

THE UNIVERSITY OF MANITOBA

THE MEASUREMENT OF AIR LEAKAGE RATES  
FOR PLASTIC COVERED GREENHOUSES  
IN MANITOBA

by

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MASTER OF SCIENCE

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IN THE NAME OF ALMIGHTY GOD

THE COMPASSIONATE

THE MERCIFUL

## ABSTRACT

THE MEASUREMENT OF AIR LEAKAGE RATES  
FOR PLASTIC COVERED GREENHOUSES  
IN MANITOBA

The air leakage rate of any enclosed structure, like a greenhouse, depends mainly on wind speed, wind direction and indoor-outdoor temperature differential. Carbon dioxide enrichment of greenhouse atmospheres can result in increased plant productivity. The loss of the enriching carbon dioxide by leakage during and after enrichment will result in higher costs of crop production. If greenhouse crop growers are aware of the leakage losses it will be easier for them to supply sufficient carbon dioxide gas to maintain a favorable concentration in order to enhance plant growth.

Air leakage rates for two research greenhouses were determined for existing indoor-outdoor temperature differentials, wind speeds and wind directions using tracer gas techniques. Air samples from the greenhouses were analyzed for carbon dioxide content using a gas chromatograph.

The effect of temperature differentials and wind velocities were separated by performing a multiple regression analysis between the dependent variable (air change rate) and the two independent variables (indoor-outdoor temperature differential and wind speed). A simple mathematical relationship was developed to predict the expected air change rate for a known temperature differential and wind velocity. The accuracy of the predicted air change rates was quite acceptable.

The maximum measured air change rate was 0.726/h at a wind speed of 31.4 km/h and an indoor-outdoor temperature differential of

11.7°C. The minimum measured air change rate was 0.053/h at a wind speed of 2.3 km/h and an indoor-outdoor temperature differential of 5.7°C.

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## CHAPTER I

### INTRODUCTION

In Manitoba, plastic covered greenhouses are the only source of fresh, locally grown vegetables in early spring, late fall and winter. When outside temperatures fall below freezing, greenhouse ventilation to circulate fresh air for plant growth becomes impossible.

Normal air contains 330 parts per million (ppm) by volume of carbon dioxide ( $\text{CO}_2$ ) (1 ppm = 1 part  $\text{CO}_2/10^6$  parts air). Carbon dioxide is converted to carbohydrates by the well-known biochemical process of photosynthesis. It has been reported that plant growth can be enhanced and the quality of the product improved by enriching the plant environment with carbon dioxide (Barksdale, 1967; Wittwer and Robb, 1964). The recommended optimal levels of carbon dioxide concentration for early, increased and better yields are reported to be from 1000 to 2400 ppm (Barksdale, 1967; Wittwer, 1970a). Higher concentrations of carbon dioxide have toxic effects (Table 2.2) on growing plants and humans (Barksdale, 1967). Prevention of these toxic effects becomes the paramount factor in carbon dioxide concentration control in greenhouse atmospheres.

As it is not economically feasible to build a completely airtight greenhouse, some loss of  $\text{CO}_2$  takes place due to leakage caused by the gas concentration gradient, wind pressure and temperature differentials. It is difficult for the average greenhouse grower to maintain the desired  $\text{CO}_2$  concentration especially in the absence of any

gas analysis facilities. If the grower is aware of the leakage losses he can compensate for the losses to ensure adequate  $\text{CO}_2$  for plant use.

Once the leakage rates of any greenhouse under different weather conditions are known, control of  $\text{CO}_2$  becomes possible and much easier. An easy, accurate method of determining the leakage rate of any enclosed structure is to release a tracer gas and then measure the rate of depletion of that gas (Dick, 1950). Release of  $\text{CO}_2$  gas as a tracer has the added advantage of presenting a truer picture of leakage since each gas has different diffusion rates. Carbon dioxide permeation through polyethylene is three times as much as for oxygen (Keveren, 1973).

The basic objectives of this research were:

1. To measure and to compare the leakage rates of greenhouses under different environmental conditions
2. To investigate the dependence of leakage rates on wind speed, wind direction and indoor-outdoor temperature differentials
3. To develop a simple mathematical relationship to predict air change rates for known wind speeds and known indoor-outdoor temperature differentials
4. To develop a computer simulation model for predicting  $\text{CO}_2$  concentration in a greenhouse at any time during or after enrichment, taking into account known leakage rates and growing plants.

## CHAPTER II

### REVIEW OF LITERATURE

#### 2.1 Plant Growth and Environmental Factors

Photosynthesis, the process by which green plants manufacture their food by assimilating the atmospheric carbon dioxide gas, is defined by Kamen (1963) as a series of processes in which radiant energy is converted to chemical free energy which can be used for biosynthesis. The rate of photosynthesis and the amount of photosynthate subsequently produced depends upon a number of environmental factors. Bildring (1973) reported that it is possible to count as many as 56 main reactions to the aerial and 36 more reactions to the root environment.

Several of the important environmental factors are grouped below:

##### 2.1.1 Environmental (Aerial) Factors

- (i) Radiation including visible light
- (ii) Carbon dioxide concentration in the air
- (iii) Atmospheric temperature
- (iv) Humidity
- (v) Wind
- (vi) Precipitation
- (vii) Atmospheric pollution

##### 2.1.2 Edaphic Factors

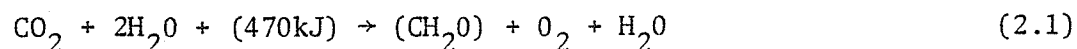
- (i) Soil compaction



- (ii) Root zone temperature
- (iii) Soil moisture
- (iv) Mineral nutrients
- (v) Soil texture and structure

## 2.2 The Role of CO<sub>2</sub> in Plant Growth

The following summary equation (2.1) illustrates the process of photosynthesis by which atmospheric carbon dioxide gas is converted to carbohydrates (Pallas, 1970; Barksdale, 1967).



Gaastra (1963) reported that the assimilation of CO<sub>2</sub> increases as light intensity and temperature increases within certain limits. This principle was formulated by the plant physiologist F. F. Blackman as the principle of limiting factors (Figure 2.1).

The principle of limiting factors is explained by Bickford and Dunn (1972). Suppose the effect of increasing the amount of CO<sub>2</sub> on the rate of photosynthesis is being studied with all other factors constant. As shown in Figure 2.1 an increase of CO<sub>2</sub> causes an increase in photosynthesis up to a certain point, A to B. Beyond that point a further increase of CO<sub>2</sub> produces no effect and the line flattens out, B to C. Some other factor, such as insufficient light or temperature, is limiting. If more of the limiting factor is supplied, the graph may be extended further (B to D), when still another factor will limit the rate, and so on.

Experiments on photosynthesis in a cucumber leaf in relation to light intensity and temperature at a limiting (0.03%) and at a saturating (0.13%) CO<sub>2</sub> concentration (Figure 2.2) verifies that

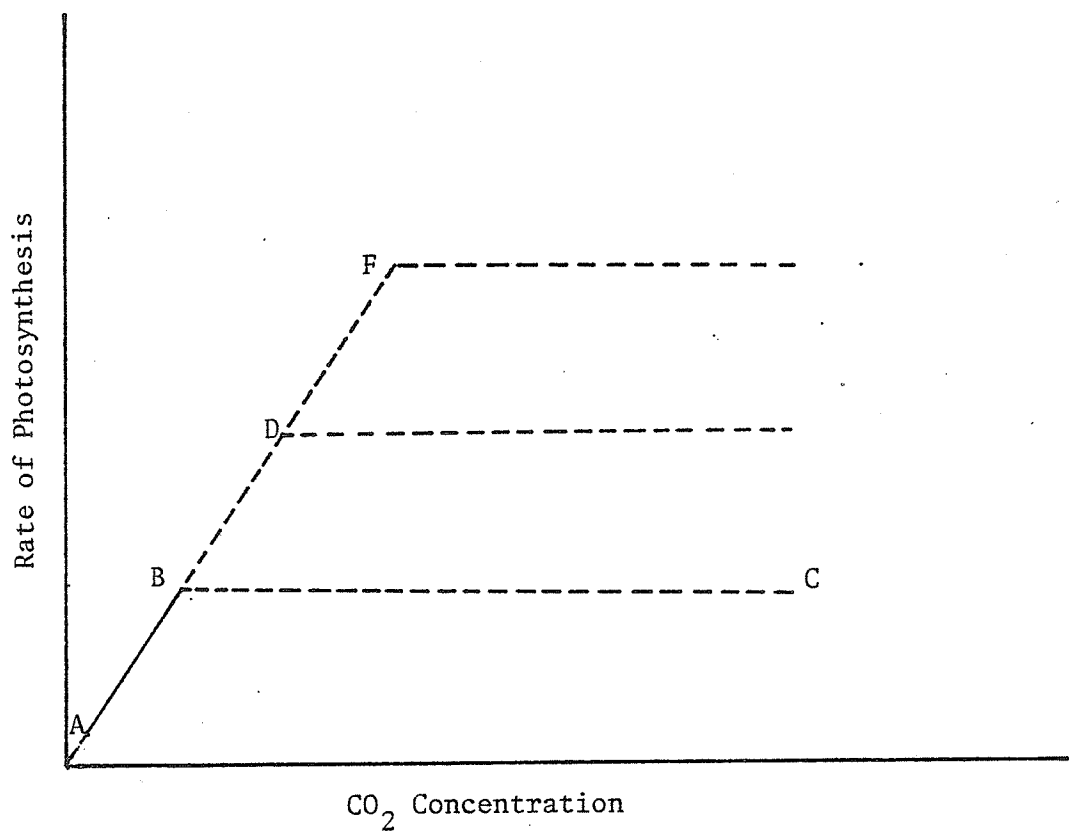


Figure 2.1 Graph of Blackman's Principle of Limiting Factors (Bickford and Dunn, 1972)

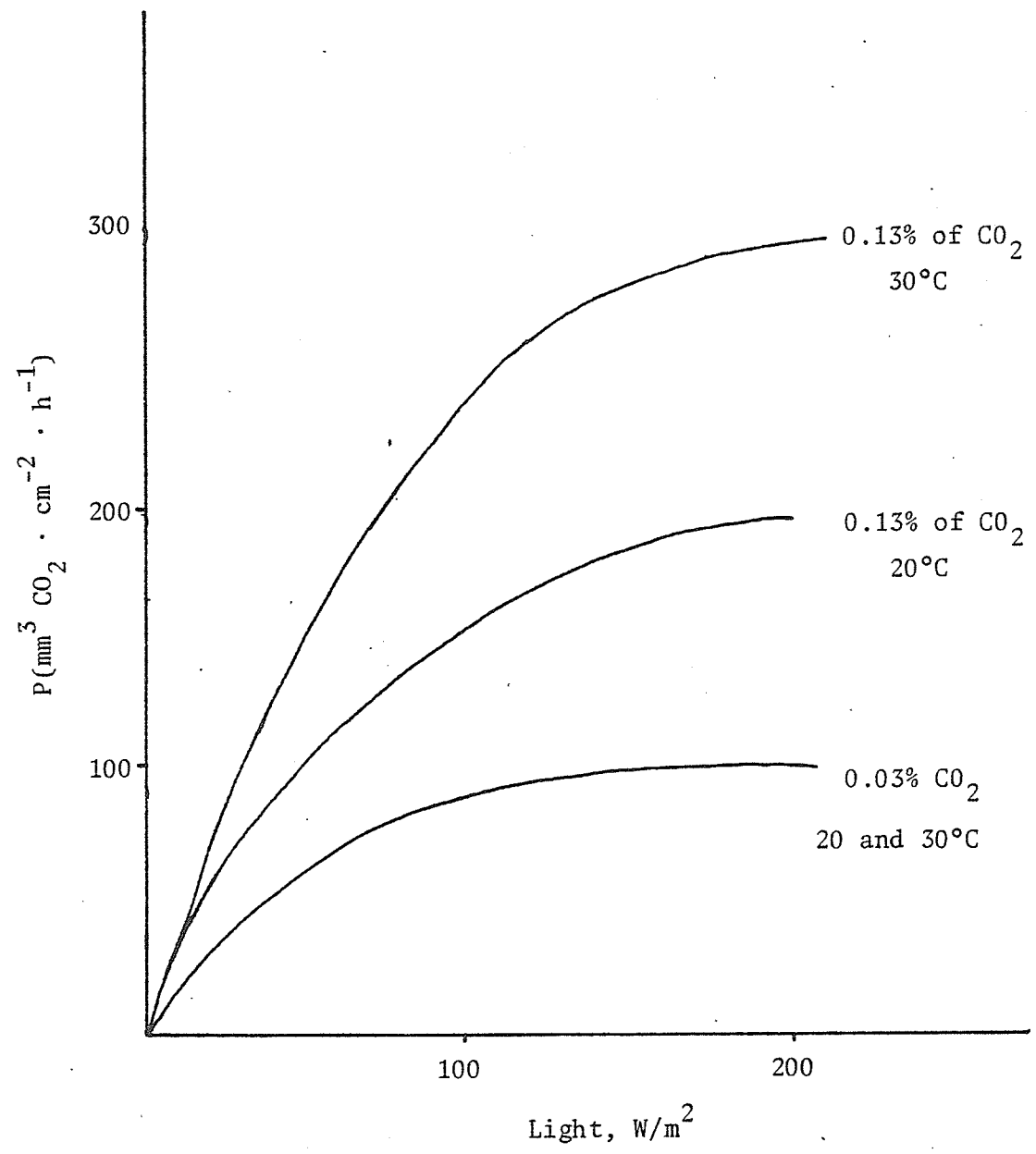


Figure 2.2 Photosynthesis (P) in a cucumber leaf at different  $\text{CO}_2$ , light and temperature levels (Gaastra, 1963).

Blackman's principle of limiting factors applies in this study (Gaastra, 1963).

### 2.2.1 CO<sub>2</sub> Enriched Atmospheres

The concentration of CO<sub>2</sub> in the atmosphere is very low. Values quoted range from 280 to 350 parts per million (ppm) by volume (Pallas, 1970; Wittwer, 1970; Wittwer and Robb, 1964; Barksdale, 1967). Wittwer and Robb (1963) reported that in the primordial world the carbon dioxide concentration in the atmosphere was 10 to 100 times that of today. Pre-industrial values are estimated at between 290 and 300 ppm (Callendar, 1958) but this level has been increasing with greater industrialization. Today's concentration of 330 ppm is approximately 12% greater than pre-industrial values. If the same increase continues within the next 60 years, the level will double (Baes et al., 1977).

Enriching a plant environment with CO<sub>2</sub> to approximately 2000 ppm increases yields and improves quality when adequate light and temperature are available (Wittwer and Robb, 1964; Kretchman and Howlet, 1970; Calvert, 1972).

### 2.2.2 Methods of CO<sub>2</sub> Enrichment

There are several sources of CO<sub>2</sub> available for commercial or experimental enrichment of greenhouse atmospheres. Each source has certain advantages and limitations. The purest form of CO<sub>2</sub> available for enrichment is bottled CO<sub>2</sub> (Slack and Calvert, 1972). Dry ice has been used successfully for enriching greenhouse atmospheres (Bailey et al., 1970). Carbon dioxide in pressurized tanks equipped with pressure regulators and flowmeters is a common source (Wittwer and Robb, 1964).

The most economical method of supplying CO<sub>2</sub> for greenhouse enrichment is from the combustion of organic fuels such as propane, natural gas, or kerosene (Kretchman and Howlett, 1970). The danger in using these fuels is from toxic gases due to the incomplete combustion of hydrocarbons. Barkei (1967) has dealt in detail with different commercially available burners for hydrocarbon fuels and the possibility of generation of toxic gases from incomplete combustion. Peterson et al. (1975) investigated the possibility of using coal mine air to enrich the greenhouse atmosphere. Coal mine air usually contains 680 to 1400 ppm of CO<sub>2</sub>.

Organic matter is perhaps the oldest technique of enriching field crops. Kretchman and Howlett (1970) reported that Ohio commercial growers regularly use animal manure and other organic materials, which can produce as much as 2700 ppm of CO<sub>2</sub> in the early part of the day due to increased microbial activities. Klougart (1967) reported a CO<sub>2</sub> level of 1200 to 1900 ppm due to organic material added in a glasshouse with a cucumber crop.

Carpenter (1966) used carbonated water for CO<sub>2</sub> fertilization and successfully maintained a level of 300 to 325 ppm of CO<sub>2</sub> compared to a greenhouse receiving no supplemental CO<sub>2</sub> in which the level ranged from 280 to 300 ppm.

### 2.2.3 Response of Crops to CO<sub>2</sub> Enrichment

Extensive research has been done to establish the response of various greenhouse vegetables, flowers and field crops to CO<sub>2</sub> levels. Results reported by some of the researchers are summarized in Table 2.1.

Table 2.1 Crop response to carbon dioxide enrichment

CROPS	REFERENCE	CO <sub>2</sub> LEVEL (ppm)	RESULTS/REMARKS
Tomato	Barksdale (1967)	1200-1500	20% more yield at 21-25°C day and 16-17°C night temperature
	Calvert (1972)	1000	90% more early yield and 30% more total yield
	Hand and Postlethwaite (1971)	800	17 to 33% more yield
	Kretchman and Howlett (1966, 1967, 1970)	1200-1500	22.8% more yield, fruit size increased.
	Madsen (1968)	2200	Highest starch content
Lettuce	Wittwer and Robb (1964)	800-2000	43% more yield
	Gardner (1966)	1000	34% increase in yield
	Wittwer and Robb (1964)	800-2000	70% increased yield
	Klougart (1967)	900-1500	35-64% increase per plant
Cucumber	Kretchman and Howlett (1970)	1000	40% more yield
	Wittwer and Robb (1964)	800-2000	Vegetative growth increased
	Kothes and Adzima (1967)	600 900 1500	15% increase in flower weight 12% increase in flower weight 11% increase in flower weight

Table 2.1 (concluded)

CROPS	REFERENCE	CO <sub>2</sub> LEVEL (ppm)	RESULTS/REMARKS
Carnation	Goldsberry (1963)	200 550 550	381 flowers ----- 37% increase 521 flowers 5% increase in dry weight as compared to 200 ppm.
Rose	Lindstrom (1965)	1200-2000	3 more roses per plant
Corn	Ford and Thorne (1967) Moss (1961)	1000 510	50% increase in dry weight at 20°C 50% greater photosynthesis as compared to 155 ppm
Soybean	Brun and Cooper (1967) Cooper and Brun (1967)	1600 1350	Rate of photosynthesis increased 57% more yield in variety Hark and 40% in Chippewa
	Hardman and Brun (1971)	1200	Significant increase in the number of pods present at maturity
	Nelson (1963)	1500	More sucrose (96% more in leaf and 44% more in stem).
Barley	Ford and Thorne (1967)	1000	Highly significant increase in leaf and stem dry weight.
Sugar beet	Ford and Thorne (1967)	1000	50% more dry weight
Spinach beet	Monteith et al. (1964)	6000	5 times more yield in summer 2 times more yield in winter

The optimal levels of CO<sub>2</sub> for most of the crops are reported to be 1000 to 2000 ppm (Barksdale, 1967; Wittwer, 1970; Peterson et al., 1975).

### 2.3 Control of the Greenhouse Environment

Effective greenhouse environmental control is necessary to maintain the optimal levels of radiant energy, temperature, relative humidity and CO<sub>2</sub> for plant growth. As reported by many researchers (Bildering, 1967; Bowman, 1968; Shipway, 1964; Winspear, 1968) the following parameters must be considered in greenhouse environment control: (i) carbon dioxide concentration, (ii) illumination, (iii) temperature, (iv) humidity, (v) ventilation, (vi) air movement and (vii) atmospheric pollutants.

### 2.4 Control of CO<sub>2</sub> Concentration in the Greenhouse

Economic delivery and utilization of supplemental CO<sub>2</sub> is the basic interest of greenhouse growers. Control of the CO<sub>2</sub> enriched atmosphere becomes necessary in order: (i) to maintain the CO<sub>2</sub> concentration at the desired level, (ii) to minimize the effect of toxic gases and (iii) to provide adequate ventilation.

#### 2.4.1 Control of CO<sub>2</sub> at the Desired Level

Several researchers have reported different techniques for controlling CO<sub>2</sub> levels in greenhouses. A detailed and comparative analysis of various possible methods for controlling CO<sub>2</sub> concentration is discussed by Bowman (1968a). Some of the methods discussed were infrared absorption, electrical conductivity in alkaline solutions, electrical conductivity of deionized water, gas chromatography and katharometry.



A constant level control system and a light modulated control system were used by Pettibone et al. (1970). In the constant level control system an infrared gas analyzer and a strip chart recorder-controller were used. The signal generated was proportional to the CO<sub>2</sub> concentration in the greenhouse. In the light modulated control system the intensity of the incoming solar radiation was used to control the gas supply.

