

MEASUREMENT OF BREATH-BY-BREATH OXYGEN CONSUMPTION
AND CARBON DIOXIDE PRODUCTION IN EXERCISING CALVES

by

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B.S., Kansas State University, 1980

A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1982

Approved by:


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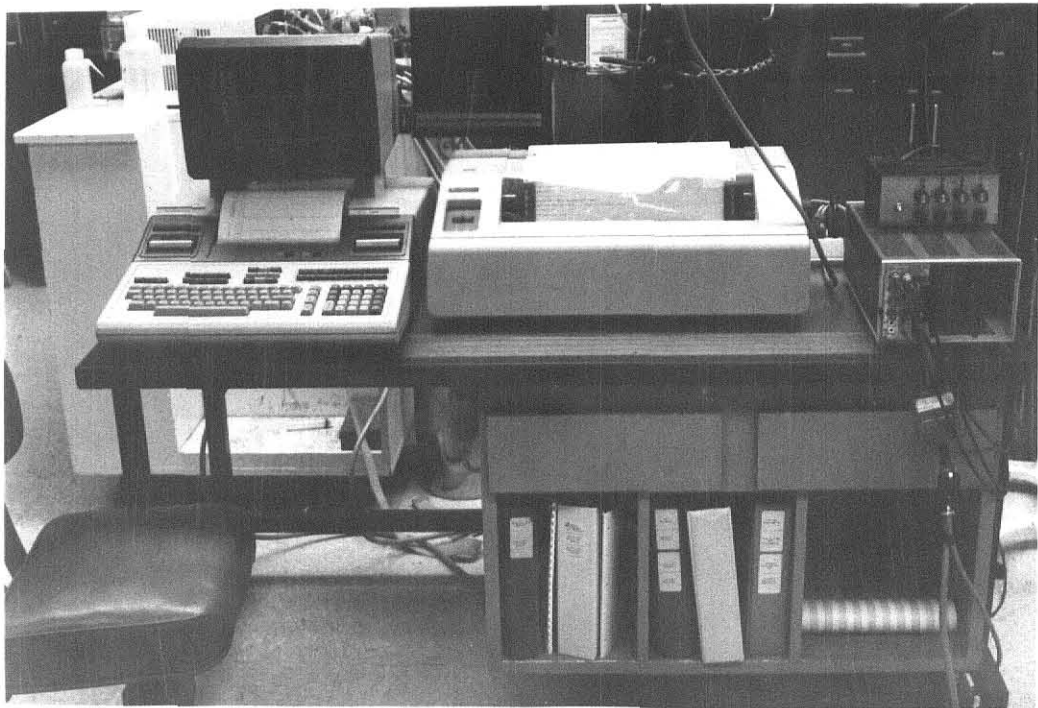
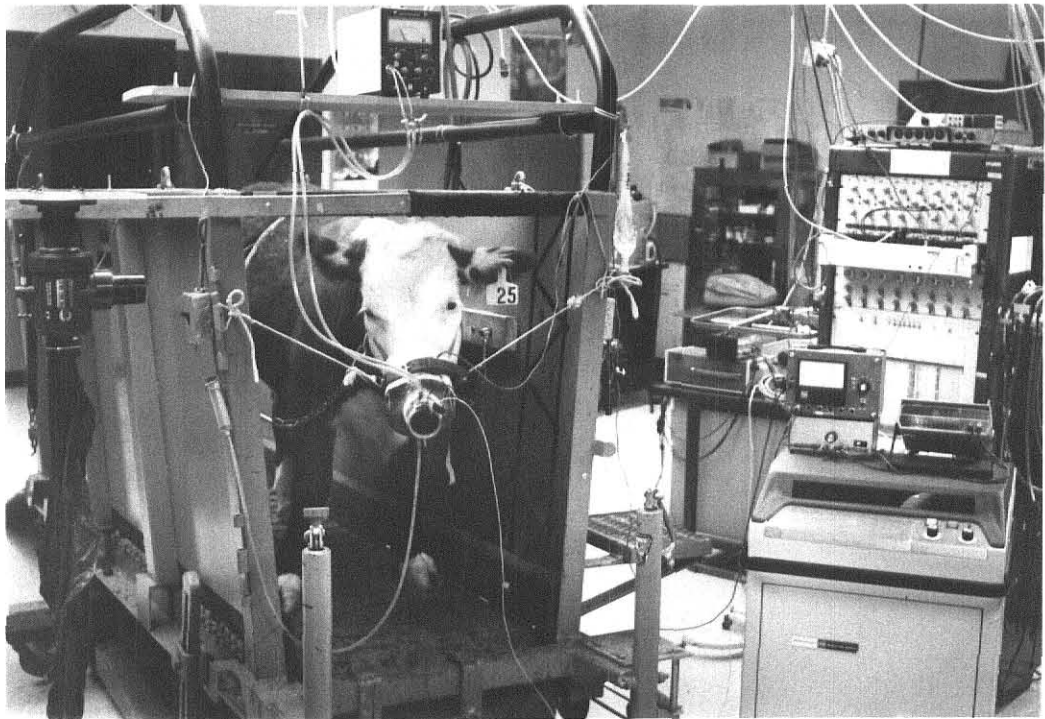
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I. INTRODUCTION

