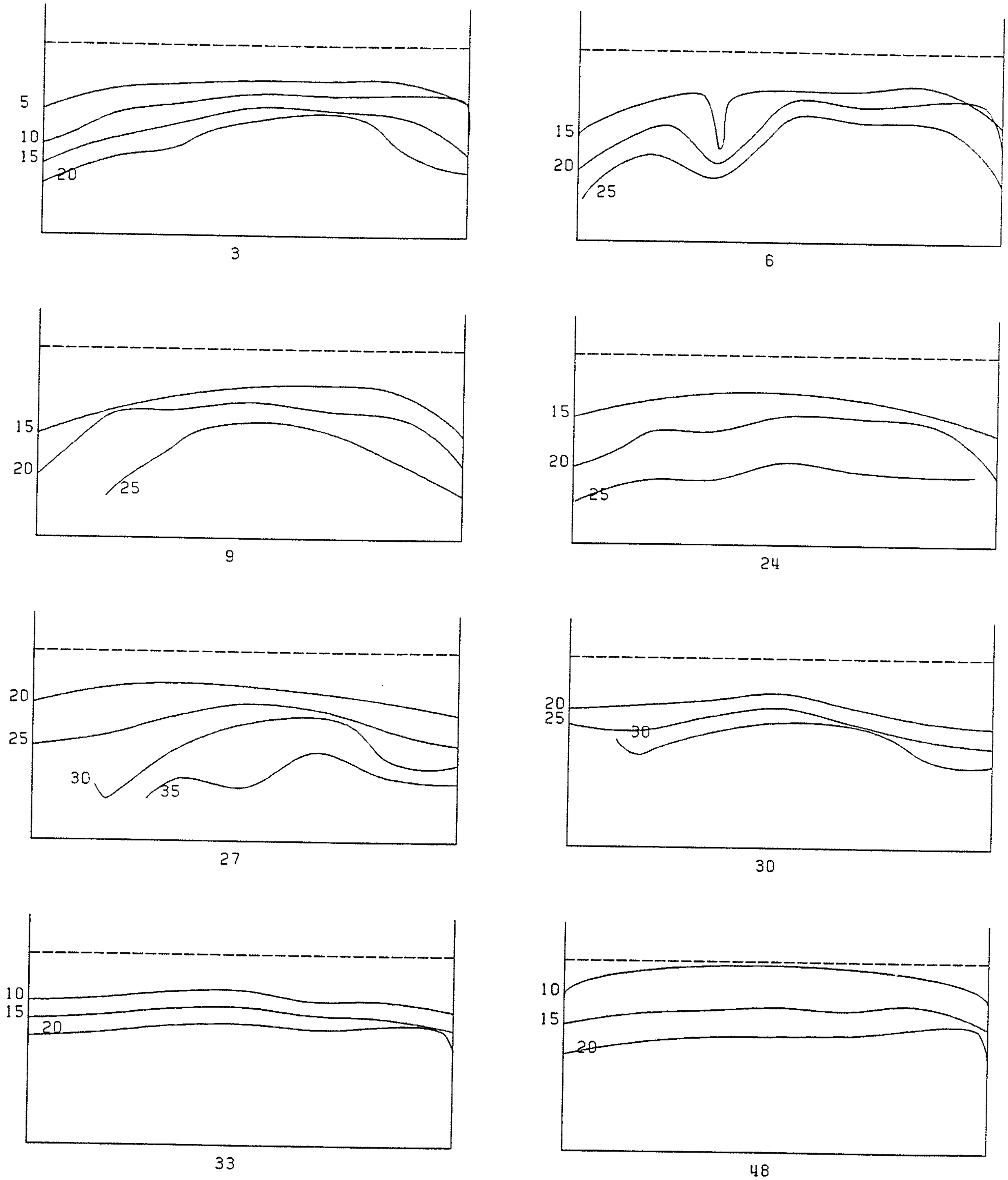

FIG.D.12. EXPERIMENT 6 (ALONG SECTION B-B)