Bailey et al. (1970) developed a CO<sub>2</sub> control system which was capable of controlling CO<sub>2</sub> concentration at the desired level in different greenhouses. An infrared gas analyzer along with a recorder-controller was used to turn the CO<sub>2</sub> on or off. Slack and Calvert (1972) described a system for controlling CO<sub>2</sub> concentration in nine separate glasshouses by using a conductimetric controller. The mean daily controlled concentration achieved over a period of five months was within ±3% of the desired value. Gas samples were bubbled through a deionized water tube. An increase in the CO<sub>2</sub> content in the air sample increased the electrical conductivity of the deionized water and a signal was generated which was proportional to the CO<sub>2</sub> concentration. The signal was used to control the CO<sub>2</sub> supply.

A similar control system was used for monitoring CO<sub>2</sub> levels using the change in electrical conductivity in an alkali solution (Bowman, 1968). A simple colorimetric method was developed by Sharp (1964) using a thymol blue indicator solution. The change in color was an indication of the CO<sub>2</sub> concentration in the air sample.

#### 2.4.2 Control of Toxic Gases

Controlling CO<sub>2</sub> concentration could also prevent the build up of

toxic gases which can be produced during the combustion of hydrocarbon fuels. The fuels are burnt to produce CO<sub>2</sub> for enrichment or for heating the greenhouse air. Table 2.2 summarizes the critical amounts of some toxic gases for plants and human beings.

Table 2.2 Toxic gases produced by incomplete combustion of hydrocarbon fuels and the critical concentrations for plants and humans

GAS	TOXIC LIMITS (ppm)		REFERENCE
	Plants	Humans	
Carbon monoxide	500	100	Thomas (1961)
Carbon dioxide	10,000	5,000	Barksdale (1967)
Ethylene	50	----	Barkel (1967)
Hydrogen sulfide	20-40	----	Thomas (1961)
Nitrogen oxide	3	500	CRC (1972)
Sulfer dioxide	0.19	----	Thomas (1961)

#### 2.4.3 Control of Ventilation

Ventilation is essential for the following reasons (Morris and Winspear, 1967): (i) to limit the temperature rise resulting from solar heat gain, (ii) to limit the humidity rise resulting from the moisture transpired from the growing plants, and (iii) to replace the CO<sub>2</sub> consumed by the photosynthesis. It has been reported that the control of CO<sub>2</sub> at higher concentrations is only possible if relative humidity can be controlled at the maximum allowable limits. High humidity can promote fungus disease problems.

Bildring (1973) reported that 2 to 3 air changes per hour in

greenhouses or growth chambers are enough to supply  $\text{CO}_2$  for photosynthesis. Many researchers have reported decreased levels of  $\text{CO}_2$  concentration (220 to 270 ppm) even when the ventilators have been opened (Burrage, 1972; Klougart, 1967; Moss, 1962) in the daytime with vigorously growing crops. Natural ventilation takes place due to the chimney effect (Winspear, 1968), and ridge ventilators are sufficient to provide a large number of air changes to keep the  $\text{CO}_2$  concentration normal. The rate of ventilation to replace the depleted carbon dioxide depends mostly on the number of plants.

Whittle and Lawrence (1960) suggested air changes of from 2 to 10 per hour for normal photosynthesis. High ventilation rates (up to 160 air changes per hour) are necessary in order to keep the inside  $\text{CO}_2$  level close to that of outside air (Klougart, 1967; Nitsch, 1972). In summer, even when the ventilators are open,  $\text{CO}_2$  levels can be reduced so that the rate of photosynthesis is also reduced. Moderate reductions of  $\text{CO}_2$  (220-270 ppm) do not affect photosynthesis seriously.

Moss (1962) reported in detail the threshold values of  $\text{CO}_2$  for different crops. Table 2.3 shows the minimum  $\text{CO}_2$  concentrations at about 75000 lx light intensity and 23°C temperature.

## 2.5 Parameters Affecting $\text{CO}_2$ Loss

Carbon dioxide loss from greenhouses takes place due to unwanted leakage of the internal atmosphere through cracks, slits, slots and holes in the covering material (Whittle and Lawrence, 1960). The magnitude of this loss depends directly upon several factors, some of which are listed below (ASHRAE, 1960; Barkel, 1967; Whittle and

Table 2.3 Minimum Levels of CO<sub>2</sub> for Photosynthesis to Occur at  
75000 lx and 23°C (Moss, 1962).

Crop	CO <sub>2</sub> (ppm)	P <sub>100</sub> /P <sub>300</sub> *
Corn	9	0.63
Sugarcane	7	0.67
Orchard Grass	60	0.22
Tobacco	60	0.33
Tomato	75	0.31
Norway Maple	145	0.00

\* Second column shows the ratio of the rate of photosynthesis at 100 ppm (P<sub>100</sub>) compared to the rate for normal fresh air (P<sub>300</sub>).

Lawrence, 1960; Malinowski, 1971): (i) wind speed and direction, (ii) temperature differential, (iii) gas concentration gradient and (iv) total diffusion area.

### 2.5.1 Wind Speed and Direction

Air flow due to wind around and over buildings creates regions in which the static pressure differs from regions of undisturbed air (ASHRAE, 1967). In general, pressures are positive on the windward side resulting in an inflow (infiltration) of air and negative on the leeward side resulting in an outflow (exfiltration) of an equal volume of air.

The leakage (or infiltration and exfiltration) rates for any enclosed volume are commonly reported in terms of an air change rate (Coblentz and Achenbach, 1963; Whittle and Lawrence, 1960). The air change rate is defined as the ratio of the volume rate at which air enters and leaves the greenhouse to the volume of the greenhouse.

Malinowski (1971) reported that air exchange of internal air depends on the wind pressure distribution on a building. The shape and size of a building, the environmental conditions and the nature of the winds determine the pressure distribution. Higher wind speeds increase the diffusion rate via openings in the greenhouse cover (Barkel, 1967). The pressure at the stagnation point due to an average steady wind of 144 km/h may increase to  $5000 \text{ N/m}^2$  (5kPa) which can lead to structural failure (Thomann, 1975). Bahnfleth et al. (1975) reported that the rate of infiltration increased with increasing wind velocity. Wind direction may also have an effect on infiltration provided there are unequal openings on various sides of the building.

It was also concluded that for each km/h increase in wind velocity the infiltration rate increased about 0.0075 air changes per hour.

### 2.5.2 Indoor-Outdoor Temperature Differential

Air exchange from any building, because of the difference in indoor-outdoor temperature, takes place due to the "chimney effect" (ASHRAE, 1960; Winspear, 1968). This process is most easily explained by the "Neutral Zone" concept (Bahnfleth et al., 1957). The neutral zone is the elevation in a building where the pressure indoors is equal to the pressure outdoors when the building is exposed only to an indoor-outdoor temperature difference. Air flows into the building below the neutral zone and out above it when the temperature indoors is greater than the temperature outdoors. The flow pattern is reversed when the outdoor temperature exceeds the indoor temperature.

Emswiler (1926) reported a detailed analysis for determining the position of the neutral zone theoretically and practically. Some of the important characteristics are listed below:

- (i) the pressure differential is proportional to the distance of the leakage site from the neutral zone
- (ii) the amount of leakage from any site is proportional to the square root of the vertical distance from the neutral zone
- (iii) for ideal conditions the neutral zone is at midheight for equally distributed openings with no temperature differential
- (iv) in general the neutral zone will shift towards the group of openings with the largest area and towards the region of the highest temperature differential

Theoretically, the expected pressure differential causing the flow can be calculated from equation 2.2

$$h = 10.87 MD/T \quad (2.2)$$

where  $h$  = pressure differential, Pa

$M$  = height of the building, m

$D$  = temperature differential, °C

$T$  = average absolute temperature, K, of warm and cold air columns

$$T = ((t_{\text{warm}} + t_{\text{cold}})/2 + 273.15)$$

$$D = (t_{\text{warm}} - t_{\text{cold}})$$

Bahnfleth et al. (1957) showed that a change of 1°C in the temperature differential was equivalent to about 0.73 km/h change in wind velocity causing the same infiltration rate. It was also shown that for each degree Celsius change in indoor-outdoor temperature differential, the infiltration rate increased approximately 0.00367 air changes per hour. Brown et al. (1963) have reported a detailed analysis of air flow due to natural convection through openings in horizontal and vertical partitions.

### 2.5.3 Combined Wind and Temperature Effects

It is unfortunate that only a few attempts have been made in the last two decades to study the dependence of leakage rates on the combined effect of wind velocity and indoor-outdoor temperature differentials. The only detailed study to separate the effect of wind speed and indoor-outdoor temperature differential was available from Bahnfleth et al. (1957, 1957a). The work reported by Banfleth et al. (1957) and Coblentz and Achenback (1963) were essentially based on a multiple regression

analysis between one dependent variable (air change rate) and two independent variables (wind speed and indoor-outdoor temperature differential).

The technique of double approximations for correction of data for constant wind speed and constant indoor-outdoor temperature differential as reported by Bahnfleth et al. (1957) was not explicit in explaining the correction factors. Equation 2.3 was developed by Coblenz and Achenback (1963) from the graphical representation of results reported by Bahnfleth et al. (1957).

$$R = 0.15 + 0.0083W + 0.0061 \Delta T \quad (2.3)$$

where R = air change rate, 1/h

W = wind speed, km/h

$\Delta T$  = indoor-outdoor temperature differential, °C

#### 2.5.4 Gas Concentration Gradient

Barkel (1967) reported that the loss of gas ( $\text{CO}_2$ ) to outside air is proportional to the difference in concentration between inside and outside air. The higher the concentration that is desired, the more  $\text{CO}_2$  will escape into the outside atmosphere.

#### 2.5.5 Diffusion Area

Loss of gas is directly proportional to the total diffusion area of the greenhouse cover (Barkel, 1967).

### 2.6 Modes of Air Leakage

Air leakage from and into any building can take place in a variety of ways. Malinowski (1971) considered the air exchange phenomenon as the resultant of the following four factors: (i) through



flow, (ii) pulsating flow, (iii) turbulent flow and (iv) static, molecular or thermal diffusion.

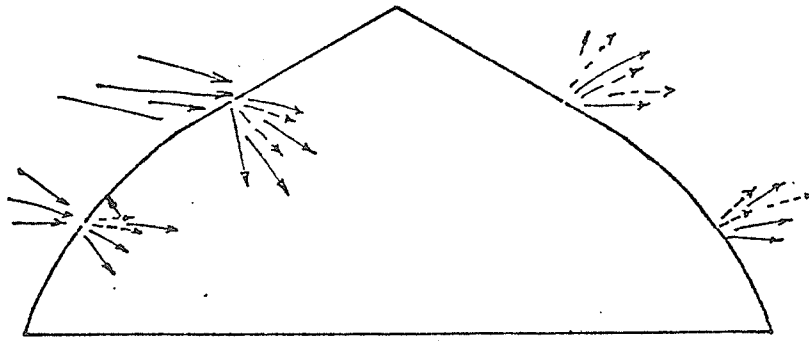
Figure 2.3(a) explains the phenomenon of through flow. It is almost the same as forced ventilation except that the rate of flow is unsteady. Through flow depends on external weather conditions and differential pressure across the openings through which the flow takes place. Pulsating flow only takes place when all the openings are located in an area with the same external pressure, or when the pressure differential is very small with oscillations in pressure with time predominating. Figure 2.3(b,c) shows this mode of leakage.

Turbulent flow or eddies are produced either due to changes in the external wind velocity or to changes in the internal convection currents. Turbulence and eddies cause air infiltration and exfiltration to take place at the same opening in the corner.

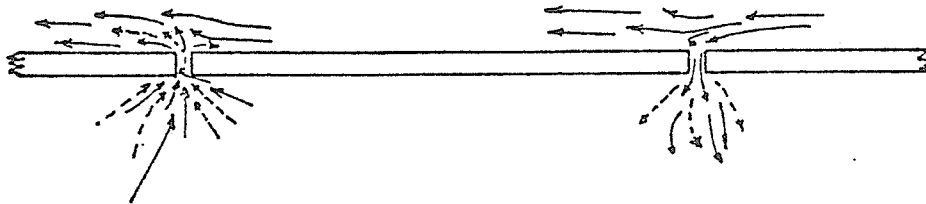
Molecular flow is perhaps the most complex type of flow taking place through openings which are not sufficiently large enough to allow the other types of flow (through, pulsating and/or turbulent flow). The essential features of this type of flow have been described by Sparrow et al. (1969). The same type of flow has been investigated in detail by Wang and Yu (1971) where the mass flow is considered due to finite pressure and temperature ratios.

## 2.7 Leakage Measurement

Two methods have been reported for determining the leakage rate of any enclosed structure such as a greenhouse. The methods are (i) a compressed air leakage method and (ii) a tracer gas technique.



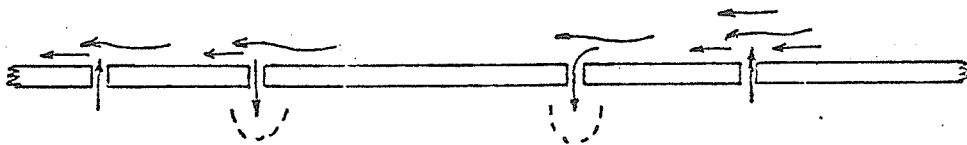
(a) Through flow



Pulse out

Pulse in

(b) Pulsating Flow (one hole)



(c) Pulsating Flow (two holes)

Figure 2.3 Different modes of air leakage

### 2.7.1 The Compressed Air Leakage Method

Pflug and Southwick (1954) devised a method using an air compressor with a variable flow capacity. The structure was pressurized to a constant pressure to ensure that all leakage would be out of the building. In this situation the rate of air being pumped in is equal to the air leaking out. Similar methods have been reported by other researchers (Wolf et al., 1969; and Zahradnik, 1968).

Limitations of this technique are the difficulty of maintaining a low constant pressure differential and excessive leakage at high pressure differentials.

### 2.7.2 Tracer Gas Techniques

The conventional method of determining leakage rates for any enclosed structure is to release a suitable gas inside and then to monitor the depletion rate (Bahnfleth et al., 1957; Bowman and Hand, 1968; and Dick, 1950). The concentration of the tracer gas decreases exponentially. When the Napierian logarithm of the tracer gas concentration is plotted against time, the slope of the plot will be the air change rate.

It is assumed that the reduction in the tracer gas concentration per unit time for the whole enclosure is equal to the amount of the tracer gas leaving that particular enclosure with the exfiltrating air in the same unit time. The concentration of the tracer gas during the decay, as shown by equation 2.4, holds true only if complete and instantaneous mixing of the replacement air with the air in the enclosure is assumed (Dick, 1950). The mathematical statement is:

$$-v \frac{dC}{dt} = xC \quad (2.4)$$

where

$C$  = concentration of tracer at time  $t$ , volume of tracer gas/  
volume of air

$x$  = volume of air entering (or leaving) the enclosure per unit  
time

$t$  = time

$v$  = volume of enclosure

The solution of the above differential equation with the initial  
condition of  $C = C_0$  at  $t = 0$  is

$$C = C_0 \text{ EXP}(-xt/v)$$

or  $C = C_0 \text{ EXP}(-Rt) \quad (2.5)$

where

$C_0$  = initial concentration of tracer gas in air

$R$  = number of air changes per unit time ( $x/v$ )

By plotting the natural logarithm of the concentration against  
time on a linear scale (abscissa) the rate of air change ( $R$ ) can be  
obtained from the slope of the best fitting line for the observed  
concentrations; i.e. from equation 2.5

$$R = (\ln(c_0/c))/t \quad (2.6)$$

Gases commonly used for leakage rate determinations are helium,  
nitrogen, hydrogen, carbon dioxide and some radioactive gases like argon  
41 and krypton 85 (ASHRAE, 1960; Coblenz and Achenback, 1963; Whittle  
and Lawrence, 1960; Dick, 1950). Results of various researchers in  
determining leakage rates of greenhouses are summarized in Table 2.4.

Table 2.4 Leakage Rates of Greenhouses and Growth Chambers

Reference	Air Change/h	Results/Remarks
Acock (1972)	0.02	The lowest air change rate achieved in airtight growing cabinets
ASHRAE (1968)	3	suggested air change rate for heating load calculations
Bowman (1968)	1.5	-----
Bowman and Hand (1968)	0.5 to 5	used in calculation of CO <sub>2</sub> loss due to ventilation
Klougart (1967)	0.8	calm weather, ventilators closed
Klougart (1967)	0.1	in most advanced greenhouses, under optimal conditions
Whittle and Lawrence (1960)	0.5 3	under calm conditions in glasshouses under windy conditions in glasshouses
Keveren (1973)	6 times	air change rate of a glasshouse as compared to a plastic-covered greenhouse

## 2.8 Methods of Measuring CO<sub>2</sub> Concentration

Various techniques of gas analysis are to be found in any standard book of chemical analysis. Some of the methods most commonly employed for CO<sub>2</sub> analysis in field and research laboratories are listed below (Bowman, 1968a):

Field Methods: (i) optical interferometer, (ii) chemical absorption (indicator tube), (iii) filtration of an alkali solution and (iv) visual comparative colorimetry.

Laboratory Methods: (i) katharometer, (ii) chemical absorption (volumetric), (iii) electrical conductivity of an alkali solution, (iv) electrical conductivity of deionized water, (v) infrared absorption and (vi) gas chromatography.

A gas chromatograph was available for use on this research project. A basic explanation of gas chromatography is given in Appendix A.

## CHAPTER III

### INSTRUMENTATION

#### 3.1 Gas Chromatograph and Recorder

An Aerograph Model A-90-P2 Gas Chromatograph was used to analyse the air samples from the greenhouse for CO<sub>2</sub> content. The response of the instrument was recorded by using a strip chart recorder (Brown Elektronik).

##### 3.1.1 The Column

The column was prepared using stainless steel tubing (3.5 m long, 3 mm OD, 2 mm ID) which was washed with toluene and rinsed with ether to make the internal surface clean and free of any grease or dirt. Porapak Q (100/120 mesh size) was used as the solid adsorbent for the gas chromatographic analysis. The column was packed using a slight vacuum and an electric vibrator. The column was coiled to fit into the oven and was conditioned at 250°C for 20 hours. The flow rate of the carrier gas during conditioning was 15 mL/min at 240 kPa.

#### 3.2 Gas Flow

Figure 3.1 shows in schematic form the gas flow through the instrument. The carrier gas from the cylinder enters the instrument through the gas valve E. The flow controller F divides the carrier gas flow into two streams. One stream flows directly to the reference arm M after passing through a flow restrictor J. The second gas stream passes through the one way check valve H into the injector chamber I

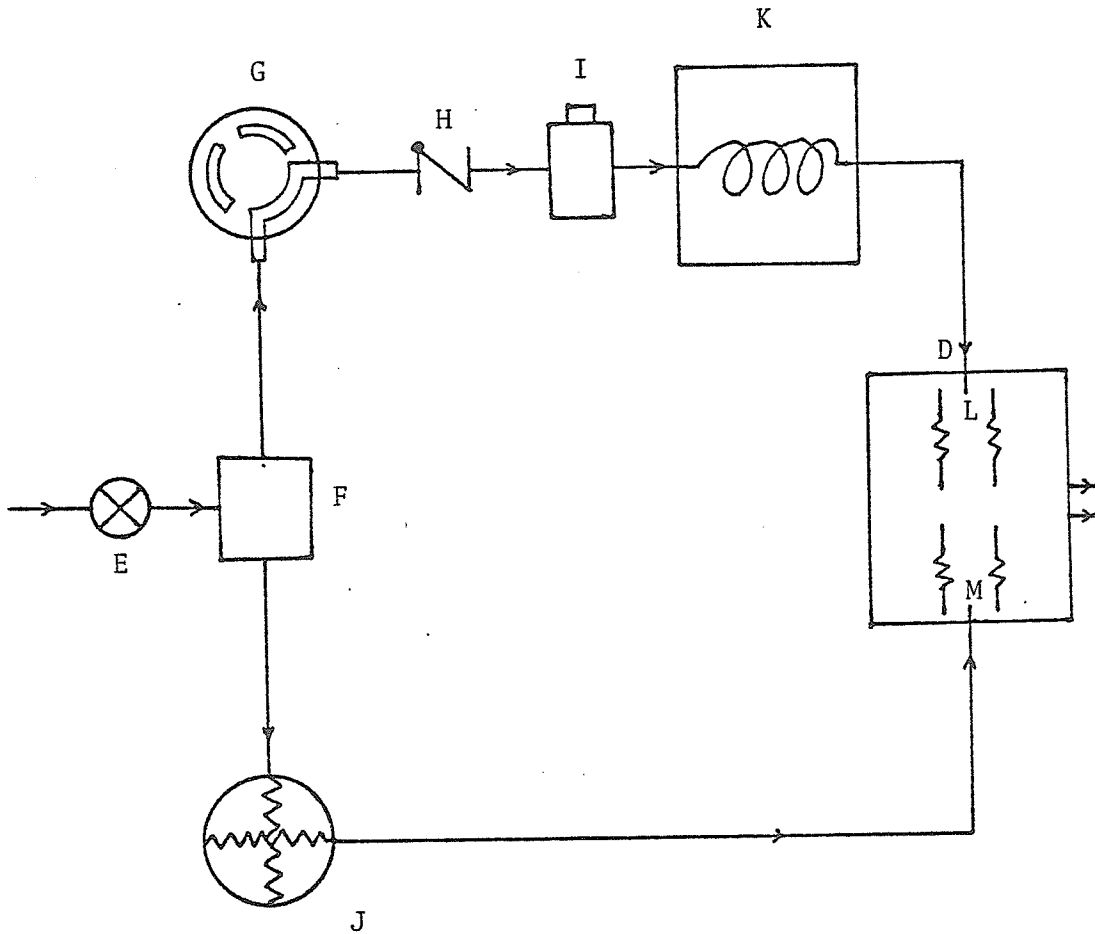


Figure 3.1 Schematic of varian A-90-P2 Gas Chromatograph used for quantitative analysis of  $\text{CO}_2$  in air samples.



and then into the column K and finally through the sensing arm L of the detector D. The gas sampling valve G (optional) is placed in the gas stream ahead of the column.