Since oxygen consumption is directly related to a variety of respiratory and cardiovascular parameters, measurement of breath-by-breath oxygen consumption and carbon dioxide production is a topic of interest among many groups within the scientific community. Quantitative oxygen consumption measurements often provide valuable research and diagnostic information pertaining to the physical health, conditioning, or well being of a test subject or patient [1].

Prior to the advent of computers and rapidly responding gas analyzers, determination of O_2 consumption and CO_2 production on a breath-by-breath basis was nearly impossible. Usually the researcher and clinician had to be satisfied with procedures utilizing blood oxygen content and the oxygen concentration in bagged collections of mixed expired respiratory gas. These techniques only allowed for the determination of the average O_2 consumption and CO_2 production over a period of several minutes or several breaths [2,3]. Aside from being time consuming and cumbersome to perform, these measurements contain little, if any information about the dynamic trends of O_2 consumption as the subject progresses between various work levels. Increasingly, a combination of sophisticated instruments and digital computers are being used to eliminate the drudgery in making respiratory measurements [4-13].

For this particular study, Hereford steers weighing 150 to 300 kg were exercised on a variable speed, variable grade treadmill to determine if factors are produced by an exercise-stressed calf which

influence its ability to combat respiratory disease (i.e., Shipping Fever). A computer controlled instrumentation system was developed which performs the necessary tasks for determining breath-by-breath O_2 consumption at the mouth, and other respiratory variables of interest. The following chapters describe the design considerations, measurement techniques, component interconnections, operation, software, animal preparation, calibration, verification, results, and error analysis for the experimental instrumentation system.

II. GENERAL SYSTEM DESCRIPTION

2.1 System Operation Overview

During an experiment a calf is positioned on the treadmill and outfitted with transducers for monitoring five physiological signals. These signals, respiratory flow, $\dot{V}$; fractional CO_2 , F_{CO_2} ; fractional O_2 , F_{O_2} ; body temperature, and respiratory flow temperature; are generated by a Fleisch pneumotachometer, a Perkin-Elmer Medical Gas Analyzer, and two Yellow Springs tele-thermometers. The $\dot{V}$, F_{O_2} , and F_{CO_2} signals are converted from analog to digital signals using a custom electronic instrument, then passed onto and stored in the memory of a digital computer. Prior to data collection, these three signals are calibrated under computer control, utilizing special calibration software written especially for this system. At the completion of data collection, a numerical integration technique is employed to calculate the volumes of air, O_2 , and CO_2 inspired and expired during each breath.

The calf's body temperature and the average inspiratory and expiratory flow temperature are monitored using rapidly responding thermistors. These variables along with humidity and barometric

pressure data are hand entered into the computer and used by the analysis routine to scale computed respiratory volumes to either BTPS or STPD conditions.

Display of analyzed results is organized in a tabular format consisting of a single row of program output for each breath, listing values for all of the calculated gas volumes and associated times. Several average and time dependent quantities are also displayed; namely, O_2 consumption, $\dot{V}_{O_2}$; CO_2 production, $\dot{V}_{CO_2}$; respiratory minute volumes, V_I and V_E ; respiratory tidal volumes, V_{TI} and V_{TE} ; respiratory frequency, total times for inspiration and expiration, t_I and t_E ; and the respiratory quotient, R .

III. INSTRUMENTATION HARDWARE FOR DATA ACQUISITION

3.1 Instrumentation Components and Interconnections

Figure 3.1 illustrates the organization and interconnections of the complete instrumentation system. A No. 4 Fleisch pneumotachometer (PTM) (Dynasciences) [14] is used to transduce respiratory flow. A closed circuit technique is used whereby both inspiratory and expiratory flow are monitored and used in the respiratory calculations, Beaver et. al., [13] recommend this procedure over the conventional open circuit technique where only expiratory flow is monitored. They suggest the closed circuit method provides a more accurate means for calculating true respiratory gas exchange volumes, and especially alveolar exchange volumes. The PTM produces a differential pressure signal proportional to the flow of gas through it. This differential pressure signal is converted to an electrical analog signal using a pneumotachograph (PTG) (Godart

