AN ABSTRACT OF THE THESIS OF

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Martin L. Hellickson

A computer simulation program, Controlled Atmosphere Simulation (CAS), was written in Microsoft Visual Basic 3.0, Professional Edition to evaluate energy use by three type of atmosphere generators used in fruit storage warehouses. The program consists of pulldown time and energy use models for a membrane air separator, an ammonia fractionating burner, and a catalytic oxygen burner. Predicted results subsequently became input to an interactive computer program, Fruit Storage Refrigeration Energy Simulation (FruSTRES), which was developed to simulate energy use by cold storage ammonia refrigeration systems. The resulting model package was then used to predict overall annual energy use in fruit storages, based on number and size of rooms, building construction, equipment operation (both refrigeration and CA), commodity stored, storage period(s), and weather conditions.

The CAS accurately predicted the pulldown time of each type of equipment under normal operation. The resulting model package (CAS and FruSTRES), will be an invaluable tool in design and analyses of ammonia refrigeration and atmosphere generation systems used in common and controlled atmosphere fruit storages.

Simulation of Energy Use by Controlled Atmosphere Generation Equipment in Fruit Cold Storages

By

Pichaya Boonprasom

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Pichaya Boonprasom, Author

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1. INTRODUCTION

Continued rapid growth in world population simultaneously creates an increased need for food. Fresh fruits and vegetables have traditionally been primary food groups in many areas of the world. Apples and pears, because of their global acceptance and increasing demand, are two commodities that are predicted to experience increase in production. Oregon state produced approximately 4 and 3.5 million boxes of apples in 1995 and 1996, respectively. In addition, Oregon produced 7 million boxes of Winter pears in 1997 (WPCC, 1997). Washington state produced approximately 2 and 2.5 million metric tons of apples in 1995 and 1996 (USDA, 1997). The Pacific Northwest produced 15.2 million boxes of winter pears in 1997. During the period from 1990 through 1994, overall domestic sales of apples increased by 8 %, approximately 2 % each year, while export sales increased 78 % overall (16 % per year) (Warner, 1996). Industry-wide, apple and pear production and storage capacity continues to increase. Based on the forecasting of world apple production in the year 2000, approximately 53.2 billion metric tons of apples will be produced. This amounts to an increase of four million metric tons in worldwide apple production compared to 1994 (O' Rourke, 1996).

Apple sales added approximately 17 million dollars to Oregon's economy and approximately 1 billion dollars to Washington's economy in 1996 (NASS, 1997). In addition, pear sales added approximately 77 million dollars to Oregon's economy and approximately 123 million dollars to Washington's economy in 1996 (NASS, 1997).

Most fresh apples and pears were placed into common (regular atmosphere) or controlled atmosphere (CA) storage for some time prior to being marketed. Apple and pear storage totaled 3.2 million gross cubic meters as of October 1, 1995, an increase of six percent from October 1, 1993. In 1995, the total apple and pear storage capacity in Washington state was approximately 172 million boxes, 114 million boxes were in controlled atmosphere storage and the remaining 57 million boxes were in regular atmosphere storage. Total apples in cold storage in the Pacific Northwest region was approximately 63 thousand metric tons as of April 1995, which accounts for about eighty five percent of the total apples in cold storage in the U.S.A. (USDA, 1995a). Ninety seven percent of the apples in the U.S.A. were placed in controlled atmosphere storage (USDA, 1995b), the remainder were held in regular atmosphere (RA) storage for some period.

The United States is the world's fifth largest producer of apples (O'Rourke, 1996). In order to compete in the world market, minimizing cost and/or increasing production efficiency is very important. Energy efficient management practices in cold and CA storage play an important role in maintaining the high quality fruit at competitive prices that is essential in the market.

Recently, an Windows interactive computer program was developed to simulate energy use by cold storage ammonia refrigeration systems. That program was developed to simulate refrigeration system energy use in fruit cold storages and can also be used to explore possibilities of improving energy use efficiency in fruit cold storages. However, the program did not include energy use by and heat gain from various CA equipment. Therefore, this research was conducted to develop a computer simulation of energy use by three types of controlled atmosphere generation equipment predominately used by the fruit storage industry. Subsequently, this simulation program was interfaced with the existing refrigeration system energy use model to provide a comprehensive model of an entire system. Based on number and size of rooms, construction, and equipment operation (both refrigeration and CA), commodity stored, storage period(s), and weather conditions, the resulting model package was then used to predict overall annual energy use in fruit storages. The program can also be used as a design tool for more accurate sizing of ammonia refrigeration systems and controlled atmosphere generation systems in fruit cold storage warehouses.

The specific objectives of this research project were;

1) To develop room pulldown time models for three types of atmosphere generators; a membrane air separator, an ammonia fractionating burner, and a catalytic oxygen burner, all incorporated with fruit respiration models.
2) To determine the additional heat load to the refrigeration system due to the use of controlled atmosphere generators.

3) To simulate electrical energy use of a fruit storage warehouse, using room pulldown times and energy consumed by the refrigeration and controlled atmosphere equipment.

2. LITERATURE REVIEW

Cold storage facilities for fresh fruits and vegetables are generally categorized into two types: conventional refrigerated storages and controlled atmosphere storages. Conventional refrigerated storages, also identified as common or regular atmosphere (RA) storages, are not sealed to control atmospheric gas contents. Commodities in RA storages are normally kept for a relatively short time before marketing. Unlike RA storages, controlled atmosphere storages, are gastight rooms in which oxygen and carbon dioxide are specifically regulated to achieve an environment that suppresses metabolic activities beyond that achievable by refrigeration alone. Controlled atmosphere storage conditions (environments) are commonly created by reducing oxygen (O_2), adding nitrogen (N_2), and allowing carbon dioxide (CO_2) to increase in the storage room or container (Hardenburg et al., 1990).

Proper use of CA can supplement temperature management. Effective temperature control helps reduce both quantitative and qualitative losses by slowing respiration and ethylene production rates. Additional benefits of CA include: less fruit softening, reduced fruit sensitivity to ethylene, ease of chilling injury of various commodities, inhibition of postharvest pathogen development and insect control.

2.1 FRUIT RESPIRATION

Harvested fruit are living tissues which continue to carry on metabolic processes. Most important of these is respiration (Hardenburg et al., 1990). Respiration is the process by which stored organic materials (carbohydrates, proteins, fats) are broken down into simple end products with an accompanying release of energy (Kader, 1992). This biological process is a series of oxidation-reduction reactions, where a variety of substrates found within the cells are oxidized. The oxidation of glucose is represented by the following equation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 686\,\text{Kcal} \quad (1)$$

Equation 1 states that for every mole of glucose, 6 moles of oxygen (O_2) are consumed to produce 6 moles of carbon dioxide (CO_2), 6 moles of water and 686 Kcal of energy (Kays, 1991).

The loss of stored food reserves in a commodity during respiration (1) hastens senescence as the reserves that provide energy to maintain the commodity's living status are exhausted; (2) reduces food value (energy value) for the consumer; (3) causes loss of flavor quality, especially sweetness; and, (4) results in loss of salable weight. The energy released as heat, known as vital heat or heat of respiration, affects post-harvest technology considerations, such as estimations of refrigeration and ventilation requirements (Kader, 1992).

Respiration rate is an indication of the overall rate of metabolism of the plant or plant part. All metabolic changes occurring after harvest are important, especially those that have a direct bearing on the quality of the product. The central position of respiration in the overall metabolism of plants or plant parts allows respiration to be used as a general measure of metabolic rate (Kay, 1991). Respiration rate can be expressed as the weight of CO_2 produced per unit of fruit weight in a given unit of time (mg CO_2 per kg-hr) or the volume unit of CO_2 produced per unit of fruit weight in a given unit of time (ml CO_2 per kg-hr). In some cases, the quantity of O_2 uptake may be used to indicate respiration activity, rather than CO_2 produced.

2.1.1 Temperature Quotient (Q_{10}) of Respiration

Temperature has a pronounced effect on metabolic rate. As product temperature increases, reaction rates increase, although not all reactions within a tissue have the same relative rates of change (e.g., the optimum temperature for photosynthesis is usually lower than the optimum temperature for respiration). Changes in the rates of reactions due to temperature are commonly characterized by using a measure called Q_{10} (Kays, 1991). The concept of Q_{10} follows Van't Hoff's rule which states that the rate of a chemical reaction approximately doubles or triples for each 10^0 C (18^0 F) temperature rise, which can be expressed as :

$$Q_{10} = \frac{R_2}{R_1} \quad = \text{a constant (approximately 2 or 3)} \qquad (2)$$

The rate of a process at a given temperature is R_1, and R_2 is the rate of the same process at a temperature 10^0 C higher. A more general form of Van't Hoff's rule can be written as:

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{\left(\frac{10}{t_2 - t_1}\right)} = \text{a constant (approximately 2 or 3)} \qquad (3)$$

Parameters t_1 and t_2 are any temperature corresponding to the rate of R_1, and R_2, respectively. Equation 3 can be used to calculate Q_{10} values, when the rate of respiration is known and the temperature difference is not 10^0 C. This equation also permits calculation of an unknown respiration rate of fruit in a regular atmosphere environment, when Q_{10} is known and the temperature difference is not 10^0 C. Change of temperature causes Q_{10} changes. However, if the respiration rate of the fruit is known at 10^0 C intervals between 0^0 C and 40^0 C, any intermediate rates can be calculated with sufficient accuracy to predict refrigeration and ventilation requirements (Ryall and Lipton, 1979).

2.1.2 Respiration Quotient (RQ)

Respiration quotient, defined as the ratio of the number of molecules of carbon dioxide given off to the number of molecules of oxygen absorbed, provides a general indication of what particular substrate is being oxidized as the major source of respiratory energy. Table1 illustrates respiration quotient values for oxidation of a common carbohydrate, lipid, and organic acid.

Type of Substrate	Substrate	Reaction	Respiratory Quotient (CO_2 / O_2)
Carbohydrate	Glucose	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$	1.00
Lipid	Palmitic acid	$C_{16}H_{32}O_2 + 11O_2 \rightarrow C_2H_{22}O_{11} + 4CO_2 + 5H_2O$	0.36
Organic acid	Malic acid	$C_4H_6O_5 + 3O_2 \rightarrow 4CO_2 + 3H_2O$	1.33

Table 1. Respiration quotients for oxidation of a common carbohydrate, lipid, and organic acid (adapted from Kays, 1991).

Detailed studies of apples, based on controlling oxygen concentrations from 21% to 14%, produced no effect on the respiration rate. Further reduction in the oxygen concentration to 4% resulted in a gradual slowing of respiration, but the RQ remained near unity (Metlitskii et al.,1983).

Bohling and Hansen (1983) reported the respiration behavior of three apple varieties: “Golden Delicious”, “Boskoop”, and “Gloster 69”. The fruit were stored in normal atmosphere storage and in controlled atmosphere compositions of : 2%, 3%, 4%, and 5% CO_2, in combination with 1%, 2%, 3%, and 4% O_2. Storage temperatures were 1.0, 2.5 and 3.5^0 C. The respiration quotient was found to fluctuate insignificantly (1.03 - 1.05); and was not influenced to any notable degree either by the different storage atmospheres, or by the different storage temperatures.

2.2 REFRIGERATED STORAGE

Temperature management is the most effective tool for extending the storage life of fresh commodities. Orderly marketing of perishable commodities often requires some storage to balance day-to-day fluctuations between product harvest and sales. Long-term storage is used to extend marketing beyond the end of the harvest season. The goals of storage are (Kader, 1992) :

1. To slow biological activity of a product by maintaining the lowest temperature that will not cause freezing or chilling injury, and by controlling atmospheric composition.
2. To slow the growth and spread of microorganisms by maintaining low temperatures and minimizing surface moisture on the product.

To reduce product moisture loss and the resulting wilting and shrivel, by reducing the difference between product and air temperatures, and maintaining high humidity in the storage room.

2.2.1 Cooling Rate

Rapid removal of field heat from harvested fruit is desirable in order to minimize the rate of deterioration. The rate of cooling of any commodity depends primarily upon accessibility of the product to the refrigeration medium, the difference in temperature between the product and the refrigerating medium, the velocity of the refrigerating medium, and the kind of cooling medium; i.e., water or air (Hardenburg et al., 1990).

Since respiration is affected by fruit temperature, the change in fruit temperature as a function of time must first be determined. Changes in respiration rate as a function of time can then be calculated.

The following assumptions have been made to determine the cooling rate of the bulk commodities.

1. Thermal properties of the products and air remained constant throughout the process. Respiration, varied with temperature (Gaffney et al., 1977 ; Baird et al., 1976).
2. No conduction heat transfer occured between individual products (Bellagha it al., 1985 ; Baird et al., 1976).
3. Air velocity in all interstices was constant (Bellagha et al., 1985 ; Gaffney et al., 1977 ; Baird et al., 1976 ; Bakker - Ardema et al., 1966 ; Gillou et al., 1958).
4. No temperature gradient existed within the product (Gaffney et al., 1977 ; Bakker - Arkerma et al., 1966 ; Gillou et al., 1958).

From Fourier's law, heat conduction in the absence of a temperature gradient implies the existence of infinite thermal conductivity. Such a condition is clearly impossible. Although the condition is never exactly satisfied, it is closely approximated if the resistance to conduction within the solid is small compared with the resistance to heat transfer between the solid and its surroundings (Incropera and Dewitt, 1990). Gillou (1958) and Gaffney et al. (1977) used the Lumped Heat Capacity analysis method to determine the cooling rate of bulk commodities. According to the principles of transient heat conduction, if an object is placed in surroundings at a constant lower temperature, the following equation can be solved to evaluate the transient heat transfer in a bulk commodity:

$$hA_s(T - T_\infty) = -\rho Vc\frac{dT}{dt} \qquad (4)$$

or

$$hA_s(T - T_\infty) = -mc\frac{dT}{dt} \qquad (5)$$

where

t = time (hr)

T = temperature of the object at time t (°C)

T_∞ = temperature of the surroundings (°C)

h = convective heat transfer coefficient (W/m^2 K)

V = volume of container (m^3)

A_s = surface area of the container (m^2)

ρ = fruit bulk density (kg/m^3)

c = specific heat of fruit (J/kg K)

Equation 4 may then be integrated with the condition that t=0 at initial product temperature T_i. Thus the solution to equation 4 becomes :

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{\left[-\left(\frac{hA_s}{\rho Vc}\right)t\right]} \qquad (6)$$

or

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{-\left(\frac{t}{\tau}\right)} \qquad (7)$$

where

T_i = initial value of T (°C)

τ = thermal time constant (hr)

The parameter τ representes $\rho Vc/hA_s$, which is the thermal time constant of the system. If the thermal time constant is known, equation 7 may be used to determine the time for the fruit to reach some temperature T. Conversely, equation 7 may be used to compute the temperature reached by the fruit at time t. Moreover, the time constant is related to the half-cooling time. The half-cooling time is the amount of time required to reduce the temperature difference between the product and its surroundings (cooling medium) by one-half. Sainsbury (1951) introduced the symbol Z for this quantity, expressed in hours or minutes. The following relation is convenient for calculating the half-cooling time from observations; or for predicting cooling method performance when the half-cooling time is known. The half-cooling time (Z) can be represented by the following equation:

$$Z = t\left(\frac{\ln 2}{\ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right)}\right) \tag{8}$$

or

$$Z = \Phi \ln 2 \tag{9}$$

and

$$\Phi = \frac{t}{\ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right)} \quad \text{(hrs)} \tag{10}$$

2.2.2 Refrigeration Load Due to the Use of CA Generators

Effluent from CA generators and infiltrating air are normally at higher temperatures than the refrigerated space at the beginning of storage period (infiltration air may be significantly colder than room air during winter months). Heat gain from the effluent and infiltrating air that is higher than the storage temperature becomes a part of the refrigeration load. The heat gain to the refrigeration system can be expressed as :

$$Q = \dot{m} \cdot (H_1 - H_2) \tag{11}$$

where

Q = rate of heat gain (kJ/hr)

$\dot{m}$ = mass flow rate of infiltrating or effluent (kg^3/hr)

H_1 = enthalpy of effluent and/or infiltrating air (kJ/kg)

H_2 = enthalpy of refrigerated air (kJ/kg)

Mass flow rate, $\dot{m}$, must first be determined to use equation 11. The following equation is used to calculate $\dot{m}$:

$$\dot{m} = \dot{V} \cdot \rho_{air} \tag{12}$$

where

$\dot{V}$ = volumetric flow rate (m^3/hr)

ρ_{air} = air density (kg/m^3)

Equations 13 through 18, are important relationships used to determine density and enthalpy of effluent, infiltrating, and refrigerated air (ASHRAE, 1985) :

$$\rho_{air} = \frac{P}{\left[(R_a \cdot T) \cdot (1 + 1.6078 \cdot W)\right]} \tag{13}$$

where

P = air pressure (kPa)

R_a = gas constant of air (287.053 J/kg-K)

T = air temperature (K)

W = humidity ratio of infiltrating air and/or effluent (kg water vapor/ kg dry air)

Air enthalpy can be estimated by :

$$H = t + W \cdot (2501 + 1.805 \cdot t) \tag{14}$$

where

H = enthalpy of air (kJ / kg)

t = air dry-bulb temperature ($^\circ C$)

W = humidity ratio (kg water vapor/ kg dry air)

Humidity ratio for the refrigerated air can be calculated by using:

$$W = 0.62198 \cdot \frac{P_W}{(P_R - P_W)} \tag{15}$$

where

P_W = partial pressure of water vapor (kPa)

P_R = pressure in the refrigerated space (kPa)

The partial pressure of water vapor at constant pressure and temperature can be estimated using:

$$RH = \frac{P_W}{P_{WS}} \cdot 100 \tag{16}$$

where

RH = relative humidity (%)

P_W = partial pressure of water vapor (kPa)

P_{WS} = partial pressure of water vapor at saturation (kPa)

Saturation water vapor pressure over ice for temperatures that range from -100 to 0^0 C can be estimated using (ASHRAE,1985):

$$\ln (P_{WS}) = C_1 / T + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 T^4 + C_7 \ln (T) \tag{17}$$

where

P_{WS} = saturation water vapor pressure (kPa)

T = absolute temperature (K)

C_1 = -5674.5359

C_2 = 6.3925247

C_3 = $-0.9677843 \cdot 10^{-2}$

C_4 = $0.62215701 \cdot 10^{-6}$

C_5 = $0.20747825 \cdot 10^{-8}$

C_6 = $0.9484024 \cdot 10^{-12}$

C_7 = 4.1635019

Saturation water vapor pressure over liquid water for temperatures that range from 0 to 200 ^{0}C can be estimated using (ASHRAE,1985):

$$\ln (P_{WS}) = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13} \ln (T) \qquad (18)$$

where

P_{WS} = saturation water vapor pressure (kPa)

T = absolute temperature (K)

C_8 = -5800.2206

C_9 = 1.3914933

C_{10} = -0.04860239

C_{11} = $0.41764768 \cdot 10^{-4}$

C_{12} = $-0.14452093 \cdot 10^{-7}$

C_{13} = 6.5459673

2.3 CONTROLLED ATMOSPHERE STORAGE

Controlled atmosphere storage technology currently plays an important role in the marketing of fresh apples and pears in fruit-growing regions of the U.S.A., New Zealand, Columbia, Chile, Italy, France, and Germany. Controlled atmosphere storage provides a means of managing supplies and makes it possible for multiple types of fruit to be available to the public for most of the year.

Controlled atmosphere storages must be sufficiently gastight to limit the entry of high oxygen air from outside, and to control the atmosphere within the storage room. Generally, apples and pears may be kept in the CA storage for 4-10 and 3-8 months, respectively, depending upon cultivars and marketing schedules. Table 2 illustrates typical CA storage atmospheres for several varieties of apples and pears.

Fruit	Oxygen (%)	Carbon Dioxide (%)	Temperature (^{0}C)
Apples			
-Boskoop	1.2 - 3.5	0.5 - 2.0	3.0 - 5.0
-Braeburn	1.0 - 2.0	1.0 - 2.0	0.0 - 0.0
-Golden Delicious	1.0 - 2.5	1.5 - 4.0	-0.5 - 2.0
-Granny Smith	0.8 - 2.5	0.8 - 5.0	-0.5 - 2.0
-Jonathan	1.0 - 3.0	1.0 - 3.0	-0.5 - 4.0
-McIntosh	1.5 - 3.0	1.0 - 5.0	2.0 - 4.0
-Red Delicious	1.0 - 2.5	1.0 - 3.0	0.0 - 2.0
Pears			
-Anjou	0.5 - 2.0	< 0.5 - 2.0	-1.0 - 0.0
-Bartlett	1.0 - 3.0	0.5 - 3.0	-1.0 - 3.0
-Bosc	0.5 - 2.0	0.0 - 1.5	-1.0 - 0.0
-Comice	0.5 - 3.0	< 0.8 - 3.0	-1.0 - 0.0

Table 2. Oxygen, Carbon Dioxide and Temperature Recommendations for CA Storage of Apples and Pears (adapted from Meheriuk, 1993).

2.3.1 Atmosphere Generating Equipment

Several types of controlled atmosphere generators are currently available. Mechanical equipment for creating low oxygen CA conditions was introduced to Europe in 1959. The principal technology employed was the combustion of oxygen and ammonia fractionation. A burner used fuel, such as propane, to burn oxygen out of the ambient air. Fractionation was accomplished by "catalytically cracking" ammonia into nitrogen and water in the presence of oxygen. This equipment gained acceptance since it became possible for CA conditions to be established within a storeroom in a matter of days. These systems are still widely used throughout the world. However, over the past decade, new commercial sales of these systems have dropped dramatically. The primary reason is because storage operators have adopted the safer use of nitrogen separated directly from air for CA applications (Malcolm, 1993). Nitrogen technologies including pressure swing adsorption systems (PSA), liquid nitrogen, and membrane air separators have grown rapidly and are gaining wide acceptance in fruit cold storage warehouses.

Both liquid nitrogen and PSA systems gained commercial acceptance in the Pacific Northwest region of the U.S.A. in the mid-1980's. However, since 1990, industry preference has shifted to membrane systems. No new PSA systems have been sold in the region since 1990, and new requirements for liquid nitrogen have been predominantly confined to specific pulldown applications. This shift has been driven by the simplicity and cost effectiveness of membrane systems (Malcolm, 1993). The three predominate types of controlled atmosphere generators presently used in the Pacific Northwest region will be discussed in this thesis.

2.3.1.1 Membrane Air Separators

Membrane air separation systems selectively divide an air stream into two sub-streams. One is a nitrogen rich stream while the other is an oxygen rich stream with trace amounts of other gases. Membrane air separators consist of bundles of small hollow fiber tubes in a vessel. The principle of separation systems is based on varying permeation rates of different gases, such as oxygen, carbon dioxide, and nitrogen, through the fiber tubes. Figure 1 is a schematic drawing of an air separation system. As compressed air flows through the tubes, oxygen and carbon dioxide permeate through the wall faster than nitrogen. This oxygen-rich permeate stream is vented to the outside. The non-permeate gas (nitrogen) outflow stream is piped into the CA storage rooms (Waelti, 1989). Figure 2 illustrates nitrogen purging using a membrane air separator.

Purity of the product stream can be adjusted by changing the output flow rate. The higher the nitrogen purity required, the lower the flow rate produced, assuming constant feed air temperature and pressure. In most cases, the greatest system efficiency is achieved at purities of 90-95%; which is adequate for nearly all gaseous nitrogen applications in fruit storages (Diedering and McReynolds, 1985).

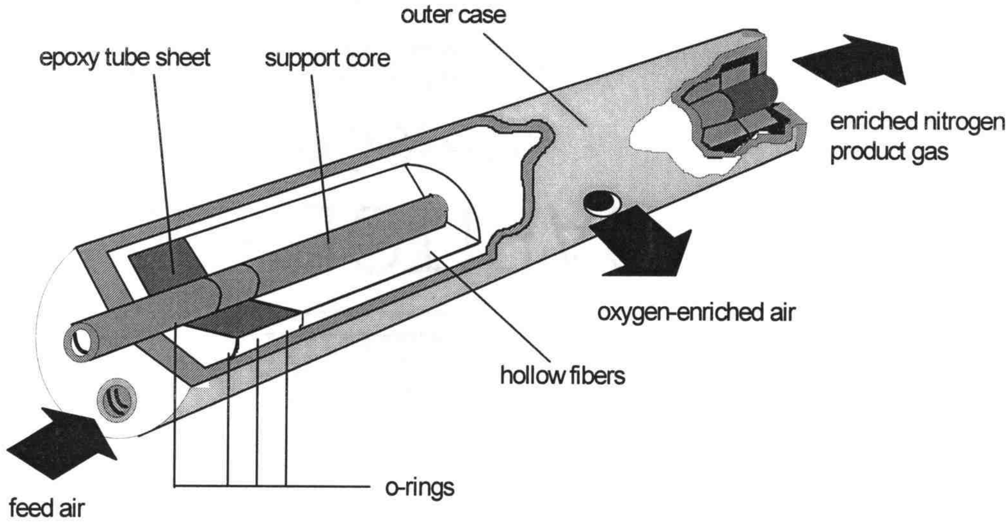

Figure 1. Schematic drawing of membrane air separator (after Diedering and McReynolds, 1985).