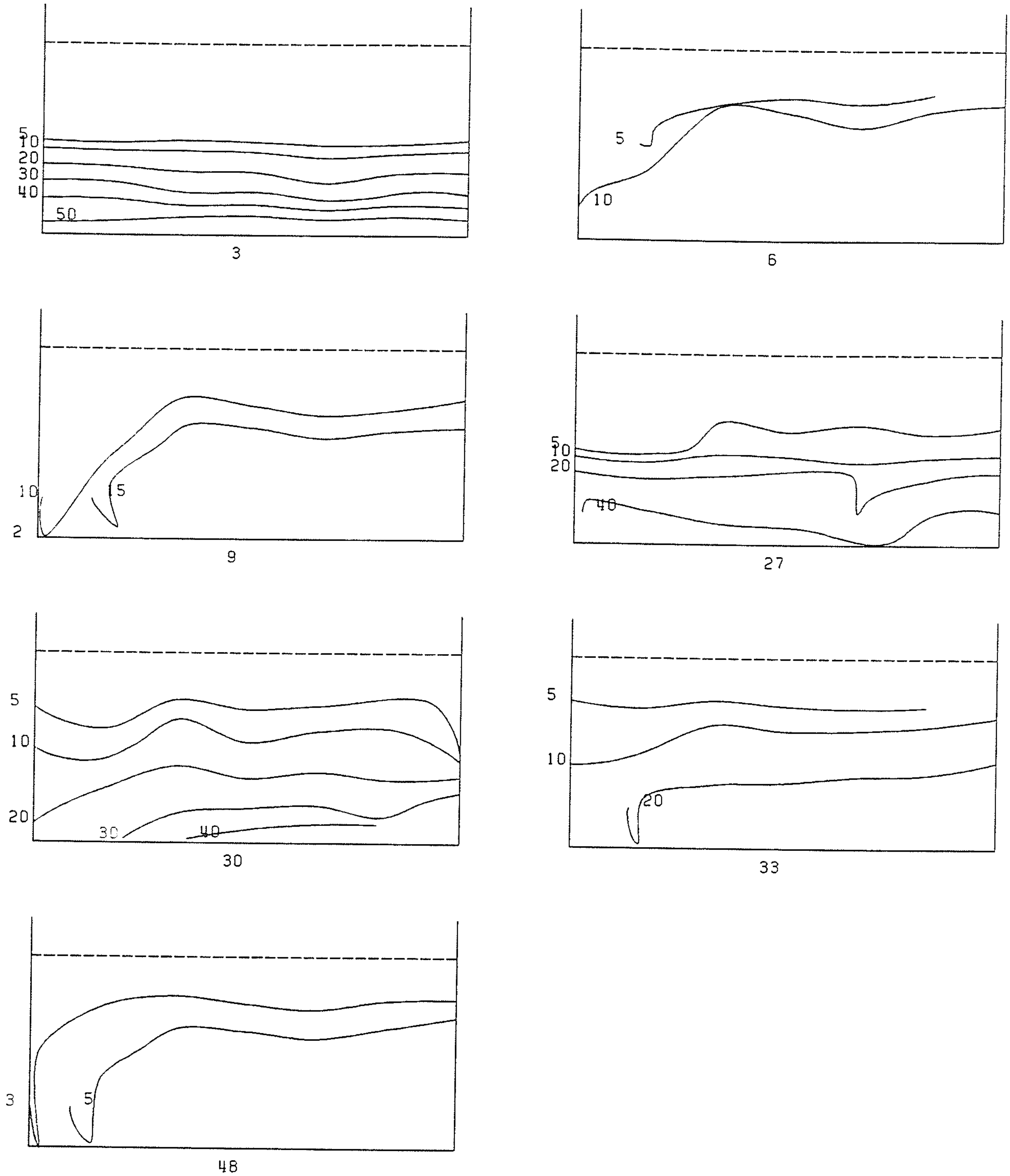

FIG.D.13. EXPERIMENT 7 (ALONG SECTION A-A)

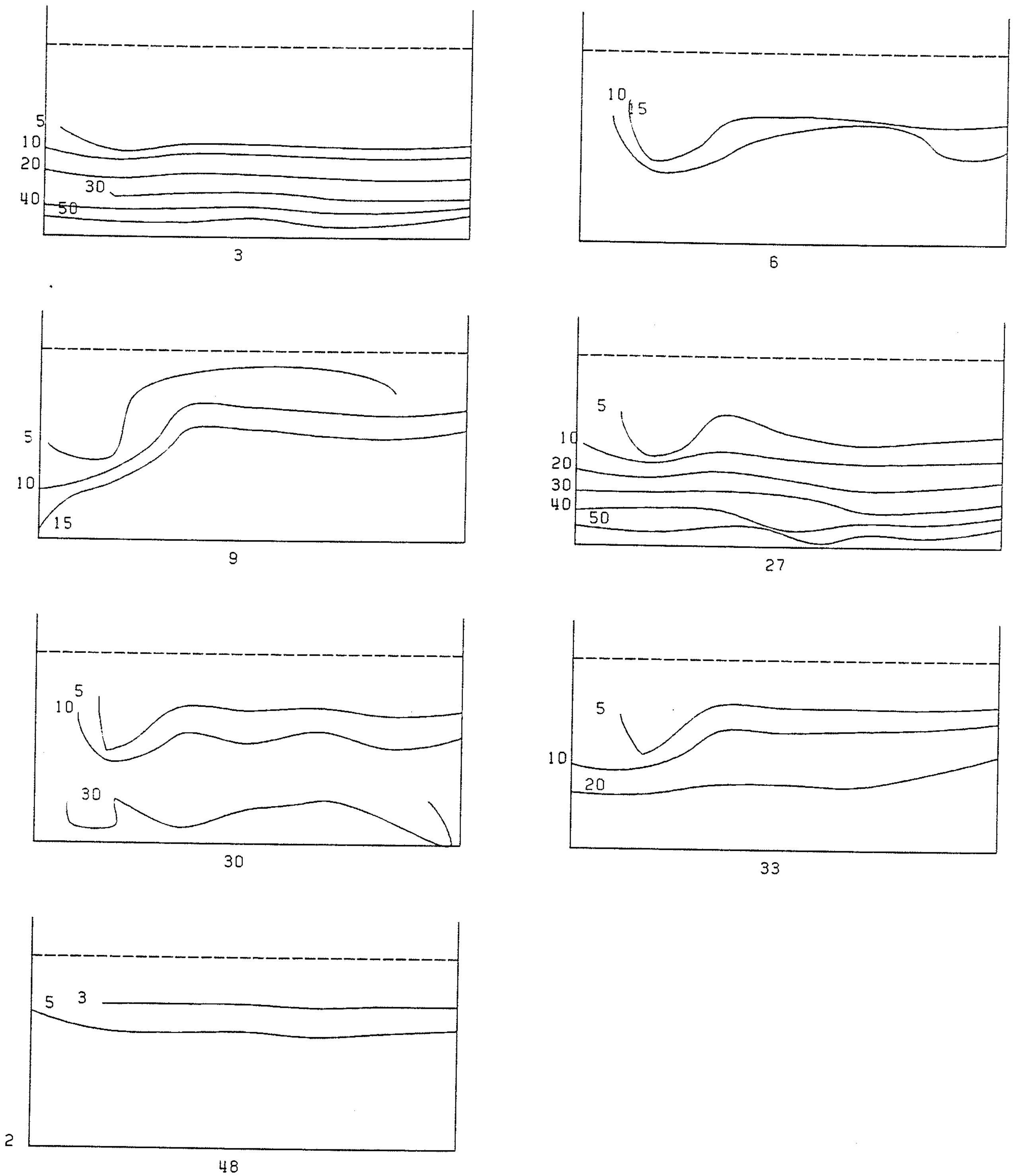

FIG.D.14. EXPERIMENT 7 (ALONG SECTION B-B)