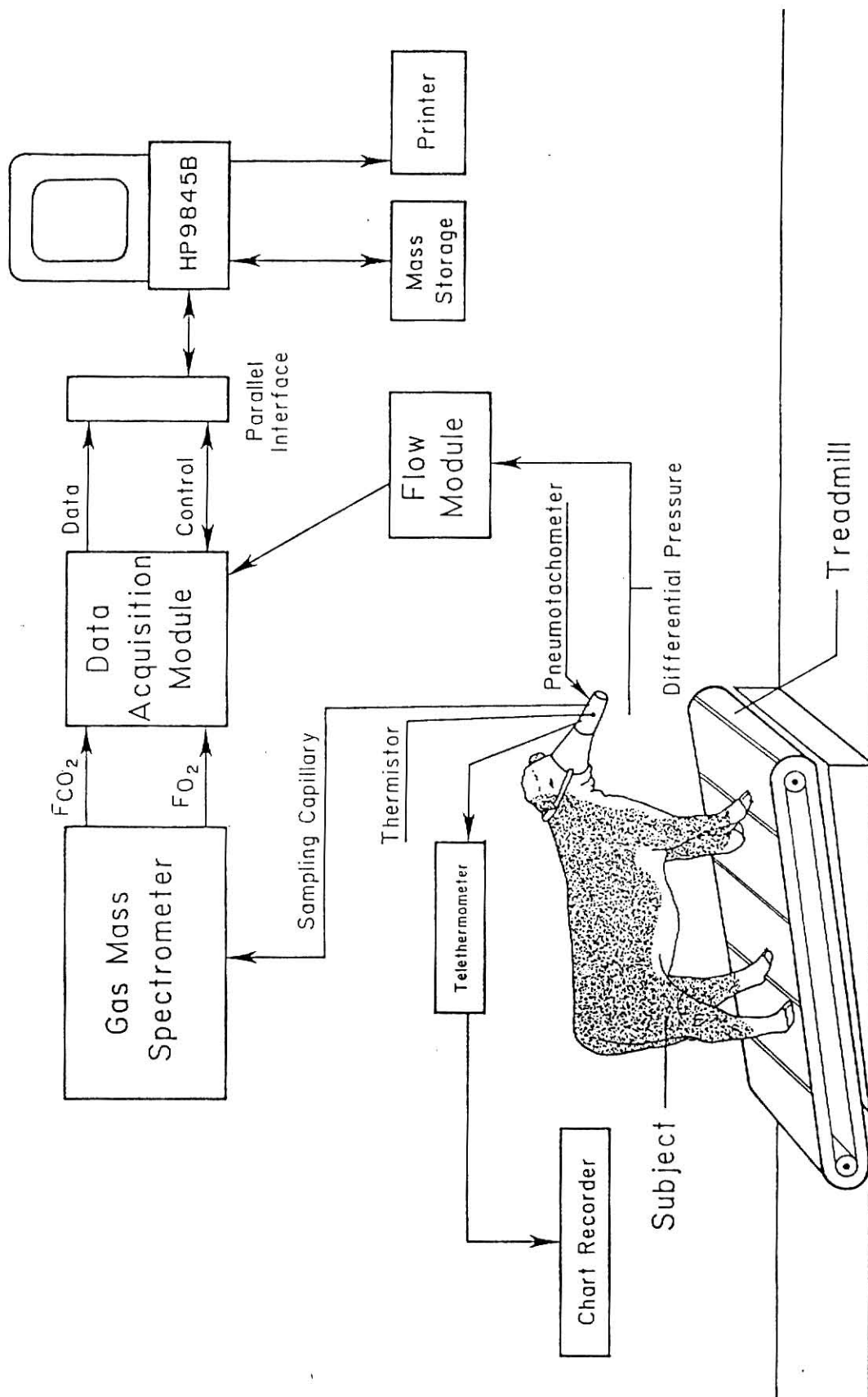
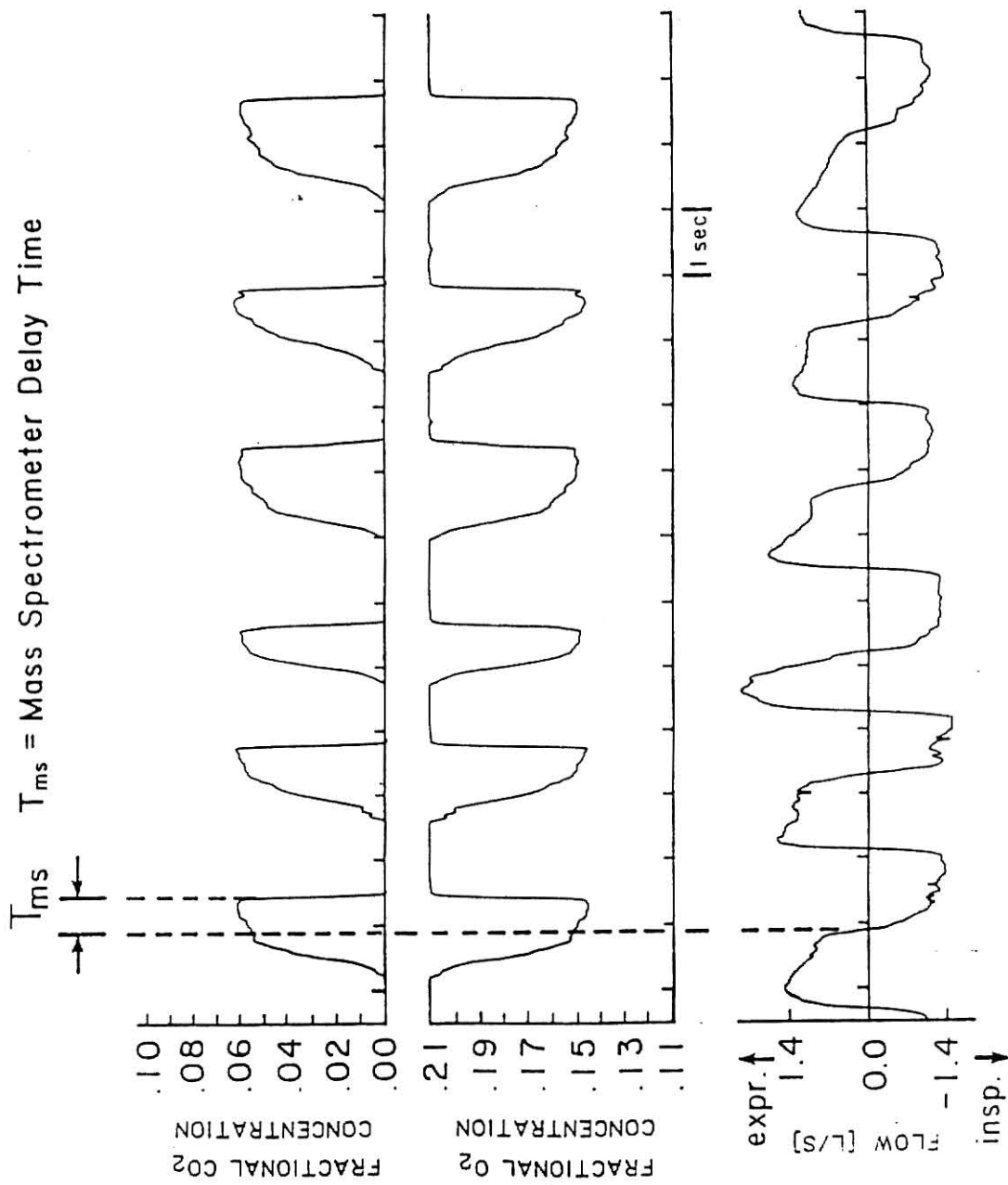