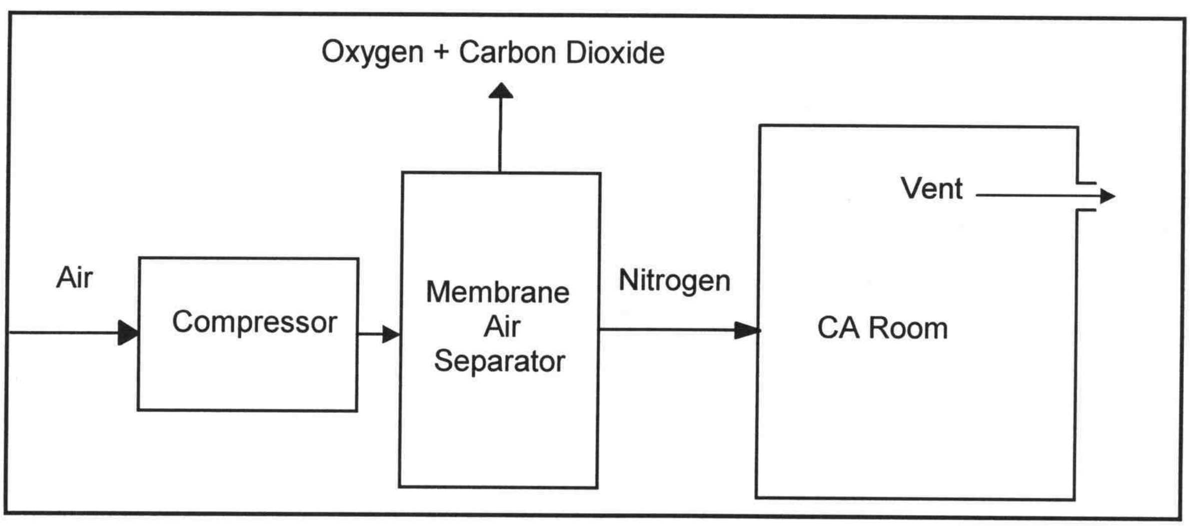

Figure 2. Nitrogen purge diagram (adapted from Waelti and Cavalieri, 1989).

2.3.1.2 Ammonia Fractionating Burners

An ammonia fractionating system is another type of nitrogen generator. Ammonia fractionating burners are also known as ammonia cracking burners or by the commercial name of "Oxydrain". This type of nitrogen generator uses anhydrous ammonia (NH_3) as its nitrogen source. With this equipment, bottled ammonia is fed to a combustion chamber where it is thermally fractionated into hydrogen and nitrogen, as shown in the following equation :

$$\text{Cracking: } 2NH_3 \rightarrow N_2 + 3H_2 \qquad (18)$$

Hydrogen molecules in the gas mixture then react with oxygen in air pulled from the storage room forming water according to the formula :

$$\text{Burning: } 2N_2 + 6H_2 + 3O_2 \rightarrow 2N_2 + 6H_2O \qquad (19)$$

An amount of 454 grams (one pound) of anhydrous ammonia reacts with 0.45 cubic meters (15.8 cubic feet) of oxygen, and returns 0.3 cubic meters (10.5 cubic feet) of nitrogen. Air replaces the 0.15 cubic meters (5.3 cubic feet) of lost volume, and adds 0.03 cubic meters (1.1 cubic feet) of oxygen for each pound of ammonia used (Bartsch et al., 1985).

The gas mixture is cooled before being returned to the storage room. Excess water condensate is discharged with the cooling water. Consequently, the return gas is saturated with water vapor when it leaves the cooling tower.

This generator is usually operated as a recirculation system rather than a purge system. Purge systems are time consuming and inefficient. Unlike the purge system, the recirculation system has a much faster oxygen pulldown rate and lower operating costs. The recirculating ammonia burner operates in the manner illustrated in the Figure 3.

During operation, both the fractionation temperature and the ratio between the quantity of oxygen and the fuel must be accurately controlled. Fractionation temperature control is needed to guarantee a complete reaction between the oxygen and the hydrogen. The amount of ammonia fuel must be adjusted to the amount of oxygen in the air, to assure that no unfractionated ammonia passes into the fruit storage room (Waelti, 1985).

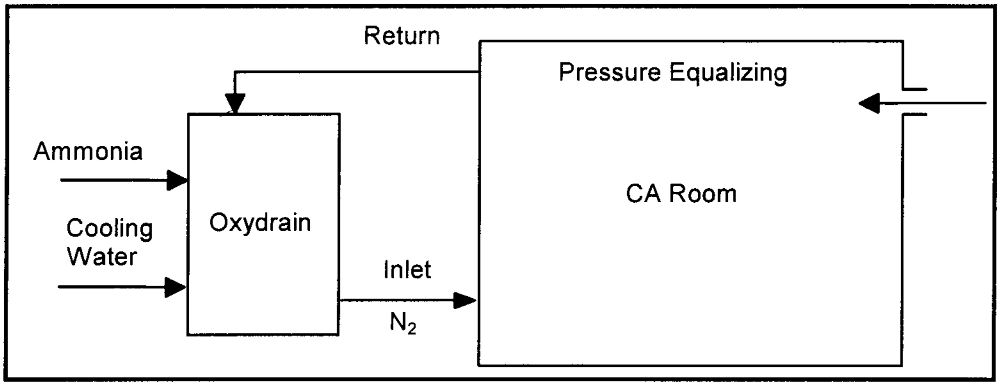

Figure 3. Recirculating atmosphere through Ammonia Cracking Burner (after Bartsch et al., 1985).

2.3.1.3 Catalytic Oxygen Burner

Catalytic Oxygen Burners (COB) are combustion generators that use propane or natural gas as a fuel, and were developed by Atlantic Research Corporation. This type of burner controls oxygen levels by recirculating storage room air.

Air from the storage room is drawn to the COB unit by a compressor blower and then preheated by a heating coil in the machine to approximately 316^0 C (600^0 F). After preheating, propane is introduced into the air stream. The gas mixture then flows across a heated platinum catalyst. Oxidation reaction starts on the catalyst where operating temperatures of 593 - 649^0 C (1,100 - 1,200^0 F) are reached. Manually adjusted oxygen ratios are necessary to provide maximum efficiency. The theoretical combustion reaction for propane and air is described in the following equation :

$$C_3H_8 + 5O_2 + 20N_2 \rightarrow 3CO_2 + 20N_2 + 4H_2O \tag{20}$$

From equation 20, 454 grams (one pound) of propane reacts with 6.54 cubic meters (231 cubic feet) of air to produce 5.4 cubic meters (190 cubic feet) of nitrogen, 0.69 cubic meter (24.4 cubic feet) of CO_2 and 0.75 kilogram (1.64 pounds) of water vapor. During recirculation, each pound of propane combines with 1.16 cubic meters (41 cubic feet) of oxygen produces 0.69 cubic meters (24.4 cubic feet) of CO_2 plus 1.64 kilogram of water vapor. Since the volume of CO_2 exhausted is less than the volume of oxygen taken in, the CA room is vented to permit air to enter and equalize the pressure. Excess oxygen in the entering air stream (0.93 cubic meter per pound of propane used) is consumed in the catalytic oxygen burner. Figure 4 illustrates recirculating storage room air through a catalytic oxygen burner. Discharge air is cooled by heat exchangers, excess water vapor is condensed in the cooler, then the air is returned to the storage room (Bartsch et al., 1985).

The large quantity of carbon dioxide produced by the generator plus that generated by the fruit which must be removed prior to returning the air to the storeroom. Thus COB systems require larger carbon dioxide scrubbers.

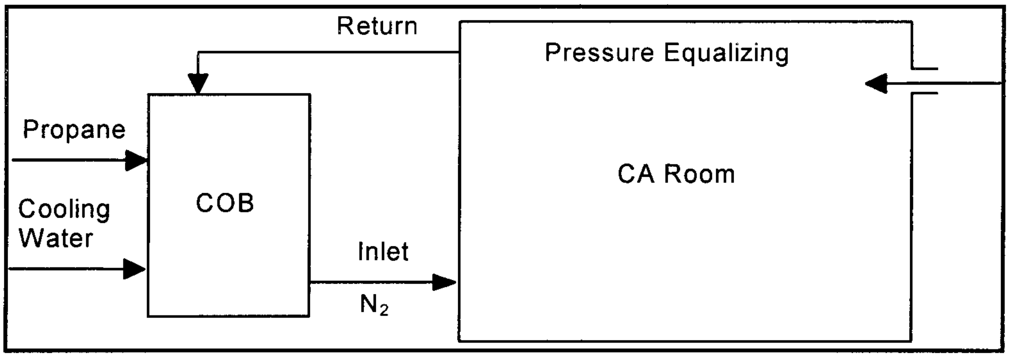

Figure 4. Recirculating atmosphere through Catalytic Oxygen Burner (after Bartsch et al., 1985).

2.3.2 Carbon Dioxide Scrubbers

Several methods are currently used to remove excess carbon dioxide from controlled atmosphere rooms. Systems used include activated charcoal scrubbers, membrane air separation scrubbers, water scrubbers, hydrated lime scrubbers, and molecular sieve scrubbers. With activated charcoal, carbon dioxide is first captured by absorption, then driven off by passage of fresh air through the medium. Carbon dioxide can also be removed by recirculating room air through a membrane air separator. Carbon dioxide and oxygen molecules will permeate through the membrane wall and will be removed from the air stream. The Nitrogen rich stream returns to the room. This research focuses on the hydrated lime scrubbers and the molecular sieve adsorbers since those methods are widely used in the Pacific Northwest storages. The fruit storage warehouse selected as a study model uses hydrated lime and a molecular seive for carbon dioxide control.

2.3.2.1 Hydrated Lime Scrubbers

Hydrated lime, high in calcium hydroxide, will absorb carbon dioxide. One mole of hydrated lime ($Ca(OH)_2$) will combine with one mole of carbon dioxide, forming one mole of calcium carbonate and one mole of water. Consequently, 3.3 grams of hydrated lime can absorb approximately 1 liter of carbon dioxide.

When hydrated lime is used as a supplement to other carbon dioxide scrubbing methods, the bags are placed directly in the CA rooms. If lime is the only method used to scrub CO_2, it is usually placed in an airtight box outside the CA room, adjacent to the wall where the evaporator is located. Pressure changes developed by the evaporator fans are usually sufficient to circulate air out of the storage room into the scrubber box (room). Air passes through stacks of lime bags and back into the storage space (Smock and Blanpied, 1972). Only fresh lime can be effective in removing carbon dioxide. A 23-kilogram (50-pound) bag of lime will weigh approximately 31 kilograms (68 pounds) when it has absorbed the maximum quantity of carbon dioxide.

2.3.2.2 Molecular Sieve Adsorbers

Molecular Sieve Adsorber (MSA) systems can be operated both in combination with a COB unit, or separately as illustrated in Figure 5, depending upon storage requirements. This system can remove carbon dioxide and small quantities of other unwanted gases such as ethylene from the storage room air. The adsorption medium is called a molecular sieve, which is made of synthetic zeolite. The synthetic zeolite was scientifically created for its superior CO_2 adsorption capacity and reactivation ability.

Molecular sieve adsorbers employ a twin-tower design which allows one tower to reactivate while the other is adsorbing. In the process tower, air is pulled from the storage room, circulated up through the sieve bed and returned to the room, as illustrated in Figure 6. During this process, CO_2 molecules are adsorbed by the molecular sieve zeolite.

Reactivation commences upon completion of an adsorption cycle. The towers switch functions. Ambient air is routed down across the heater banks and sieve beds, and then discharged to the outside atmosphere. Heating causes the molecular sieve to more easily release carbon dioxide molecules.

3. COMPUTER MODELING AND SIMULATION

A computer simulation program was developed to predict total energy use during the pulldown period in controlled atmosphere fruit storage rooms. Controlled Atmosphere Simulation (CAS) simulates operation of commonly used equipment including: membrane air separators, catalytic oxygen burners, ammonia fractioning burners, and scrubbers. Predicted results have been formatted to combine with the results of another simulation program 'Fruit Storage Ammonia Refrigeration System Energy Simulation' or FruStRES written by Adre and Hellickson, 1995. Both simulation programs were written in Microsoft Visual Basic 3.0, Professional Edition. The integrated programs are capable of simulating energy use by both the refrigeration system and the atmosphere generating equipment. The user can select the type of controlled atmosphere equipment to be simulated from a menu in the main window of the FruStRES program. Thus, to use the CAS program, the user must first start the FruStRES program.

When the user starts FruStRES, the main window will be displayed. At this point, the window only displays 'File' menu on its menu bar. The user then must select 'Open Client file' from the 'File' menu and enter a 3 digit client identification (ID) number to create a new client file or open an existing client file. Without opening a client file, the main windows will not display other menus, including the CA equipment menu.

Menu display of simulation options depends upon the client file. If the client file is new, the menu will display all simulation options. If the client file is an existing file, the menu will display only those options that exist in the CA data file. For example, if the existing client file contains a catalytic oxygen burner, the menu enables the 'Catalytic Oxygen Burner' option and disables the 'Membrane Air Separator' and the 'Ammonia Fractionating Burner' options.

Each CA equipment type simulation has a separate window. Analysis data are entered through the user interface screen. Then, each data set (each CA room or zone) can be simulated individually (a single zone simulation) or collectively (all zone simulations). The simulation result is displayed on the screen, either numerically, or graphically based on user option. An output file is also generated for each zone calculation and can be used as reference later. Moreover, the program also calculates the additional heat load due to the use of a CA generator. This amount of heat is added to the total cooling load of the refrigeration system. Finally, the program adds the results of the energy used by the CA equipment during pulldown to the energy used by the refrigeration system and creates an on-screen report form which can also be printed.

The simulating process determines the electrical energy consumption of a controlled atmosphere generator from equipment energy consumption and the length of time used during pulldown. The program is capable of analyzing user input such as room size, type of fruit being stored and the number of bins in the room. Other important factors, such as gas flow rate and purity of the air product stream (% nitrogen), that affect the simulation result are considered as well.

The differential equations that describe the change of gas concentration in a room as a function of time are too complicated to be directly integrated. Therefore, the Runge-Kutta numerical method was selected to solve the pulldown time equations.

Runge-Kutta methods of higher order give more accurate results. One of the most popular is the following fourth-order method:

$$Y_{n+1} = Y_n + \left[\frac{1}{6}\left(\Delta Y_1 + 2\Delta Y_2 + 2\Delta Y_3 + \Delta Y_4\right)\right]\Delta t \qquad (22)$$

where

$$\Delta Y_1 = f\left(t_n, Y_n\right) \qquad (22a)$$

$$\Delta Y_2 = f\left(t_n + \frac{\Delta t}{2}, Y_n + \frac{\Delta Y_1 \Delta t}{2}\right) \qquad (22b)$$

$$\Delta Y_3 = f\left(t_n + \frac{\Delta t}{2}, Y_n + \frac{\Delta Y_2 \Delta t}{2}\right) \qquad (22c)$$

$$\Delta Y_4 = f\left(t_n + \Delta t, Y_n + \Delta Y_3 \Delta t\right) \qquad (22d)$$

Equation(21a) is the explicit Euler method ΔY , equation (21b) is the midpoint method ΔY based on the Euler method as a predictor, equation (21c) is the midpoint method ΔY based on the first midpoint method as a predictor, and equation (21d) is the implicit Euler method ΔY based on second midpoint method as a predictor.

3.1 FACILITY DESCRIPTION

Three storage facilities, located at Duckwall-Pooley Fruit Company, Odell, OR. were selected for simulation. Odell Cold Storage #1 consists of 7 RA and 7

CA rooms. Odell Cold Storage #2 includes 15 CA rooms and 3 common storage rooms. The Van Horn Facility consists of 4 common storage rooms and 7 controlled atmosphere storage rooms. Figures 7, 8, and 9 illustrate room capacities and layout in Odell Cold Storage #1, Odell Cold Storage #2, and Van Horn Plant, respectively.

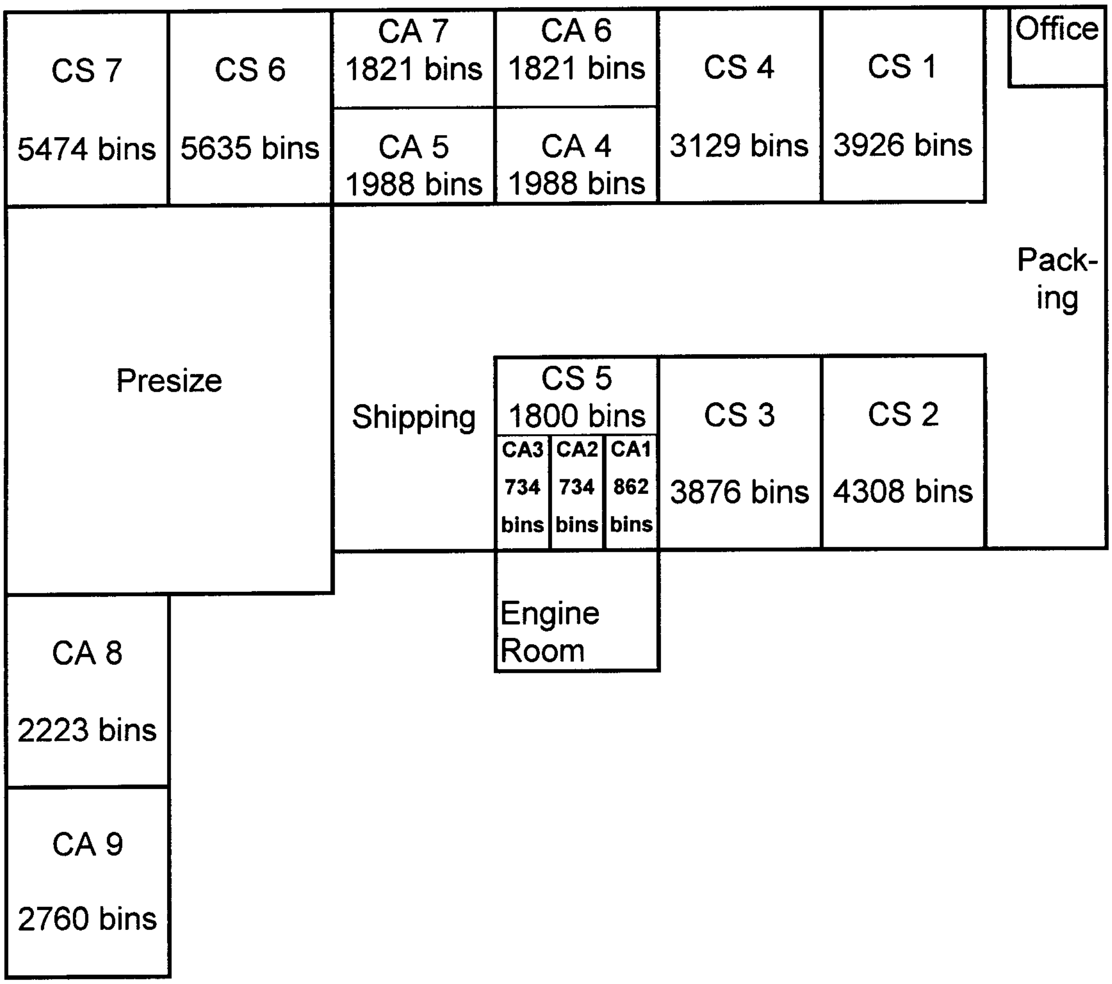

Figure 7. Schematic Diagram of Odell Cold Storage #1 facility, Duckwall-Pooley Fruit Company.

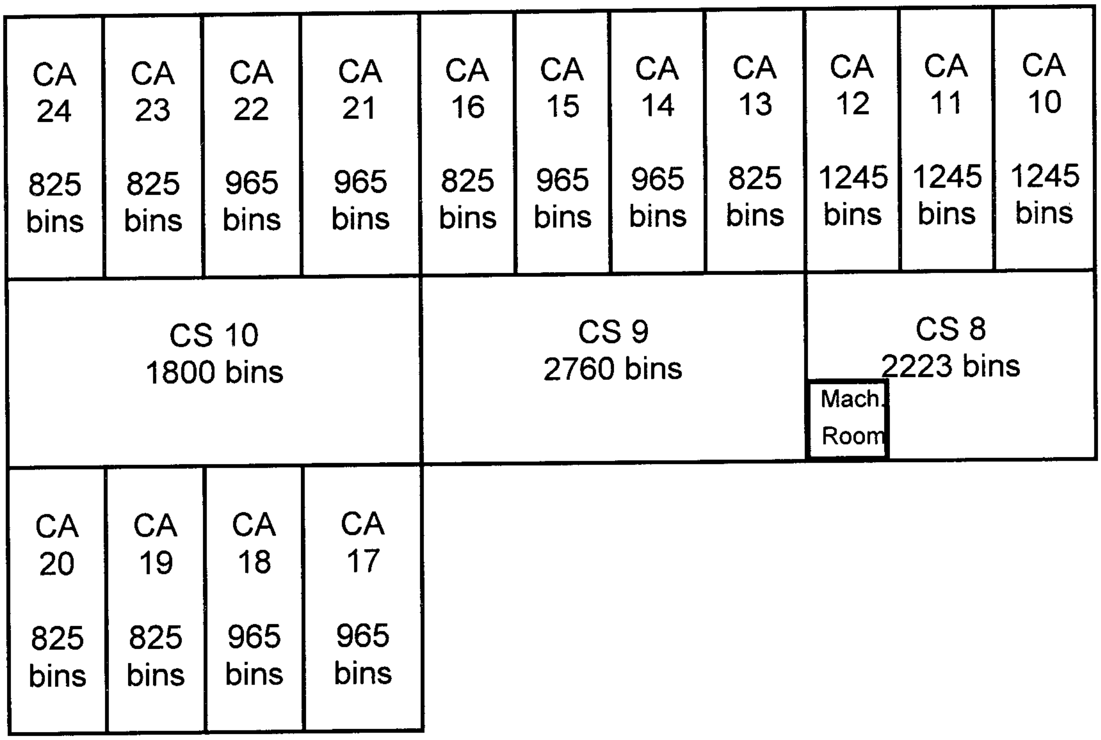

Figure 8. Schematic Diagram of Odell Cold Storage # 2 facility, Duckwall-Pooley Fruit Company.

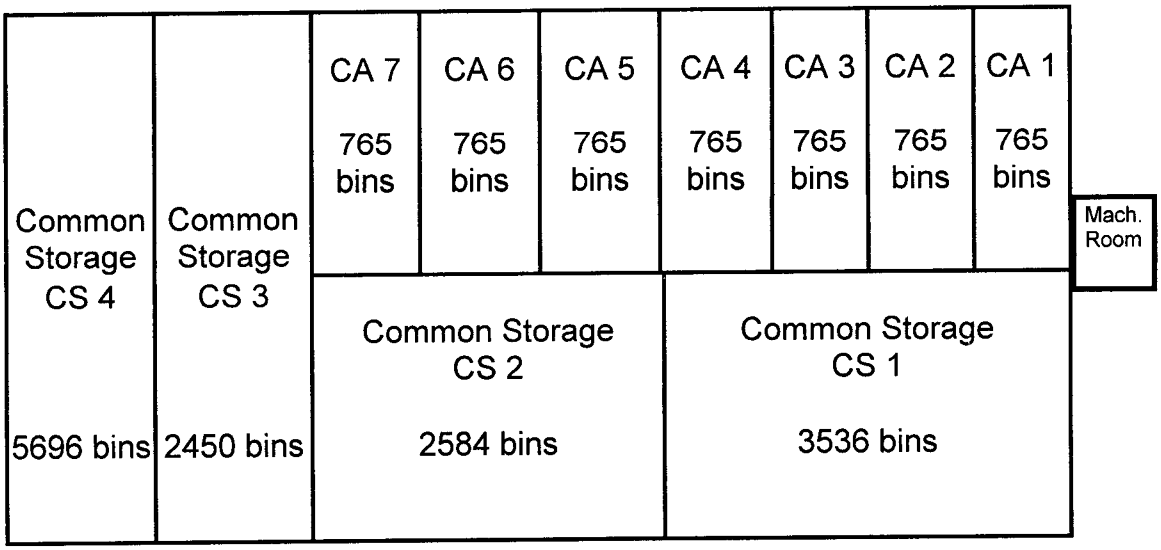

Figure 9. Schematic Diagram of Van Horn Cold Storage facility, Duckwall-Pooley Fruit Company.

3.2 FRUIT RESPIRATION MODEL

A fruit respiration model was developed to describe the relationship of respiration rate of apples and pears to temperature utilizing the data from USDA Handbook 66 (1990). Carbon dioxide (CO_2) production at various temperatures is given in mg/(kg hr). These data were taken in the 1950's and do not include the effects of modified atmospheres.