### 3.2.1 Gas Sampling Valve

A six part gas sampling valve (Figure A.3) manufactured by Carle Instruments Inc., California, was used to introduce the air samples into the gas chromatograph.

### 3.2.2 Gas Sampling Loop

The gas sampling valve was provided with two capillary connecting tubes. Each tube was 25 cm long, 1.5 mm OD and 1 mm ID with a total volumetric capacity of 0.4 mL (CT in Figure A.3). A piece of stainless steel tubing 19 cm long, 3 mm OD and 2 mm ID with a volumetric capacity of 0.6 mL was coupled (SL in Figure A.3) to the two tubes of the gas sampling valve using reducing swagelok fittings resulting in a net volume of 1.0 mL for the sample loop.

### 3.3 The Gas Dry Filter Trap

A gas dry filter trap (Figure 3.2) was used in order to absorb any moisture present in the sample to avoid contamination of the column packing material and the detector filaments. A 6 mm OD glass tube about 6 cm long was filled with anhydrous magnesium perchlorate. Both ends of the glass tube trap were plugged with glass wool. One end of the moisture trap was connected to the gas sampling valve injection port (using a reducing swagelok fitting). The other end was modified to accept a Luer lock syringe (Figure 3.2).

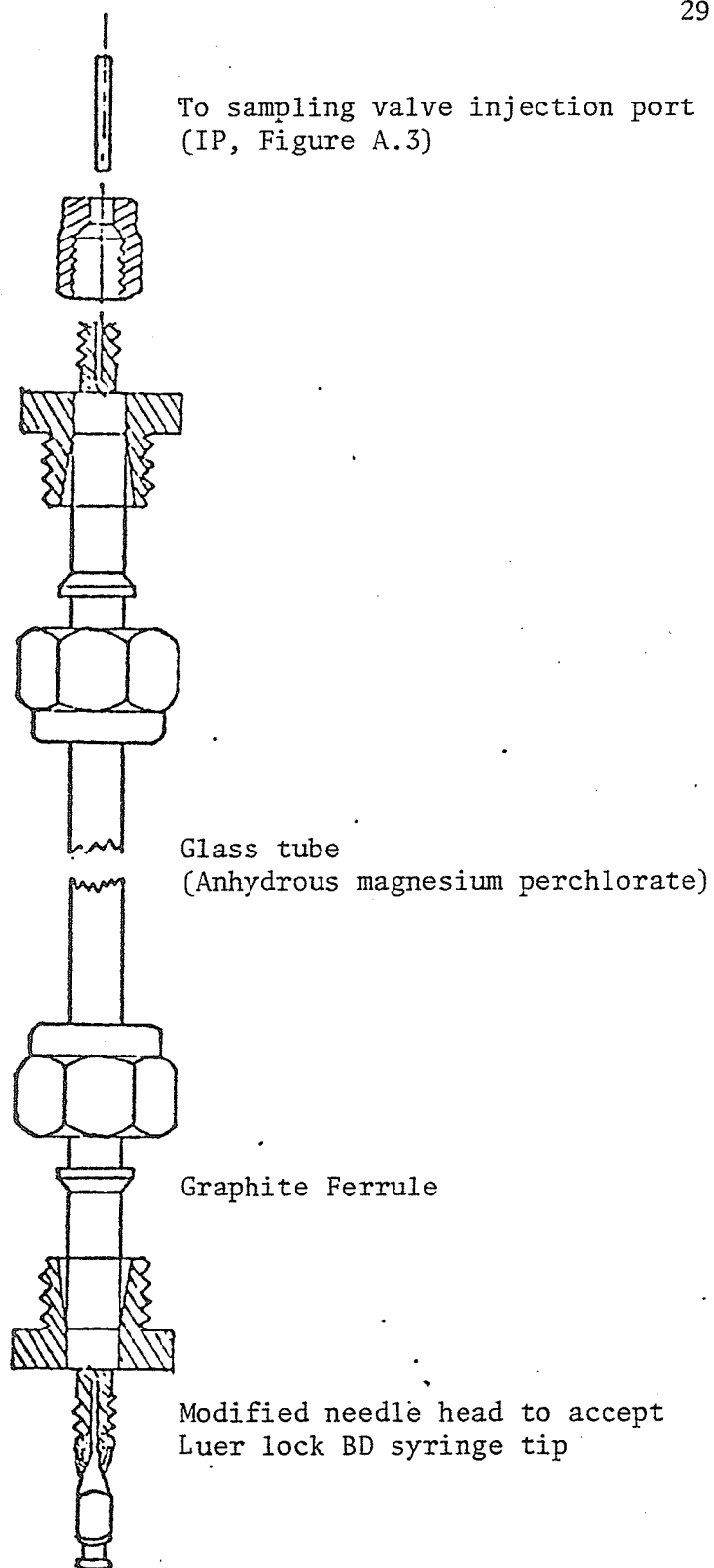


Figure 3.2 Gas-Dry filter trap with modified female syringe adapter.

### 3.4 Syringes

Two Hamilton gas-tight syringes of 1 mL and 2.5 mL capacity were used for trial injections to choose an appropriate sample size (Section A.6). Both gas-tight syringes were also used to prepare samples with known concentrations of CO<sub>2</sub>. The CO<sub>2</sub> was mixed in nitrogen. These samples were used for the basic calibration and also for daily calibration of the gas chromatograph.

Another 30 mL glass Luer lock syringe was used to draw samples (standard mixtures for calibration or air samples from the greenhouse) from the gas sampling bottles. The gas sampling loop (Figure A.3) was designed to hold a 1 mL sample for injection. A 30 mL sample drawn from the gas sampling bottle was used to flush the gas sampling loop. When the carrier gas path was shifted by turning the handle of the gas sampling valve a 1 mL sample was swept into the column for analysis.

### 3.5 Description of Greenhouses

Research greenhouses (numbers one and two) of the Plant Science Department at the University of Manitoba were selected for determination of the leakage rates. The greenhouses had a double covering. The external covering material was glass reinforced plastic sheets while the inner lining was flexible polyethylene. Both greenhouses had wooden rafter construction. The inner lining of greenhouse number one was replaced just a few days before the experiment was conducted. The dimensions of and other information for both greenhouses are presented in Table 3.1.

The south walls of both greenhouses contained two exhaust fans with a jet fan in the middle at the top for drawing in fresh air through

Table 3.1 Description of the Experimental Greenhouses

	Greenhouse Number	
	1	2
Year of construction	1970	1971
Oriented	NS	NS
Length, m	15.3	15.3
Width, m	9.5	11.9
Height, m	4.2	5.2
Volume, m <sup>3</sup> *	382.81	590.43
Floor area, m <sup>2</sup>	145	182

\* Crosssectional area was calculated by the trapezoidal rule (Thomas, 1966) by assuming a top inclination angle of 30° and a base curve tangent angle to the horizontal of 20° giving the radius of arc, r,

$$r = (b/2)/\cos 20$$

where

b = base width of greenhouse (Chandra, 1976)

the damper motor operated louvers. The north walls were fitted with suction lift louvers to admit fresh air.

### 3.6 The CO<sub>2</sub> System

Carbon dioxide was supplied from compressed gas cylinders (Figure 3.3). One cylinder was kept in the laboratory for preparing known concentrations of CO<sub>2</sub> gas in nitrogen for calibrations (Section 4). A second CO<sub>2</sub> gas cylinder was used to enrich the greenhouse air. During the first three tests the total amount of CO<sub>2</sub> added for enrichment was measured using a wet test meter. Figure 3.3 shows the schematic gas supply system for the greenhouse enrichment. A two stage pressure regulator was used. Flow was controlled with a needle valve. The gas was distributed in the greenhouse through the jet fan to ensure uniform mixing of the CO<sub>2</sub> gas with the greenhouse air.

An infrared heat lamp was used during gas enrichment to avoid any possible gas choking due to freezing of CO<sub>2</sub> in the pressure regulator.

### 3.7 The Gas Sampling System

Air samples were collected near the centre of each greenhouse. Two sampling bottles were flushed by using an air blower (Figure 3.4). The stopcocks of the sampling tubes were lubricated with "Apiezon" grease grade M to make a vacuum tight seal. The gas sampling bottles used for making the standard gas mixtures were calibrated with water to determine the volume.

### 3.8 Temperature Measurement

Two mercury thermometers were used to measure indoor and

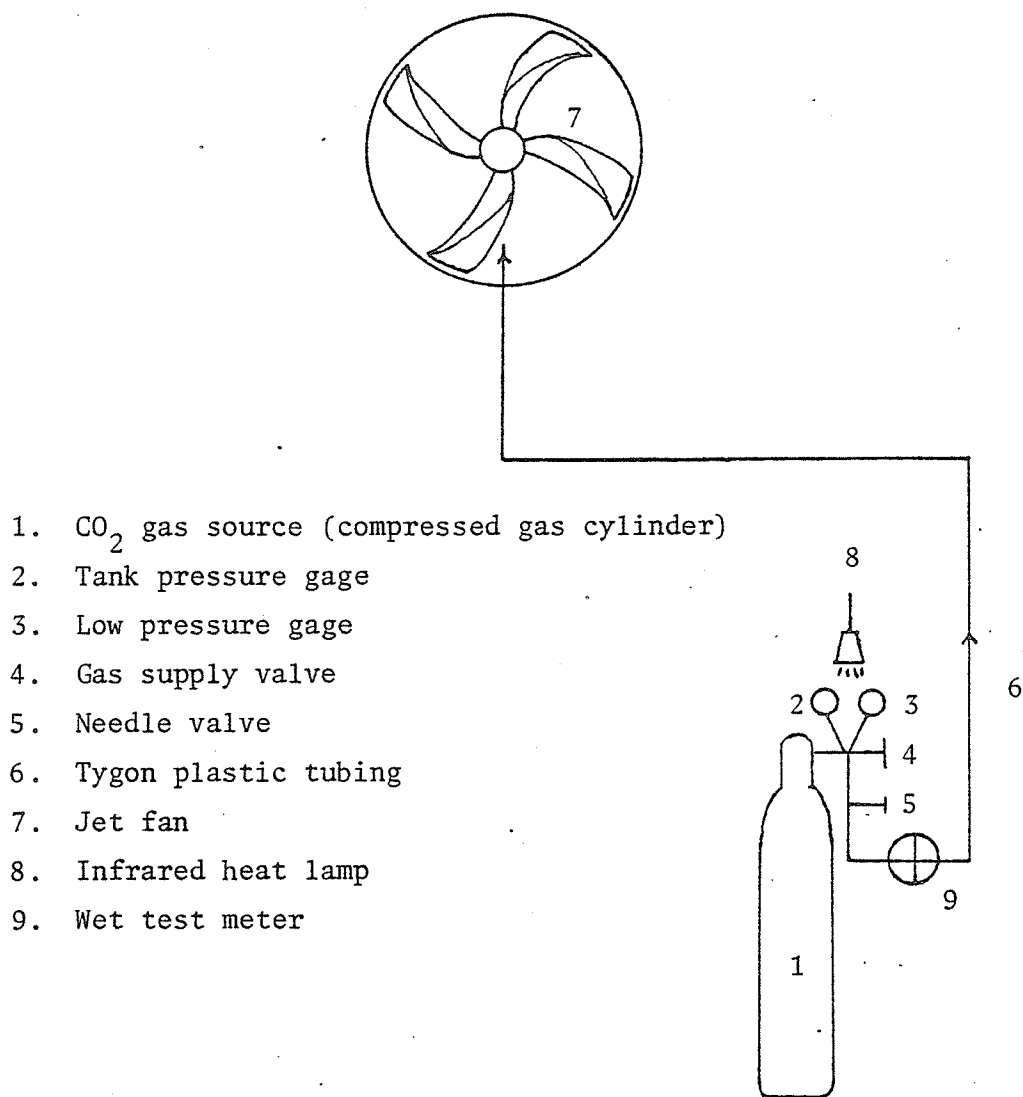


Figure 3.3 Schematic diagram of the CO<sub>2</sub> supply to the greenhouse

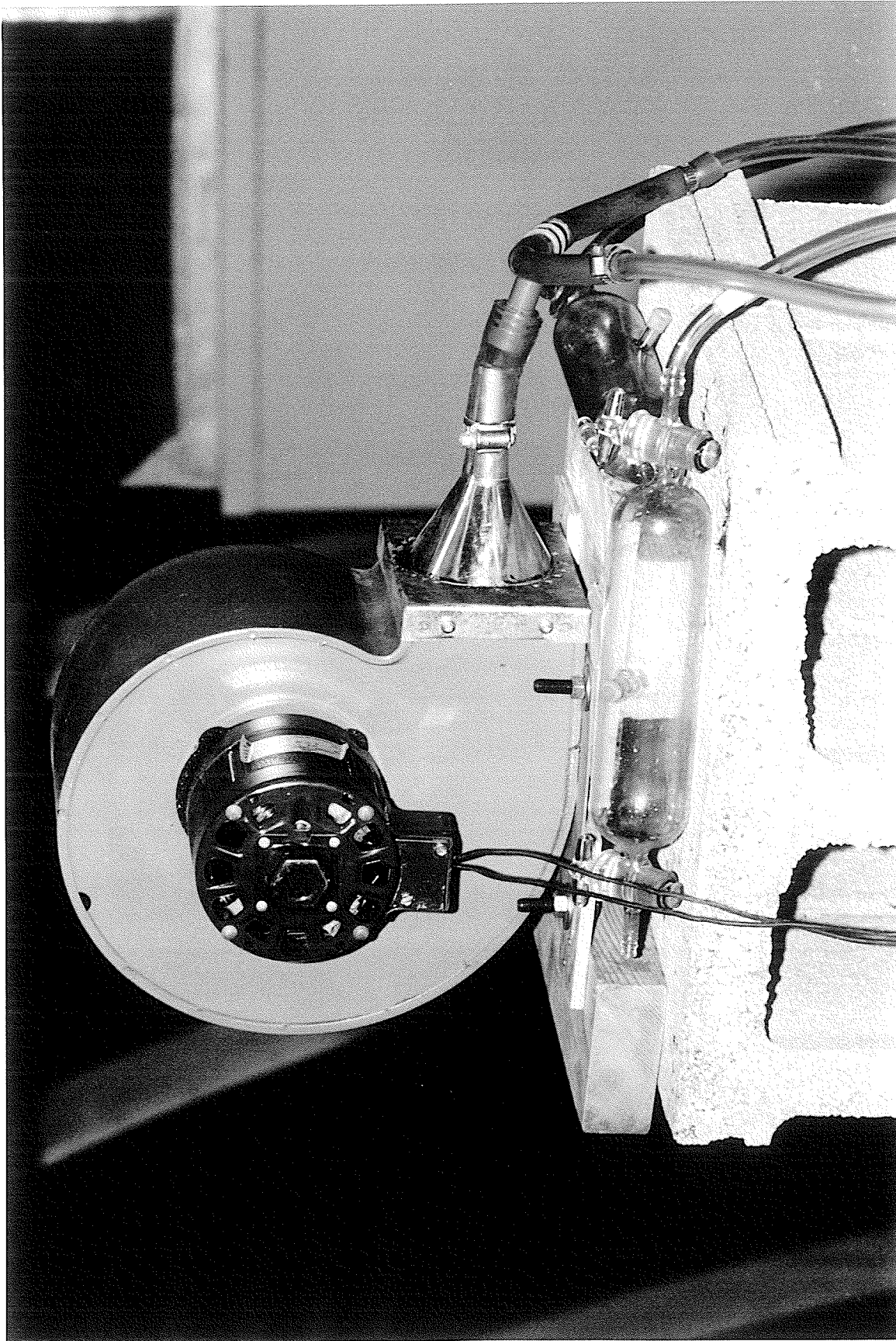


Figure 3.4 Blower assembly (air sampling system for gas analysis).

outdoor temperature every 30 minutes during each test.

### 3.9 Wind speed and Direction Measurement

Wind speed was recorded by a 3 cup anemometer installed 2 m above the greenhouse (number 2) roof. The wind direction was observed on a simple wind vane which was fabricated in the Agricultural Engineering workshop. Figure 3.5 shows the instruments used for determining wind speed and indicating wind direction.

### 3.10 The Liquid Displacement System

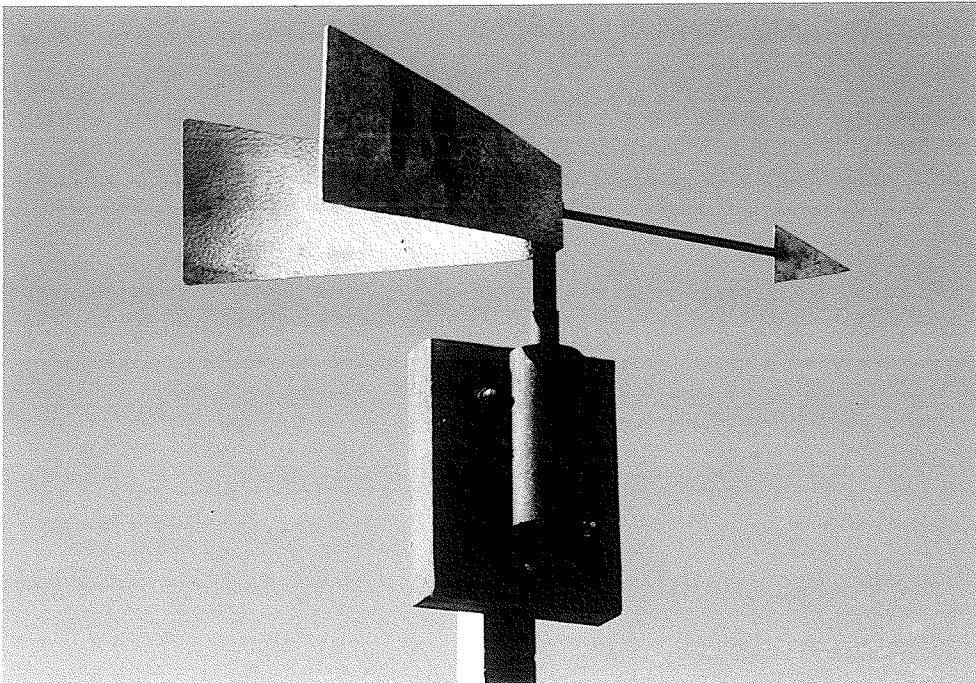
The gas sampling bottles with an average capacity of 300 mL were used to collect the air samples for determination of CO<sub>2</sub> content. The gas samples were drawn in a 30 mL syringe for flushing the gas sampling loop for injection. It was not possible to draw a sample of 30 mL from a 300 mL flask without admitting a displacing liquid into the sampling tube. Paraffin oil was used (because it does not absorb CO<sub>2</sub>) to replace the volume of sample drawn by the syringe. Before connecting the paraffin oil line to the sampling tube, one arm of the tube was filled with paraffin oil in order to expel any trapped air which otherwise would result in a significant error.

The pressure in both vessels (gas sampling bottle and funnel, Figure 3.6) was not equalized by adjusting the liquid level. Any high pressures in the samples in the 30 mL syringe were automatically released when the hypodermic needle was removed from the syringe prior to introducing the sample to the gas sampling loop. Figure 3.6 shows the paraffin displacement assembly.