Figure 3.1 Functional Block Diagram of Instrumentation System Component Interconnections.

17212, a differential pressure-to-analog signal converter module) [14].

The respiratory gas is continually sampled close to the subject's nostril through a small capillary tube 3 meters long, connected to a rapidly responding Gas Mass Spectrometer (GMS) (Perkin-Elmer 1100 Medical Gas Analyzer) [15]. Both the sampling capillary and the PTM are secured to the calf using a custom fitted face mask which fits over the muzzle. The GMS provides electrical analog signal outputs proportional to the instantaneous fractional concentrations of O_2 and CO_2 in the respiratory flow. Inconveniently, a significant amount of time elapses (300-500 msec) while the gas sample is in transport from the calf to the GMS. A small additional time delay occurs due to the electrical response time of the GMS. This total time delay in the fractional concentration signals must be compensated for so that the respiratory variables of interest can be accurately calculated. Figure 3.2 is a reproduction of a strip chart recording illustrating the effects of the gas transport and electrical response delay time. T_{ms} represents the time by which the fractional concentration signals lag the respiratory flow signal. The flow signal must be accurately time aligned with the fractional O_2 and CO_2 signals before the signals can be used in the computation of respiratory variables.

During an experiment, the calf's respiratory flow temperature is monitored using a rapidly responding thermistor (200 msec time constant) connected to a tele-thermometer (Yellow Springs YSI Model 41). The output of the tele-thermometer is monitored using a chart



recorder. Temperature information from the chart recording is utilized during data analysis to correct calculated gas volumes to BTPS (Body Temperature and Pressure, Saturated) or STPD (Standard Temperature and Pressure, Dry) conditions. Figure 3.3 illustrates a typical respiratory flow temperature signal. The subject's body temperature is also monitored using a thermistor and tele-thermometer. This thermistor has a slow response time, but is acceptable for measuring slowly changing rectal temperatures.