Metabolic rate of harvested fruit follows Van't Hoff's rule quite closely. Multiplying both sides of equation 3 can by the power of $\frac{(t_2 - t_1)}{10}$ allows the expression to be rewritten as:

$$R_2 = R_1 \cdot Q_{10}^{\left(\frac{t_2 - t_1}{10}\right)} \qquad (23)$$

By setting t_1, the reference temperature equal to $0^\circ C$, equation 23 can be modified to:

$$R_a = R_0 \cdot Q_{10}^{\left(\frac{t}{10}\right)} \qquad (24)$$

where

R_a = respiration rate (rate of CO_2 production) (mg/kg hr)

R_0 = respiration rate at reference temperature (mg/kg hr)

t = fruit temperature ($^\circ C$)

Q_{10} = temperature quotient of respiration

Nonlinear regression analysis was used to fit the respiration model (equation 24) to the data from USDA Handbook 66 (1990), as illustrated in

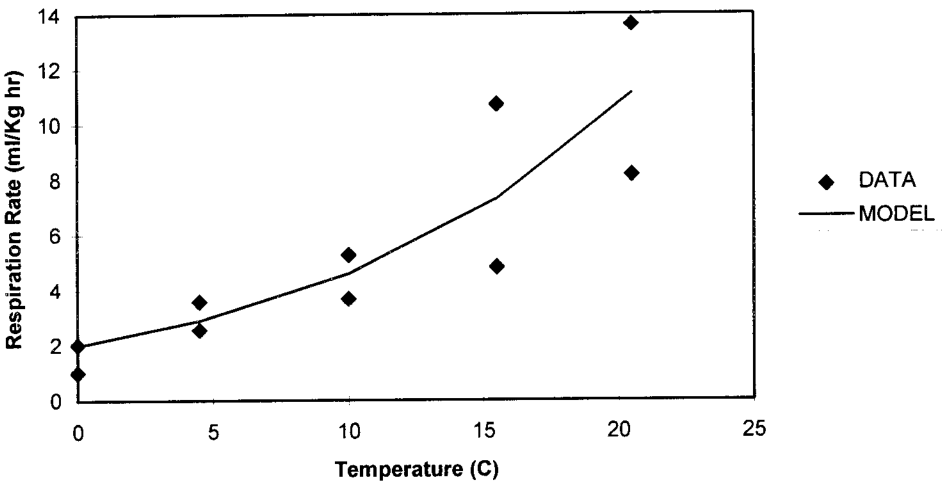

Figure 10. Respiration rate of apples at different temperatures (data versus model). Data obtained from USDA Handbook 66 (1990).

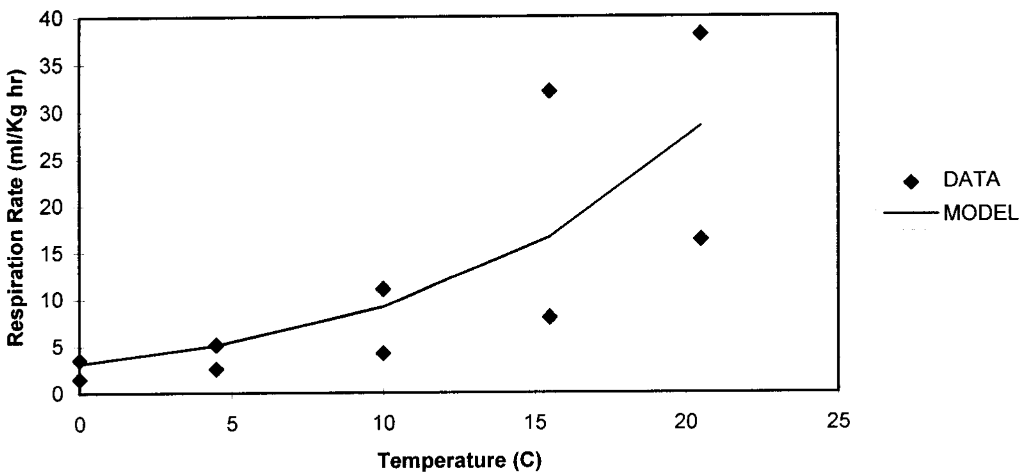

Figure 11. Respiration rate of pears at different temperatures (data versus model) Data obtained from USDA Handbook 66 (1990).

Figures 10 and 11. The values of R_0 and Q_{10} for apples were found to be 1.99 ml/kg-hr and 2.3 (squared error of 36), respectively. Values for pears were found to be 3.13 ml/kg-hr and 2.9 (squared error of 591.56), respectively.

The rate of fruit temperature changes as a function of time, described by equation 7, was substituted into equation 24 to become:

$$R_a = R_0 \cdot Q_{10}^{((e^{(\frac{-t}{\tau})} \cdot (T_i - T_S)) + T_S)/10} \tag{25}$$

Where

R_a = respiration rate (rate of CO2 production in mg/kg-hr)

R_0 = the respiration rate at reference temperature (mg/kg-hr)

t = time (hr)

Q_{10} = temperature quotient of respiration

τ = cooling time constant (hrs)

T_S = storage set temperature (°C)

T_i = initial fruit temperature (°C)

The cooling rate model (equation 7) is valid if refrigerant temperature in the evaporator coil remains constant. The values of τ used in the simulation are 20 and 15 hours for apples and pears, respectively (Adre and Hellickson, 1995). The coefficient τ depends on the type of fruit, initial fruit temperature, location in the room, and evaporator performance characteristics (Adre and Hellickson, 1995).

Respiration rate is not only a function of temperature, but also affected by carbon dioxide and oxygen concentrations in the fruit's atmosphere. Metlitskii et al. (1983) derived certain equations describing the dependence of respiration rate on oxygen and carbon dioxide concentrations in an atmosphere as follows:

$$K_{O_2} = 0.368 + 2.786 O_2 \tag{26}$$

$$K_{CO_2} = 0.991 - 2.391 CO_2 \tag{27}$$

Where

K_{O_2} = respiration rate reduction factor at lower oxygen concentrations

K_{CO_2} = respiration rate reduction factor at higher carbon dioxide concentrations

O_2 = oxygen concentration in the CA room

CO_2 = carbon dioxide concentration in the CA room

During the combined action of the increased carbon dioxide and reduced oxygen concentration in relation to atmospheric air, the corresponding values of the equations 26 and 27 are multiplied as follows:

$$K = K_{O_2} \cdot K_{CO_2} \tag{28}$$

then equation 25 can be rewritten as:

$$R = R_a \cdot K \tag{29}$$

Equation 29 is the mathematical model, or respiration rate equation that includes the effect of temperature and oxygen and carbon dioxide concentration. This equation can be used on the assumption that the room pressure remains constant.

3.3 DETERMINATION OF PULLDOWN TIME

A major component of the program was development of a model to predict the time required to establish the desired atmospheric conditions in each CA room. Separate models were designed for a membrane air separator, a catalytic oxygen burner and an ammonia fractionating (cracking) system. Each simulation was based on a dynamic balance of oxygen and carbon dioxide. The affects of fruit respiration rate, respiration quotient and carbon dioxide absorption by lime (if present) in the rooms were also included. Simulations included the following assumptions :

1. Room atmosphere was thoroughly mixed. Refrigeration evaporator fans operated continuously during fruit cool down.
2. Room pressure was constant. Pressure relief valves were present in each room.
3. The volume of oxygen consumed by apples and pears was equal to the volume of carbon dioxide produced, i.e. respiration quotient = 1.0.
4. Room air infiltration or leakage was negligible.
5. Carbon dioxide absorption rate by hydrated lime was constant.

Incorporating respiration rate into the material balance equations adds a degree of complexity to the analysis since material balances can no longer be directly integrated. The integration was performed by using initial oxygen and carbon dioxide values which were provided from actual pulldown data recorded at the three Duckwall-Pooley Fruit Company warehouses.

3.3.1 Membrane Air Separator

Membrane air separators establish CA room conditions by purging the atmosphere with an nitrogen rich gas flow. As nitrogen is introduced into the room, an equal volume of air must be vented out.

Equations 30 and 31 describe oxygen and carbon dioxide mass balances for a purge system. In equation 30, the number of moles of oxygen entering the CA room, less the amount exiting the room and that consumed by respiration, equals the accumulation of oxygen in the room.

$$\left(F_i \cdot X_{O_2,in}\right) - \left(F_{out} \cdot X_{O_2}\right) - \left(R \cdot \frac{1}{RQ} \cdot W\right) = V \cdot \frac{dX_{O_2}}{dt} \tag{30}$$

$$(R \cdot W) - F_{lime} - \left(F_{out} \cdot X_{CO_2}\right) = V \cdot \frac{dX_{CO_2}}{dt} \tag{31}$$

where

F_i = inlet gas flow rate (m^3/hr)

F_{out} = outlet gas flow rate, $F_i - F_{lime}$ (m^3/hr)

F_{lime} = rate of CO_2 absorbed by hydrated lime, if lime is present (m^3/hr)

$X_{O_2,in}$ = mole fraction of O_2 in the inlet stream

X_{O_2} = mole fraction of O_2 in the room at time t

X_{CO_2} = mole fraction of CO_2 in the room at time t

W = weight of fruit (kg)

V = room void volume (m^3)

R = respiration rate of fruit (m^3 of CO_2 / kg hr)

RQ = respiration quotient (moles of CO_2 / moles of O_2)

t = time (hrs)

Room void volume can be calculated by room volume minus fifty-five percent, which is the usual part of the total bin volume occupied by fruit and wood (Adre and Hellickson, 1995).

The change of CO_2 concentration as a function of time multiplied by volume can be determined with equation 31. The accumulation of carbon dioxide in the room equals to number of moles of carbon dioxide produced by the fruit minus the number of moles of carbon dioxide existing the room and that absorbed by hydrated lime.

Once the input data are known, simulations to predict the pulldown time of each CA room can be performed. The time required for the oxygen concentration in the CA room to change from the initial value at t = 0 to the set point was determined by numerical integration rountine with a step size of 0.5 hour.

The following input data are required for pulldown time simulations.

1. Zone or room number

2. Number of bins in zone
3. Storage volume
4. Starting pulldown time.
5. Fruit temperature at room closure.
6. Oxygen set point of zone (%)
7. Type of fruit (apples or pears)
8. Weight of lime present
9. Nitrogen purity of the air product stream (%)
10. Air product flow rate

When the user selects to start the membrane air seperation simulation from the 'CA Equipment' menu, the MBS section is loaded and displayed by the monitor. The display consists of two main parts: the user input field boxes and the command buttons. The input field boxes are used to accept, edit, and display zone information. The command buttons such as save, compute, and exit, are used to execute user requests.

A single zone calculation is initialed by clicking the 'Compute Each Zone' button. The event procedure shown in Figure 12 is begun. First, the selected zone number on the screen determines which zone will be computed. Next, the zone data are read. Given the data, the subroutine will execute other subroutines to obtain additional information needed to the solve the MBS equation. These parameters include weight of fruit, void volume, and absorption rate of the hydrate lime if present. Actual computation of the oxygen pulldown is calculated by calling two functions 'Compute hourly O_2 concentration in CA room' and 'Compute hourly CO_2 concentration in CA room'. Hourly heat introduced to the CA room by the atmosphere generating system is also calculated here.

Figures 13 and 14 illustrate function flow as described above. The functions use Runge-Kutta integration to determine oxygen and carbon dioxide concentrations. The oxygen level is then compared to the oxygen set point. When the level equals the specific set point, the sequence stops and returns the oxygen value to the subroutine in Figure 12. The result of the calculation is shown on the screen and written to a data file. The program then returns to the user ready mode. Computer calculation sequences for the ammonia fractionating burner and catalytic oxygen burner systems are the same as for the MBS.

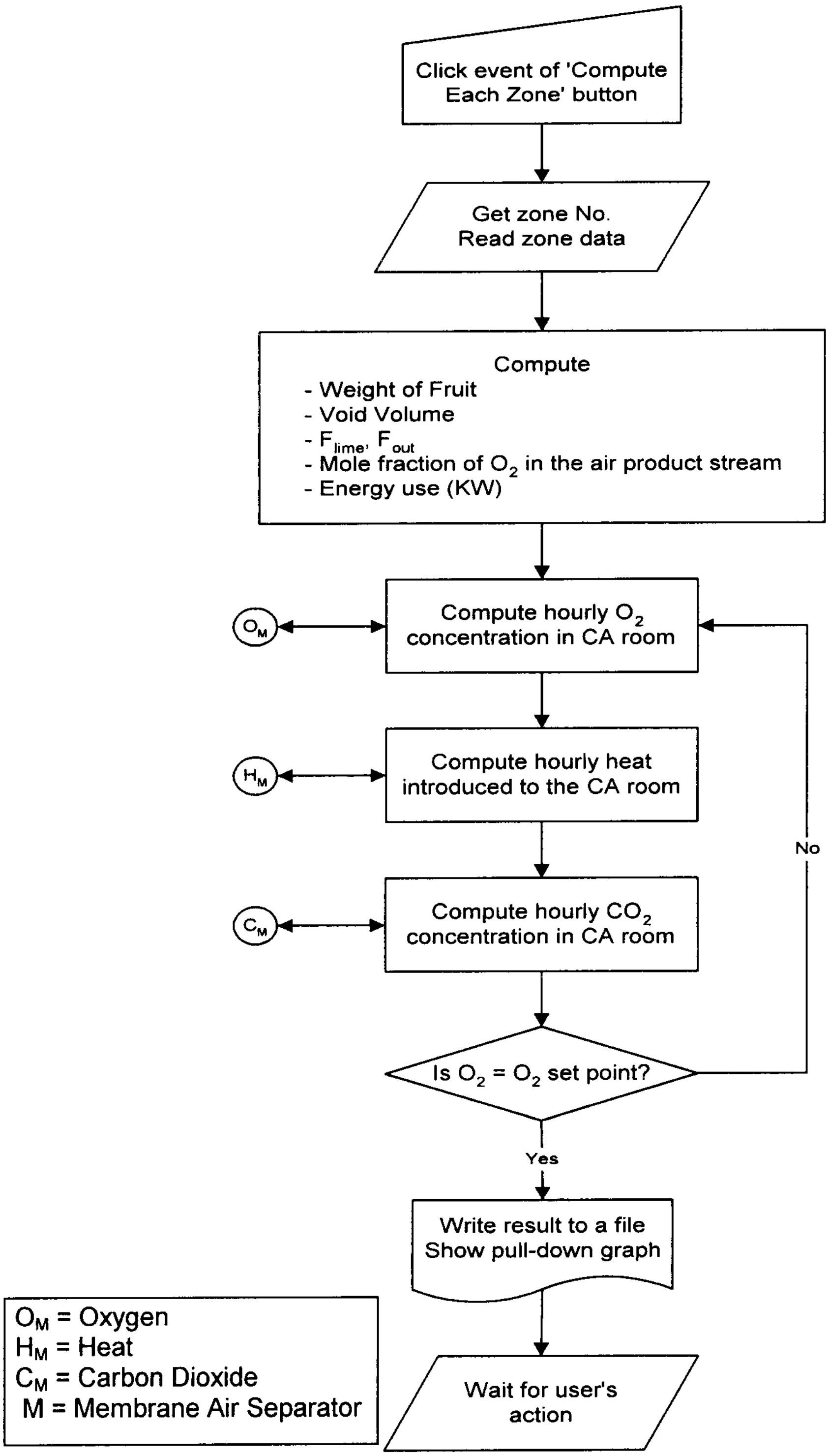

Figure 12. Click event sequence for “Compute Each Zone” selection.

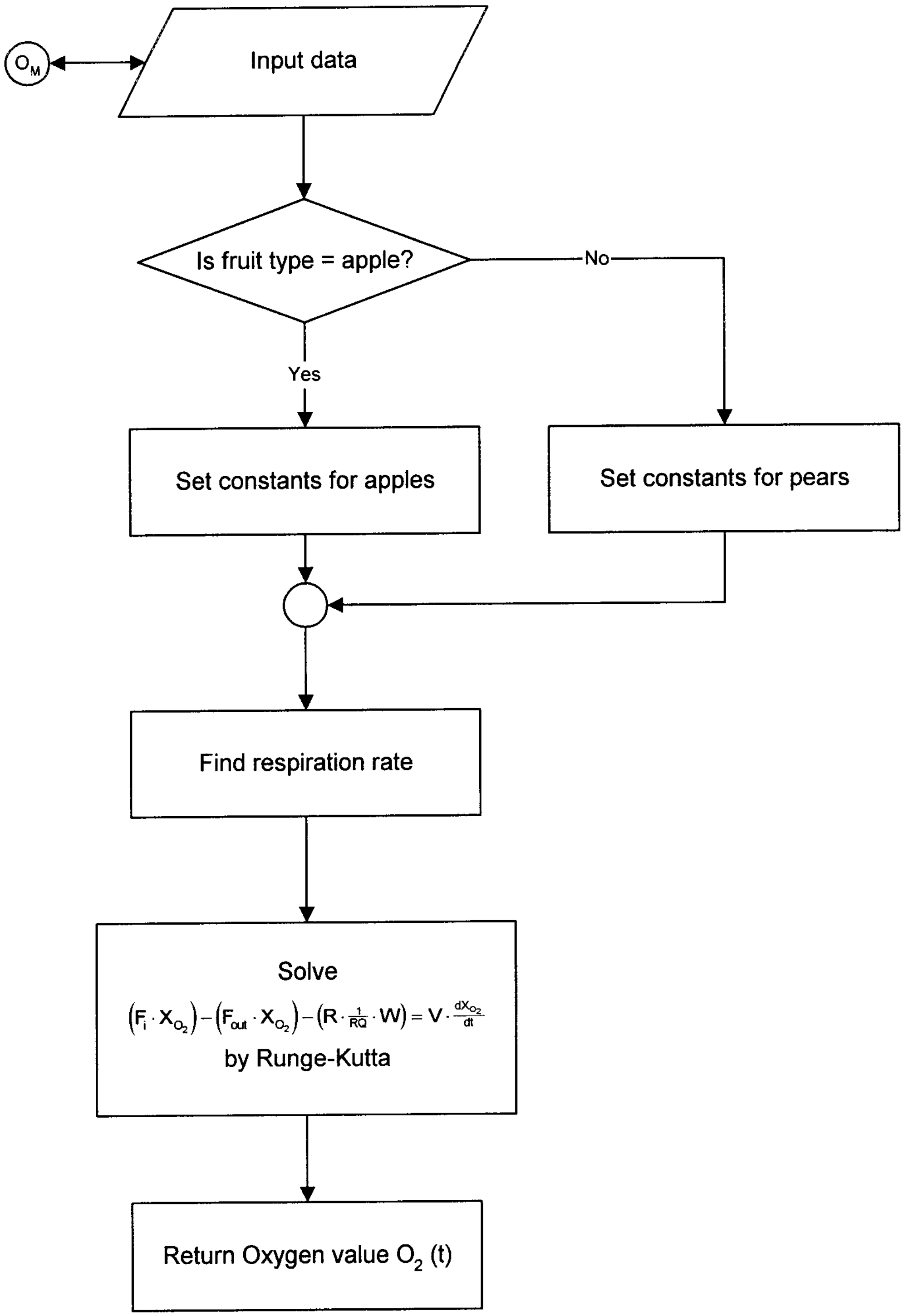

Figure 13. Function sequence to determine hourly O_2 level for a membrane air separator.

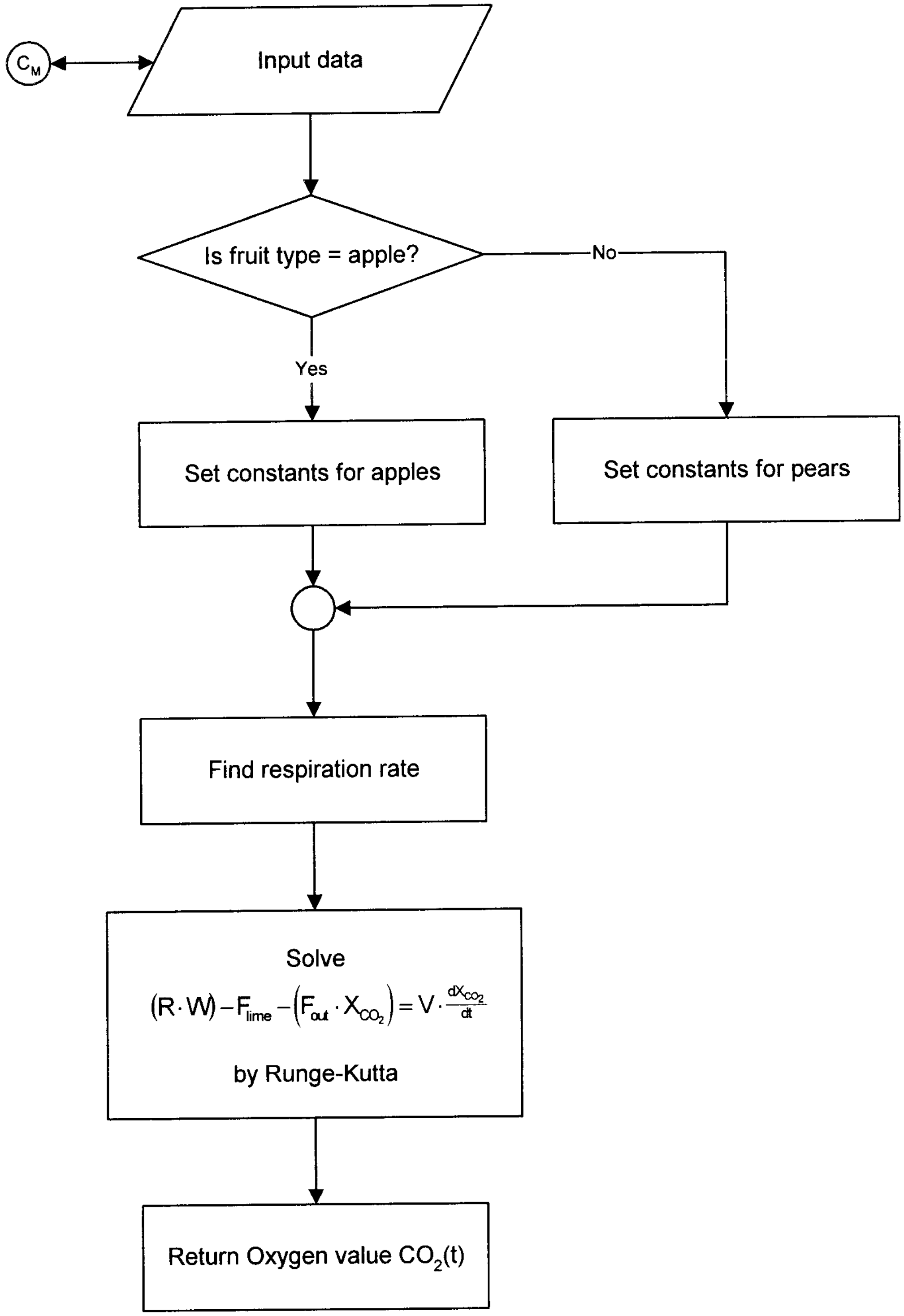

Figure 14. Function sequence to determine hourly CO_2 level for a membrane air separator.

3.3.2 Ammonia Fractionating Burner

Ammonia fractionating burners are recirculating systems. The rate of change in the amount of room oxygen and carbon dioxide were determined with equations 32 and 33, respectively. Under normal operation of an ammonia fractionating burner, a scrubber is also used if the amount of hydrated lime is insufficient to control carbon dioxide in the room. The number of moles of oxygen entering the room, less the number of moles of oxygen consumed by respiration and that removed by the ammonia fractionating burner, equals to the accumulation of oxygen in the room as illustrated in equation 33.

$$\left(F_i \cdot X_{O_2,air}\right) - \left(R \cdot W \cdot \frac{1}{RQ}\right) - \left(\eta \cdot F_{burner} \cdot X_{O_2}\right) = V \cdot \frac{dX_{O_2}}{dt} \qquad (32)$$

$$\left(F_i \cdot X_{CO_2,air}\right) + (R \cdot W) - F_{scrubber} - F_{lime} = V \cdot \frac{dX_{CO_2}}{dt} \qquad (33)$$

where

F_i = infiltrating air flow rate (m^3/hr.)

F_{burner} = rate of gas flow into the burner (m^3/hr)

$F_{scrubber}$ = rate of CO_2 removed by scrubber, if scrubbers are used (m^3/hr)

F_{lime} = rate of CO_2 absorbed by lime, if lime is present in the room

X_{O_2} = mole fraction of O_2 in the room at time t

X_{CO_2} = mole fraction of CO_2 in the room at time t

$X_{O_2,air}$ = mole fraction of O_2 in the ambient air, a constant of 0.21

$X_{CO_2,air}$ = mole fraction of CO_2 in the ambient air, a constant of 0.0003

RQ = respiration quotient, moles of CO_2 / moles of O_2

W = weight of fruit (kg)

V = room void volume (m^3)

R = respiration rate of fruit (ml /kg-hr)

t = time (hrs)

η = burner efficiency, assumed independent of O_2 concentration

In equation 33, the number of moles of carbon dioxide entering the room plus the amount produced by respiration minus the amount removed by the scrubber and lime is equal to accumulation of carbon dioxide in the room. Infiltrating air flow rate (F_i) from equations 32 and 33 can be described as rate of air replacing the volume loss. This replacement is to compensate for the volume lost from operating the Ammonia Fractionating Burner unit ($\frac{5.3}{15.8}\cdot\eta\cdot F_{burner}\cdot X_{O_2}$) plus rate of air to compensate for the carbon dioxide removed by the hydrated lime and/or a scrubber.