(a) Wind speed meter



(b) Wind direction vane

Figure 3.5 Instruments for measuring wind speed and direction

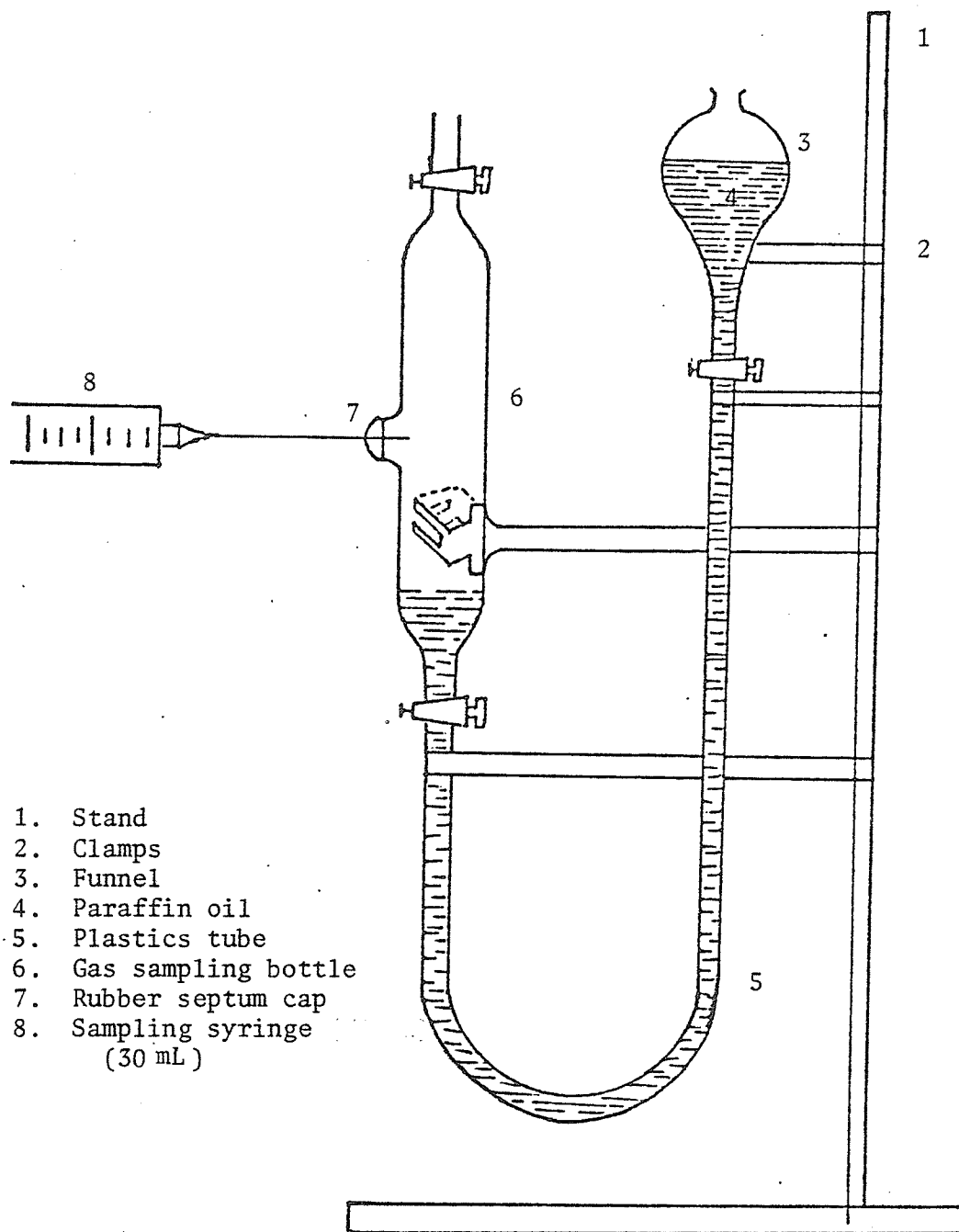


Figure 3.6 Paraffin displacement system

## CHAPTER IV

### PROCEDURES FOR MEASURING LEAKAGE RATES AND DEVELOPMENT OF A SIMULATION MODEL TO PREDICT CARBON DIOXIDE CONCENTRATION

Air change rates for two research greenhouses at the University of Manitoba were measured during the months of July and August, 1977. Four tests were conducted in greenhouse No. 2 which was built in 1971 while three tests were conducted in greenhouse No. 1 which was built in 1970.

For simplicity, greater reliability and ease of continuous recording (Dick, 1950) it was decided to use a tracer gas technique (Section 2.7.2) for determining the leakage rates for two research greenhouses. A step by step flow diagram of the experimental procedure is presented in Figure 4.1.

The gas chromatograph was calibrated after controlling all the operating parameters (temperatures of the column, the injector, and the detector, carrier gas flow rate and selection of an appropriate attenuation for maximum sensitivity). Carbon dioxide mixed in nitrogen at known concentrations was used in 1 mL samples for all calibrations.

The greenhouse atmosphere was enriched by releasing CO<sub>2</sub> gas (Figure 3.3). Air samples from the greenhouse were collected after each 0.5 h and were analyzed by gas chromatography in the Pesticide Research Laboratory. Enrichment was continued until a predetermined

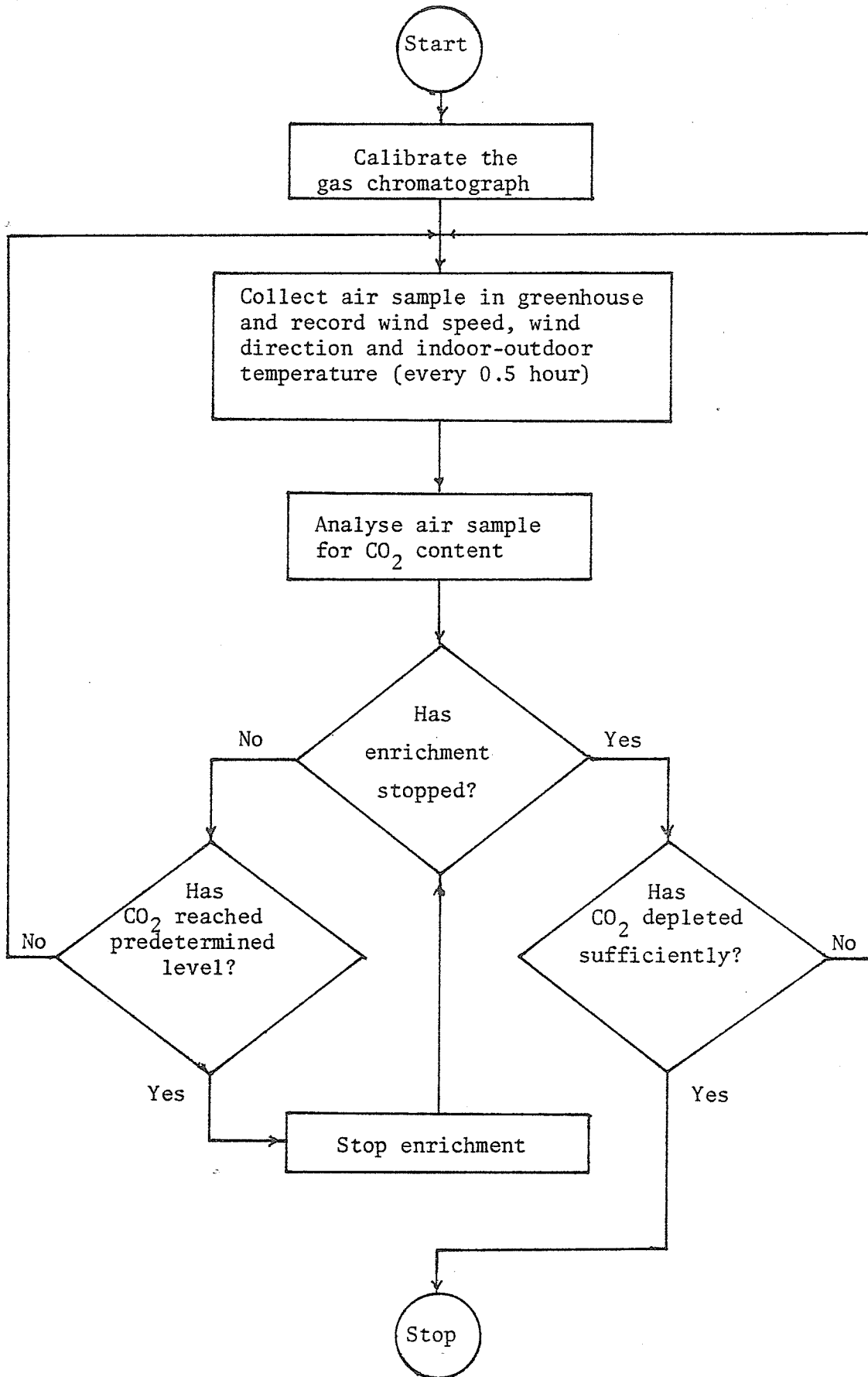


Figure 4.1 Flow diagram for procedure of data collection for enrichment and depletion

maximum concentration of CO<sub>2</sub> was achieved. The CO<sub>2</sub> supply was shut off and sampling and analysis of greenhouse air was begun for the depletion of CO<sub>2</sub>. Sampling continued until sufficient data were obtained or until instrument response became too low. Data for wind speed, wind direction and indoor and outdoor temperatures were collected at each 0.5 h interval during enrichment and depletion.

Air change rates or air leakage rates for the greenhouses were determined by performing an exponential regression analysis between the two variables, time in hours and CO<sub>2</sub> concentration in ppm. A multiple regression analysis was performed with air change rate as the dependent variable and wind speed and indoor-outdoor temperature differentials as the independent variables.

#### 4.1 Selection of Operating Parameters (Gas Chromatograph)

A large number of trial analyses were made to select the optimal operating parameters (carrier gas flow rate, column and detector temperatures) for maximum sensitivity and maximum separation of CO<sub>2</sub> from air. All the analyses were done at a column temperature of 30°C, detector temperature of 170°C and carrier gas flow rate of 45 mL/min. The recommended filament current of 150 mA at maximum attenuation was used.

#### 4.2 Static Calibration

After selecting the parameters for optimal operating conditions the instrument response was calibrated to establish the linearity and sensitivity of the detector.

#### 4.2.1 Making of Standard Gas Mixtures

The accuracy of prepared gas mixtures of known concentration is imperative for the calibration and performance testing of any gas analysis instrument. A batch mixing technique was used to prepare the various CO<sub>2</sub> concentrations in nitrogen gas. The following simple relationship was used to calculate the exact volume of CO<sub>2</sub> required to get a desired concentration (Cotabish et al., 1961).

$$V_r = C_{\text{ppm}} V_c 10^{-6}$$

where

$V_r$  = the required volume of CO<sub>2</sub>, mL

$C_{\text{ppm}}$  = desired concentration of CO<sub>2</sub>, ppm

$V_c$  = volume of mixing container, mL.

Two separate gas sampling bottles were flushed continuously with nitrogen and carbon dioxide. The stop-cocks of the sampling bottles were closed and excessive pressure was released by opening one end of each tube momentarily. A Hamilton gas-tight syringe was flushed several times with pure CO<sub>2</sub> and a measured volume of CO<sub>2</sub> was injected into the sampling bottle containing nitrogen. Before injection an equal amount of nitrogen was removed to ensure that the mixing took place at atmospheric pressure.

Due to a lack of low volume gas-tight syringes and in order to minimize errors it was necessary to use large sampling bottles. The large sampling bottles were manufactured by the glass blowing shop in the Chemistry Department, University of Manitoba. Three different bottles (847, 329 and 49 mL) were used to make the standard calibration mixtures.

#### 4.2.2 Basic Calibration

The instrument response for linearity and sensitivity was determined by performing a basic calibration with samples of known concentrations of up to 50000 ppm of CO<sub>2</sub>. Samples were taken in a 30 mL glass syringe by displacing the same volume with paraffin oil as already discussed in Section 3.10. These samples were used for flushing the gas sampling valve loop for the injection of a sample of one mL.

Table 4.1 shows the various concentrations used for calibration purposes and the corresponding peak heights measured at various attenuations.

Table 4.1 Calibration Data for Gas Chromatograph

Volume of Mixing Bottle, mL	N <sub>2</sub> removed and CO <sub>2</sub> added, mL	CO <sub>2</sub> concentration, ppm	Average of 4 peak heights, mm
*	--	330	8.4
**	--	1000	33.2
847	0.5	590	16.0
847	0.85	1000	31.5
847	1.70	2000	63.6
329	1.75	5300	175.3
329	3.3	10000	329.3***
49	1.0	20400	678.0***
49	2.5	51000	1640.0***

\* Fresh air sample

\*\* 1000 ppm CO<sub>2</sub> in Helium (Applied Science Laboratories)

\*\*\* Peak heights above 200 mm were measured at lower attenuations



A regression analysis of the data in Table 4.1 gave the following calibration equation:

$$C = 30.98 h - 62.24$$

where

$C$  = CO<sub>2</sub> concentration, ppm

$h$  = response (peak height), mm

The correlation coefficient was 1.00.

The instrument sensitivity (Holman, 1971; Lawson and Miller, 1966) was measured as the ratio of the change in instrument response (mm of peak height) to the change in concentration (ppm of CO<sub>2</sub> in standard mixtures). Thus the sensitivity is given as

$$S = \Delta h / \Delta C$$

where

$S$  = sensitivity, mm/100 ppm

$\Delta h$  = change in peak height, mm

$\Delta C$  = change in concentration, 100 ppm

For this instrument the sensitivity was 0.03228 mm/ppm for the basic calibration.

#### 4.3 Routine Calibration

To avoid changing operating conditions of ambient temperature and fluctuations in the power supply from day to day a quick routine calibration was carried out before each set of analyses in order to establish the daily response. Only three samples were used for this purpose. Normal atmospheric air samples were assumed to contain 330 ppm while a commercially prepared CO<sub>2</sub> mixture in helium of 1000 ppm (Applied Science Laboratories) was used as a second sample. A third



concentration of 6000 ppm was also made for injection.

The sensitivity as determined at each routine calibration varied from the basic sensitivity. Regression equations for routine calibrations to determine the CO<sub>2</sub> concentrations (C, ppm) for a known instrument response (h, mm) are listed below. The values quoted in parentheses for equations 4.3 to 4.9 are the sensitivities as determined from the routine calibration.

$$C = 30.21 h + 13.94 \quad [S = 0.03310 \text{ mm/ppm}] \quad (4.3)$$

$$C = 28.25 h + 6.81 \quad [S = 0.03540 \text{ mm/ppm}] \quad (4.4)$$

$$C = 28.76 h + 15.32 \quad [S = 0.03477 \text{ mm/ppm}] \quad (4.5)$$

$$C = 29.21 h + 2.91 \quad [S = 0.03423 \text{ mm/ppm}] \quad (4.6)$$

$$C = 28.59 h + 22.54 \quad [S = 0.03498 \text{ mm/ppm}] \quad (4.7)$$

$$C = 28.38 h + 21.73 \quad [S = 0.03524 \text{ mm/ppm}] \quad (4.8)$$

$$C = 27.23 - 0.04 \quad [S = 0.03672 \text{ mm/ppm}] \quad (4.9)$$

Correlation coefficient in all the regression equations (4.3 to 4.9) was 1.0.

#### 4.4 CO<sub>2</sub> Enrichment of Greenhouses

Most of the experiments were conducted at night since the greenhouses were too hot during the daytime. CO<sub>2</sub> gas was released (Figure 3.3) at a rate of about 800 to 900 L/h. Samples of greenhouse air were collected each 0.5 hour after enrichment was started. The air samples were taken to the Pesticide Research Laboratory where they were analysed for CO<sub>2</sub> concentration. The analysis was completed before the next sampling period.

#### 4.5 Analysis of Air Samples

Air samples from the greenhouses were collected in 300 mL gas sampling glass bottles using a blower (Figure 3.4). The samples were taken during the enrichment and depletion of the tracer gas. Samples were drawn at the middle of the greenhouses. Two samples were taken for each test.

One mL samples were injected into the chromatograph column using the gas sampling valve. A 30 mL sample was first displaced into the syringe with paraffin oil. The detector response for each sample was recorded on a strip chart recorder. The peak height determined the concentration of CO<sub>2</sub> in ppm in conjunction with the routine calibration curves.

#### 4.6 Temperature Measurement

Indoor and outdoor temperatures were recorded each 0.5 hour during the enrichment and depletion.

#### 4.7 Wind Speed and Direction Measurement

Wind speed in km/h and wind directions were also recorded each 0.5 hour during enrichment and depletion.

#### 4.8 Development of the Simulation Model

The demands of economists and engineers have made the technique of using computer simulation models for continuous system program management important. The specific purpose of this simulation model is to predict the concentration of carbon dioxide in the greenhouse at any time during or after CO<sub>2</sub> enrichment when the following parameters are known:

- (i) the rate of  $\text{CO}_2$  coming into the greenhouse due to infiltration of external air
- (ii) the rate of  $\text{CO}_2$  input (depends on the source of  $\text{CO}_2$ )
- (iii) the rate of  $\text{CO}_2$  leakage out of the greenhouse due to exfiltration of the internal air
- (iv) the uptake rate of  $\text{CO}_2$  by plants

#### 4.8.1 Assumptions

The following assumptions have been made:

(i) Infiltration and exfiltration are the normal air changes per hour (a) and are in the range of 0.01 to 1.0/h depending on the tightness of the greenhouse, wind speed and direction, indoor-outdoor temperature differential and the concentration gradient of  $\text{CO}_2$  between the inside and the outside of the greenhouse

(ii) The volume of  $\text{CO}_2$  added for enrichment is very small as compared to the greenhouse total volume and therefore the volumes of air infiltrating and exfiltrating are assumed to be equal

(iii) The normal concentration of  $\text{CO}_2$  in the air is assumed to be constant at 330 ppm

(iv) Instantaneous and homogeneous mixing of  $\text{CO}_2$  (due to infiltration or enrichment) is assumed so that the outgoing air contains the instantaneous  $\text{CO}_2$  concentration

(v) The  $\text{CO}_2$  input rate is proportional to the source of  $\text{CO}_2$  (i.e. assuming complete combustion of the hydrocarbon fuel and the burners rated capacity, W)

#### 4.8.2 General Solution

The change in the amount of CO<sub>2</sub> in the greenhouse can be expressed as

$$CD = CD_i - CD_o \quad (4.10)$$

where

$CD$  = CO<sub>2</sub> change, L/min

$CD_i$  = sum of CO<sub>2</sub> inputs, L/min

$CD_o$  = sum of CO<sub>2</sub> losses, L/min

The inputs are:

$$CD_i = CDI + CDA \quad (4.11)$$

where

$CDI$  = CO<sub>2</sub> in due to infiltration, L/min

$CDA$  = CO<sub>2</sub> added by enrichment, L/min

The losses are:

$$CD_o = CDO + CDC \quad (4.12)$$

where

$CDO$  = CO<sub>2</sub> lost by exfiltration, L/min

$CDC$  = CO<sub>2</sub> consumed by plants, L/min

Combining equations 4.11 and 4.12 into the equation 4.10 gives:

$$CD = CDI + CDA - CDO - CDC \quad (4.13)$$

From equation 4.13  $CDI$  can be expressed in terms of air volumes and air changes per minute as

$$CDI(\text{CO}_2, \text{L/min}) = C_n V a / 10^6 \quad (4.14)$$

where

$C_n$  = normal concentration of CO<sub>2</sub> in atmospheric air, ppm

$C_n = 330$  ppm

$V$  = volume of greenhouse, L

$a$  = infiltration rate for air, air changes/min

In equation 4.13 CDA can be expressed as

$$\text{CDA}(\text{CO}_2, \text{L/min}) = B \quad (4.15)$$

where

$B$  = a constant  $\text{CO}_2$  rate (L/min) which depends on the source of the  $\text{CO}_2$  for enrichment. The most common sources of  $\text{CO}_2$  for the enrichment of a greenhouse atmosphere have been discussed in Section 2.2.2. Most of the commercial burners are rated in terms of watts (or kilowatts). The following conversion factors (K1) are used to convert burner ratings in W to L of  $\text{CO}_2$ /min output:

(i) Kerosene  $(2.1257)(10^{-3})$

(ii) Propane  $(1.8176)(10^{-3})$

(iii) Natural gas  $(1.5997)(10^{-3})$

(iv)  $\text{CO}_2$  gas from cylinders is measured directly from the flow meter (L/min).