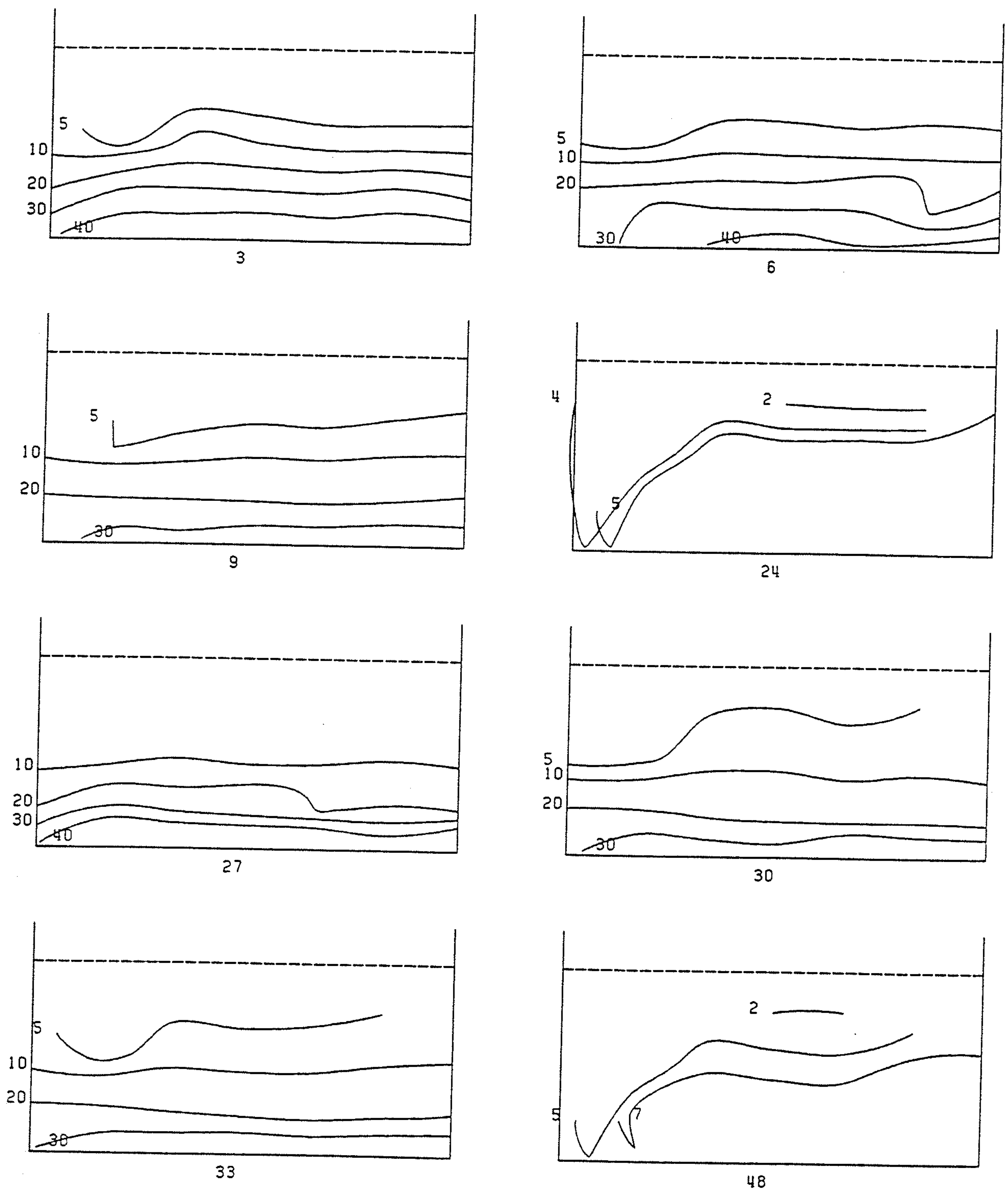

FIG.D.15. EXPERIMENT 8 (ALONG SECTION A-A)