After the input data were entered, the pulldown time simulation was performed from initial value at t = 0 to the value of O_2 set point by numerical integration routine with a step size of 0.5 hour. Input data needed for the simulation are:

1. Zone or room number
2. The number of bins

3. Storage volume
4. Starting pulldown time
5. Fruit temperature when closing the room
6. Oxygen set point (%)
7. Type of fruit (apple or pear)
8. Weight of lime
9. Rate of oxygen removal
10. Air product flow rate

Pulldown time simulation for an ammonia fractionating burner can be represented by the following flowcharts; Figure 15, 16, and 17.

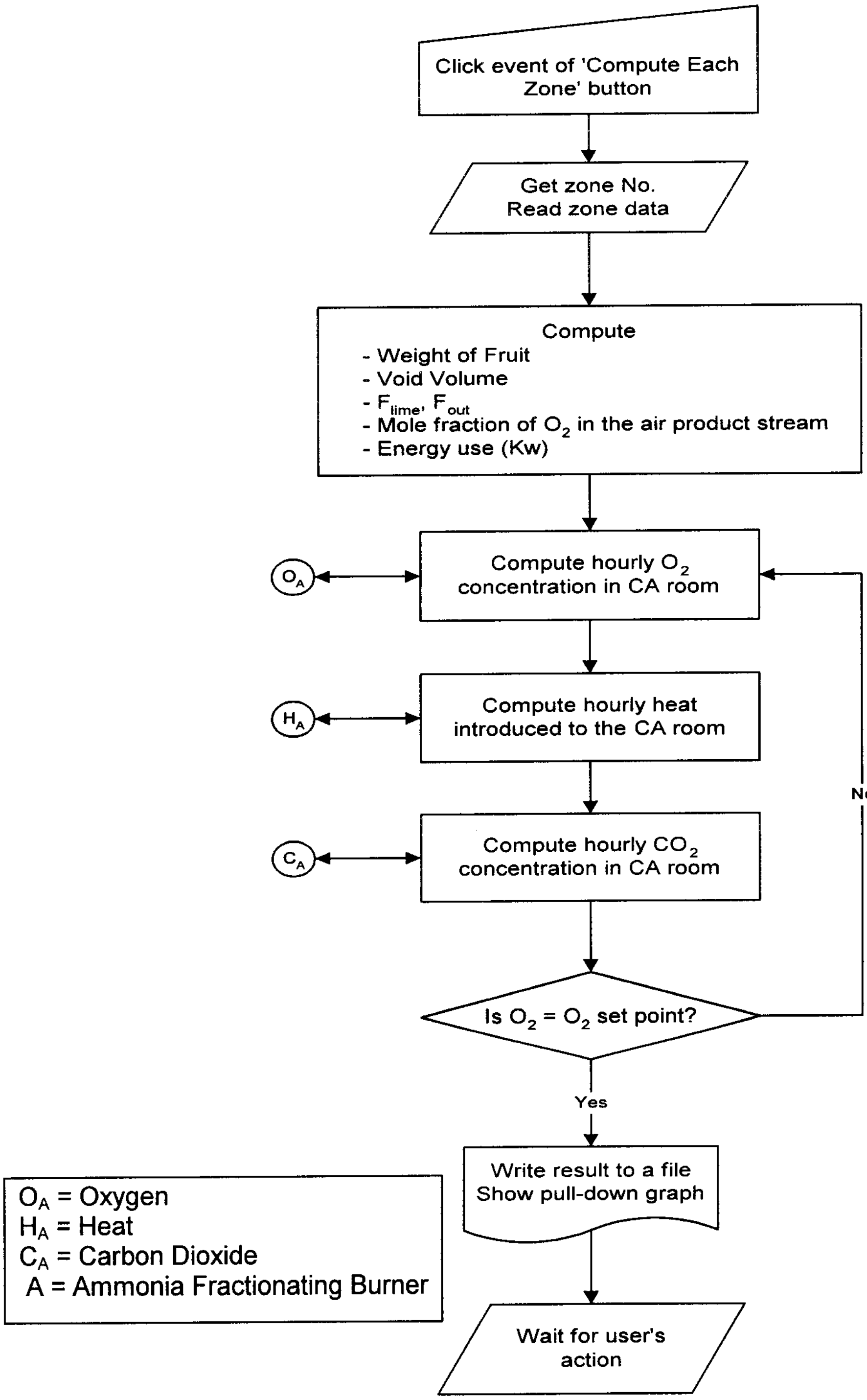

Figure 15. Click event sequence for "Compute Each Zone" selection.

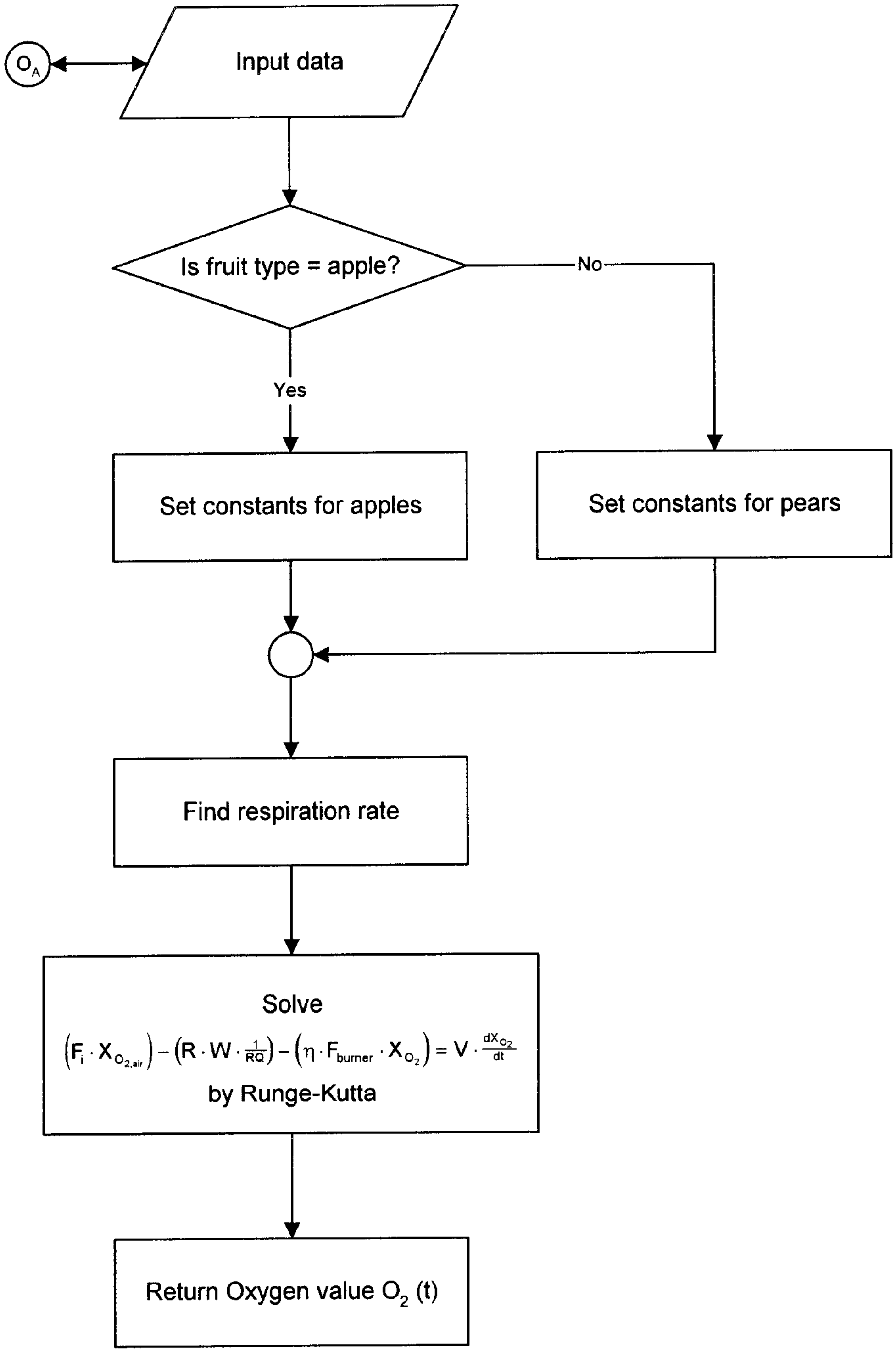

Figure 16. Function sequence to determine hourly O_2 level for an ammonia fractionating burner.

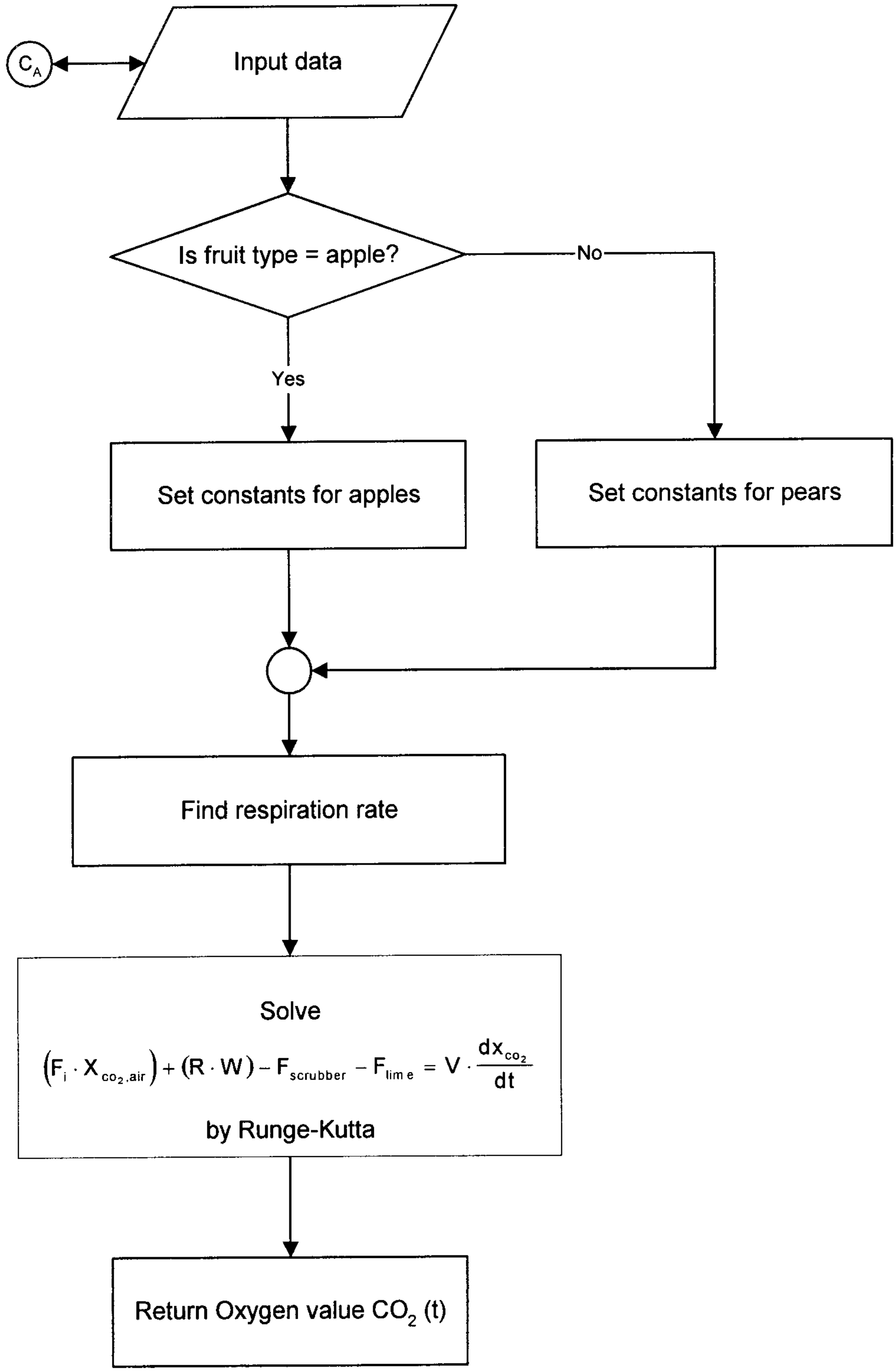

Figure 17. Function sequence to determine hourly CO_2 level for an ammonia fractionating burner.

3.3.3 Catalytic Oxygen Burner

Catalytic Oxygen Burners are operated in a recirculating mode as shown in Figure 4. The change in the number of moles of oxygen and carbon dioxide in the CA storage room, as a function of time, can be expressed as equations 34 and 35, respectively.

$$\left(F_i \cdot X_{O_2,air}\right) - \left(R \cdot \frac{1}{RQ} W\right) - \left(\eta \cdot F_{burner} \cdot X_{O_2}\right) = V \cdot \frac{dX_{O_2}}{dt} \tag{34}$$

$$\left(F_i \cdot X_{CO_2,air}\right) + (R \cdot W) + \left(\frac{24.4}{41} \cdot \eta \cdot F_{burner} \cdot X_{CO_2}\right) - F_{scrubber} - F_{lime} = V \cdot \frac{dX_{CO_2}}{dt} \tag{35}$$

where

F_i = infiltrating air flow rate (m^3/hr)

F_{burner} = rate of gas flow into the burner (m^3/hr)

$F_{scrubber}$ = rate of CO_2 removed by scrubber, if scrubber is used (m^3/hr)

F_{lime} = rate of CO_2 absorbed by lime, if lime is presented in the room

X_{O_2} = mole fraction of O_2 in the room at time t

X_{CO_2} = mole fraction of CO_2 in the room at time t

$X_{O_2,air}$ = mole fraction of O_2 in the ambient air, a constant of 0.21

$X_{CO_2,air}$ = mole fraction of CO_2 in the ambient air, a constant of 0.0003

RQ = respiration quotient, moles of CO_2 / moles of O_2

W = weight of fruit (kg)

V = room void volume (m^3)

R = respiration rate of fruit (ml/kg-hr)

t = time (hrs)

η = burner efficiency, assumed independent of O_2 concentration

Infiltration air flow rate (F_i) from both equations can be described as rate of air replaced per hour. This replacement is to compensate the volume lost from operating the COB unit ($\frac{16}{41} \cdot \eta \cdot F_{burner} \cdot X_{O_2}$) plus the air flow rate necessary to compensate for carbon dioxide removed by hydrated lime and/or a scrubber.

In Equation 34, the number of moles of oxygen entering the room, less the number of moles of oxygen consumed by respiration and that removed by the COB, equals to the number of moles of oxygen in the CA storage room with respect to time.

Equation 35 described the rate of change of number of moles of carbon dioxide in the room at each hour. This is equal to the number of moles of carbon dioxide entering the CA room plus the number of moles of carbon dioxide produced by the fruit and the COB unit during combustion minus the amount absorbed by lime and/or removed by a scrubber. Combustion combines 1.16 cubic meters (41 cubic feet) of oxygen with a pound of propane giving 0.69 cubic meters (24.4 cubic feet) of carbon dioxide. The time required for the oxygen concentration in the CA room to change from the initial value at t = 0 to the set point was found by numerical integration using a fourth-order Runge-Kutta routine with a step size of 0.5 hour.

The following input data are needed in the analysis.

1. Zone number
2. The number of bins
3. Storage volume
4. Starting pulldown time
5. Fruit temperature when closing the room
6. Oxygen set point (%)
7. Type of fruit (apples or pears)
8. Weight of lime
9. Rate of oxygen removal
10. Air product flow rate

Pulldown time simulation of a catalytic burner can be represented by the following flowcharts; Figures 18, 19, and 20.

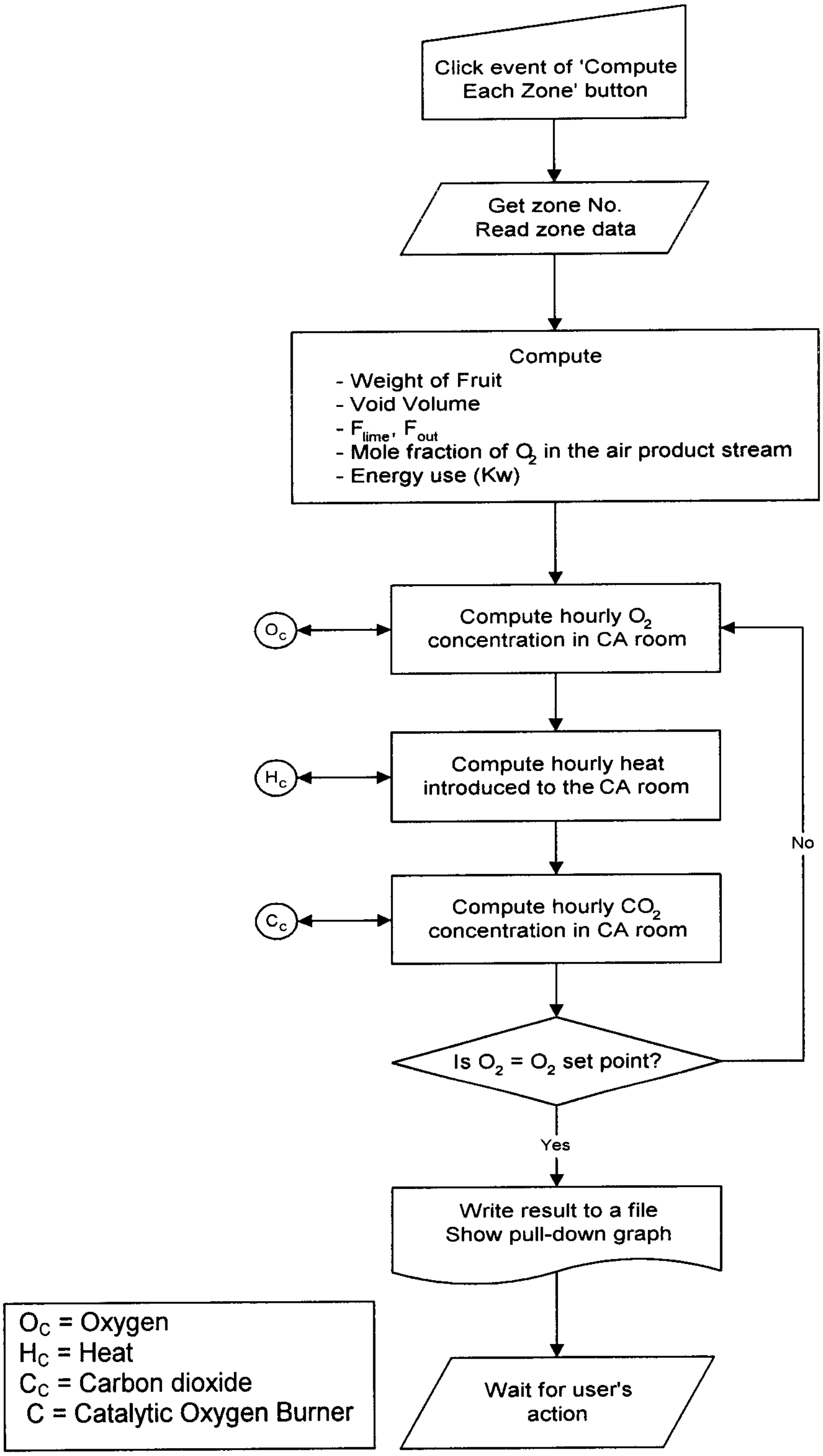

Figure 18. Click event sequence for “Compute Each Zone” selection.

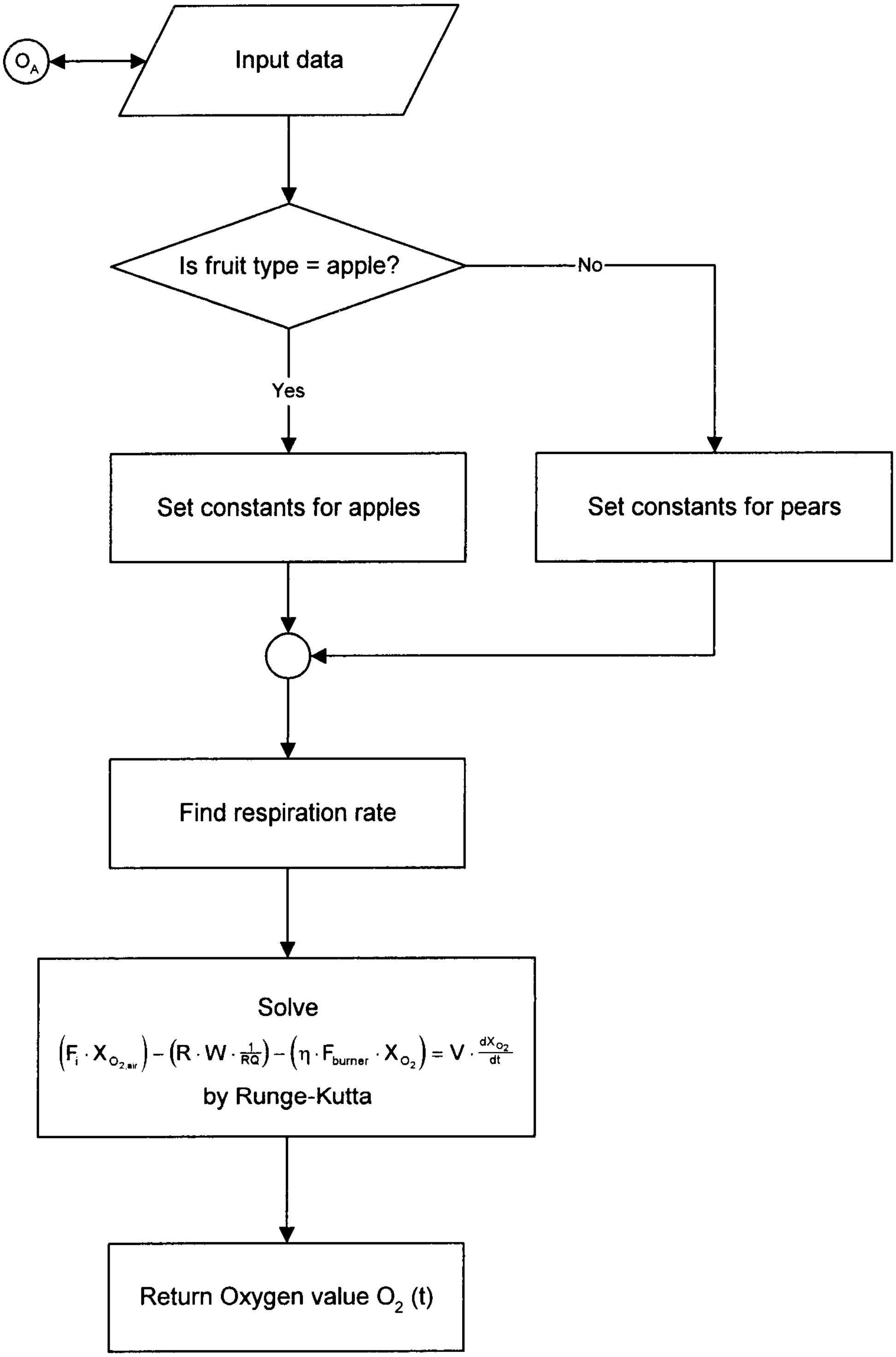

Figure 19. Function sequence to determine hourly O_2 level for a catalytic oxygen burner.