In a similar manner the  $\text{CO}_2$  losses can be expressed as:

$$\text{CDO}(\text{CO}_2, \text{L/min}) = \text{CVA}/10^6 \quad (4.16)$$

where

$C$  = instantaneous concentration of  $\text{CO}_2$  in the greenhouse air,

ppm

$$\text{CDC}(\text{CO}_2, \text{L/min}) = \text{PLU} \quad (4.17)$$

where

$\text{PLU}$  =  $\text{CO}_2$  used by plants, L/min.

It has been reported in Section 2.2.3 that as the  $\text{CO}_2$  concentration in the greenhouse atmosphere is increased the rate of

photosynthesis is also increased. Table 4.2 shows CO<sub>2</sub> uptake for increasing CO<sub>2</sub> concentrations for tobacco (Hesketh and Moss, 1963).

Table 4.2 The effect of CO<sub>2</sub> concentration on the rate of photosynthesis in single leaves of tobacco\*

CO <sub>2</sub> uptake [mg/(dm <sup>2</sup> · h)]	CO <sub>2</sub> concentration [ppm]
10	150
24	300
48	600
29	1000

\*The experiments were conducted at a light intensity approximately twice that of normal sunlight, 400 nm ≤ λ ≤ 700 nm with leaf temperatures between 25 and 31°C.

The simulation model assumes that these data can be used for qualitative comparisons. The data of Table 4.2 were used in an exponential regression analysis.

The form of the regression equation is:

$$UU = m \exp (nC) \quad (4.18)$$

where

UU = plant use of CO<sub>2</sub>, mg/(dm<sup>2</sup> · h)

m and n are constants

C = instantaneous CO<sub>2</sub> concentration, ppm

The regression analysis determined the values of m and n in equation 4.18. The values were

$$m = 10.09 \text{ mg}/(\text{dm}^2 \cdot \text{h})$$

$$n = 0.002116 \text{ 1/ppm}$$

Substituting these values into equation 4.18 gives the final expression for estimating  $\text{CO}_2$  consumption on a unit basis

$$UU = 10.09 \exp (0.002116C) \quad (4.19)$$

The total  $\text{CO}_2$  consumed by a growing crop depends on several factors. One of the major factors is the total leaf area (TLA) of the crop. The total leaf area is a function of the plant leaf area index (PLAI), the floor utilization factor (FUF) and the greenhouse length (GHL) and width (GHW). PLAI varies from crop to crop and is in the range of 4 to 8 (Zelitch, 1971). PLAI is the ratio of leaf area to soil surface area used by or allotted to each plant. The total leaf area ( $\text{cm}^2$ ) can be calculated as

$$\text{TLA} = (\text{PLAI})(\text{FUF})(\text{GHL})(\text{GHW}) \quad (4.20)$$

when greenhouse length and width are measured in centimetres. Then plant use of  $\text{CO}_2$  (L/min) can be expressed as

$$\text{PLU} = (K_2)(UU)(\text{TLA}) \quad (4.21)$$

where  $K_2$  is a dimensions conversion factor. For the dimensions used in this simulation

$$K_2 = 8.4848(10^{-8}) (\text{L}/\text{min}) / (\text{mg} \cdot \text{cm}^2 / (\text{dm}^2 \cdot \text{h}))$$

Similarly

$$\text{CD} = V(dC/dt)/10^6$$

where

$dC/dt$  = rate of change of concentration of  $\text{CO}_2$  in greenhouse air,  
ppm/min

Equation 4.13 can now be written as

$$V(dC/dt)/10^6 = C_n V_a/10^6 + B - CV_a/10^6 - \text{PLU} \quad (4.22)$$

Dividing by  $V$  and multiplying by  $10^6$  in equation 4.23 after some rearranging

$$dC/dt = C_n a - Ca + (B/V - PLU/V) 10^6 \quad (4.23)$$

or

$$dC/dt + Ca = C_n a + (B/V - PLU/V) 10^6 \quad (4.24)$$

Equation 4.24 is an ordinary first order differential equation with constant coefficients. The general solution of equation 4.24 is

$$C = K \exp(-at) + C_n + (B/(Va) - PLU/(Va)) 10^6 \quad (4.25)$$

where  $K$  is a constant determined from the initial conditions  $C = C_o$  at  $t = 0$ ,

$$K = C_o - C_n - (B/(Va) - PLU/(Va)) 10^6 \quad (4.26)$$

Substituting the value of  $K$  into equation 4.25 results in

$$C = (C_o - C_n - (B/(Va) - PLU/(Va)) 10^6) \exp(-at) + C_n + (B/(Va) - PLU/(Va)) 10^6 \quad (4.27)$$

#### 4.8.3 CSMP Continuous System Modeling

A computer simulation model, based on equation 4.23, was developed using the CSMP system/360 continuous system modeling program number 360A-CX-16X. The program was capable of predicting  $CO_2$  concentration (ppm) at any time during or after enrichment. The dynamic segment of the program (Figure 4.3) is the main part of the simulation while the variables used are defined in Figure 4.2.



CN = NORMAL CONCENTRATION OF CARBON DIOXIDE , PPM  
 PPMCC = CONSTANT TO CONVERT L/MIN TO PPM/MIN  
 PPM =PARTS PER MILLION  
 C = CONCENTRATION OF CO2 AT ANY TIME, PPM  
 CDOT = CHANGE IN CO2 CONCENTRATION, PPM/MIN  
 ACPM = AIR CHANGE PER MINUTE  
 ACPH = AIR CHANGE PER HOUR  
 RIN = RATE OF CO2 INPUT, L/MIN  
 K1 = CO2 SOURCE UNITS CONVERSION TO L/MIN ( SECTION 3.3.1 )  
 K1 = 2.1257E-03 FOR KEROSENE ;1.8176E-03 FOR PROPANE  
 K1 = 1.5997E-03 FOR NATURAL GAS ; 1.6667E-02 FOR CO2 GAS FROM CYLINDERS  
 SOCD = THERMAL RATING OF BURNER , W , WHEN CO2 IS SUPPLIED FROM  
 COMPLETE COMBUSTION OF KEROSENE , PROPANE , OR NATURAL GAS  
 SOCD = L/H FOR CO2 FROM CYLINDERS  
 VOL = VOLUME OF GREENHOUSE , L  
 GHW = GREENHOUSE WIDTH , CM  
 GHL = GREENHOUSE LENGTH , CM  
 TLA = TOTAL LEAF AREA , CM\*\*2  
 FUF = FLOOR UTILIZATION FACTOR  
 K2 = CONSTANT FOR UNIT CONVERSION FROM MG CO2/(DM\*\*2\*H) TO L/MIN  
 UU = UNIT USE OF CO2 BY PLANTS , MG CO2 / (DM\*\*2\*H)  
 PLU = PLANT USE OF CO2 , L/MIN  
 CIN = INITIAL CONCENTRATION OF CO2 , PPM  
 INITIAL = COMPUTES THE INITIAL CONDITION VALUES  
 PARAMETER = ASSIGNS THE VALUES TO VARIABLES USED IN THE DYNAMIC SEGMENT  
 OF THE PROGRAM  
 INCON = ASSIGNS VALUES TO PARAMETERS  
 DYNAMIC = MATHEMATICAL DESCRIPTION OF THE SYSTEM DYNAMICS  
 TIMER = CONTROL STATEMENT SPECIFYING RUN TIME, RUN LENGTH, ETC.  
 OUTDEL = PRINT INCREMENT FOR THE PRINT-PLOT OUTPUT  
 FINTIM = MAXIMUM SIMULATION VALUE FOR THE INDEPENDENT VARIABLE  
 FINISH = SPECIFIES TERMINATING CONDITION IN ADDITION TO FINTIM  
 PRTPLOT = SPECIFIES WHICH VARIABLES ARE TO BE PRINTER PLOTTED  
 LABEL = SPECIFY A HEADING FOR EACH PAGE OF PRINT-PLOT OUTPUT

Figure 4.2 Nomenclature of Computer Simulation Model

```

INITIAL
CN = 330.0
PPMCC = 1.0E06

DYNAMIC
C = INTGRL( CIN , CDOT )
CDOT = CN*ACPM+RIN*PPMCC/VOL-PLU*PPMCC/VOL-C*ACPM
ACPM = ACPH/60.0
RIN = K1*SOC
UU = 10.095*EXP(2.116E-03*C)
TLA = PLAI*FUF*GHL*GHW
PLU = K2*UU*TLA
K1=1.6667E-02, SOCD=0.0, VOL=9.6327E05, GHL=1522.0
GHW=1190.0, FUF=0.80
K2= 8.4848E-08, ACPH = 0.272
PLAI = (0.0, 4.0)
CIN=2657.0
CARBON DIOXIDE CONCENTRATIONS DURING DEPLETION
C(CDOT,UU)
OUTDEL = 2.0 , FINTIM = 50.0
C=200.0

PARAMETER
PARAMETER
PARAMETER
PARAMETER
INCON
LABEL
PRTPLT
TIMER
FINISH
END
STOP

```

Figure 4.3 CSMP/360 Computer Simulation Program (See Figure 4.1 for description of symbols).

## CHAPTER V

### RESULTS AND DISCUSSIONS

#### 5.1 Gas Chromatographic Analysis

The Porapak Q packed column was used to separate the CO<sub>2</sub> gas in the air. A complete separation was obtained under optimal analysis conditions. Response of the thermal conductivity detector was found to be linear to 50000 ppm (5%) CO<sub>2</sub> concentration as shown by the basic calibration equation (Section 4.2.2). The separations were performed at an average operating temperature of 30, 31, 164 and 136°C for the column, injector, detector and collector respectively. The observed CO<sub>2</sub> concentrations as determined by gas chromatographic analysis of the air samples are listed in Table 5.1. Sample calculations for these data are shown in Appendix B.

In most of the tests the indoor-outdoor temperature difference and the wind velocity were not constant throughout the whole test period. Therefore, infiltration rates could not be expected to be constant for the test periods. In order to detect changes in leakage rates for a particular test due to changing indoor-outdoor temperature differences and changing wind velocities, the data of Table 5.1 were plotted on semilogarithmic graph paper with time as the linear scale (Figure 5.1). It can be seen from Figure 5.1 that each test showed a shift in the slope of the leakage rate curve with the exception of Test No. 6. The duration of each leakage rate in a particular test was established by examining the change in slope of the curves of

Table 5.1 Measured CO<sub>2</sub> Concentrations for the Tests

Sample No.	Time h	Test Number						
		Greenhouse No. 2				Greenhouse No. 1		
		1	2	3	4	5	6	7
1	0.0	2657	2148	2009	2588	3254	2803	2524
2	0.5	2400	1702	1491	1990	2710	2363	1688
3	1.0	2228	1510	1160	1507*	2167	2094	1171
4	1.5	1978	1340	927	1268	1924	1810	817
5	2.0	1857	1207	849	1005	1761	1620	708
6	2.5	1637	1213	705	707	1558	1347	572
7	3.0	1343	1193	662	508	1324	1120	525
8	3.5	1041	1151	611	465	1223	964	485
9	4.0	959	---	547	456	1095	831	---
10	4.5	763	1136	447	368	966	669**	---
11	5.0	---	---	---	---	880	---	---
12	5.5	---	1066	---	---	817	---	---
13	6.5	---	973	---	---	---	---	---
14	7.25	---	919	---	---	---	---	---
15	8.0	---	911	---	---	---	---	---

\* measured at 0.92 hours

\*\* measured at 4.75 hours

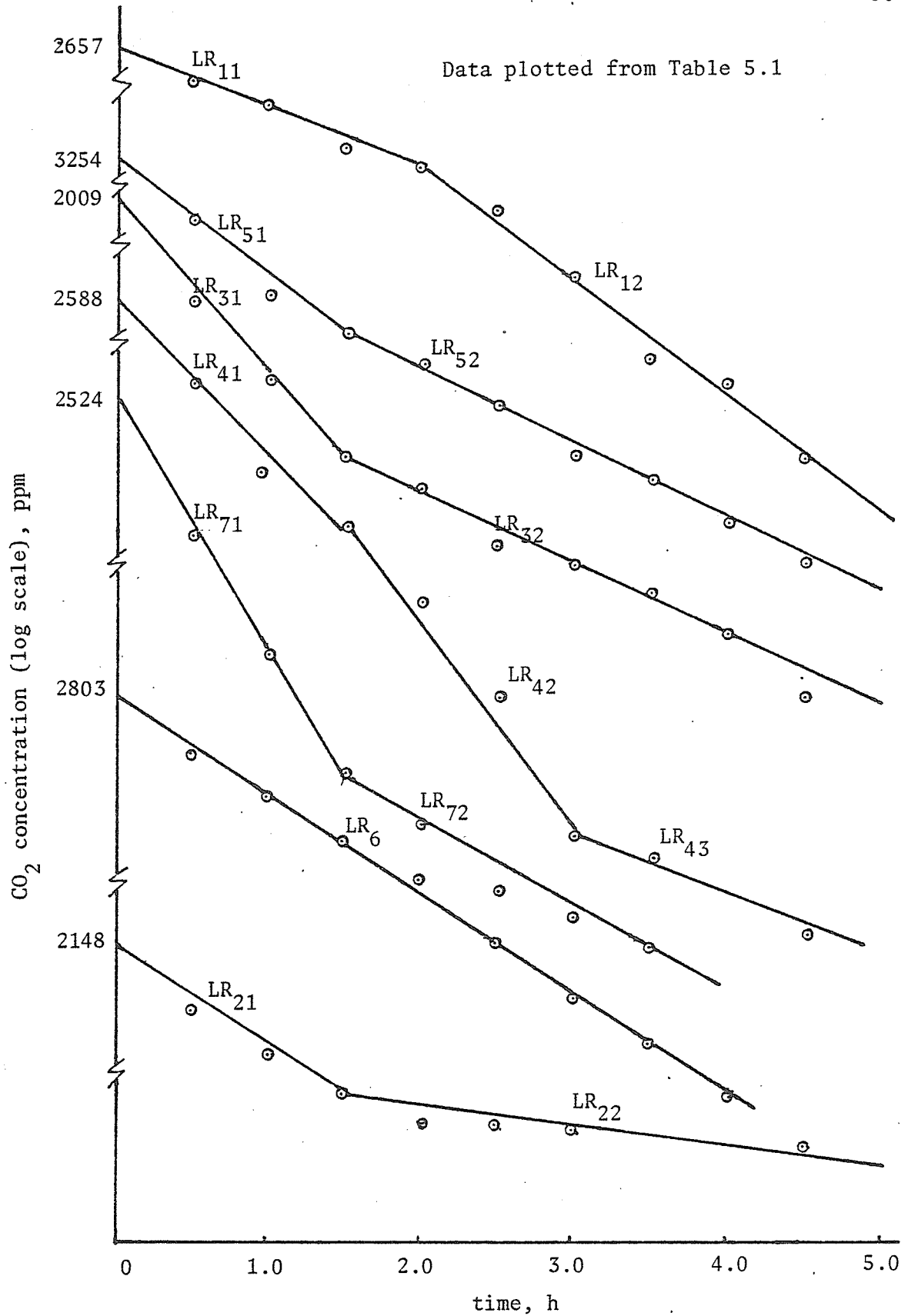


Figure 5.1 Change of leakage rates due to changing indoor-outdoor temperature differentials and wind velocities.

Figure 5.1. The leakage rates and the average air change rates for each test were calculated by performing an exponential regression analysis. Sample calculations of such an analysis are shown in Appendix C for Test 1.

Table 5.2 summarizes the results for the seven tests conducted in both greenhouses along with the main factors affecting the leakage rates. Both greenhouses were oriented almost north-south. The wind direction was recorded with respect to the greenhouses assuming a north-south orientation. The 16 point direction concept as reported by Middleton and Spilhaus (1953) was used. Wind components on the long and the narrow sides as reported in Table 5.2 were obtained by resolving the prevailing wind into two components by using the following relationships:

$$W_{LS} = W \sin \theta \quad (5.1)$$

$$W_{NS} = W \cos \theta \quad (5.2)$$

where

$W_{LS}$  = wind component on long side, km/h

$W_{NS}$  = wind component on narrow side, km/h

$W$  = prevailing wind speed, km/h

$\theta$  = angle of prevailing wind with respect to long side of greenhouse, degrees

For example a wind speed of 26.1 km/h in test 4 from the WNW direction gives the following results:

$$\begin{aligned} W_{LS} &= 26.1 \sin 67.5 \\ &= 24.1 \text{ km/h} \end{aligned}$$

and  $W_{NS} = 26.1 \cos 67.5$

Table 5.2 Leakage Rates and Other Factors for the Tests

Test	Leakage Rate	Duration Hours	Air Change $h^{-1}$	Average wind speed $W$ km/h	Wind Direction	Indoor-Outdoor Temp. Diff. $\Delta T$ , °C	Wind speed component normal to long side $W_{LS}$	Wind speed component normal to narrow side $W_{NS}$
1	LR <sub>11</sub>	2.0	0.182	6.5	N	5.7	0.0	6.5
	LR <sub>12</sub>	2.5	0.372	15.0	SE	4.6	10.6	10.6
	R	4.5	0.272	10.8	ENE	5.2	9.9	4.1
2	LR <sub>21</sub>	1.5	0.239	4.8	NNW	6.3	1.8	4.4
	LR <sub>22</sub>	6.5	0.053	2.3	<u>2/</u>	5.7	-	-
	R	8.0	0.071	3.6	NNW	6.0	1.4	3.3
3	LR <sub>31</sub>	1.5	0.475	20.3	ENE	9.4	18.8	7.8
	LR <sub>32</sub>	3.0	0.231	12.3	NE	7.0	8.7	8.7
	R	4.5	0.272	15.3	NE	8.2	10.8	10.8
4	LR <sub>41</sub>	1.5	0.441	20.0	WNW	10.0	18.5	7.7
	LR <sub>42</sub>	1.5	0.661	29.7	WNW	13.4	27.4	11.4
	LR <sub>43</sub>	1.5	0.234	28.7	WNW	10.7	26.5	11.0
	R	4.5	0.431	26.1	WNW	11.4	24.1	10.0
5	LR <sub>51</sub>	1.5	0.343	3.0	WSW	10.1	2.8	1.1
	LR <sub>52</sub>	4.0	0.221	4.3	SW	7.9	3.0	3.0
	R	5.5	0.234	3.6	SW	9.0	2.5	2.5
6	R	4.75	0.305	10.4	SW	6.2	7.4	7.4

Table 5.2 (concluded)

Test	Leakage Rate	Duration Hours	Air Change $h^{-1}$	Average wind speed $W$ km/h	Wind Direction	Indoor-Outdoor Temp. Diff. $\Delta T$ , °C	Wind speed component normal to long side $W_{LS}$	Wind speed component normal to narrow side $W_{NS}$
7	LR <sub>71</sub>	1.5	0.726	31.4	WNW	11.7	29.0	12.0
	LR <sub>72</sub>	2.0	0.244	29.7	NW	16.3	21.0	21.0
	R	3.5	0.407	30.6	NW	14.0	21.6	21.6

1/ Average leakage rates (R) were measured on all the data for a particular test (Table 5.1)

2/ Wind was continuously changing directions



= 10.0 km/h

### 5.2 The Effect of Wind Speed on Leakage Rates

The phenomenon of infiltration or exfiltration is highly dependent on wind velocity and the indoor-outdoor temperature differential. The effect of wind velocity on the observed leakage rates can be observed in Table 5.2. It can be seen that the measured leakage rates are higher when the wind speed has increased. In tests 4 and 5 the indoor-outdoor temperature differentials are the same for  $LR_{41}$  and  $LR_{51}$ . The wind direction is not the same but with respect to the long side the effects should be similar. Therefore any increase or decrease in wind speed should result in a corresponding increase or decrease in the leakage rate. It can be seen from Table 5.2 that  $LR_{41}$  and  $LR_{51}$  where the wind speed changed from 20.0 km/h to 3.0 km/h, respectively, the leakage rate changed from 0.441/h to 0.343/h. Another illustration of the effect of wind velocity on leakage rates can be seen in test 3 and 4. The leakage rates  $LR_{31}$  and  $LR_{41}$  are approximately equal since all other parameters remained approximately equal for both tests. The wind directions in the two tests above were not the same but the components on the long and on the narrow sides appeared to have equal effects.

### 5.3 The Effect of Wind Direction on Leakage Rates

It was not possible to measure the effect of wind direction on leakage rates. This was so since each test was of a limited duration and a long time interval was required for sample analysis. However in some cases it was possible to note the effect of wind direction. For

example, in test 7 (LR<sub>71</sub> and LR<sub>72</sub>), it can be seen that in spite of the fact that the indoor-outdoor temperature differential for LR<sub>72</sub> increased the velocity remained the same. The increased temperature differential should have increased the leakage rate, but the leakage rate was much lower compared to LR<sub>71</sub>. The only changing parameter was the wind direction which changed from WNW to NW resulting in a decreased wind component on the long side of the greenhouse.