The flow and fractional concentration signals of the gas are inputs to a custom built, computer controlled Data Acquisition Module (DAM) [16]. The primary function of the DAM is to convert incoming analog signals to digital signals which the computer will accept. Essentially, the DAM collects simultaneous samples from the analog inputs at discrete, regular time intervals and assigns each sample an appropriate binary value. These binary data are passed onto and stored in the memory of the computer (Hewlett-Packard 9845T), in a binary coded decimal (BCD) format, using a 16-bit GPIO parallel interface (Hewlett-Packard 98032A [17]). The DAM has five unipolar input channels (0 to 10 volts) designed for use with the GMS, and three bipolar input channels (-5 to 5 volts) for use with transducers having bipolar outputs such as the Godart PTG. The block diagram illustrated in Figure 3.4 summarizes the functional groups within the DAM. The sampling frequency is the same for all channels and is easily altered at any point during operation using the system software. Sampling frequencies between 10 Hz and 10 kHz are possible, depending on the operating speed of the host computer and the number of channels being sampled.

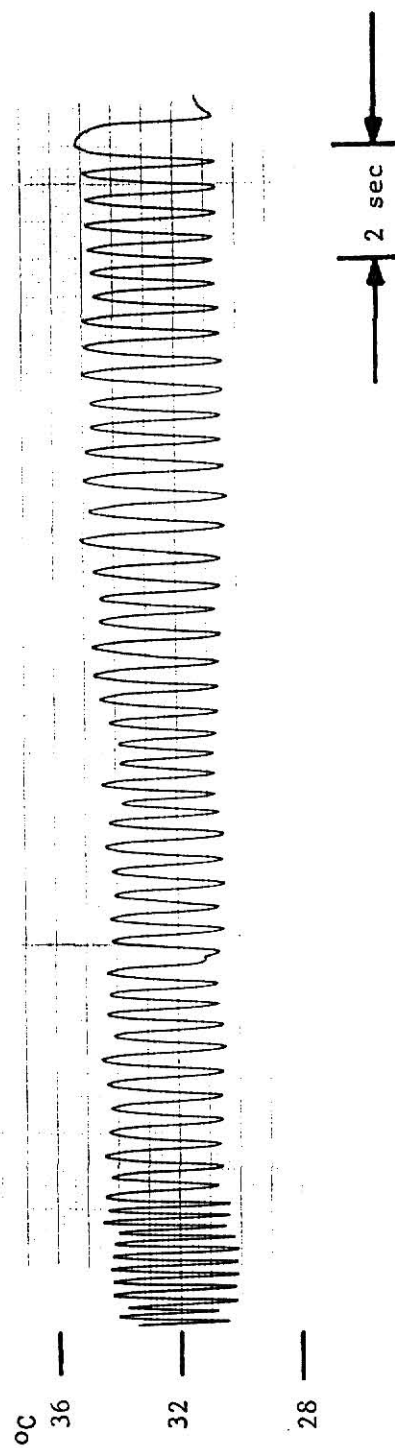


Figure 3.3 Respiratory Flow Temperature Signal.