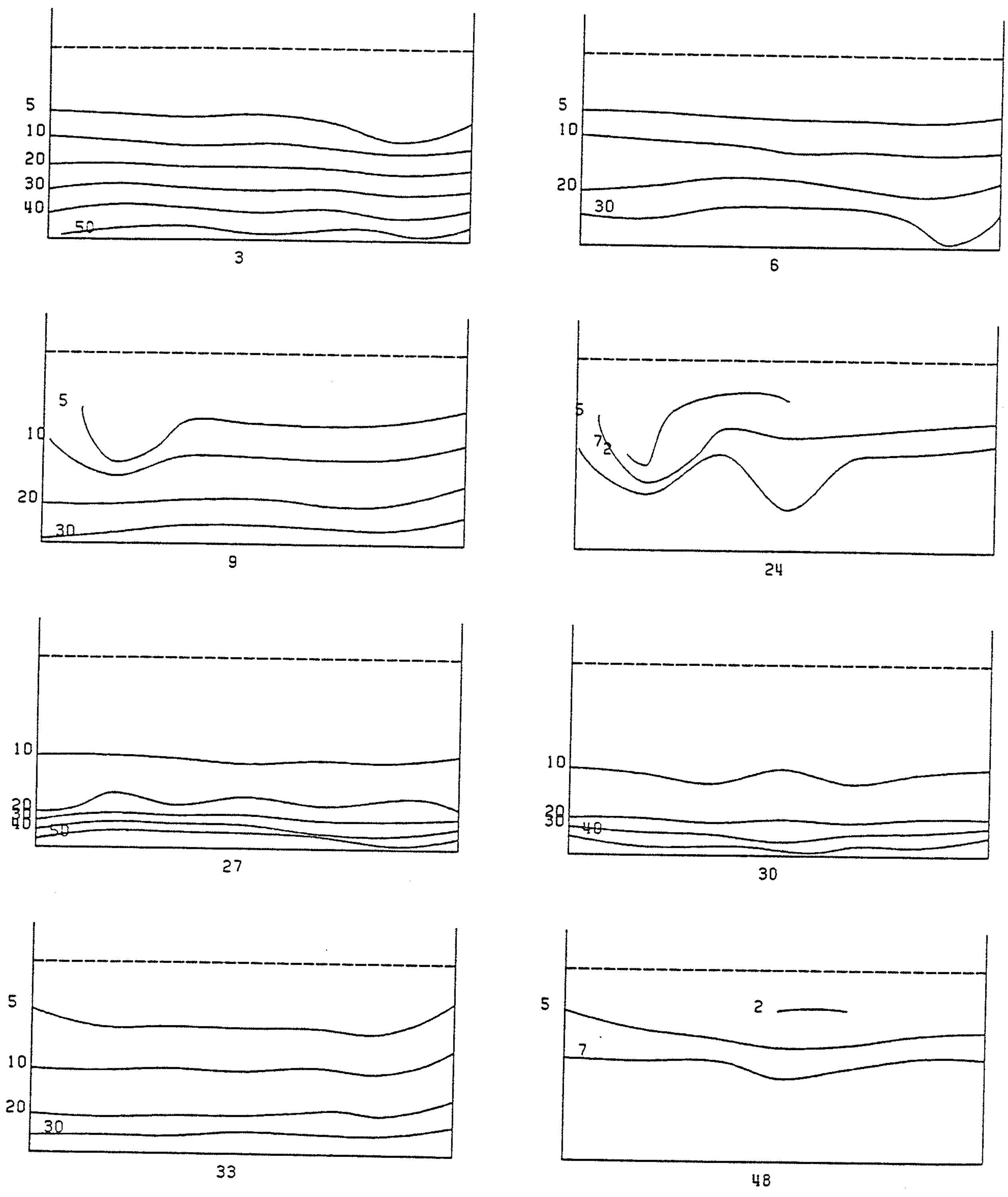

FIG.D.16. EXPERIMENT 8 (ALONG SECTION B-B)