Another example of the effect of wind direction on the leakage rates is presented in test 5 (LR<sub>51</sub> and LR<sub>52</sub>). The wind speed and indoor-outdoor temperature differentials were approximately equal. When the wind direction changed from WSW to SW resulting in a decreased wind component on the long side of the greenhouse the observed leakage rate also dropped from 0.343/h to 0.221/h.

#### 5.4 The Effect of Temperature Differential on Leakage Rates

Any increase in the indoor-outdoor temperature differential will result in increased infiltration rates. In these tests it was not possible to maintain a constant indoor-outdoor temperature differential. Therefore it was a matter of chance in obtaining data to explain the effect of temperature differentials on the air change rates.

In test 4 of Table 5.2 the leakage rate changed only due to changing temperature while all other parameters remained reasonably constant. Another example can be seen in test 5 where the leakage rate decreased with decreasing wind velocity and indoor-outdoor temperature differential.

### 5.5 Predicting Air Change Rates from Observed Wind Speeds and Indoor-Outdoor Temperature Differentials

The technique of double approximation for separating the effect of wind speed and indoor-outdoor temperature differentials was not explicit in explaining the correction factors<sup>1</sup> (Section 2.5.3). A multiple regression analysis using the data reported by Bahnfleth et al. (1957) yielded equation 5.3

$$AC = 0.15 + 0.0045 W + 0.007 \Delta T \quad (5.3)$$

The accuracy of the prediction equation 2.3 developed by Coblenz and Achenbach (1963) was compared to that of equation 5.3. The average errors in the predicted air change rates from the observed data for wind speed and indoor-outdoor temperature differentials from both equations were 22% from equation 2.3 and 12% from equation 5.3. Better accuracy for predicting leakage rates was achieved from equation 5.3 which was obtained from a multiple regression analysis.

Multiple regression analysis was used on the data of Table 5.2 to separate the effect of wind speed and temperature differentials on leakage rates. A multiple regression analysis for two independent variables requires a minimum of four data points. The data for greenhouse number 1 were insufficient for multiple regression analysis. There were nine data points for greenhouse number 2 (Table 5.2).

The multiple regression analysis resulted in the following regression equation:

$$R = 0.0383 + 0.00929 W + 0.0171 \Delta T \quad (5.4)$$

where  $R$  = predicted air change rate (leakage rate), 1/h

$W$  = wind speed, km/h

$\Delta T$  = indoor-outdoor temperature differential, °C

The multiple correlation coefficient was 0.75.

An attempt was made to account for wind direction. The wind speed component normal to the long side was used in the multiple regression analysis but the multiple correlation coefficient was less than for equation 5.4.

Equation 5.4 is of the following form:

$$R = R_{00} + \alpha W + \beta \Delta T \quad (5.5)$$

where

$R$  = predicted air change rate, 1/h

$R_{00}$  = air change rate for no wind and no temperature difference, 0.0383/h

$\alpha$  = increase in air change rate per unit increase in wind velocity, (0.0929/h)/(km/h)

$\beta$  = increase in air change rate per unit increase in indoor-outdoor temperature difference, (0.0171/h)/°C.

Leakage rates predicted by equation 5.4 were not accurate when wind speed was less than 5 km/h and temperature differential was also less than 5°C. Table 5.3 shows the percent errors in the predicted air change rates compared to the measured rates. The average inaccuracy of the predicted air change rates (excluding Test 2) was not more than 16%.

Figures 5.2 and 5.3 were plotted for constant wind velocities and indoor-outdoor temperature differential from equation 5.4. An air change rate of 0.0383/h for no wind and no temperature difference could be due to molecular diffusion of the gases through the covering material due to the concentration gradient. Figures 5.2 and 5.3 can be used directly to determine the expected air change rates when wind

Table 5.3 Percentage Error of Predicted Air Change Rates When Compared to Average Measured Rates (Table 5.2)

Test #	Air Change Rate		% Error
	Measured (average)	Predicted	
1	0.276	0.227	18
2	0.071	0.174	145*
3	0.272	0.330	21
4	0.431	0.475	-10
5	0.234	0.226	4
6	0.305	0.241	21
7	0.407	0.562	38

\* Average error excluding value of test 2 - 16%

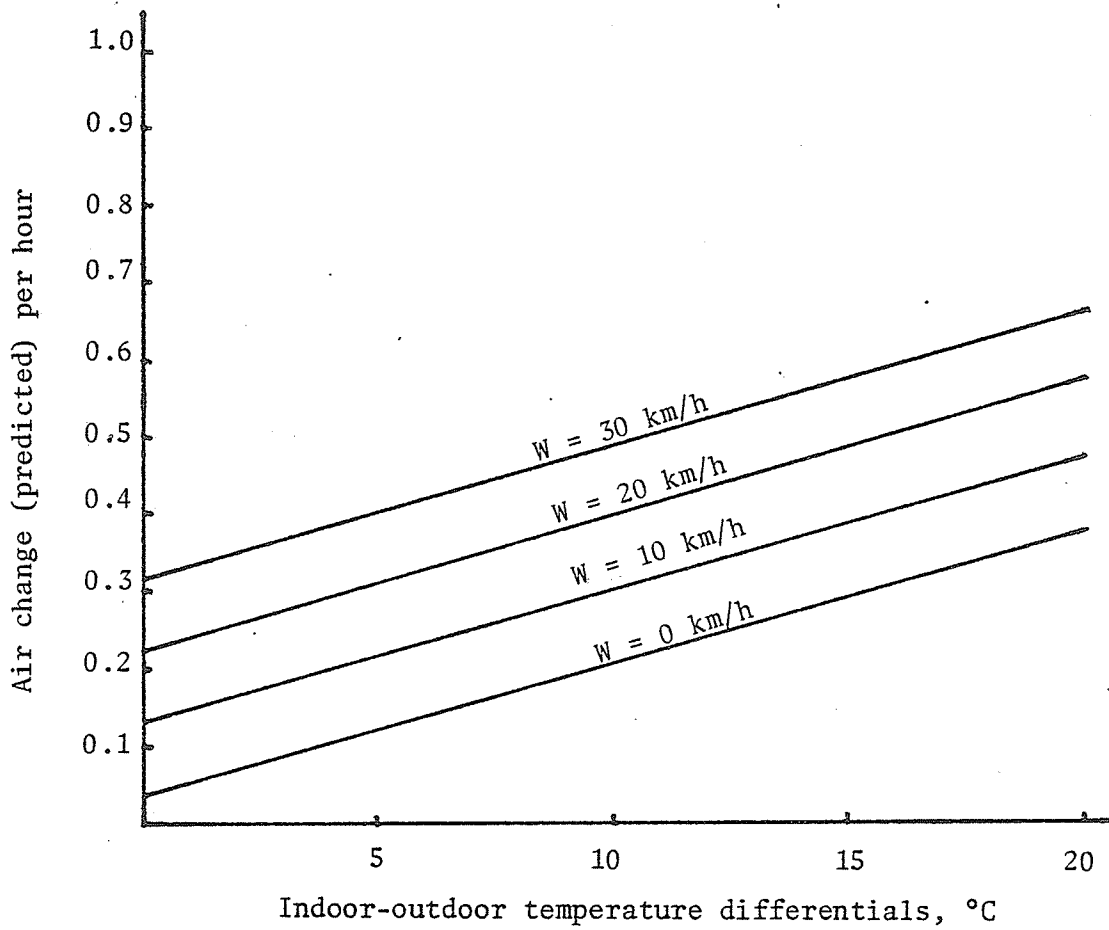


Figure 5.2 Air change rates vs. indoor-outdoor temperature differentials at constant wind velocities.

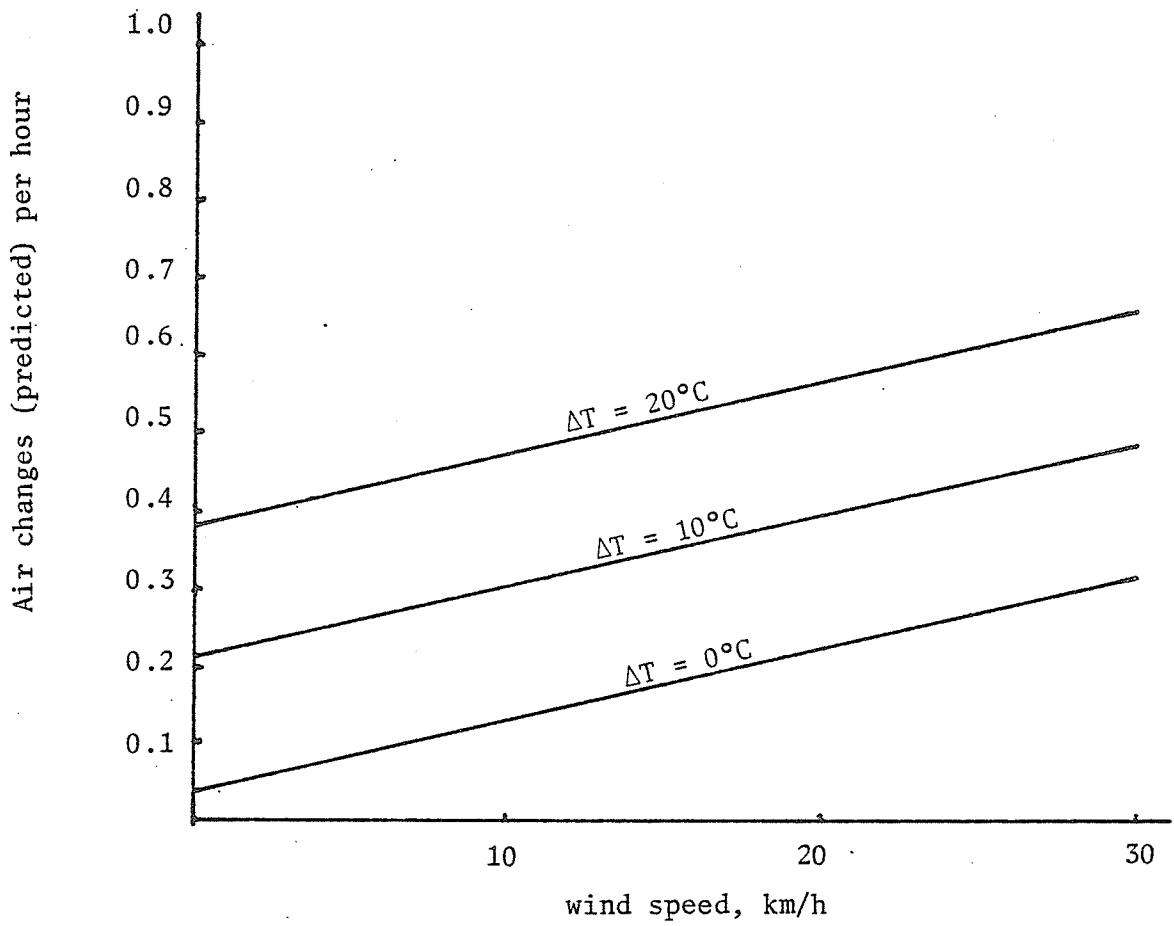


Figure 5.3 Air change rates vs. wind velocities at constant indoor-outdoor temperature differentials.

velocities and indoor-outdoor temperature differentials are known.

The data points plotted in Figures 5.2 and 5.3 are from both greenhouses. The points shown in Figure 5.2 are the corresponding air change rates observed for various indoor-outdoor temperature differences whereas the data points shown in Figure 5.3 are the air change rates for observed wind speeds.

#### 5.6 Sample Outputs of the Simulation

Outputs of the mathematical simulation model for Test 1 are shown in Figures 5.4 to 5.7 for enrichment and depletion in the presence and absence of a crop. A measured air change rate of 0.272/h (Table 5.2) and a known input rate of 954.5 L/h of CO<sub>2</sub> from a gas cylinder (wet test meter; Figure 3.3) were used in all simulations of enrichment. During the simulation of CO<sub>2</sub> depletion the input rate of CO<sub>2</sub> was set to zero and the initial concentration was set equal to the maximum measured concentrations in Table 5.2. For the simulation the initial CO<sub>2</sub> concentration was assumed to be 370 ppm, a value that was measured in the greenhouse. When a growing crop was assumed the floor utilization factor (FUF) was assumed to be 0.8 and the plant leaf area index (PLAI) was assumed to be 4.0 (Zelitch, 1971).

The measured concentrations of CO<sub>2</sub> in the greenhouse atmosphere during depletion have been reported in Table 5.1 while the measured leakage rates (LR<sub>ij</sub>) and average leakage rates are listed in Table 5.2. The concentrations of CO<sub>2</sub> during enrichment were recorded only for the first three tests in order to compare them to the simulated CO<sub>2</sub> concentrations obtained from the computer simulation model (Section 4.7.3). Table 5.4 shows the measured CO<sub>2</sub> concentrations during the



TIME (MIN)	C (PPM)	MINIMUM I	C PLAI = 0.0	VERSUS TIME	MAXIMUM I
0.0	3.7000E+02	3.7000E+02			2.8130E+03
1.0000E+01	5.2969E+02				
2.0000E+01	6.8230E+02				
3.0000E+01	8.2815E+02				
4.0000E+01	9.6754E+02				
5.0000E+01	1.1007E+03				
6.0000E+01	1.2281E+03				
7.0000E+01	1.3497E+03				
8.0000E+01	1.4660E+03				
9.0000E+01	1.5771E+03				
1.0000E+02	1.6833E+03				
1.1000E+02	1.7848E+03				
1.2000E+02	1.8818E+03				
1.3000E+02	1.9745E+03				
1.4000E+02	2.0630E+03				
1.5000E+02	2.1477E+03				
1.6000E+02	2.2286E+03				
1.7000E+02	2.3059E+03				
1.8000E+02	2.3798E+03				
1.9000E+02	2.4504E+03				
2.0000E+02	2.5179E+03				
2.1000E+02	2.5824E+03				
2.2000E+02	2.6440E+03				
2.3000E+02	2.7029E+03				
2.4000E+02	2.7592E+03				
2.5000E+02	2.8130E+03				

Figure 5.4 Simulated CO<sub>2</sub> Concentrations During Enrichment Without Any Growing Crop (Test 1)

TIME (MIN)	C (PPM)	MINIMUM	C	VERSUS TIME	MAXIMUM
0.0	3.7000E+02	3.7000E+02	PLAI	= 4.0000E+00	2.8130E+03
1.0000E+01	4.1387E+02	I			I
2.0000E+01	4.4617E+02	+			
3.0000E+01	4.6951E+02	-+			
4.0000E+01	4.8614E+02	-+			
5.0000E+01	4.9786E+02	-+			
6.0000E+01	5.0606E+02	-+			
7.0000E+01	5.1175E+02	-+			
8.0000E+01	5.1570E+02	-+			
9.0000E+01	5.1843E+02	-++			
1.0000E+02	5.2031E+02	-++			
1.1000E+02	5.2160E+02	-++			
1.2000E+02	5.2249E+02	-++			
1.3000E+02	5.2311E+02	-++			
1.4000E+02	5.2353E+02	-++			
1.5000E+02	5.2382E+02	-++			
1.6000E+02	5.2401E+02	-++			
1.7000E+02	5.2415E+02	-++			
1.8000E+02	5.2424E+02	-++			
1.9000E+02	5.2431E+02	-++			
2.0000E+02	5.2435E+02	-++			
2.1000E+02	5.2438E+02	-++			
2.2000E+02	5.2440E+02	-++			
2.3000E+02	5.2442E+02	-++			
2.4000E+02	5.2443E+02	-++			
2.5000E+02	5.2443E+02	-++			

Figure 5.5 Simulated CO<sub>2</sub> Concentrations During Enrichment in the Presence of Growing Plants (Test 1)

TIME(MIN)	C(PPM)	MINIMUM	C	VERSUS TIME	MAXIMUM
0.0	2.6570E+03	2.6411E+02	PLAI = 0.0		2.6570E+03
2.0000E+00	2.6360E+03				
4.0000E+00	2.6152E+03				
6.0000E+00	2.5946E+03				
8.0000E+00	2.5741E+03				
1.0000E+01	2.5539E+03				
1.2000E+01	2.5338E+03				
1.4000E+01	2.5139E+03				
1.6000E+01	2.4942E+03				
1.8000E+01	2.4747E+03				
2.0000E+01	2.4553E+03				
2.2000E+01	2.4361E+03				
2.4000E+01	2.4171E+03				
2.6000E+01	2.3983E+03				
2.8000E+01	2.3796E+03				
3.0000E+01	2.3611E+03				
3.2000E+01	2.3428E+03				
3.4000E+01	2.3246E+03				
3.6000E+01	2.3066E+03				
3.8000E+01	2.2888E+03				
4.0000E+01	2.2711E+03				
4.2000E+01	2.2536E+03				
4.4000E+01	2.2362E+03				
4.6000E+01	2.2190E+03				
4.8000E+01	2.2019E+03				
5.0000E+01	2.1850E+03				

Figure 5.6 Simulated CO<sub>2</sub> Concentrations During Depletion Without Any Growing Crop (Test 1)

TIME(MIN)	C(PPM)	MINIMUM	C	VERSUS TIME	MAXIMUM
0.0	2.6570E+03	2.6411E+02	PLAI = 4.0000E+00		2.6570E+03
2.0000E+00	1.7269E+03				
4.0000E+00	1.4295E+03				
6.0000E+00	1.2466E+03				
8.0000E+00	1.1140E+03				
1.0000E+01	1.0101E+03				
1.2000E+01	9.2459E+02				
1.4000E+01	8.5208E+02				
1.6000E+01	7.8916E+02				
1.8000E+01	7.3366E+02				
2.0000E+01	6.8406E+02				
2.2000E+01	6.3927E+02				
2.4000E+01	5.9849E+02				
2.6000E+01	5.6108E+02				
2.8000E+01	5.2658E+02				
3.0000E+01	4.9458E+02				
3.2000E+01	4.6479E+02				
3.4000E+01	4.3694E+02				
3.6000E+01	4.1082E+02				
3.8000E+01	3.8625E+02				
4.0000E+01	3.6308E+02				
4.2000E+01	3.4117E+02				
4.4000E+01	3.2041E+02				
4.6000E+01	3.0070E+02				
4.8000E+01	2.8196E+02				
5.0000E+01	2.6411E+02				

Figure 5.7 Simulated CO<sub>2</sub> Concentrations During Depletion in the Presence of Growing Plants (Test 1)

greenhouse atmosphere enrichment.

The expected CO<sub>2</sub> concentrations were calculated using actual measured parameters for greenhouse volume, air change rate, CO<sub>2</sub> input rate, etc., for the condition when there was no crop growing in the greenhouse. The simulation CO<sub>2</sub> concentrations for the first three tests for greenhouse 2 are shown in Table 5.5. A graphical representation of the results from Tables 5.4 and 5.5 is shown in Figure 5.8.

The irregular build up of CO<sub>2</sub> concentration for Test 1 (Figure 5.5) was the result of freezing of CO<sub>2</sub> in the regulator. Freezing occurred twice during the second and the third hour after the enrichment was started. An infrared heat lamp (Figure 3.3) was used in the remaining tests to avoid any possible restriction of gas flow due to gas freezing.

It can be seen from Figure 5.8 (simulation test 1, with crop) that for a known air change rate of 0.272/h and a CO<sub>2</sub> input rate of 954.4 L/h the maximum CO<sub>2</sub> concentration increased to only 524 ppm after two hours (Table 5.5). There was no further build up. This shows that if the CO<sub>2</sub> level was to be increased to 2000 ppm (optimal level; Section 2.2.3) then the CO<sub>2</sub> input rate would have to be increased.