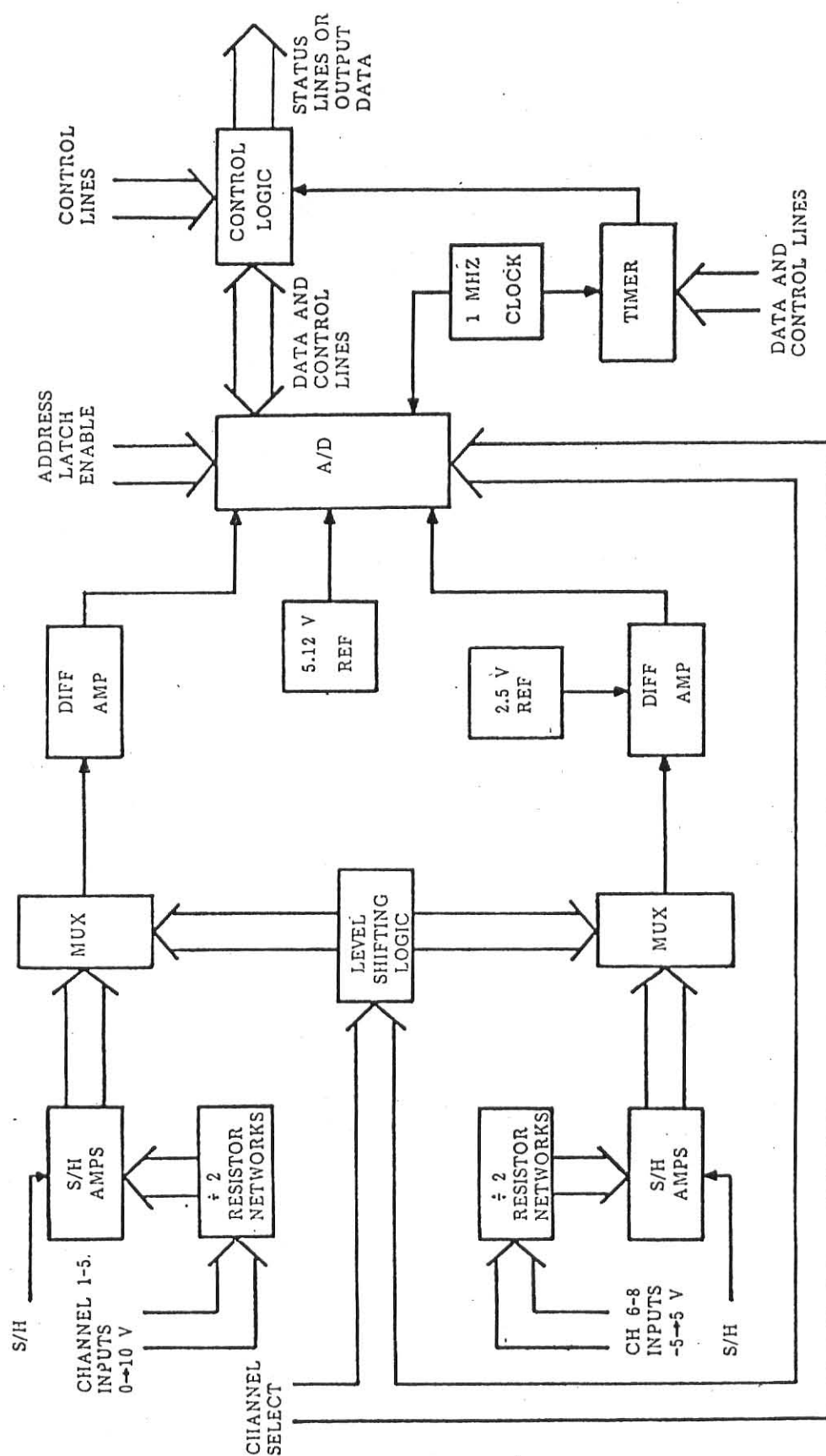


Figure 3.4 Block Diagram of a General Purpose Data Acquisition Module (DAM) with Unipolar and Bipolar Input Capability.

A unique feature of the DAM is the Sample/Hold (S/H) amplifier present on each of the input channels. They were included in the design so that effectively, if desired, each of the eight input channels could be sampled simultaneously [16]. For determining breath-by-breath oxygen consumption this feature is useful because the correct time alignment of the respiratory signals is extremely important. The effect of the S/H amplifiers on the incoming analog signals is illustrated in Figures 3.5 and 3.6. In Figure 3.5.1 identical sinusoidal input signals are applied to channels one and two, with the S/H inactive. Because the control logic (which operates the analog multiplexer, generates handshake signals, etc.) requires a finite time to operate, and the A/D converter cannot perform a conversion instantaneously, channels one and two do not get sampled at precisely the same instant. The net result (Figure 3.5.2) is that non-identical digital outputs are obtained for identical analog inputs. Although the output waveforms are identical in shape, they are shifted in time with respect to one another by an amount equal to the sum of the software execution time required to operate the control logic, and the conversion time required to generate the digital equivalent of the analog input.

In Figure 3.6.1 identical analog inputs are again applied to channels one and two, but this time the S/H amplifiers are active. When a rising edge occurs on the S/H control line, the output of each S/H maintains its output voltage at the current value of the analog input voltage (Figures 3.6.2 and 3.6.3). The digital samples are obtained during the time when the outputs of the S/H amplifiers are fixed. The net result, shown in Figure 3.6.4 is that the DAM