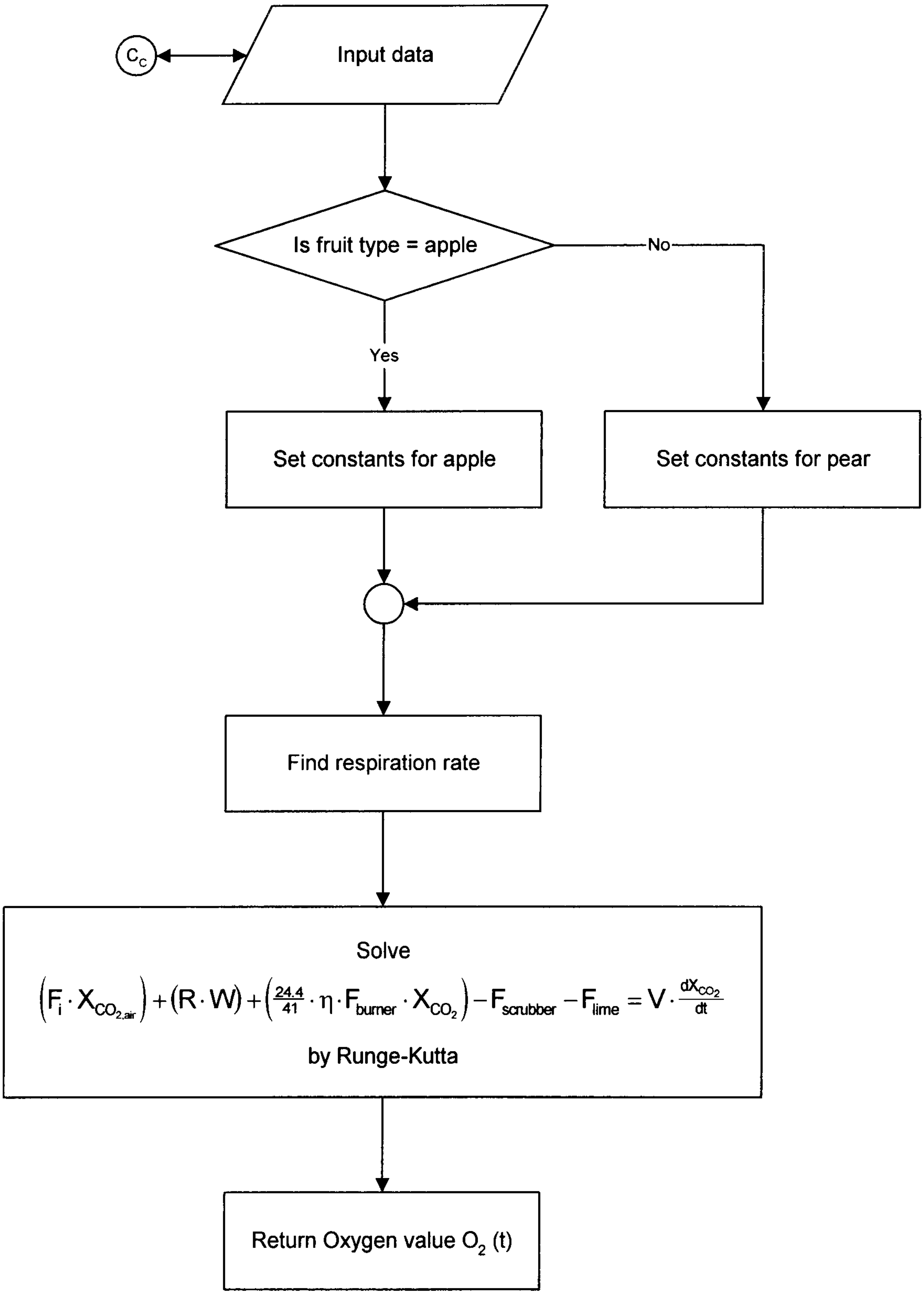

Figure 20. Function sequence to determine hourly CO_2 level for a catalytic oxygen burner.

3.4 REFRIGERATION LOAD DUE TO THE USE OF CA GENERATORS

Unlike RA rooms, CA rooms have additional heat introduced by the CA generator which becomes part of the refrigeration load. Air products from CA generators normally enter the room at a higher temperature than the air in the storage room. Therefore, it adds an extra load to the refrigeration system. Hourly effluent density and enthalpy can be calculated using equations 12 and 13, respectively. With a known dew point temperature, partial pressure of the water vapor in the room can be computed from equations 16 or 17, depending upon storage set temperature. Equation 14 was used to calculate the humidity ratio with the input data of air product pressure. Finally, the effluent heat gain was computed using equation 10.

To compensate for volume loss of air due to operation of the ammonia fractionating burner and COB, the pressure relief valve allows outside air to enter the CA room. This infiltrating air may also introduce additional heat. Hourly dry-bulb temperature and dew point were used to compute the density and the enthalpy of the infiltrating air by using equations 12 and 13, respectively. The relative humidity in the CA room was assumed, for the purpose of this simulation, to be constant at 90%. Saturation vapor pressure inside the storage space was computed by using either equation 16 or equation 17 depending on the desired storage temperature. Then the infiltrating air heat gain can was calculated using equation 10.

After the constant relative humidity inside storage space was assumed, and saturation water pressure was computed, equation 15 was used to compute indoor air partial water vapor pressure. Equation 14 was used to compute the humidity ratio of the refrigerated air. Refrigerated air density and enthalpy were calculated by using equations 12 and 13, respectively. The following input data were also needed for computation:

1. Air product temperature
2. Air product pressure
3. Dew point temperature of air product

Figures 21, 22, and 23 show the heat functions of the membrane air separator, the catalytic oxygen burner, and the ammonia fractionating burner, respectively. Each function is called by the zone calculation subroutine. The function returns the hourly values of the heat introduced into the CA room. First, the input is passed from the calling routine. Then, another sub-function is used to retrieve input values, dry-bulb and dew point temperatures, from a weather data file. After collecting all necessary data input, the heat function uses these input data to invoke sub-functions to find infiltrating air enthalpy, refrigerated air enthalpy, effluent enthalpy, infiltrating air density, refrigerated air density, and effluent air density. The results from the sub-functions are then used to calculate the rate of heat production. Finally, the heat value is assigned to the function name to return to the calling zone calculation subroutine.

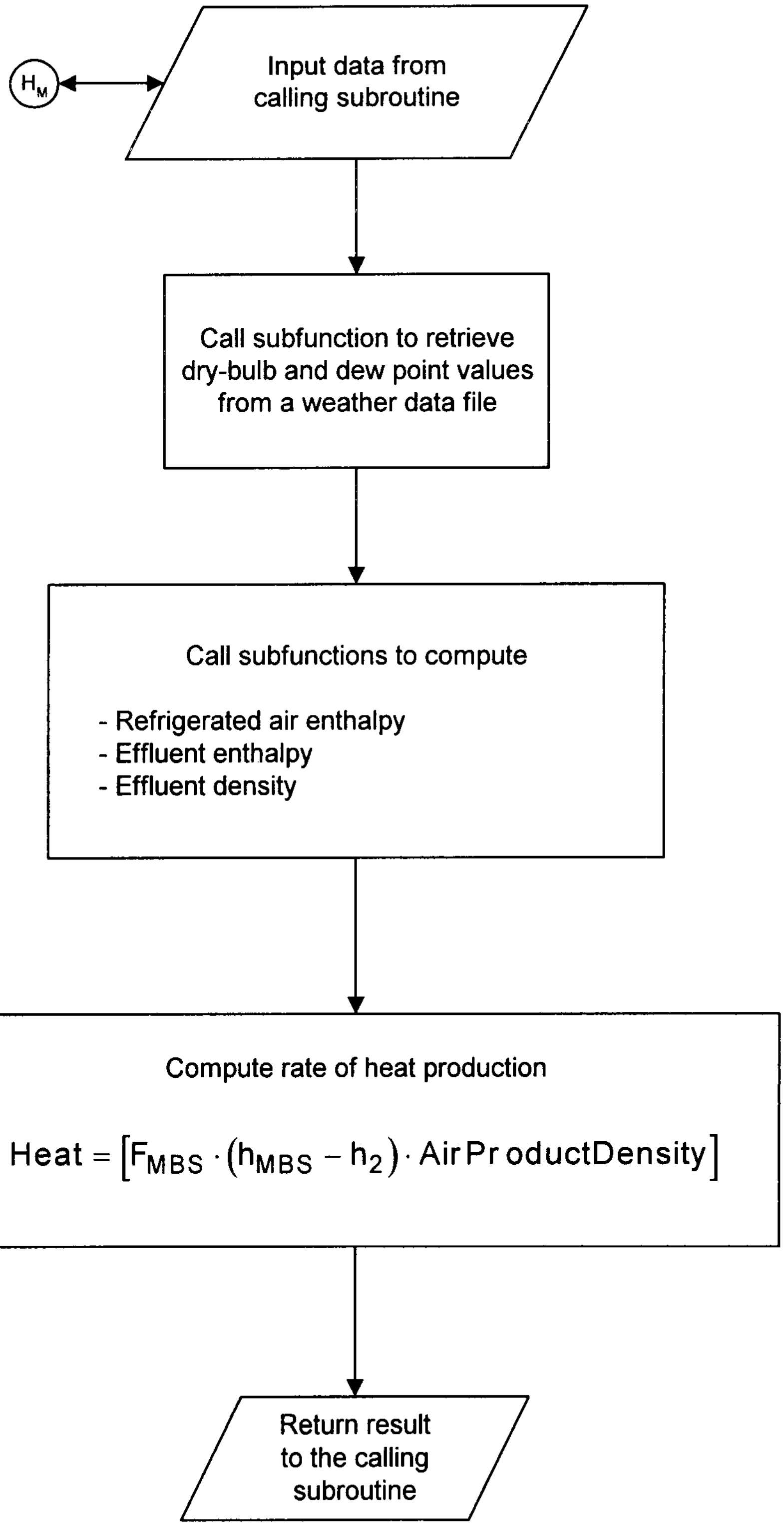

Figure 21. The membrane air separator heat function sequence.

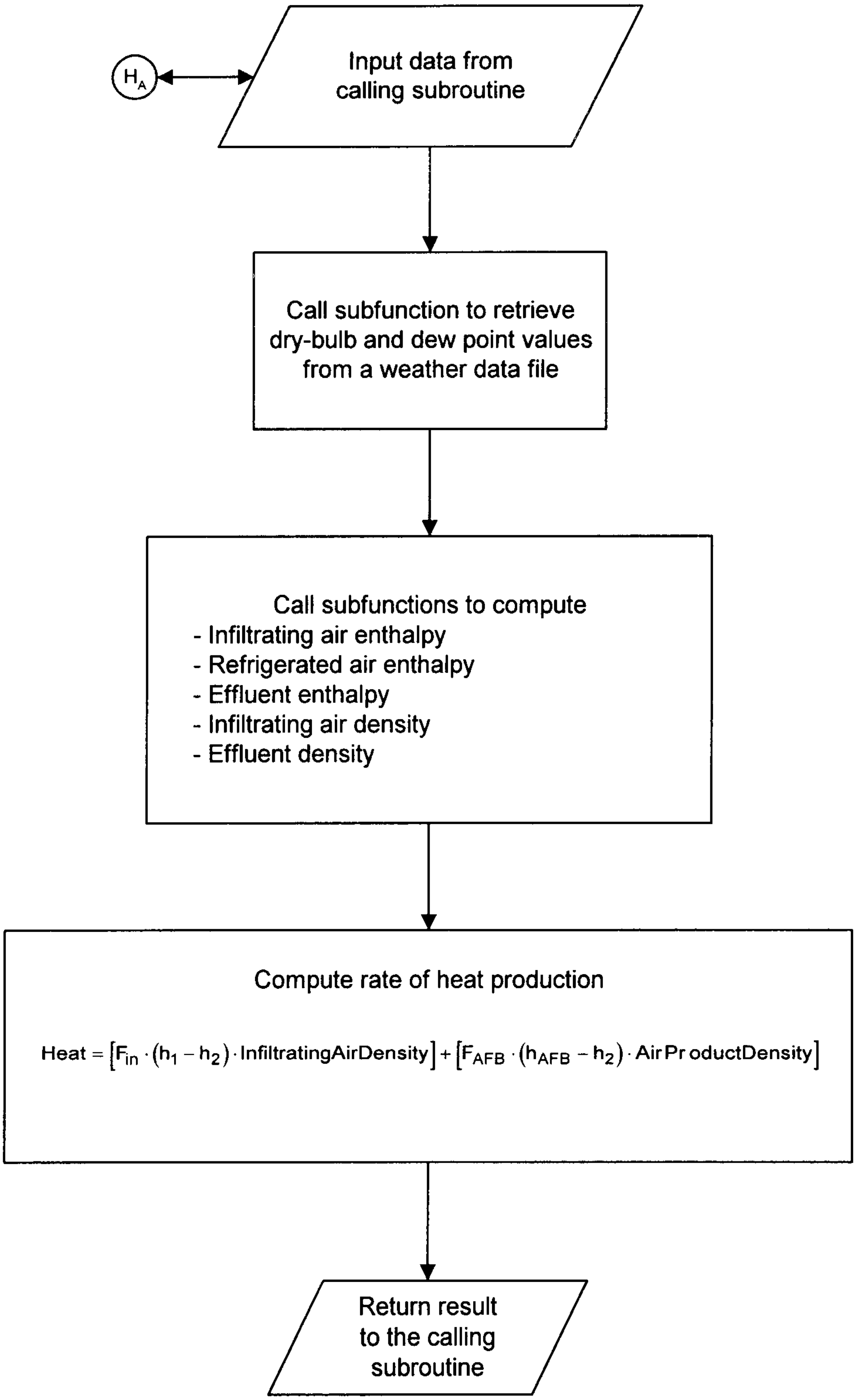

Figure 22. The ammonia fractionating burner heat function sequence.

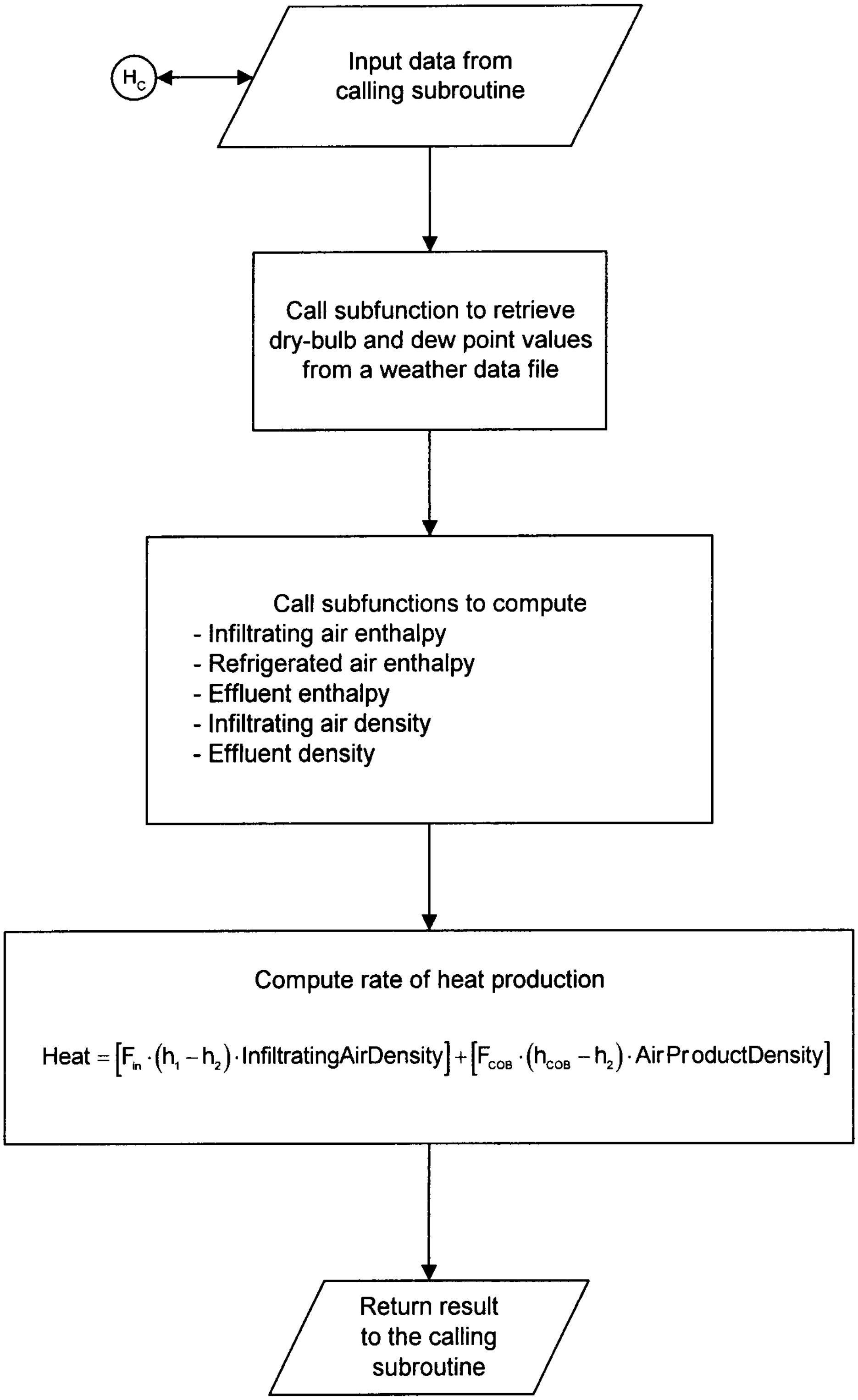

Figure 23. The catalytic oxygen burner heat function.

3.4 CONTROLLED ATMOSPHERE EQUIPMENT ENERGY USE

The hourly total energy use by the CA equipment is the sum of energy used by the atmosphere generators and scrubbers in a storage building. The hourly electrical energy use of the CA equipment is calculated by using:

$$E = \sqrt{3} \cdot V \cdot I \cdot \cos\theta \tag{35}$$

This equation can be used for a balanced 3-phase load.

Where

E = Hourly electrical energy use (watts)

V = Voltage (volts)

I = Line current (amperes)

$\cos\theta$ = Power factor

The hourly electrical energy use of motors can be computed by

$$E_m = \frac{0.746 \cdot Hp \cdot 100}{\eta} \tag{36}$$

Where

E_m = Hourly electrical energy use of motor (watts)

Hp = Horse power rating of specific pump

η = Motor efficientcy (%)

The following are a list of the input data required to determine the additional heat introduced to a CA room:

1. Make, model, voltage, and ampere of the CA generators and scrubber.
2. Make, model, motor size, and motor efficiency of the pumps.
3. Carbon dioxide removal rate of the scrubber.

Figure 24 illustrates how to incorporate the calculation results of the hourly energy use of the CAS program to those of the FruStRES program.

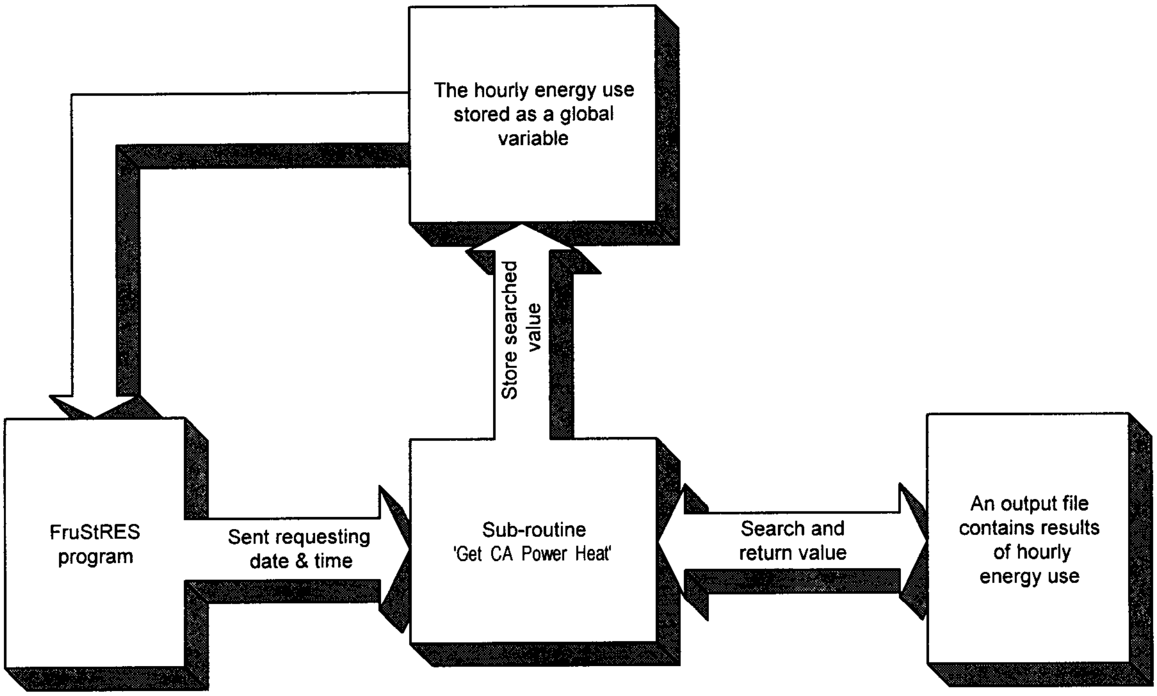

Figure 24. The *FruStRES* (**Fru**it **S**torages **A**mmonia **R**efrigeration **E**nergy **S**imulation) program calling a sub-routine 'Get CA Power Heat' to search for hourly energy use.

First, an output file of hourly energy use is created by clicking 'compute all zones' button of the CAS program. A calculation output file of the CAS program will include the hourly energy use.

Next, the FruStRES program accesses the output file by calling the subroutine 'Get CA Power & Heat' (As the name implies, the subroutine is also used to retrieve the results of the hourly heat introduced to the CA room). Given the date and time, the sub-routine searches for a single value of energy use in the output file and places the value in the global variable. The FruStRES program, then, looks for the search result in the variable. Since the sub-routine returns a single value at a time, the code that invokes the sub-routine is put in the zone calculation loop inside the FruStRES program. This loop computes the heat load of the FruStRES hourly; therefore, the searched value will be added here hourly.

4. RESULTS AND DISCUSSION

The results of this research were based on equipment operation at the Duckwall-Pooley Fruit Company fruit storage warehouses. Simulation results include; fruit cool-down times, heat gained due to operation of CA generation equipment, energy consumption of three types of CA generation systems (a membrane air separator, an ammonia fractionating burner, and a catalytic oxygen burner). Pulldown time data for the membrane air separator and catalytic oxygen burner were obtained from operation of these systems during the 1995-96 fruit storage season. Data for the ammonia fractionating burner was obtained from operation during the 1993-94 storage season.

Tables 3, 5, and 7 list operating dates, type and variety of fruit (apples or pears), stored in each CA room using a membrane air separation system (Van Horn cold storage), a catalytic oxygen burner (Odell cold storage #1), and an ammonia fractioning burner (Odell cold storage #2). The pulldown time of each CA room was predicted by running the simulation using the same conditions as during actual operation. The average fruit pulp temperature prior to room closing used in the simulation was 0 ^{0}C for apples and 3.3 ^{0}C for pears. Normally, rooms are filled with fruit as quickly as possible. However, apple rooms commonly require 5-7 days to fill in the Hood River area. By the time the room is closed and atmosphere generation commences, the apples have cooled to near the room set point. Room filling time for pears is typically three days. Therefore, the average pear temperature before room closing was higher than the average

Room	Closing Date	Fruit Type	Fruit Variety
CA1	10/17/95	apples	Newtown
CA2	10/30/95	apples	Braeburn
CA3	10/04/95	pears	D' Anjou
CA4	10/23/95	apples	Granny
CA5	09/28/95	apples	Golden
CA6	09/18/95	pears	D' Anjou
CA7	09/16/95	pears	D' Anjou

Table 3. Closing date, type of fruit, and fruit variety of CA rooms in Van Horn Cold Storage facility.

Room	Room oxygen set point(%)	Pulldown time (data) (hrs)	Pulldown time (model) (hrs)	MSE*
CA1	4.74	25	24	0.29(N=24)
CA2	2.70	72	40	8.16(N=40)
CA3	2.60	37	37	0.18(N=37)
CA4	1.70	70	71	0.13(N=70)
CA5	2.70	40	39	0.04(N=39)
CA6	2.70	40	37	0.07(N=37)
CA7	2.70	41	40	0.41(N=40)

* = Mean Squared Error

Table 4. Pulldown time (data versus model) of CA rooms in Van Horn Cold Storage facility.

Room	Operating Date	Fruit Type	Fruit Variety
CA1	09/21/95	pears	Bosc
CA2	10/04/95	pears	Bosc
CA3	10/11/95	pears	Bosc
CA4	09/14/95	pears	D' Anjou
CA5	09/17/95	pears	D' Anjou
CA6	09/29/95	pears	D' Anjou
CA7	09/25/95	pears	D' Anjou

Table 5. Closing date, type of fruit, and fruit variety of CA rooms in Odell Cold Storage #1 facility.

Room	Room oxygen set point(%)	Pulldown time (data) (hrs)	Pulldown time (model) (hrs)	MSE*
CA1	2.00	47	27.5	1.54(N=27)
CA2	3.50	22	22.0	0.19(N=22)
CA3	1.60	27	25.5	0.35(N=25)
CA4	0.94	57	61.5	0.04(N=57)
CA5	2.20	57	27.0	28.0(N=27)
CA6	0.98	71	54.5	17.3(N=54)
CA7	0.88	68	68.0	0.15(N=68)

* = Mean Squared Error

Table 6. Pulldown time (data versus model) of CA rooms in Odell Cold Storage #1 facility.

Room	Closing Date	Fruit Type	Fruit Variety
CA10	09/21/93	pears	D' Anjou
CA11	10/12/93	pears	D' Anjou
CA12	09/16/93	pears	Bartlett
CA13	10/01/93	apples	Red Delicious
CA14	09/27/93	pears	Bartlett
CA15	10/19/93	pears	D' Anjou
CA16	10/19/93	apples	Red Delicious
CA17	10/19/93	apples	Newtown
CA18	10/11/93	apples	Newtown
CA19	10/05/93	pears	D' Anjou
CA20	10/03/93	pears	D' Anjou
CA21	09/14/93	pears	D' Anjou
CA22	09/24/93	apples	Newtown
CA23	01/17/94	pears	D' Anjou
CA24	12/16/93	pears	D' Anjou

Table 7. Closing date, type of fruit, and fruit variety of CA rooms in Odell Cold Storage #2 facility.