The results for simulation CO<sub>2</sub> concentrations during depletion using the measured air change rates and the maximum measured CO<sub>2</sub> concentrations as the initial concentrations in the simulation model are summarized in Table 5.6. When these simulated values are compared with the actual measured values of CO<sub>2</sub> concentrations in Table 5.1, a great deal of deviation is noted. The maximum deviations of the simulated values of CO<sub>2</sub> concentrations were found for Test 2, whereas

Table 5.4 Measured CO<sub>2</sub> Concentrations during Enrichment

Sample No.	Time h	CO <sub>2</sub> Concentrations, ppm		
		Test 1	Test 2	Test 3
1	0.0	370	289	339
2	0.5	981	690	943
3	1.0	1358	1066	1187
4	1.5	1706	1377	1504
5	2.0	1917	1710	1777
6	2.5	2023	1928	1871
7	3.0	2286	-	1986
8	3.5	2379	-	2009
9	4.0	2787	-	-
10	4.5	2959	-	-

Table 5.5 Simulated CO<sub>2</sub> Concentrations during Enrichment

Sample No.	Time h	CO <sub>2</sub> concentrations, ppm			
		Test 1 (no crop)	Test 1 (crop)	Test 2 (no crop)	Test 3 (no crop)
1	0.0	370	370	289	339
2	0.5	828	469	655	721
3	1.0	1228	506	1009	1054
4	1.5	1577	519	1351	1346
5	2.0	1881	522	1680	1600
6	2.5	2148	524	1998	1822
7	3.0	2380	524	-	2015
8	3.5	2582	524	-	2184
9	4.0	2759	524	-	-

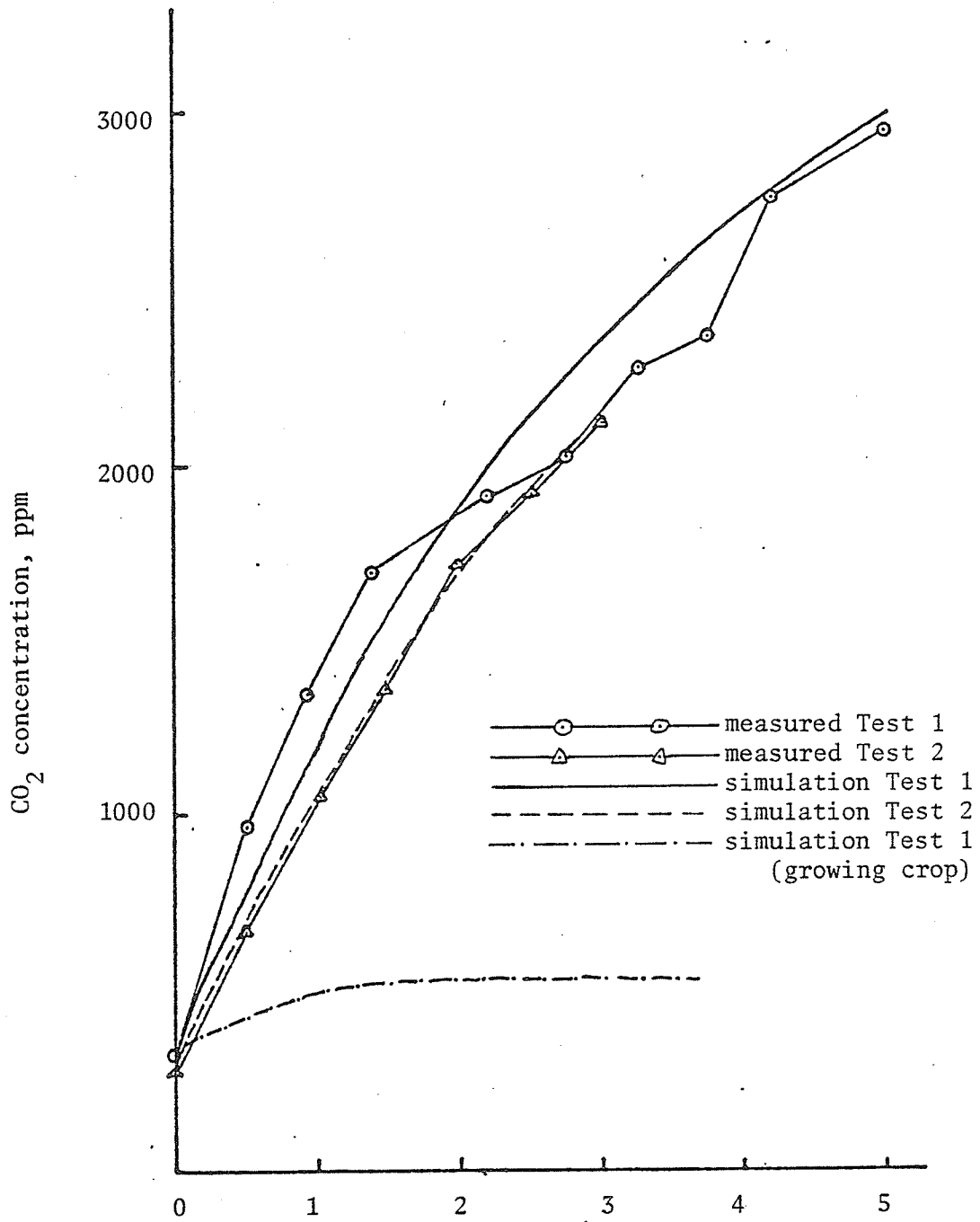


Figure 5.8 Measured and simulated CO<sub>2</sub> concentrations during enrichment (Greenhouse 2).



Table 5.6 Prediction of CO<sub>2</sub> concentration by simulation for CO<sub>2</sub> depletion

Sample No.	Time h	Test 1 no crop	Test 1 with crop	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
1	0.0	2657	2657	2148	2009	2588	3254	2803	2524
2	0.5	2361	494	2094	1795	2180	2931	2453	2120
3	1.0	2103	186	2023	1609	1797	2644	2152	1790
4	1.5	1877	-	1964	1446	1513	2388	1895	1522
5	2.0	1680	-	1907	1304	1284	2161	1673	1302
6	2.5	1509	-	1852	1180	1099	1959	1484	1123
7	3.0	1359	-	1799	1072	950	1779	1320	977
8	3.5	1228	-	1748	978	830	1619	1180	857
9	4.0	1114	-	1698	895	733	1477	1060	760
10	4.5	1014	-	1650	823	654	1350	956	681
11	5.0	927	-	1517	760	591	1238	868	617

the best match was found in Test 1 and 6 as shown in Figure 5.9.

The effects of changing wind speed, wind direction and indoor-outdoor temperature differential have already been discussed (Sections 5.2, 5.3 and 5.4; Figure 5.1). The measured  $\text{CO}_2$  concentrations were determined for changing leakage rates whereas the simulated values reported in Table 5.6 were obtained by considering average air change rates (Table 5.2) for each test.

When the leakage rates ( $\text{LR}_{ij}$ , Table 5.2) for different times were used with the corresponding initial  $\text{CO}_2$  concentrations in the simulation model, the deviations of the simulated values from the measured values were much less. An example of such a comparison for Test 5 is shown in Figure 5.10 and Table 5.7.

The depletion rate of  $\text{CO}_2$  gas was also considered by simulating the plant consumption assuming the same parameters as discussed for test 1 (Figure 5.9). It was found that the  $\text{CO}_2$  concentration dropped from 2657 ppm to 264 ppm within 50 minutes. These results indicate and confirm the need for  $\text{CO}_2$  enrichment in order to maintain favorable  $\text{CO}_2$  levels for optimum photosynthetic rates in greenhouses.

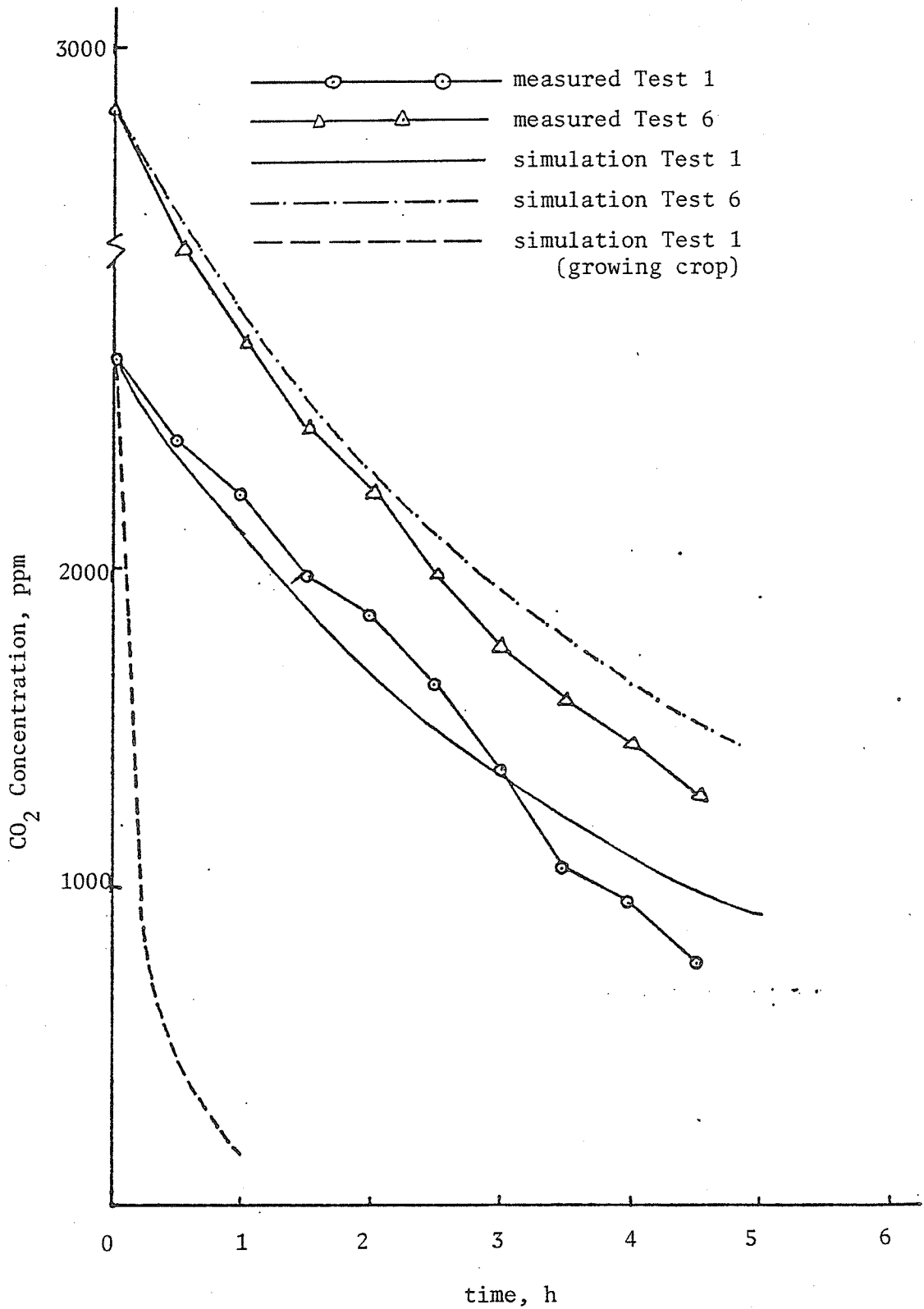


Figure 5.9 Measured and simulated CO<sub>2</sub> concentrations during CO<sub>2</sub> depletion (Greenhouse 1 and 2)

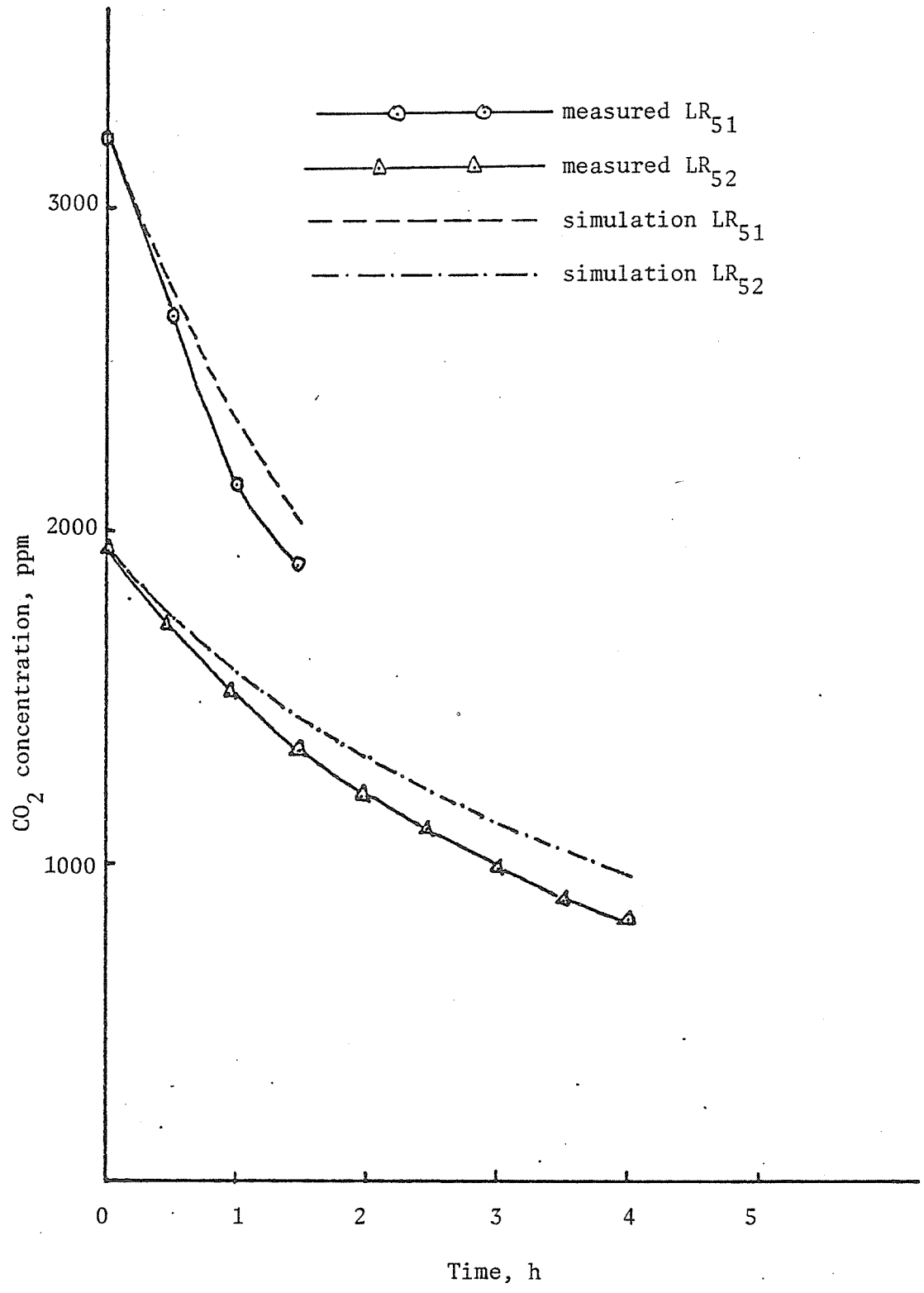


Figure 5.10 Measured and simulated values of CO<sub>2</sub> concentration for CO<sub>2</sub> depletion, Test 5 using two leakage rates; LR<sub>51</sub> and LR<sub>52</sub> (Table 6.3).

Table 5.7 Comparison of measured and simulated CO<sub>2</sub> concentrations for CO<sub>2</sub> depletion (Test 5)

Sample No.	Time h	Carbon Dioxide Concentration (ppm)			
		LR <sub>51</sub>		LR <sub>52</sub>	
		measured	simulated	measured	simulated
1	0.0	3254	3254	-	-
2	0.5	2710	2793	-	-
3	1.0	2167	2400	-	-
4	1.5	1924	2078	1924	1924
5	2.0	-	-	1761	1757
6	2.5	-	-	1558	1608
7	3.0	-	-	1324	1474
8	3.5	-	-	1223	1354
9	4.0	-	-	1095	1247
10	4.5	-	-	966	1151
11	5.0	-	-	880	1065
12	5.5	-	-	817	988

## CHAPTER VI

### CONCLUSIONS

The following conclusions were drawn from this research:

1. The maximum measured air change rate was 0.726/h at a wind speed of 31.4 km/h and an indoor-outdoor temperature differential of 11.7°C. The minimum air change rate was 0.053/h at a wind speed of 2.3 km/h and a temperature differential of 5.7°C.

2. The air change rate was found to be highly dependent on indoor-outdoor temperature differentials and wind velocity. The effect of wind direction on the air change rate was inconclusive.

3. Air change rates can be estimated by the following empirical formula:

$$R = 0.0383 + 0.00929 W + 0.0171 \Delta T$$

where

R = Air change rate, 1/h

W = Wind speed, km/h

$\Delta T$  = Indoor-outdoor temperature differential, °C.

4. The CO<sub>2</sub> concentrations predicted by the computer simulation model were quite close to the measured concentrations of CO<sub>2</sub> during enrichment with or depletion of CO<sub>2</sub> in the greenhouses.

5. Porapak Q was found to be a satisfactory column packing material for the analysis of carbon dioxide as a tracer gas in the greenhouse air by gas chromatography.

## CHAPTER VII

### SUGGESTIONS FOR FUTURE INVESTIGATIONS

1. Air change rates under different environmental conditions should be used to estimate heat loss due to leakage.
2. Air change rates should be taken into account in studies of plant uptake of CO<sub>2</sub> in greenhouses.
3. The feasibility of CO<sub>2</sub> concentration control at any desired value should be investigated in greater detail.
4. The possibility of developing a gas chromatographic controller to control the concentration of CO<sub>2</sub> in a greenhouse should be investigated.
5. A large number of tests for determining air change rates should be conducted on an isolated greenhouse under controlled indoor temperatures and existing wind speeds in order to separate the effect of different parameters like indoor-outdoor temperature differentials, wind speeds and wind directions.
6. Wind tunnel investigations are highly recommended to establish the dependence of air change rate on indoor-outdoor temperature differentials, wind speed and directions.

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APPENDIX A  
GAS CHROMATOGRAPHY



## APPENDIX A

## GAS CHROMATOGRAPHY

A.1 Principles of Gas Chromatographic Separation

The mixture of gases to be analyzed is injected into a stream of carrier gas at the head of a column containing a solid adsorbent (Jeffery and Kipping, 1972; Jones, 1970). On passing through, the adsorbent part of the sample is adsorbed by the adsorbent and an equilibrium is established between the adsorbed sample and the portion of the sample remaining in the carrier gas phase. When the moving phase (carrier gas and part of sample) moves forward, a part of the sample in the carrier gas is again adsorbed and at the same time a part of the previously adsorbed sample returns to the carrier gas phase. This continuous change in equilibrium results in the compact movement of the sample through the column.

The separated components leaving the column in the stream of carrier gas are measured by the detector. A response is obtained corresponding to changes in a suitable property of the carrier and sample gas mixture. For example, a suitable property that can be measured is thermal conductivity. The response is usually converted to an electrical signal for ease of amplification and recording. A schematic block diagram of a gas chromatograph operation is shown in Figure A.1.

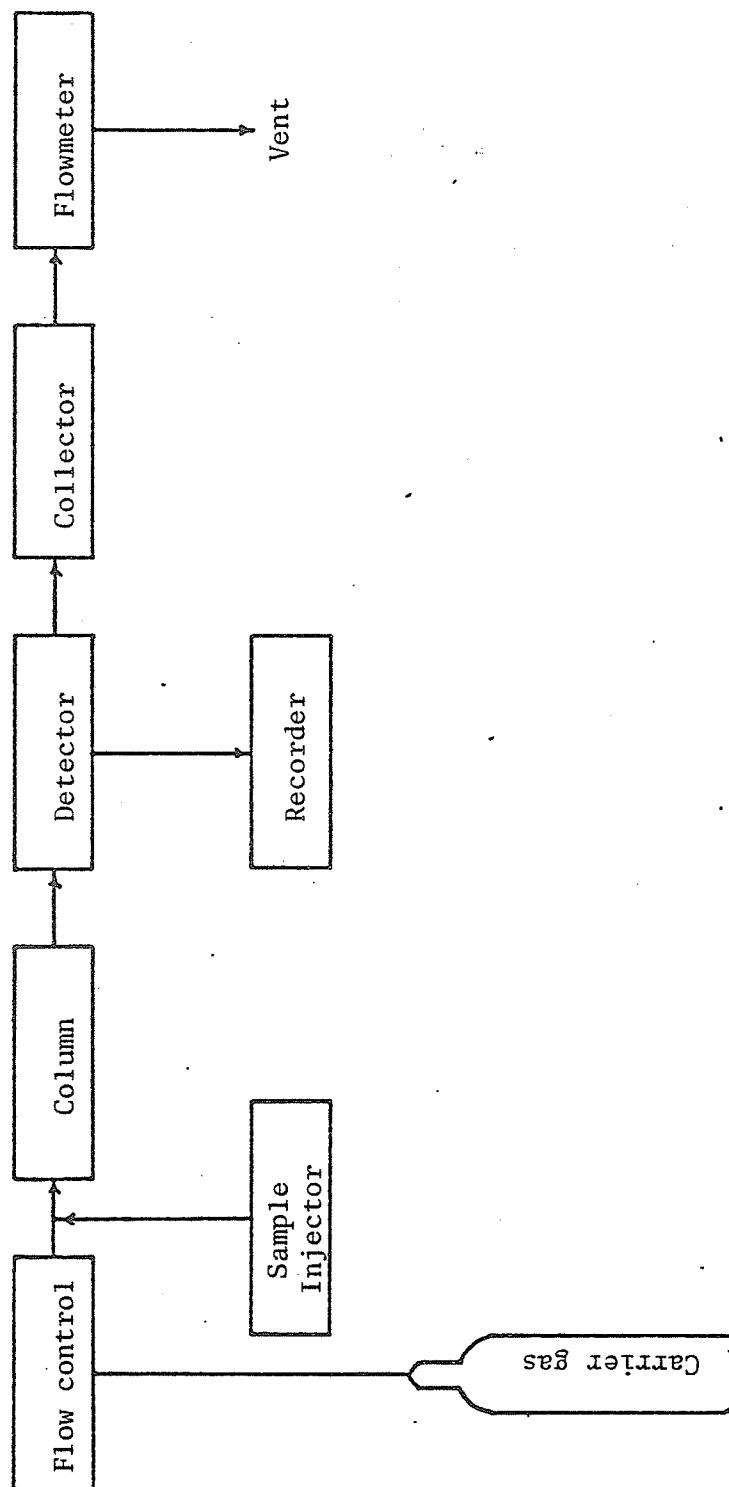


Figure A.1 Schematic Block Diagram of a Typical Gas Chromatograph

## A.2 The Choice and Role of the Column

In most cases conventionally packed columns are preferred for the purpose of tracer gas analysis. A complete review of literature of adsorbents is available (Palframan and Walker, 1967). In analysing a given mixture, the aim in choosing an adsorbent is to secure the required separation of each component from every other component. Jeffery and Kipping (1972) have reported the following five solid adsorbents which are commonly used in gas-solid chromatography: (i) alumina, (ii) charcoal, (iii) molecular sieve, (iv) silica gel and (iv) porous polymer beads.