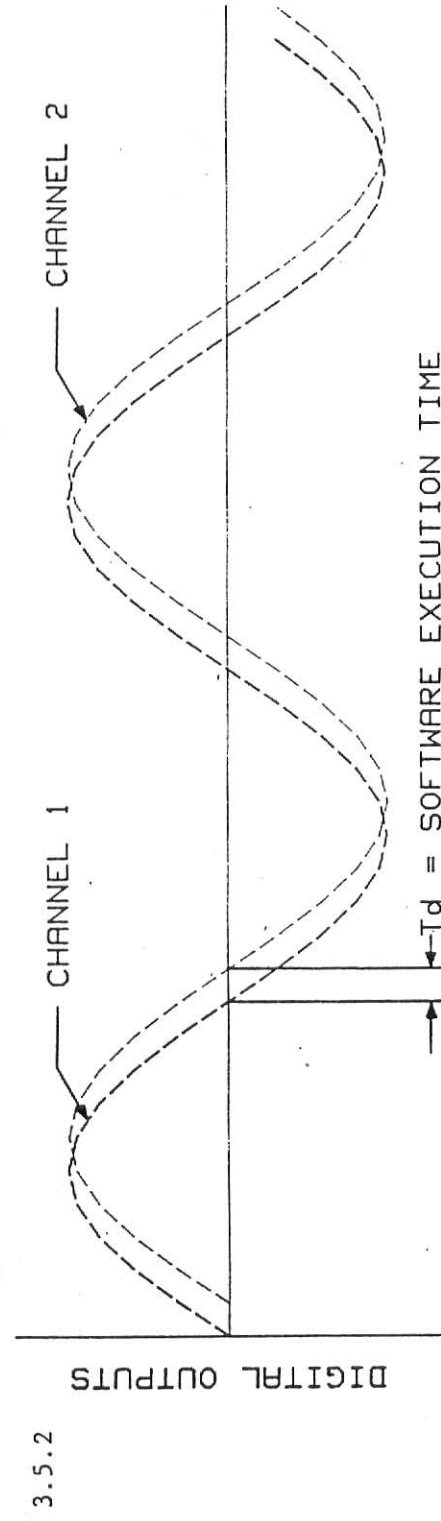
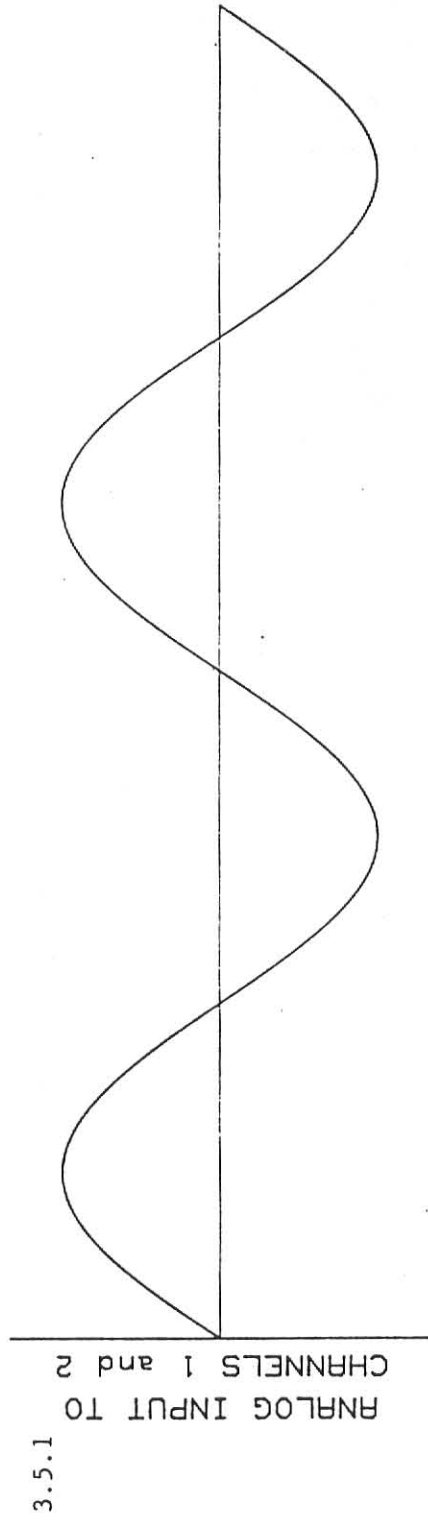


Figure 3.5 Effect of Software Execution Time on the Time Alignment of Multiple Input Signals.