Room	Room oxygen set point(%)	Pulldown time (data)-(hrs)	Pulldown time (model)-(hrs)	MSE*
CA10	2.30	38	38.0	0.03(N=38)
CA11	2.30	37	39.0	0.18(N=37)
CA12	2.10	42	40.0	0.45(N=40)
CA13	2.60	24	24.0	0.06(N=24)
CA14	2.89	29	29.0	0.77(N=29)
CA15	2.25	**	31.5	**
CA16	2.00	**	32.5	**
CA17	2.42	**	30.0	**
CA18	2.25	**	31.5	**
CA19	2.32	30	30.5	0.39(N=30)
CA20	2.25	**	32.5	**
CA21	2.25	**	31.5	**
CA22	2.25	**	31.5	**
CA23	2.70	30	26.5	0.71(N=26)
CA24	2.20	29	29.0	0.15(N=68)

* = Mean Squared Error   ** = no data available

Table 8. Pulldown time (data versus model) of CA rooms in Odell Cold Storage #2 facility.

apple temperature. Approximately 2.2 pounds of hydrated lime per bin of fruit were placed in each CA room as a supplement to other CO_2 scrubbing methods. Actual pull-down time data versus model predicted time for Van Horn Cold Storage, Odell cold storage #1, and Odell cold storage #2 are reported in Tables 4, 6, and 8, respectively. Mean Square Error (MSE) values of the data were calculated to indicate how well the model predicted the pulldown time of each CA generation system.

The nitrogen purging stream was set at 70.79 m^3 (2500 CFH) at 98% purity for simulation of the membrane air separation system. The pull-down time curves (data versus model) of CA1, CA2, CA3, CA4, CA5, and CA6 are illustrated in Figures 25 through 31, respectively. The pull-down curves and the MSE of all CA rooms except CA2 indicate that the model can accurately predict operation of membrane air separation. The model curve for CA2 departs from the data and the MSE is high compared to the other rooms. The reason of the difference is that, the nitrogen purity was adjusted during the establishment of the CA rooms, thus the curve of the data is not as smooth as the other CA curves. The model can not predict the pull-down accurately if the nitrogen purity is adjusted during the pull-down operation. Increasing nitrogen purity causes the nitrogen purge stream flow rate to be lower. In practice, most CA storages using membrane air separation to establish CA conditions do not set the oxygen set point level lower than 2% because a very high purity reduces the air product flow capacity dramatically. The flow capacity can be reduced to the point where it may not be practical to operate due to cost considerations.

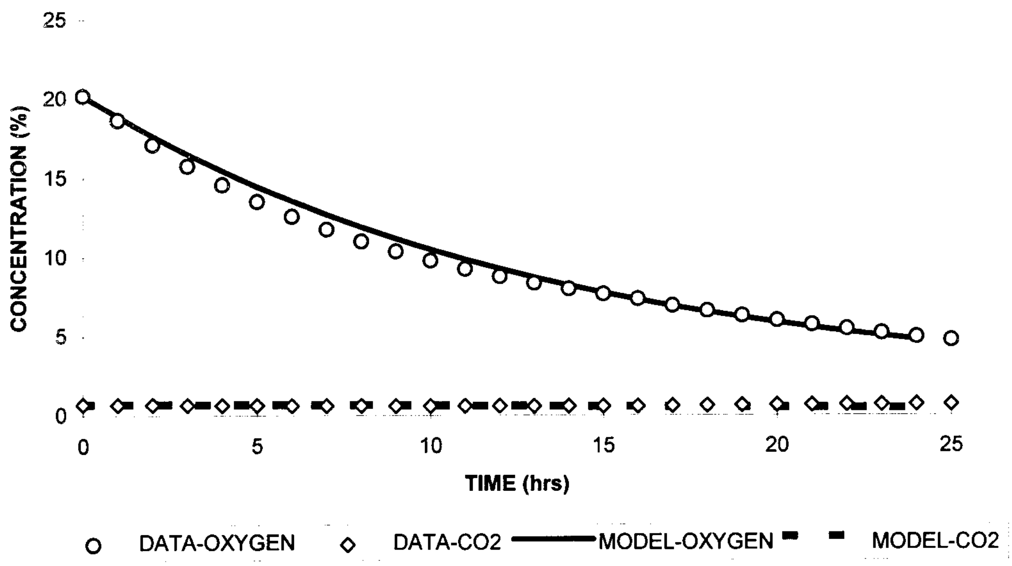

Figure 25. Pulldown curve of CA1 using the membrane air separation system in the Van Horn Cold Storage facility.

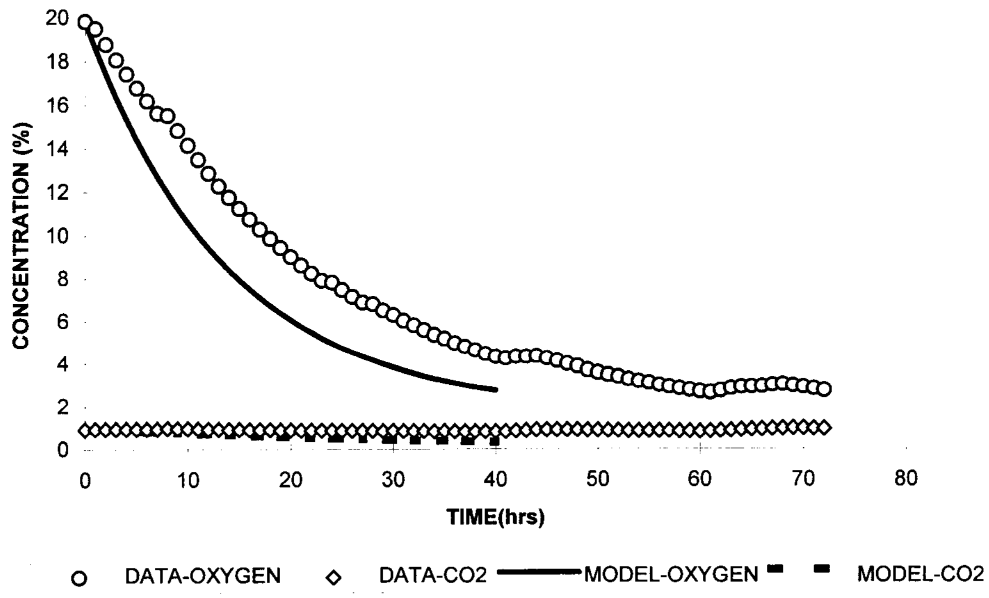

Figure 26. Pulldown curve of CA2 using the membrane air separation system in the Van Horn Cold Storage facility.

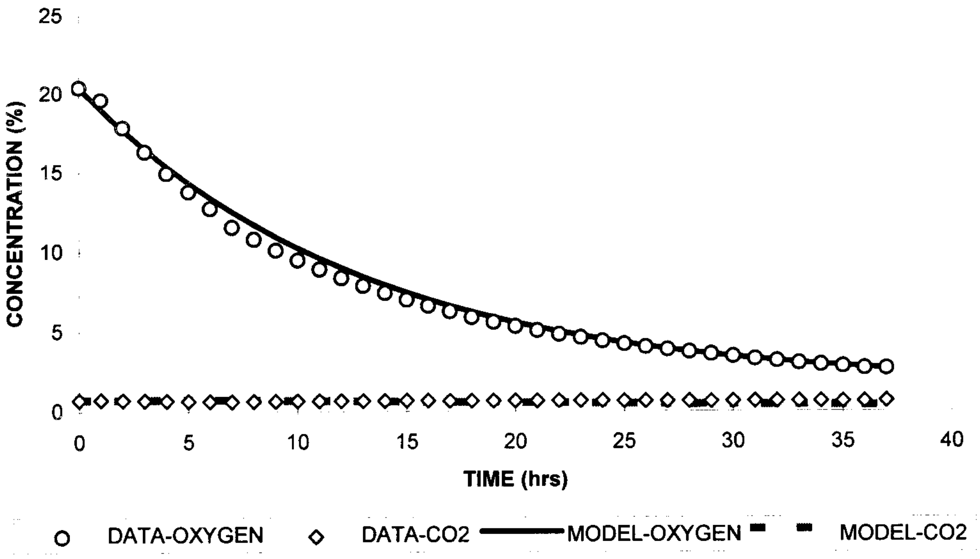

Figure 27. Pulldown curve of CA3 using the membrane air separation system in the Van Horn Cold Storage facility.

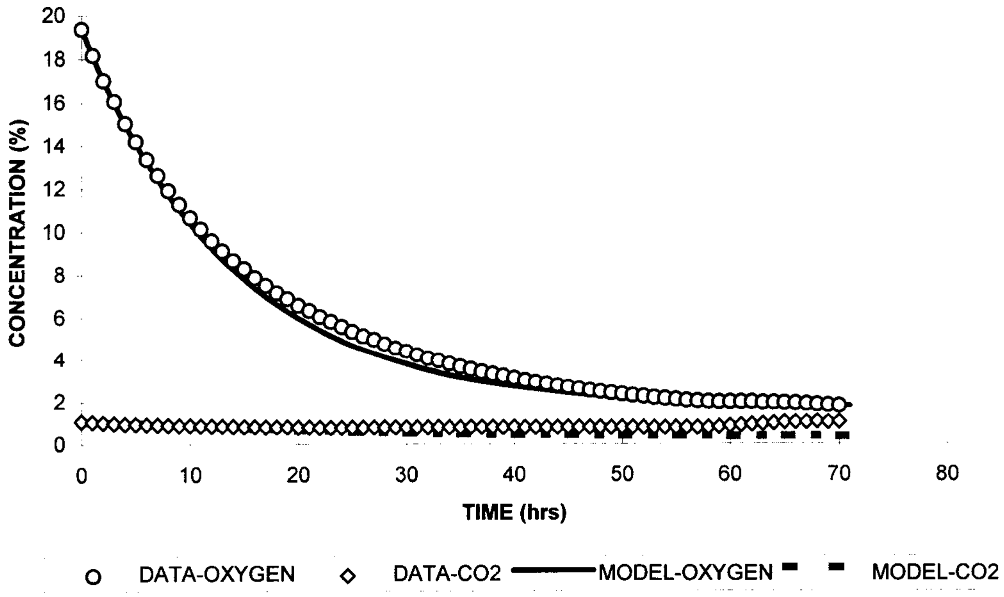

Figure 28. Pulldown curve of CA4 using the membrane air separation system in the Van Horn Cold Storage facility.

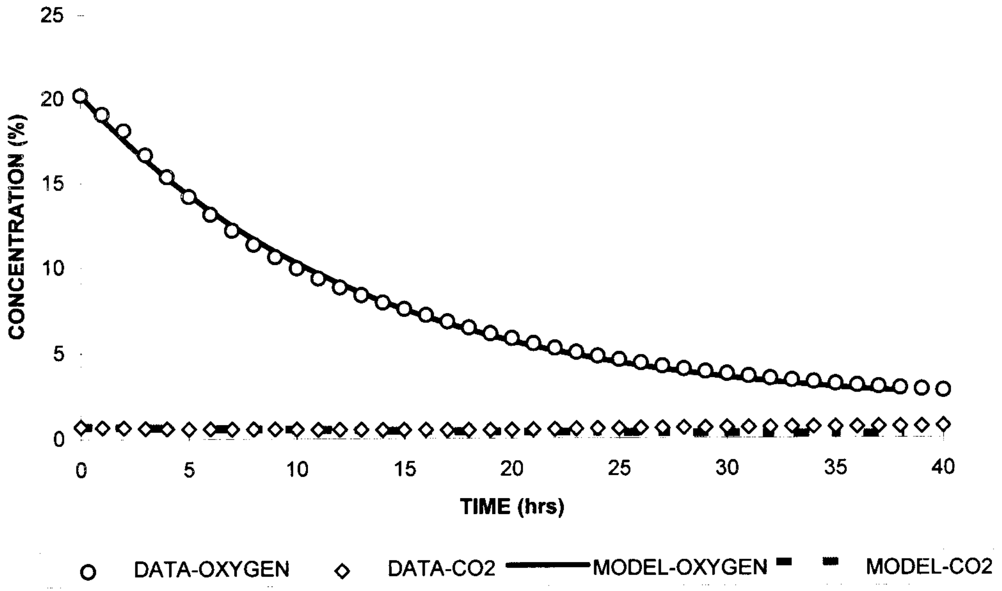

Figure 29. Pulldown curve of CA5 using the membrane air separation system in the Van Horn Cold Storage facility.

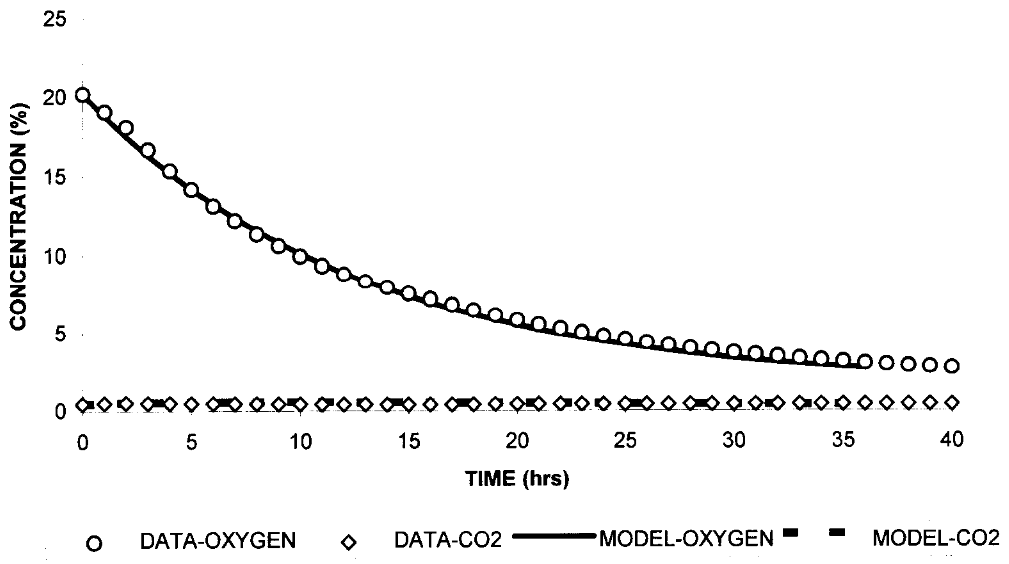

Figure 30. Pulldown curve of CA6 using the membrane air separation system in the Van Horn Cold Storage facility.

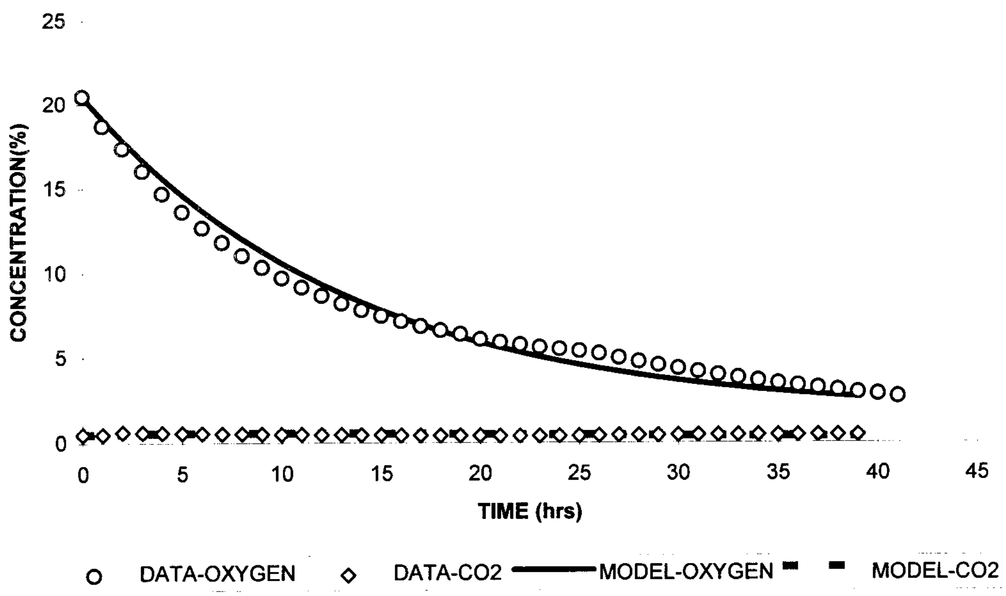

Figure 31. Pulldown curve of CA7 using the membrane air separation system in the Van Horn Cold Storage facility.

Figures 32 through 38 illustrate the pull-down time curves of CA1, CA2, CA3, CA4, CA5, CA6, and CA7 by using the catalytic oxygen burner in Odell Cold Storage #1. The air flow rate flows to the converter was 390.77 m^3 (13,800 cuft/hr). The conversion efficiency of the catalytic oxygen burner was determined experimentally by measuring the incoming and outgoing oxygen concentration of the gas stream through the burner. The efficiency is:

$$\eta = 1 - \frac{C_2}{C_1} \tag{37}$$

C_1 = oxygen concentration at the entrance

C_2 = oxygen concentration at exit

The efficiency of the catalytic oxygen burner used in the simulation was 0.65.

Since the catalytic oxygen burner produced CO_2, a scrubber was also used during the pull-down period to removed excess CO_2. The pull-down curves and the MSE of CA2, 3, 4, and 7, compared to the measured data (Figures 33, 34, 35, and 38) suggest that the model can accurately predicted pull-down times for a catalytic oxygen burner. Comparison of simulated data and measured data of CA1, 5, and 6 (Figures 32, 36, and 38) show that the actual pulldown time for decreasing the oxygen concentration in those rooms were much longer than the theoretical time calculated by the model. The difference may have been caused by the oxidation temperature was not maintained correctly thus leading to incomplete conversion of oxygen. Another possibility was that the oxygen conversion in the catalyst bed was higher at the beginning than the end of the

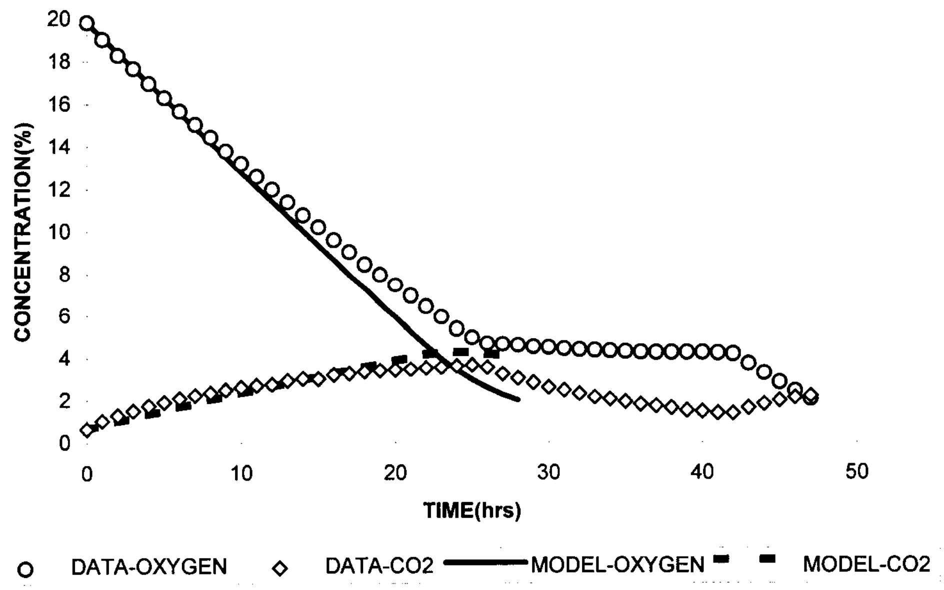

Figure 32. Pulldown curve of CA1 using the catalytic oxygen burner in the Odell Cold Storage #1 facility.

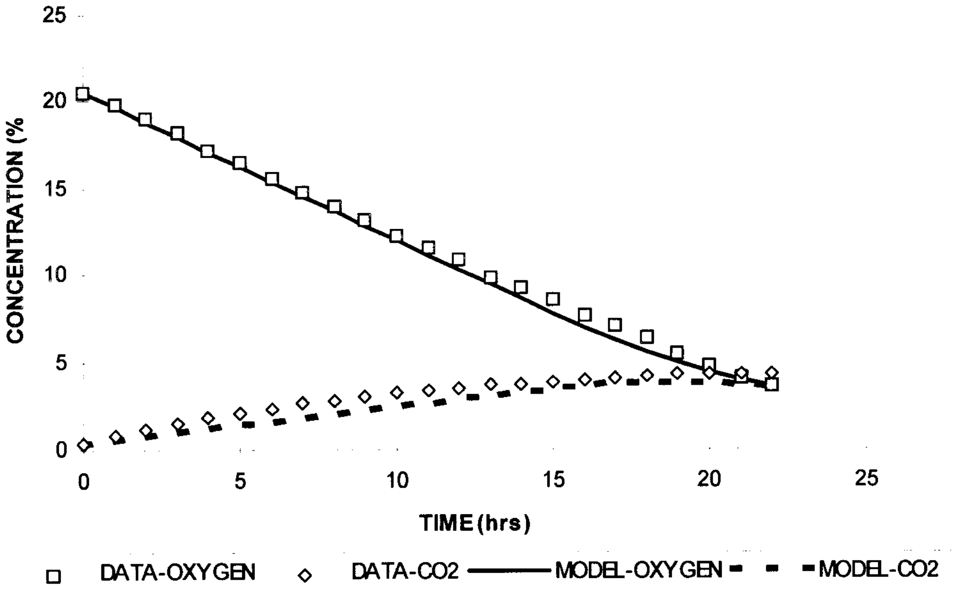

Figure 33. Pulldown curve of CA2 using the catalytic oxygen burner in the Odell Cold Storage #1 facility.

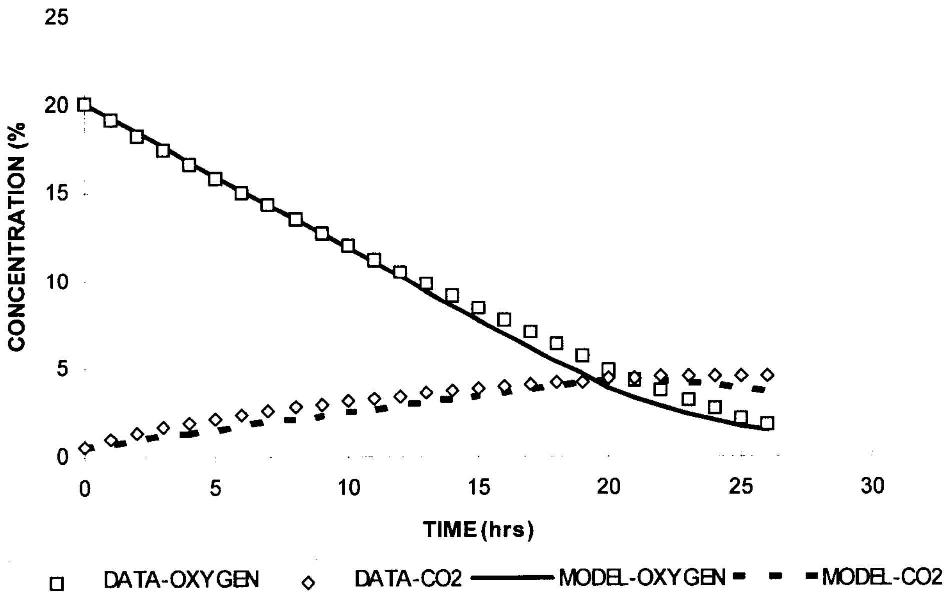

Figure 34. Pulldown curve of CA3 using the catalytic oxygen burner in the Odell Cold Storage #1 facility.

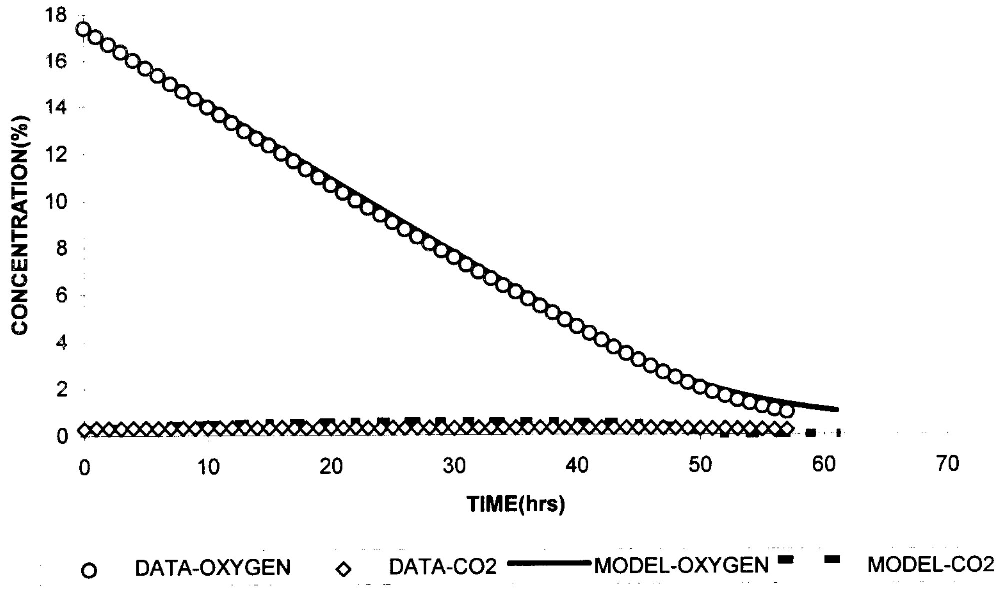

Figure 35. Pulldown curve of CA4 using the catalytic oxygen burner in the Odell Cold Storage #1 facility.