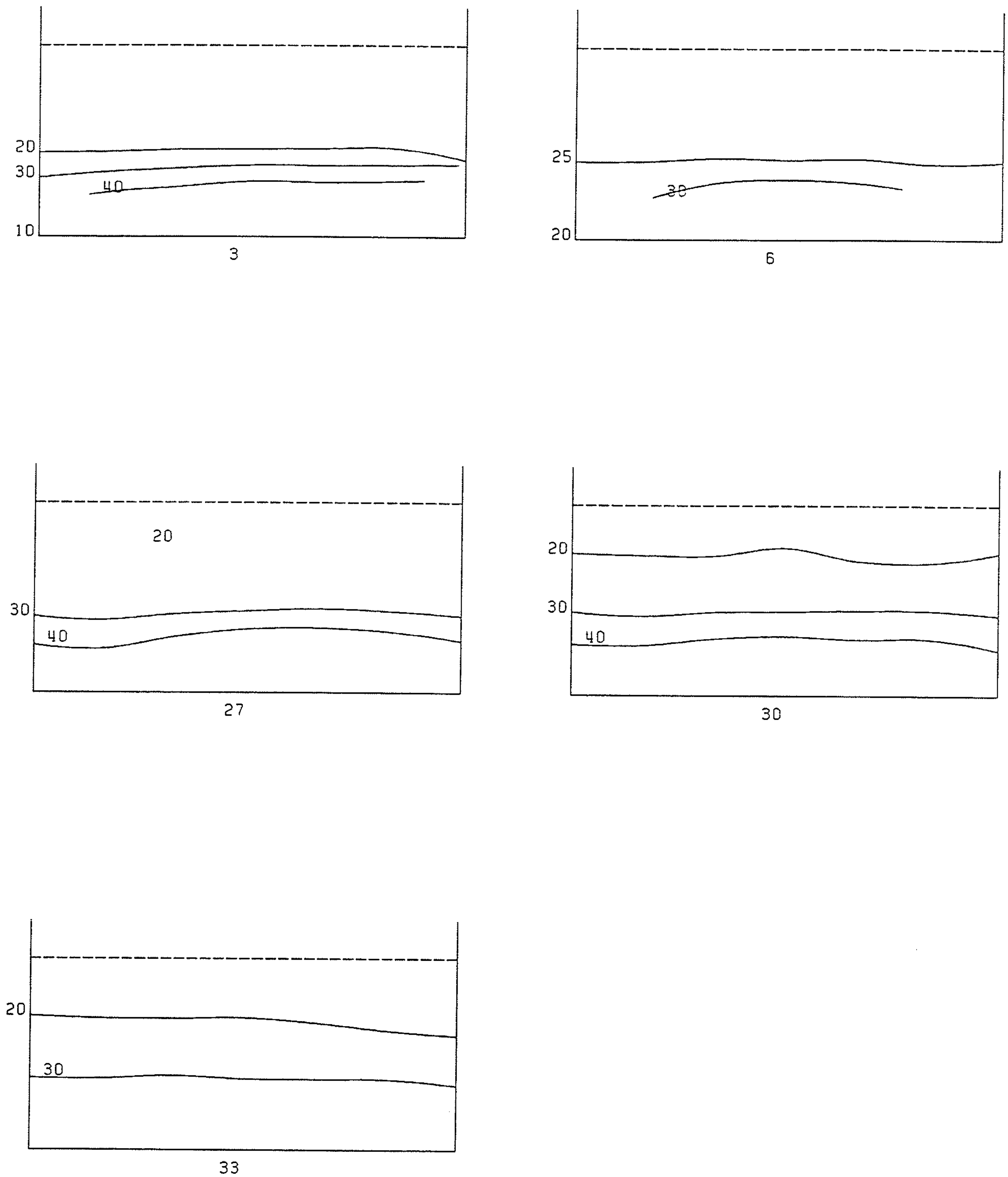

FIG.D.17. EXPERIMENT 9 (ALONG SECTION A-A)

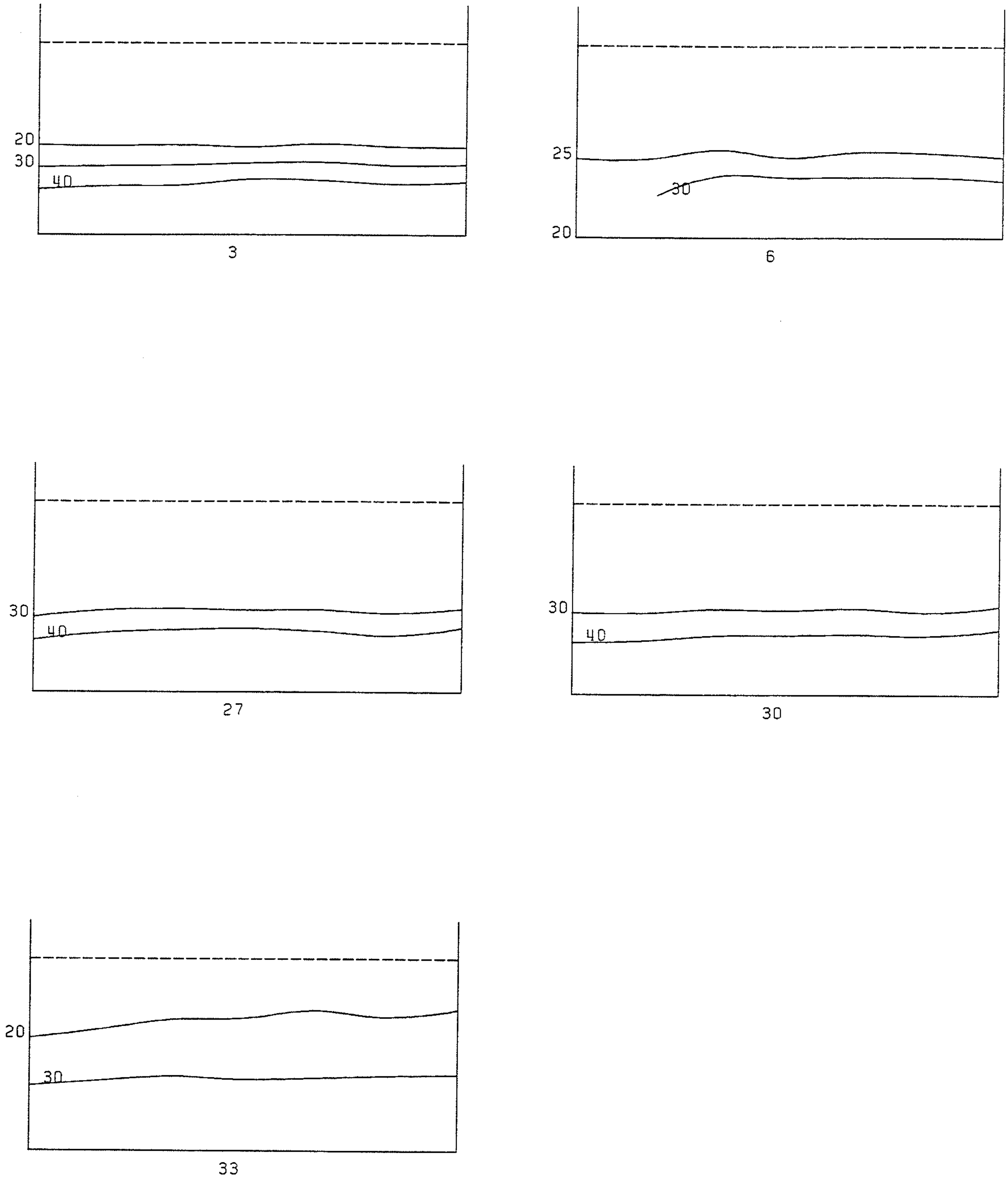

FIG.D.18. EXPERIMENT 9 (ALONG SECTION B-B)