## A.3 Porous Polymer Beads

Hollis (1966) developed porous polymer beads that are commercially available as Porapak (P, Q, R, S and T) from Water Associates Inc., Massachusetts, U.S.A. and other chromatographic suppliers. Porapak Q is ethylvinylbenzene (EVB) with divinylbenzene (DVB) as a crosslinker. Porapak Q has a large surface area ( $660 \text{ m}^2/\text{g}$ ) offering excellent chromatographic utility. Various advantages and limitations of Porapak Q are listed below:

(i) sharp and symmetrical peaks are obtained (Jeffery and Kipping, 1972)

(ii) the beads are stable at high temperatures of 200 to  $280^\circ\text{C}$  (Wilhite and Hollis, 1968; Forsey, 1968).

(iii) the separation of  $\text{CO}_2$  from air ( $\text{O}_2$  and  $\text{N}_2$ ) is difficult at higher temperatures (Ponzi et al., 1970) but adequate at low temperatures.

Several researchers have used Porapak Q to separate  $\text{CO}_2$  gas

from other gases. A summary of CO<sub>2</sub> analyses with Porapak Q is presented in Table A.1.

#### A.4 Thermal Conductivity Detectors

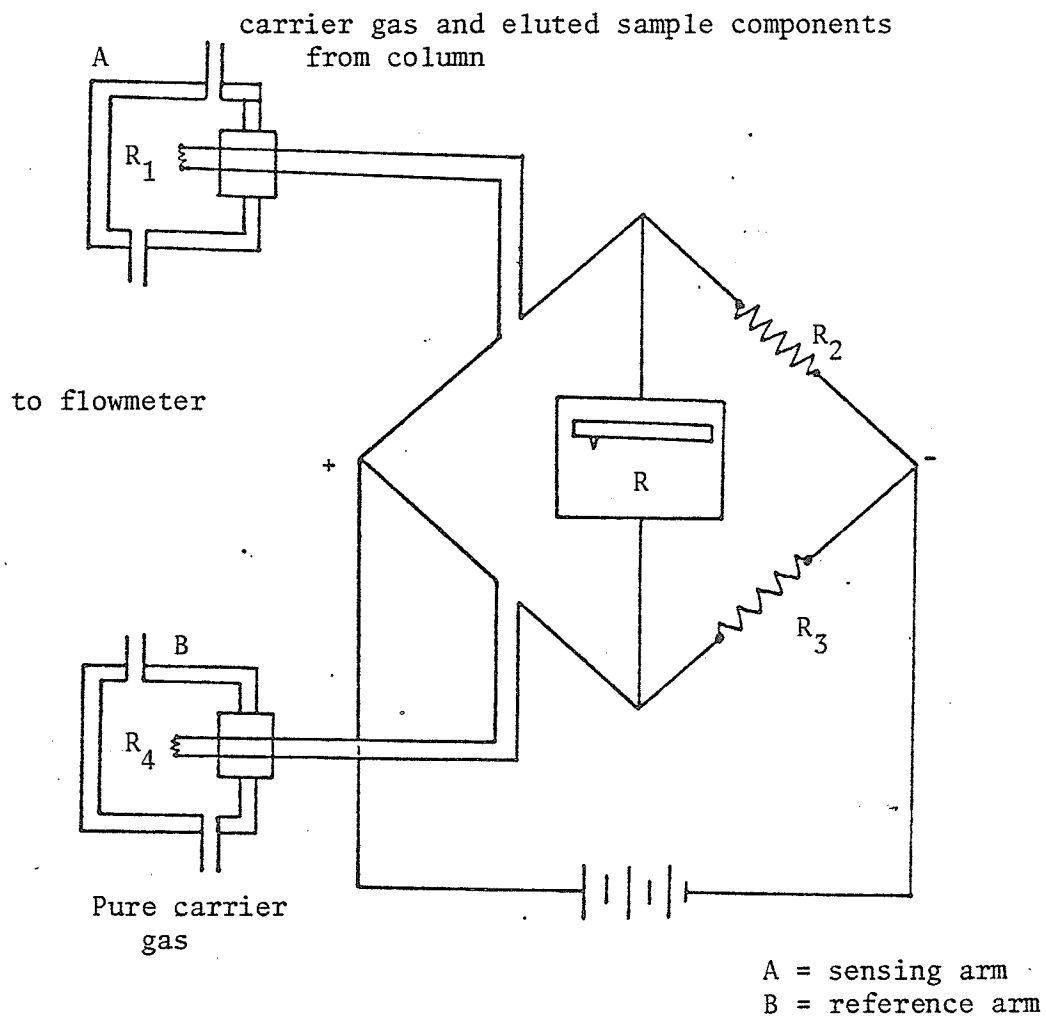
The principle of operation of the thermal conductivity detector can be explained as follows. When an electrically heated wire is placed in a stream of gas, the temperature attained by the filament will depend largely upon the rate of conductive and convective heat loss to the gas if the flow is kept constant. Any change in the conductivity of the gas will lead to a temperature change in the hot wire and hence the wire resistance. These changes in resistance can be detected and measured electrically (Jeffery and Kipping, 1972; Pattison, 1969).

In the thermal conductivity detector there are two passages containing heated filaments (arms of a Wheatstone bridge, Figure A.2) through which the carrier gas passes. Through one of the arms known as a "reference arm" only pure carrier gas passes. Through the other arm known as the "sensing arm" the separated components along with the carrier gas pass. The bridge remains balanced when only pure carrier gas is passing through both arms. When any other component having a thermal conductivity different from that of the carrier gas is passing through the sensing arm a change in heat dissipation results in a filament temperature change, and consequently a change in resistance. The out-of-balance potential across the bridge depends upon the extent of the temperature change and can be conveniently displayed on a potentiometric recorder. The magnitude of the response depends on the difference in thermal conductivity of the separated sample component

Table A.1 Summary of CO<sub>2</sub> analysis using Porapak Q

REFERENCE	C O L U M N *				Detector Type	Temp °C	Bridge Current (mA)	Sample Size (mL)	CARRIER*		
	L	id	M	Q					T	Gas	V (mL/min)
Bell (1966)	3.7	2.2	SS	100	30	TC	100	0.5	He	30	391
					200						
Carle (1970)	7	1	SS	100	20	TC	---	0.1	He	15	---
					200						
Cross (1966)	3	4.8	--	80	30	--	---	---	He	40	205
					100						
Grice and David (1969)	1.8	3	--	50	40	--	---	---	He	20	225
					80						
Hollis (1966)	3.7	4.7	--	--	27	--	---	---	He	50	---
Lorenzo (1970)	1.5	---	--	35	20	TC	---	1	He	40	---
					60						
Obermiller and Chalier (1968)	3	1.2	--	50	--	--	---	---	He	27	349
					80						
Tunstall (1970)	4	2	--	50	40	TC	---	---	H <sub>2</sub>	50	---
					80						

\* L = column length, m; id = column inside diameter, mm; M = column material  
SS = stainless steel; Q = Porapak Q mesh size; T = column temperature, °C  
TC = thermal conductivity detector; V = carrier gas flow rate  
p = inlet pressure



$R_1, R_2, R_3, R_4$  = Bridge arm resistances  
R = recorder

Figure A.2 Thermal conductivity detector

relative to the carrier gas. The direction of the response results from whether the thermal conductivity is greater or lesser than that of the carrier gas. The following three features are basic to good detector response (Littlewood, 1970; Pattison, 1969): (i) good sensitivity, (ii) linearity and (iii) a reasonable time constant.

#### A.4.1 Thermal Conductivity Detector Response

The response of a thermal conductivity detector is reported to be linear for many substances with helium as the carrier gas. The response is proportional to the concentration and the thermal conductivity of the eluted component and also to the filament current (Lawson and Miller, 1966).

#### A.4.2 Calibration of the Detector

Two major difficulties in accurate analysis of multicomponent gas mixtures by gas chromatography have been reported (Smith and Bowden, 1964). The difficulties are (i) the tendency of the calibration curves (detector response vs. amount injected) to shift because of day to day variations in instrument conditions and (ii) the dependence of the thermal conductivity detector response on sample size. It has also been reported that the calibration of a thermal conductivity detector is necessary because the relation between the detector response and sample quantity is seldom linear over the entire concentration range used (Jeffery and Kipping, 1972). The detector response is principally dependent on sample size (Littlewood, 1970) and therefore the range of linearity for the calibration curve using the peak height measurement is likely to be small.

#### A.5 The Choice of and the Role of Detector Temperature

The choice and accurate control of detector temperature is very important for maximum sensitivity (Littlewood, 1970). As reported in Table A.2 an increase in temperature will cause an increase in the thermal conductivity of the gases which will result in increased sensitivity.

#### A.6 The Choice of Sample Size and Injection Technique

Littlewood (1970) has reported that sample size has a definite and complex effect on retention volumes. An increase in sample size can cause either an increase or a decrease in retention volume depending on the specific situation. In most cases, the greater the sample mass (size) chromatographed, the lower the performance of the apparatus. Wet and Pretorious (1960) have analysed in detail the effect of sample size on various column parameters. Many researchers have reported that sample size should be within certain limits. A large sample volume will overload the column resulting in poor separation and band broadening (Martin, 1966).

##### A.6.1 Sample Injection Techniques

The purpose of a sample transfer system is to transfer a measured amount of the sample material for maximum chromatographic separation without column overloading. Jeffery and Kipping (1972) have reported the following two techniques which are most commonly used for gas analysis:

(i) Gas-Tight Syringes are used to transfer a sample directly at the column mouth through a leaktight septum in the injection port.



Table A.2 Thermal Conductivity and Molecular Weights of Some Common Gases

Gas	Thermal Conductivity* W/(m.K)			Molecular Weight** (gram molecular weight)
	0°C	100°C	170°C***	
Argon	0.0162	0.0213	0.0249	39.994
Carbon Dioxide	0.0142	0.0212	0.0261	44.010
Helium	0.1406	0.1667	0.1850	4.003
Hydrogen	0.1657	0.2089	0.2391	2.016
Nitrogen	0.0238	0.0300	0.0343	28.016
Oxygen	0.0238	0.0311	0.0362	32.000

\* Langes Handbook of Chemistry (1973)

\*\* CRC Handbook of Chemistry and Physics (1972-73)

\*\*\* Extrapolated values assuming straight line relationship

This technique of sample injection with a hypodermic needle is only suitable for qualitative analysis. For the purposes of a quantitative analysis, reproducibility becomes a problem especially when the carrier gas flow is at a high pressure. These conditions could cause leakage of the sample from the septum and syringe plunger. This method is not recommended where quantitative accuracy is required.

(ii) A Gas Sampling Valve is the alternative method for transferring a known volume of the gas sample usually at atmospheric pressure and temperature. The gas sample is held in a loop and then swept into the column by redirecting the carrier gas path temporarily. Figure A.3 illustrates the most common six port (rotating disc) gas sampling valve. The known volume of the sample loop ensures constant sample size and transfer without any loss or interference with the carrier gas flow rate is ensured.

#### A.7 Calibration Techniques

(i) The Classical Method relies on the preparation of special gas mixtures covering the concentration range of interest. These standard mixtures are made in gas containers using gastight syringes or some other method (Jeffery and Kipping, 1972). This method is theoretically sound but very inconvenient and time consuming.

Folmer (1971) reported a method of preparing gas mixtures of known concentrations for the purpose of calibration by using only a gastight syringe. Both the sample and the diluting gas are mixed in situ. A method of eliminating the error due to residual gas in the needle is also given through the use of a dilution factor. Derge (1972)

has reported this technique for preparing gas mixtures for the purpose of calibration as the source of very important statistical and methodological errors.

(ii) Exponential Dilution Flask - This technique has been reported for detector response calibration (William and Winefordner, 1966). The detector is directly connected to a flask through which the carrier gas stream passes, sweeping the gas generated in the flask to the detector. The decay of the generated gas in the flask is exponential and the concentration of the calibrating gas at any time,  $t$ , can be calculated.

(iii) The Method of Internal Standards is a very useful technique which eliminates possible errors due to (i) slight nonlinearity of the detector, (ii) slow drift of response base line and (iii) any loss of sample being injected. Derge (1972) reported that this method was very successful in improving accuracy, reproducibility and, in general, the capability of gas chromatographic analysis. The internal standard is a substance of a known quantity and quality that is added to the original sample. The advantage of this technique is that a calibration factor can be easily established if the response is linear. This avoids the necessity of measuring each peak height or area for each concentration.

(iv) The Use of Calibration Gases for the purpose of detector calibration is perhaps the most convenient method of calibration. Calibration mixtures in almost every concentration are available commercially from Union Carbide, Canada and Applied Science Laboratories, U.S.A.

(v) Other methods reported for detector calibration are constant volume pipets, gas permeation tubes, gas proportioning pumps and slow injection devices (Jeffery and Kipping, 1972). These methods are only suitable for specific purposes.

APPENDIX B  
SAMPLE CALCULATION

## APPENDIX B

## SAMPLE CALCULATION

The instrument response for one of the sample analysis (Sample 1, test 6) is shown in Figure B.1. The first peak area  $P_A$  represents the major air constituents (nitrogen and oxygen) and the next peak  $P_C$  shows the relative concentration of  $CO_2$  in the air. The instrument response (peak height) for  $CO_2$  was measured in mm after establishing the base line. The measured peak height from Figure B.1 was 98 mm. The corresponding  $CO_2$  concentration can be calculated from equation 4.8:

$$\begin{aligned} C &= 28.38 (98) + 21.73 \\ &= 2803 \text{ ppm} \end{aligned}$$

The uncertainty in this measurement, calculated in the absolute sense, was approximately  $\pm 7.9$  percent (Doebelin, 1966).

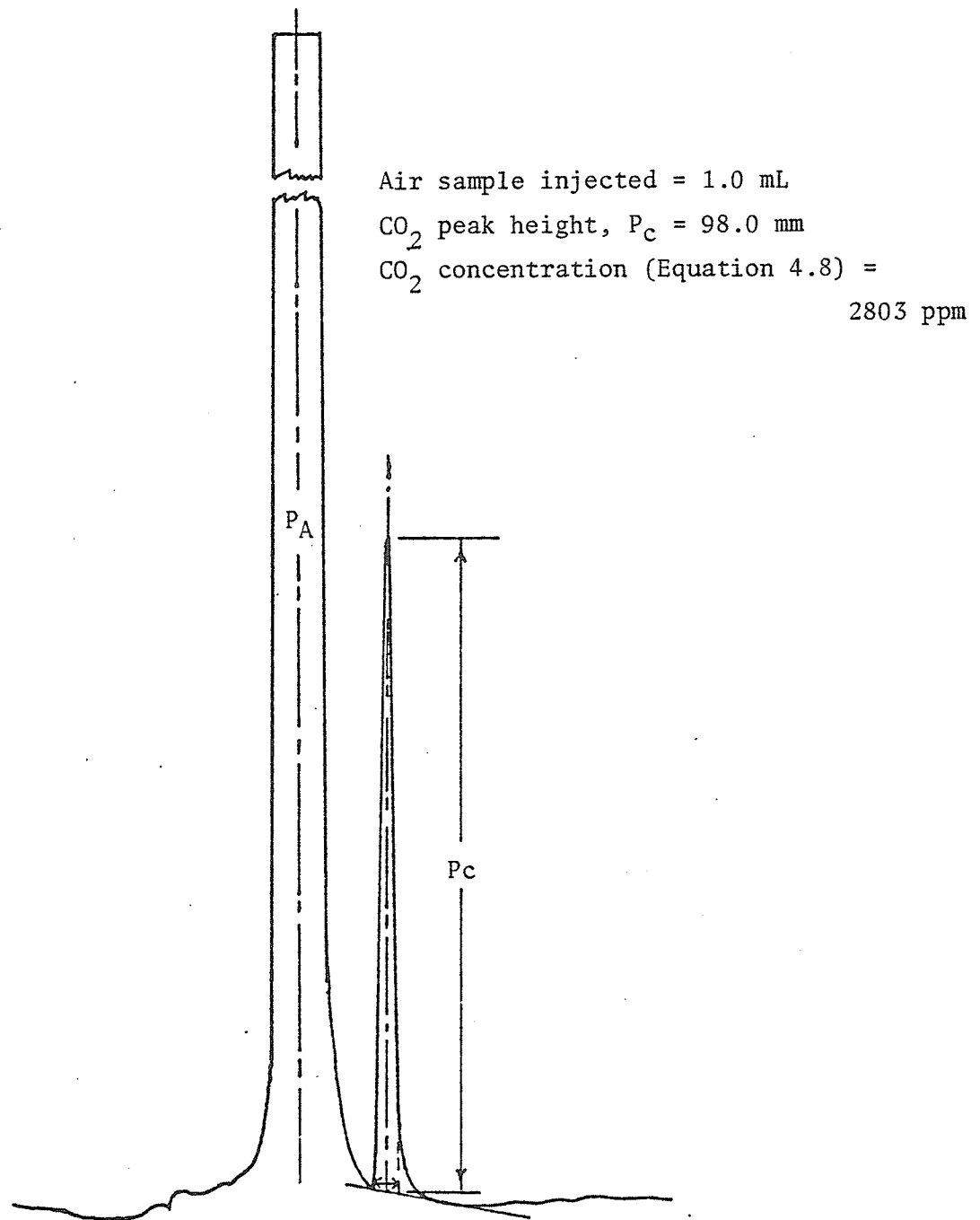


Figure B.1 Typical chromatogram for CO<sub>2</sub> concentration in air  
(Test 6, sample 1)

APPENDIX C  
EXPONENTIAL REGRESSION ANALYSIS



## APPENDIX C

## EXPONENTIAL REGRESSION ANALYSIS

After examining the data as plotted in Figure 5.1 it was obvious that different leakage rates were occurring over the test period. For example the duration of the first leakage rate,  $LR_{11}$ , was two hours. An exponential regression analysis was performed for the first 5 data points as shown in Table C.1. Similarly for the second leakage rate the regression was performed for the next six data points and finally all the data points were used to perform an exponential regression analysis to get the average air change rate for test 1.

The exponential regression analysis to determine the values of  $R$  and  $C_0$  in equation 2.5 was done using a library program for a Hewlett-Packard calculator (Model 9100 A, 1970).

Table C.1 Sample of Regression Analysis with Grouping of Data

Grouping Number	Rate (L/h)	Time (h)	CO <sub>2</sub> Concentration (ppm)	C <sub>o</sub> (ppm)	Correlation Coefficient r
LR <sub>11</sub>	0.182	0.0	2657	2988	0.997
		0.5	2400		
		1.0	2228		
		1.5	1978		
		2.0	1857		
LR <sub>12</sub>	0.372	0.0	1857	1938	0.991
		0.5	1630		
		1.0	1343		
		1.5	1041		
		2.0	959		
		2.5	763		
Average R	0.276	0.0	2627	3497	0.984
		0.5	2400		
		1.0	2228		
		1.5	1978		
		2.0	1857		
		2.5	1636		
		3.0	1343		
		3.5	1041		
		4.0	959		
4.5	763				