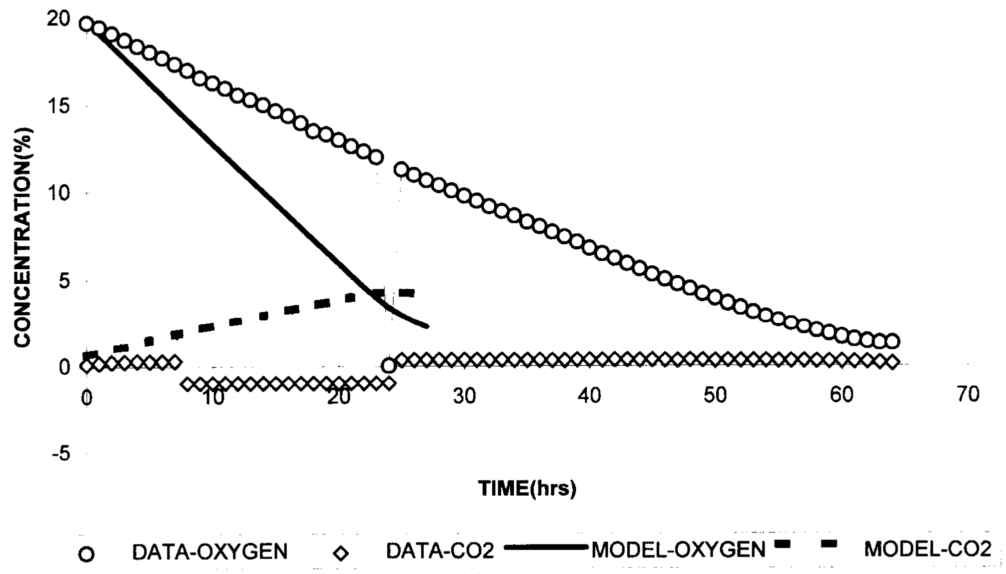

Figure 36. Pulldown curve of CA5 using the catalytic oxygen burner in the Odell Cold Storage #1 facility.

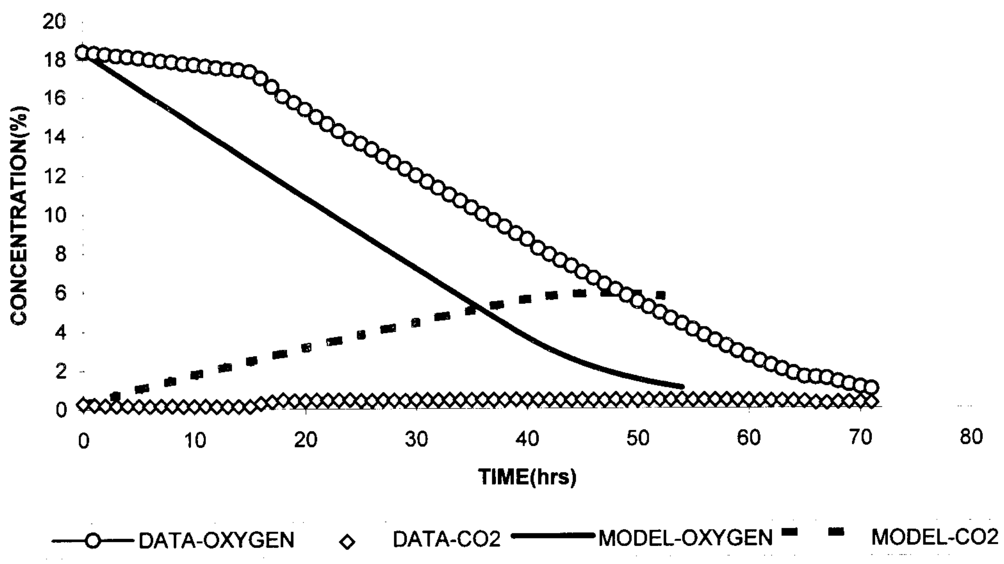

Figure 37. Pulldown curve of CA6 using the catalytic oxygen burner in the Odell Cold Storage #1 facility.

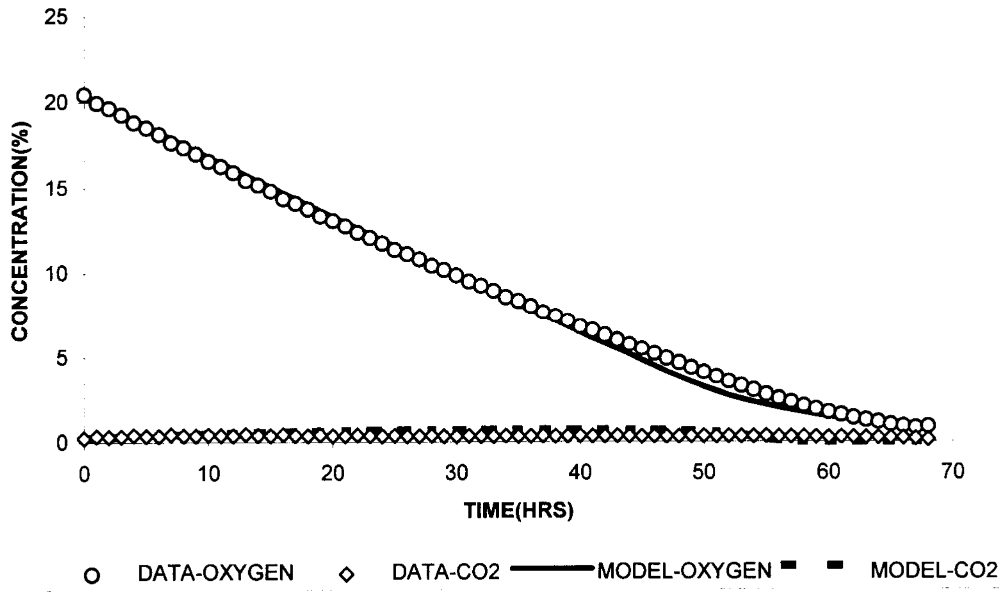

Figure 38. Pulldown curve of CA7 using the catalytic oxygen burner in the Odell Cold Storage #1 facility.

process. This can be explained by the fact that the rate of catalytic oxidation of oxygen (η) was lower at low concentrations of oxygen. The CO_2 measurement data in Figure 36 (CA5) was lower than 0% and one O_2 data point suddenly dropped to zero, indicating a malfunction of the oxygen and carbon dioxide analyzers.

Figures 39 through 46 display comparisons of pull-down curves of calculated and measured data when operating the ammonia fractionating burner in Odell Cold Storage #2 in CA10, 11, 12, 13, 14, 19, 23, and 24, respectively. The flow rate of air flow to the ammonia fractionating burner used in the simulation was 339.80 m^3 (12,000 cuft/hr). The conversion efficiency of the ammonia fractionating burner was also determined experimentally by measuring the incoming and outgoing oxygen concentration of the gas stream through the burner. The efficiency of the ammonia fractionating burner used in the simulation was 0.55. Mean squared error values for CA10, 11, 12, 13, 14, 19, 23, and 24 were shown in Table 7. The pulldown curves and MSE in all rooms indicate that the model can accurately predict pulldown times of an ammonia fractionating burner. However, the predicted oxygen concentration of most CA rooms established by the ammonia fractionating burner were lower than the recorded oxygen concentrations in the first 20 hours. Predicted values tended to catch up to recorded values from this point forward. This variation can be explained by the following reasons; the rate of oxygen conversion (η) was lower at low oxygen concentrations and temperature maintaining of the thermal plates during the operation was not consistent (Baskins, 1996).

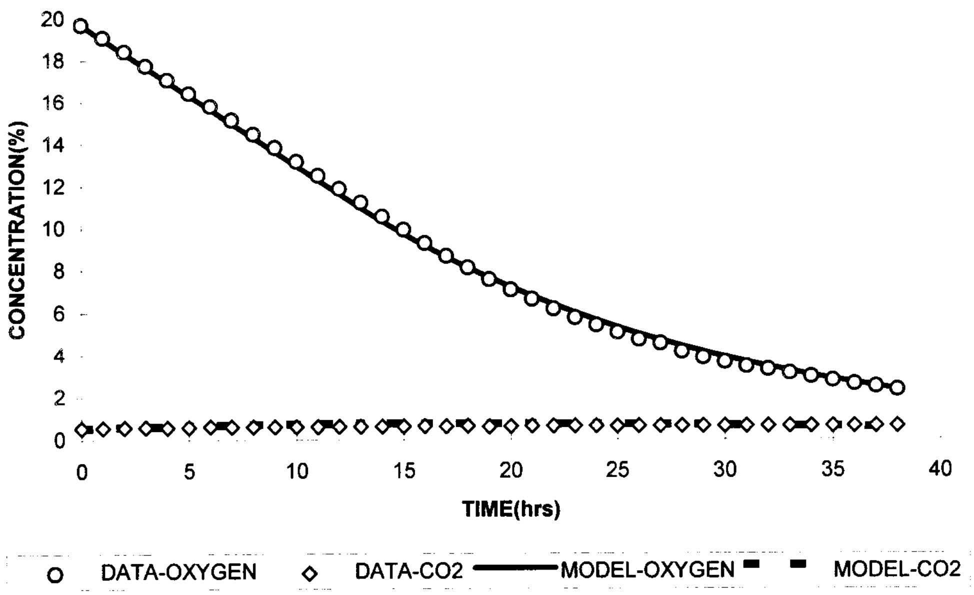

Figure 39. Pulldown curve of CA10 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

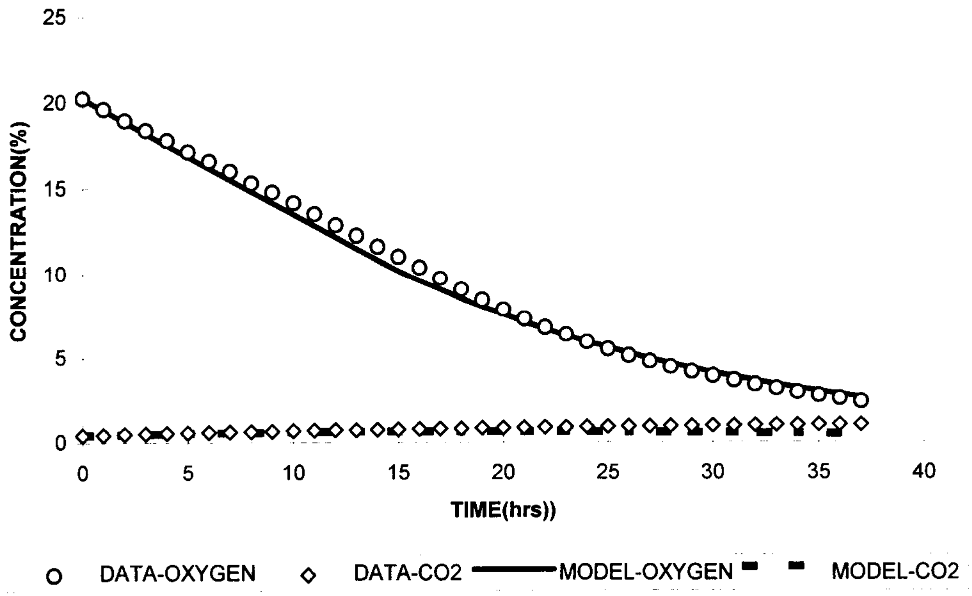

Figure 40. Pulldown curve of CA11 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

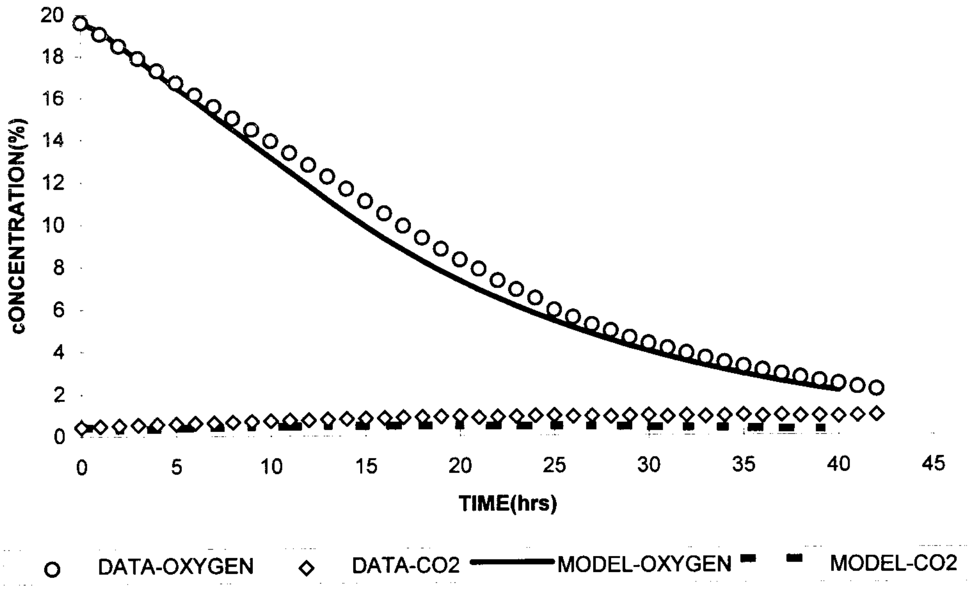

Figure 41. Pulldown curve of CA12 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

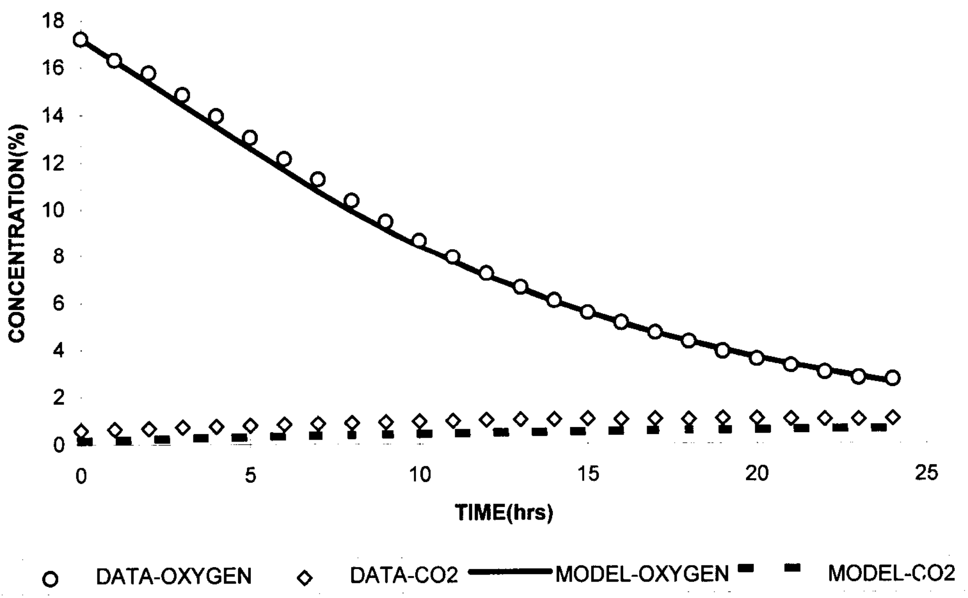

Figure 42. Pulldown curve of CA13 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

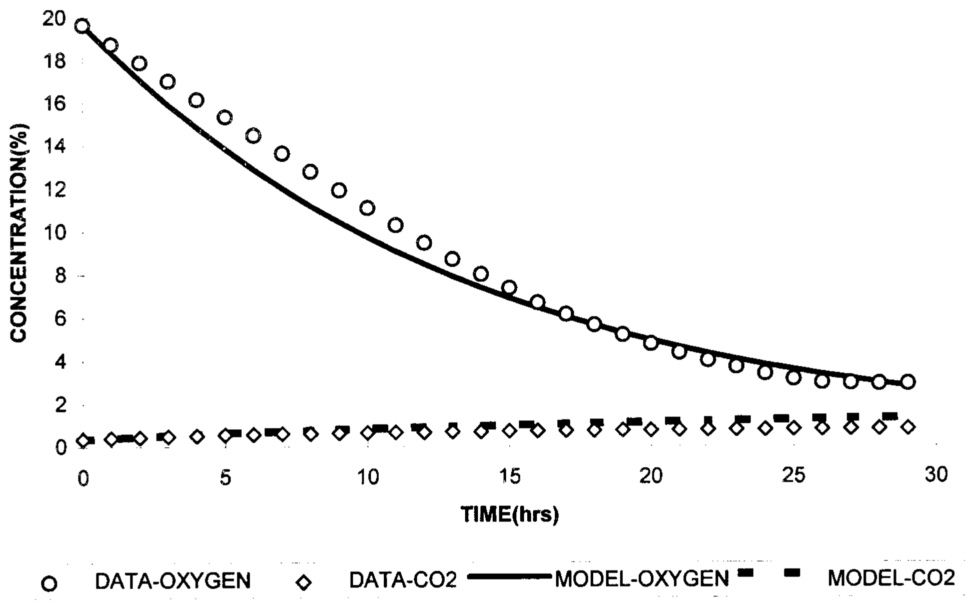

Figure 43. Pulldown curve of CA14 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

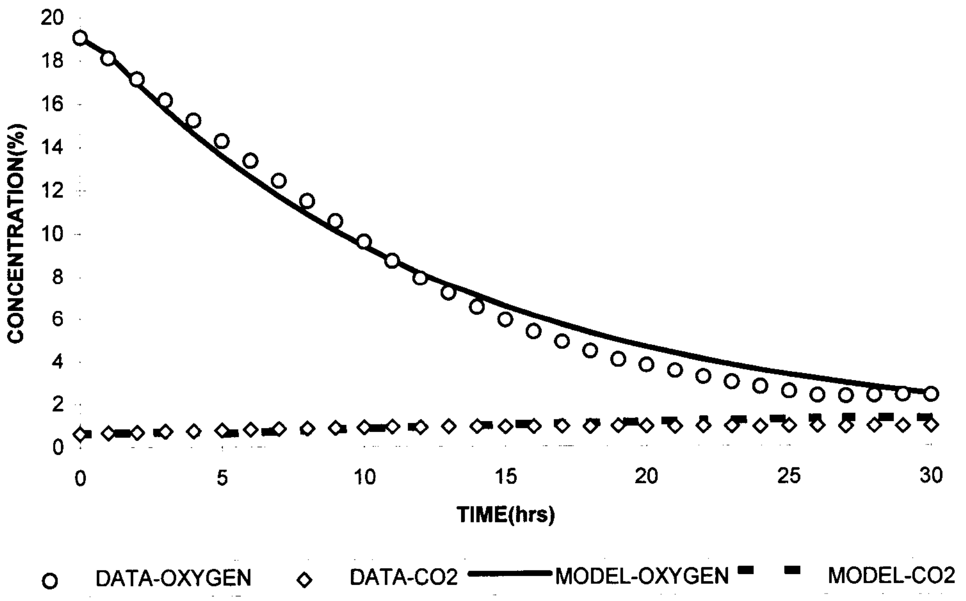

Figure 44. Pulldown curve of CA19 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

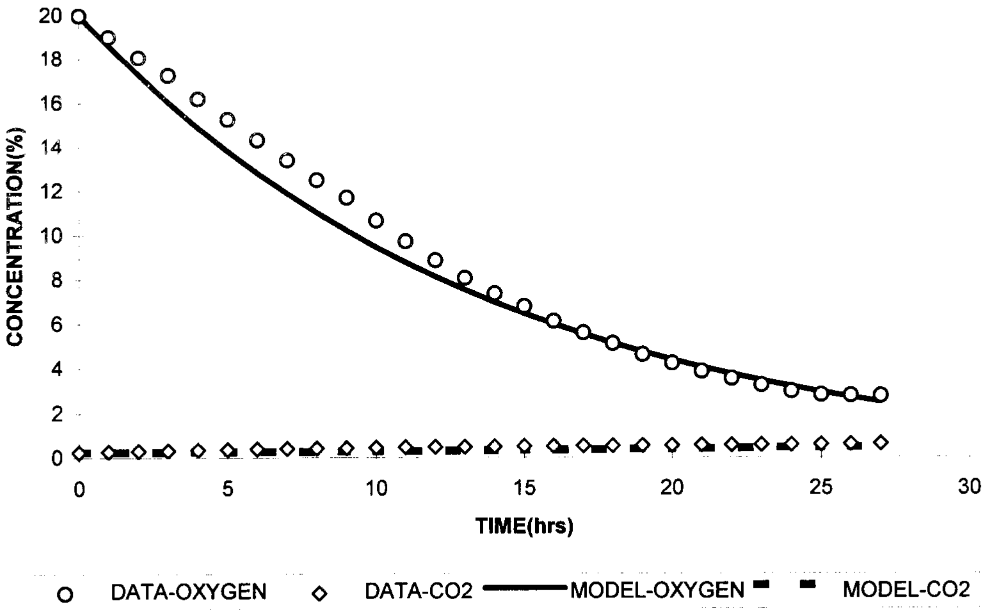

Figure 45. Pulldown curve of CA23 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

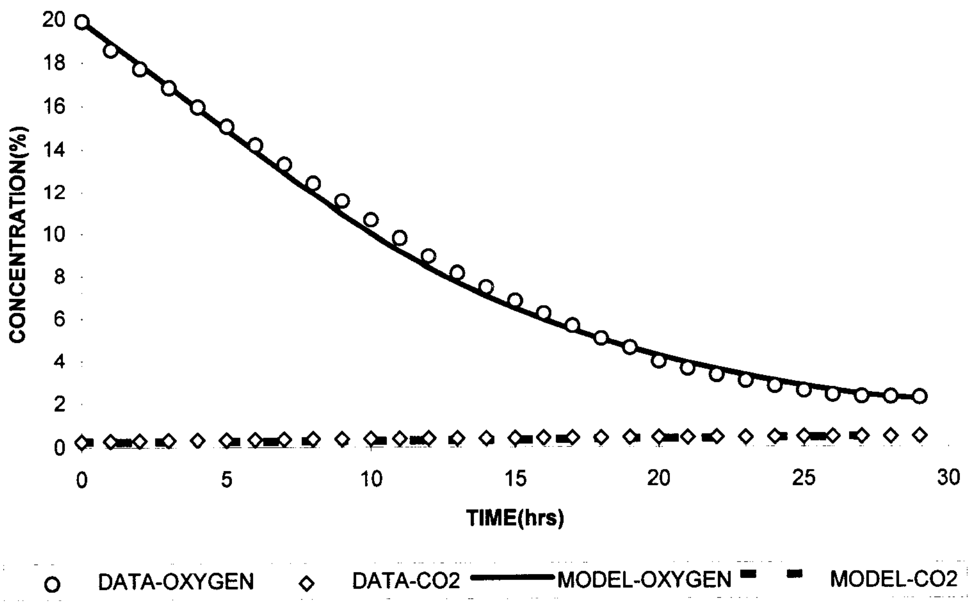

Figure 46. Pulldown curve of CA24 using the ammonia fractionating burner in the Odell Cold Storage #2 facility.

Simulation values of the additional heat gain to the refrigeration load caused by operating the CA equipment in the Van Horn Cold Storage, Odell Cold Storage #1, and Odell Cold Storage #2 are illustrated in Figure 47, 48, and 49, respectively. Total additional heat gains due to the membrane air separator, the catalytic oxygen burner, and the ammonia fractionating burner were 635 kJ (9/16/95 to 11/1/95), 11,653 kJ (9/14/95-10/12/95), and 2,532 kJ (09/14/93-1/18/94), respectively.

Simulation total energy used in the Van Horn Cold Storage, Odell Cold Storage #1, and Odell Cold Storage #2 are illustrated in Figure 50, 51, and 52, respectively. The total energy used in the Van Horn Cold Storage, Odell Cold Storage #1, and Odell Cold Storage #2 was 9,680 kWh (9/16/95 to 11/1/95), 12,662 kWh (9/14/95-10/12/95), and 16,214 kWh (09/14/93-1/18/94), respectively. Comparison of simulated values to actual energy use was not possible. The refrigeration and CA systems were not metered separately from the rest of the facility.