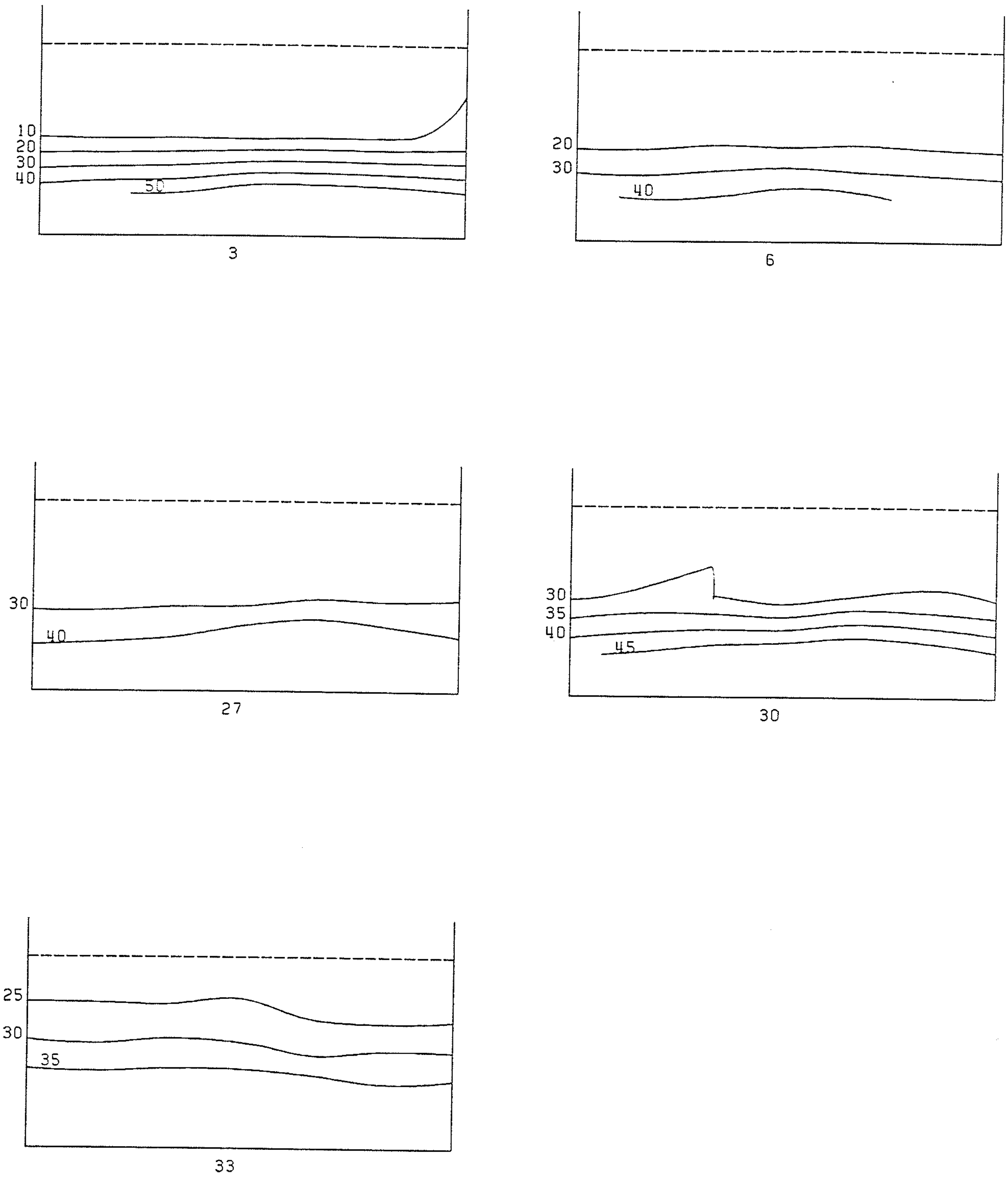

FIG.D.19. EXPERIMENT 10 (ALONG SECTION A-A)

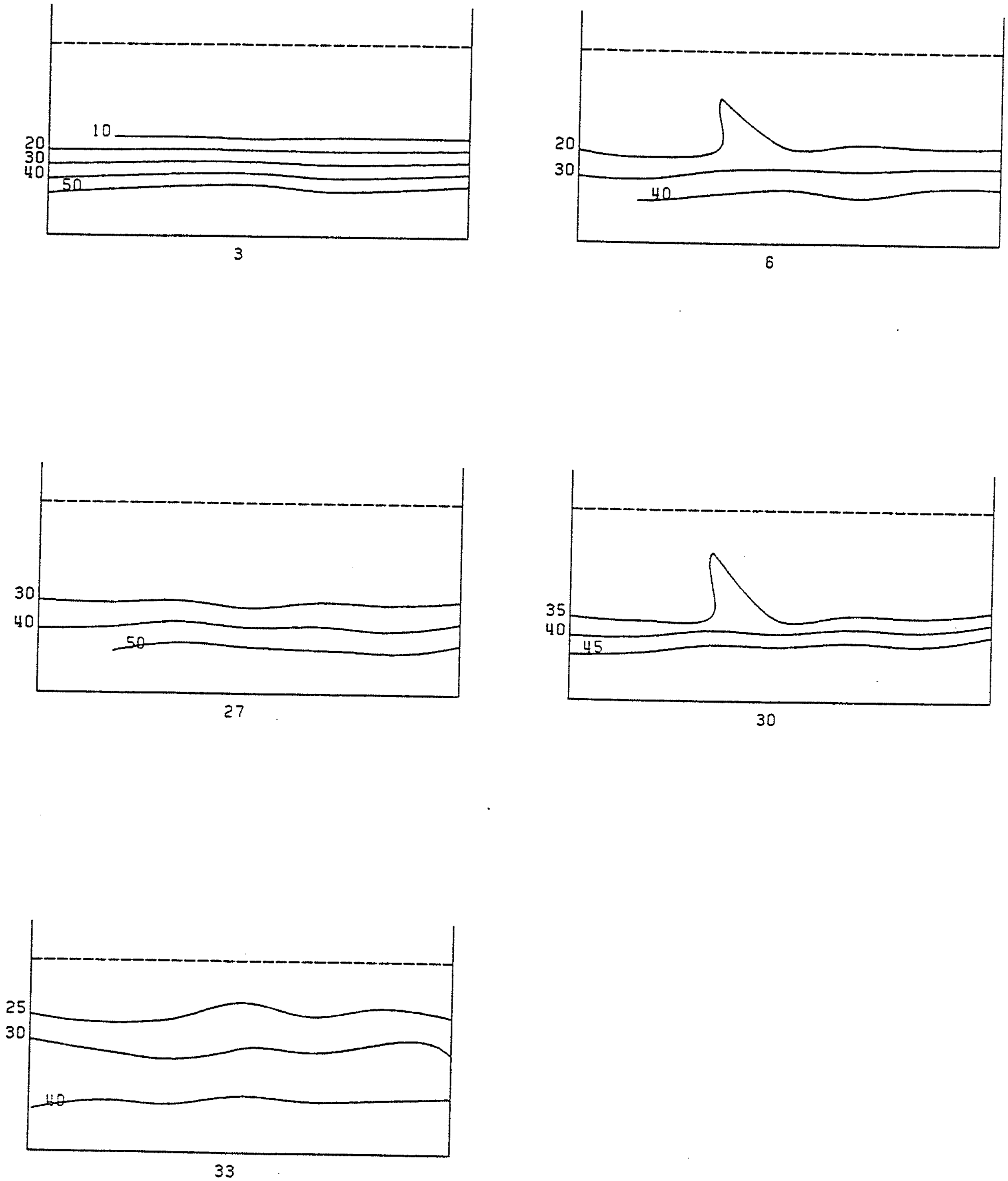

FIG.D.20. EXPERIMENT 10 (ALONG SECTION B-B)

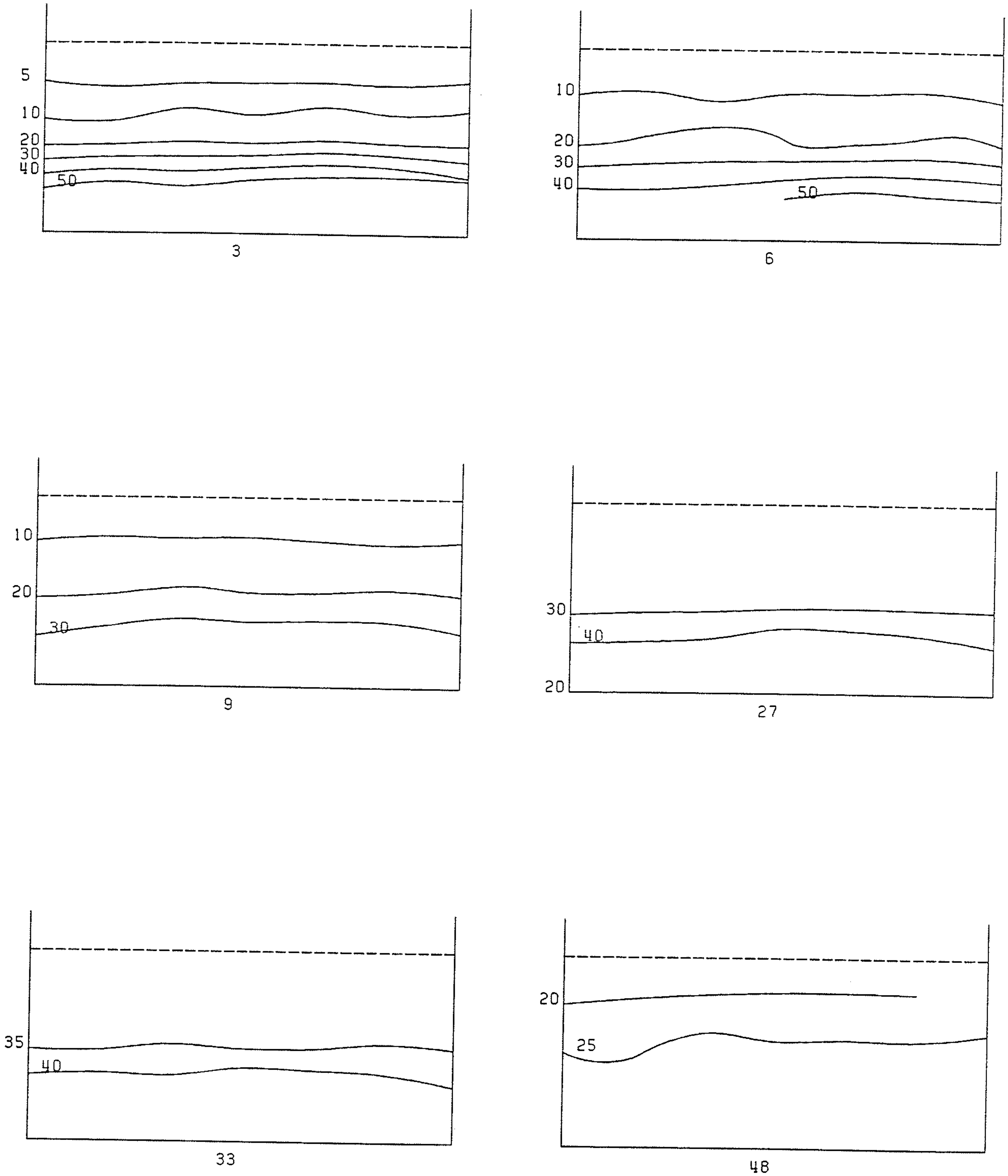

FIG.D.21. EXPERIMENT 11 (ALONG SECTION A-A)