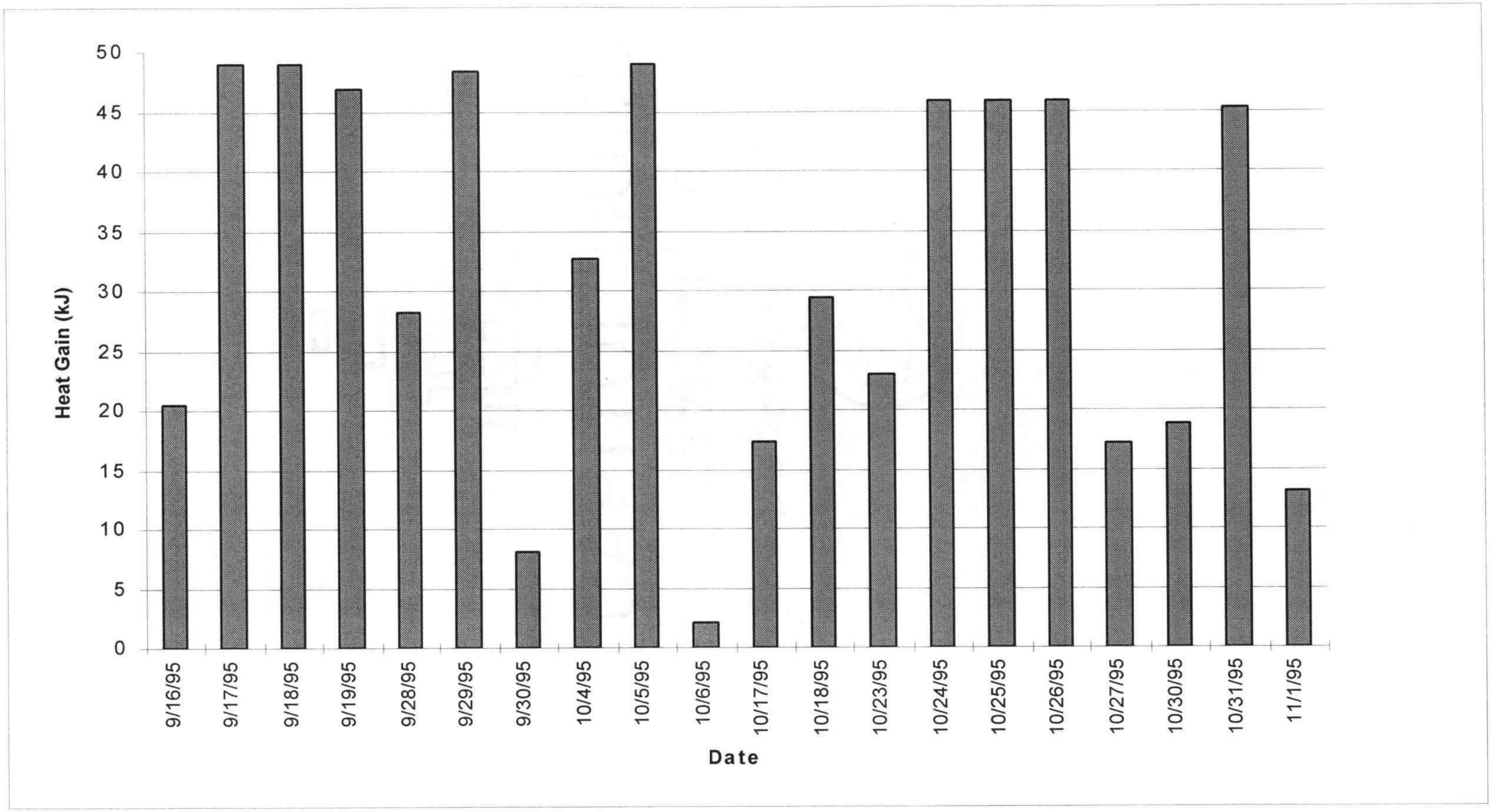

Figure 47. Additional heat gain to the refrigeration load caused by the membrane air separation system in the Van Horn Cold Storage facility.

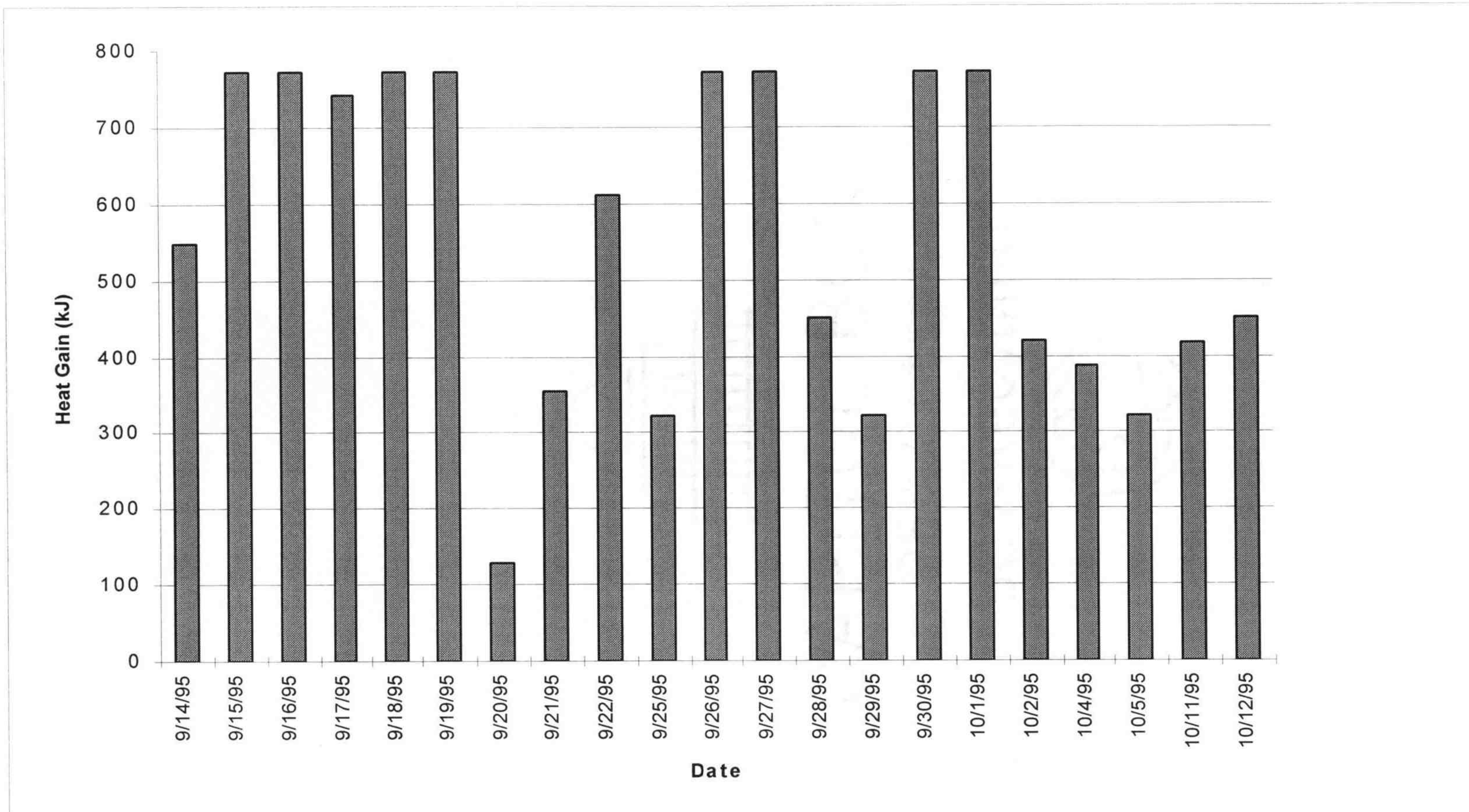

Figure 48. Additional heat gain to the refrigeration load caused by the catalytic oxygen burner in the Odell Cold Storage #1 facility.

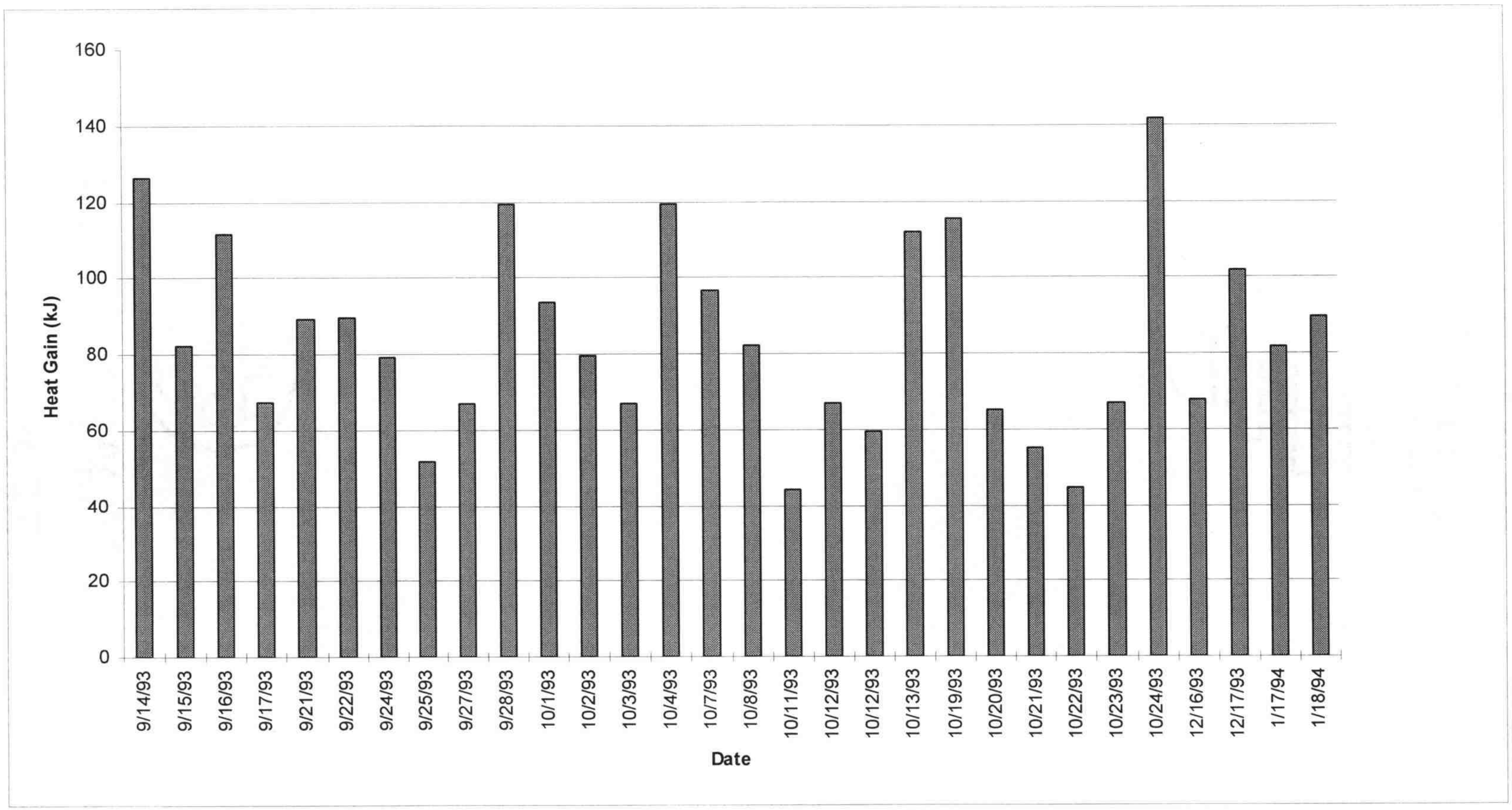

Figure 49. Additional heat gain to the refrigeration load caused by the ammonia fractionating burner in the Odell Cold Storage #2 facility.

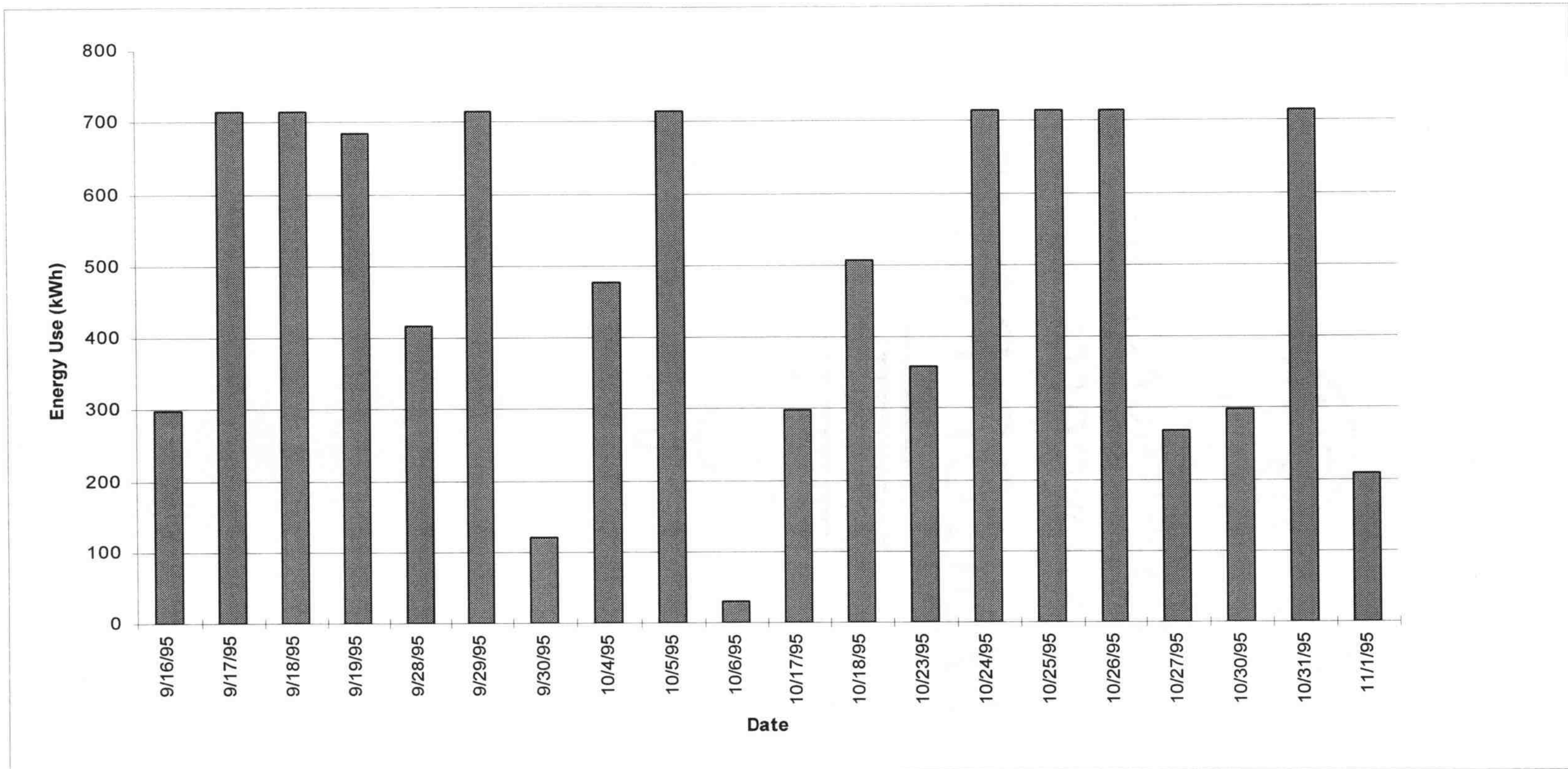

Figure 50. Energy use by membrane air separator at the Van Horn Cold Storage facility.

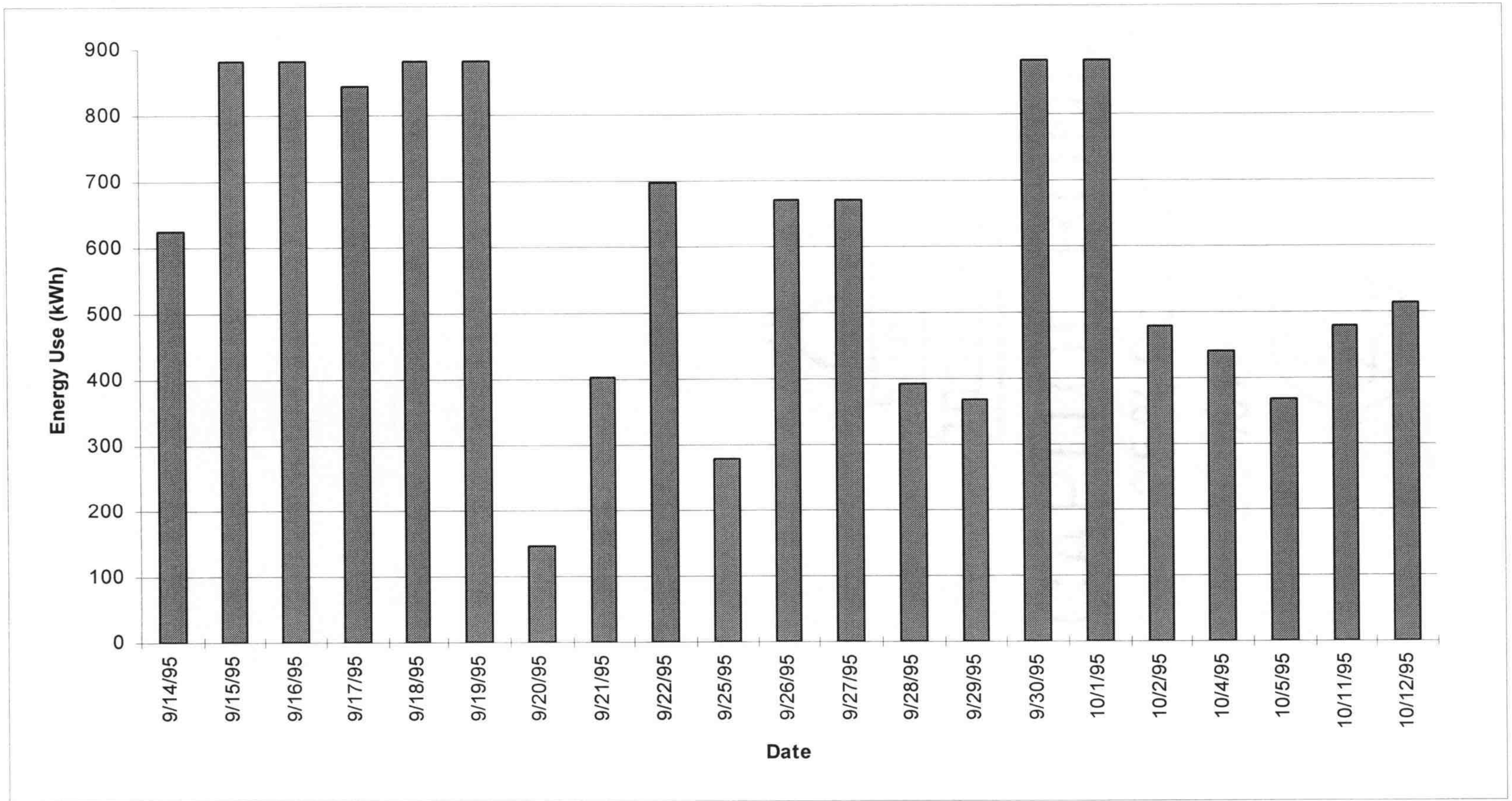

Figure 51. Energy use by catalytic oxygen burner at the Odell Cold Storage #1 facility.

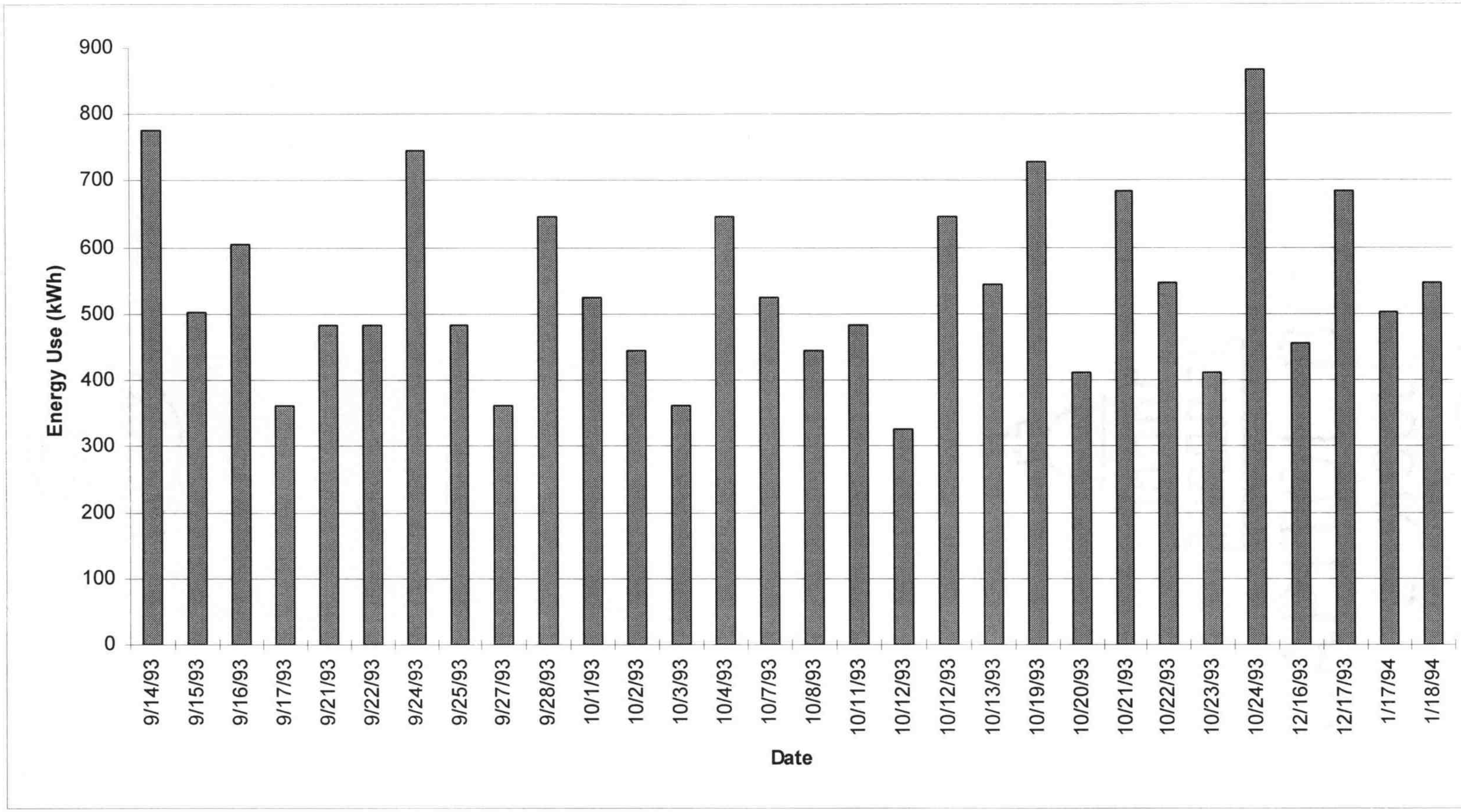

Figure 52. Energy use by ammonia fractionating burner at the Odell Cold Storage #2 facility.

5. CONCLUSIONS AND RECOMMENDATION

The apple and pear industry are of significant economic importance to the Pacific Northwest States of Oregon and Washington. Controlled atmosphere storages play an important role in maintaining high quality fruit. Efficient energy use helps maintain competitive prices. A computer simulation program, Controlled Atmosphere Simulation (CAS), was developed to simulate three types of commonly used atmosphere generators including: membrane air separators, catalytic oxygen burners, and ammonia fractionating burners.

The simulation program predicts the pulldown time of each CA generation system in cold storage rooms by using fruit respiration models and cooling rate models. The predicted pulldown time results can subsequently be used to determine the additional heat gain to the refrigeration system and estimate electrical energy use by the CA generation equipment. The additional heat gain is then added to the total cooling load of the refrigeration system. Electrical energy use results become input to an interactive computer program ' **Fru**it **S**torage **R**efrigeration **E**nergy **S**imulation ' (FrusTRES). The resulting model package can then be used to predict overall annual energy use in fruit cold storages.

The Controlled Atmosphere Simulation (CAS) and FrusTRES are both written in Microsoft Visual Basic 3.0, Professional Edition and are Windows interactive computer programs, thus allow individualized input by the user. The CAS can graphically illustrate pulldown time trends and provide output files of pulldown data, additional heat load, and energy use by CA equipment throughout the season in apple and pear cold storage warehouses. FrusTRES then provides total energy use (both refrigeration system energy use and CA equipment energy use) output files for the fruit storage building.

Several conclusions were derived from this study:

1.The Controlled Atmosphere Simulation (CAS) can accurately predict the pulldown time for three types of atmosphere generators; a membrane air separator, an ammonia fractionating burner, and a catalytic oxygen burner under normal operation.

2.The simulation results of additional heat gain to the refrigeration system and CA equipment energy use were promising since the accuracy of those results depend upon the pulldown time model.

3.The resulting model package (CAS and FruSTRES), provides a previously unavailable tool to improve design and analyses of ammonia refrigeration and atmosphere generation systems used in common and controlled atmosphere fruit storages.

The following recommendations for additional research are presented:

1.The Controlled Atmosphere Simulation (CAS) accurately predicted the pull-down time of each type of equipment under normal operation. However, the respiration models for apples and pears were developed from published data from fruit held in common storage atmospheres and measured cooling temperature profiles. To obtained more accurate results, respiration data of each apple and pear variety, measured under controlled atmosphere conditions, should be used if available.

2. The model package (CAS and FruSTRES) needs to be upgraded to later versions of Microsolf Visual Basic, as they become available, in order to obtain maximum efficiency.

3. Use the combined model (CAS and FruSTRES) to simulate energy conservation management options such as computer controlled evaporator fan cycling and floating head compressor operation.

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