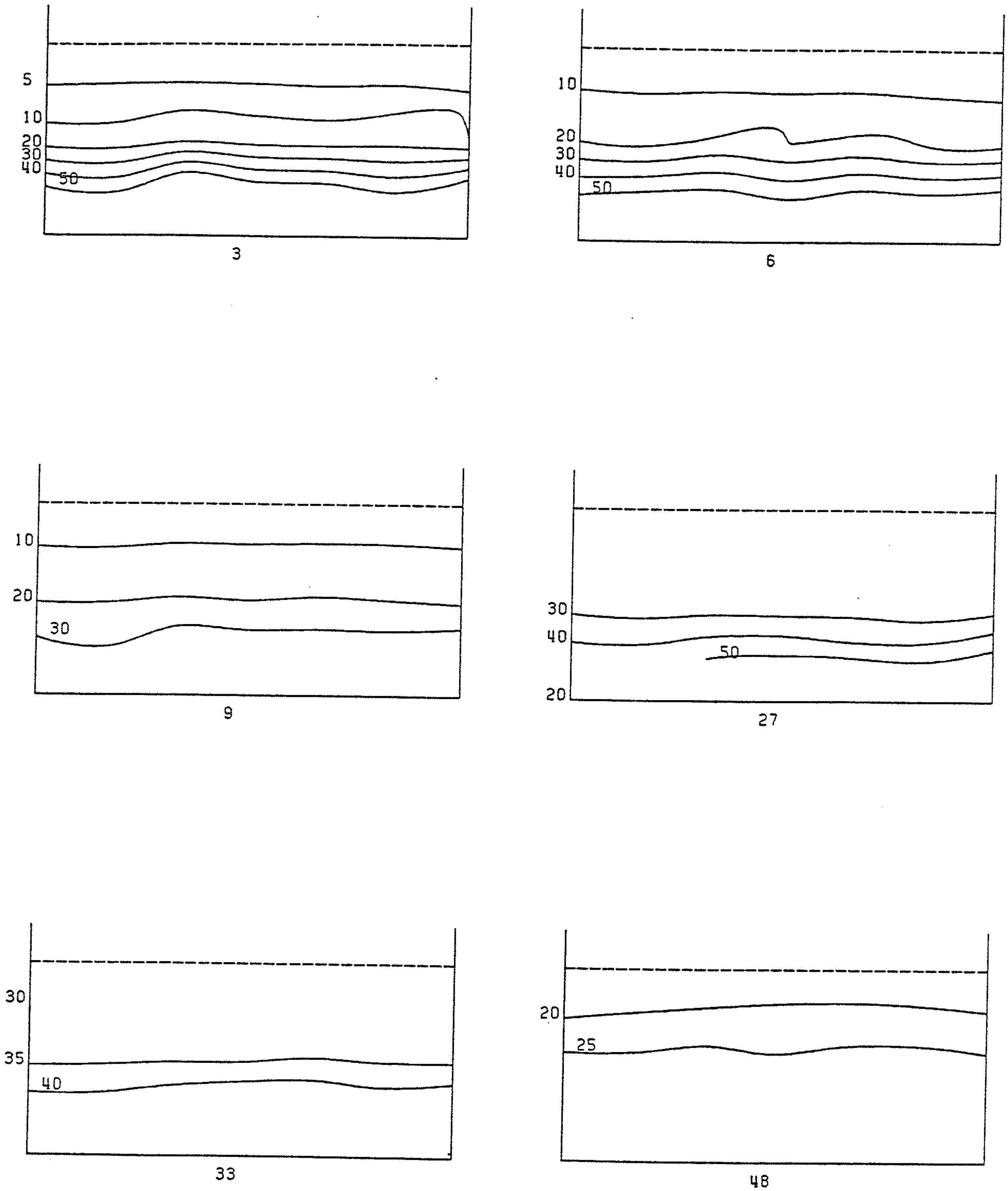

FIG.D.22. EXPERIMENT 11 (ALONG SECTION B-B)

APPENDIX E

Table E.1: Weighted volume average carbon dioxide concentraions (%) and mortality (%) of rusty grain beetle adults in test and control bins at various sampling levels.

Time elapsed (h)	Height from the floor			
	0.55 m	1.30 m	2.05 m	Average
WEIGHTED VOLUME AVERAGE CO_2 CONCENTRATIONS (%)				
IN TEST BIN				
24	26.50	20.71	15.23	21.04
48	30.61	20.47	12.25	21.51
72	29.24	20.32	13.00	21.20
96	33.09	25.19	21.96	27.04
144	17.22	9.11	3.95	10.41
168	37.55	26.10	21.32	28.76
192	35.11	26.49	21.22	27.94
216	27.69	20.47	14.90	21.31
240	23.49	17.05	12.12	17.80
IN CONTROL BIN				
24	0.10	0.09	0.10	0.09
48	0.17	0.15	0.13	0.15
72	0.13	0.12	0.13	0.13
96	0.14	0.12	0.09	0.12
144	0.09	0.10	0.08	0.09
168	0.09	0.09	0.11	0.10
192	0.08	0.11	0.11	0.10
216	0.07	0.07	0.08	0.07
240	0.09	0.09	0.11	0.10
MORTALITY (%)				
IN TEST BIN				
48	12.82	12.98	12.09	12.63
96	46.44	35.08	9.32	30.28
144	72.89	47.92	21.22	47.34
192	84.31	61.80	25.90	57.34
240	90.70	71.28	32.47	64.82
IN CONTROL BIN				
48	2.47	4.80	5.21	4.16
96	6.44	5.38	2.92	4.91
144	9.60	6.92	3.28	6.60
192	3.76	7.28	4.39	4.39
240	4.78	6.23	4.06	5.02