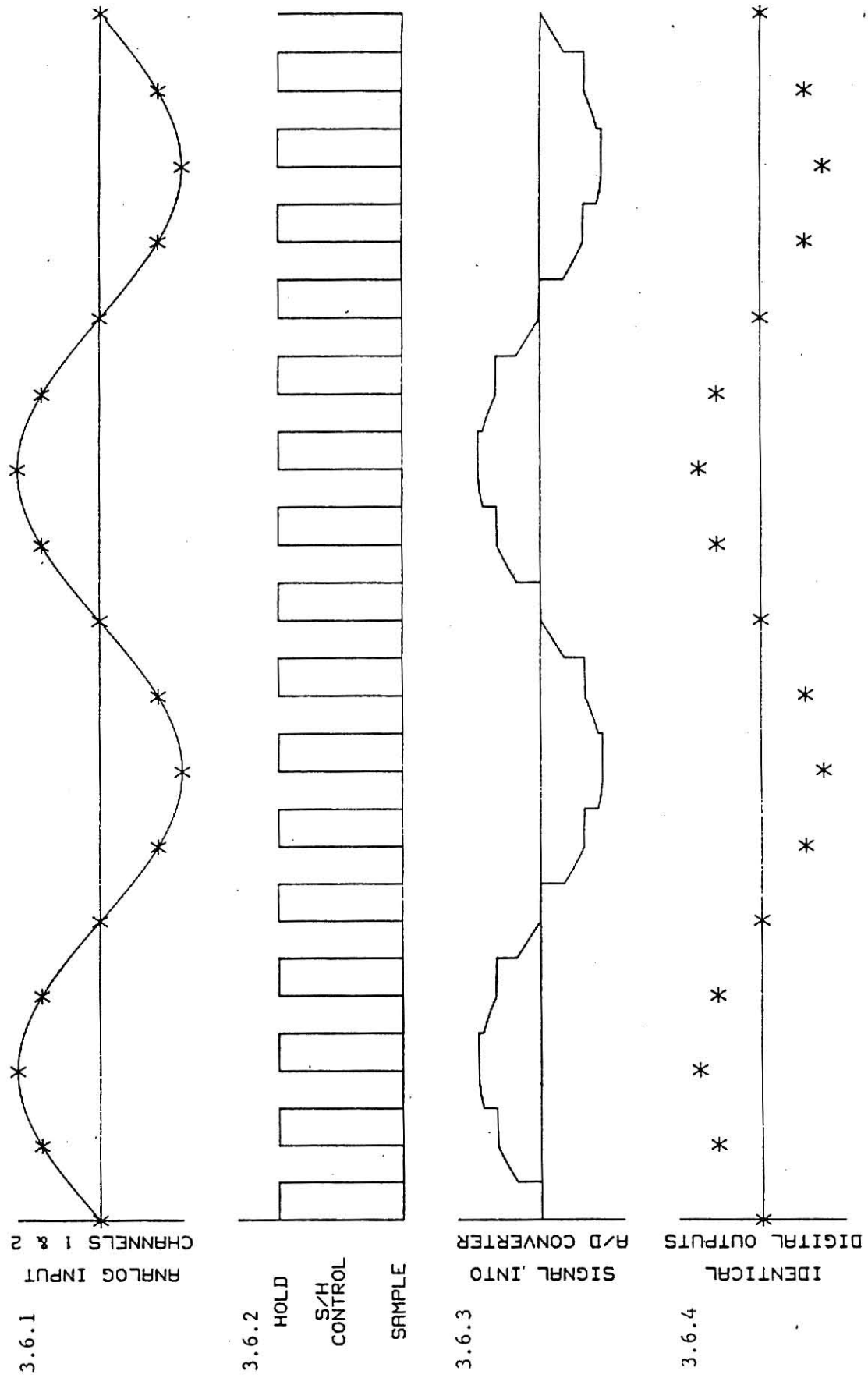


Figure 3.6 Compensation for Software Execution Time Using Sample/Hold Amplifiers.

produces identical digital outputs for identical analog inputs, thus eliminating any further time alignment problems associated with the incoming analog input signals.

A Hewlett-Packard 9845T desk top computer controls the acquisition, processing, and display of data. The computer is programmable in both BASIC and Hewlett-Packard assembly language, and has a 8"x10" CRT display with full graphics capabilities. The computer is interfaced to a high speed Hewlett-Packard 2631B dot matrix printer [18] for hard copy of program listings and experimental results. A Hewlett-Packard 98034A HPIB (IEEE 488 standard) [19] is used to interface the printer to the computer. The computer system also has two tape drives that accommodate magnetic tapes, each with 217K bytes of storage capacity, and 187K bytes of user random access memory for programming and data storage. The computer system is very versatile, instrumentation control oriented, and incredibly "user friendly" [20].

3.2 Calibration Hardware

To facilitate the procedure for correcting for the capillary gas transport and GMS response delay time, a small electronic switch debounce circuit was constructed [21]. The circuit was implemented to prevent erroneous signals from being transmitted to the computer, and also to prevent large voltage spikes from damaging the computer interface. Figure 3.7 illustrates the additional calibration hardware. During the correction determination procedure, the GMS sampling capillary probe is placed in a 9% CO₂ gas mixture and then rapidly removed to room air simulating a step CO₂ input to the GMS. As the sampling capillary is removed to room air, a photo-electric

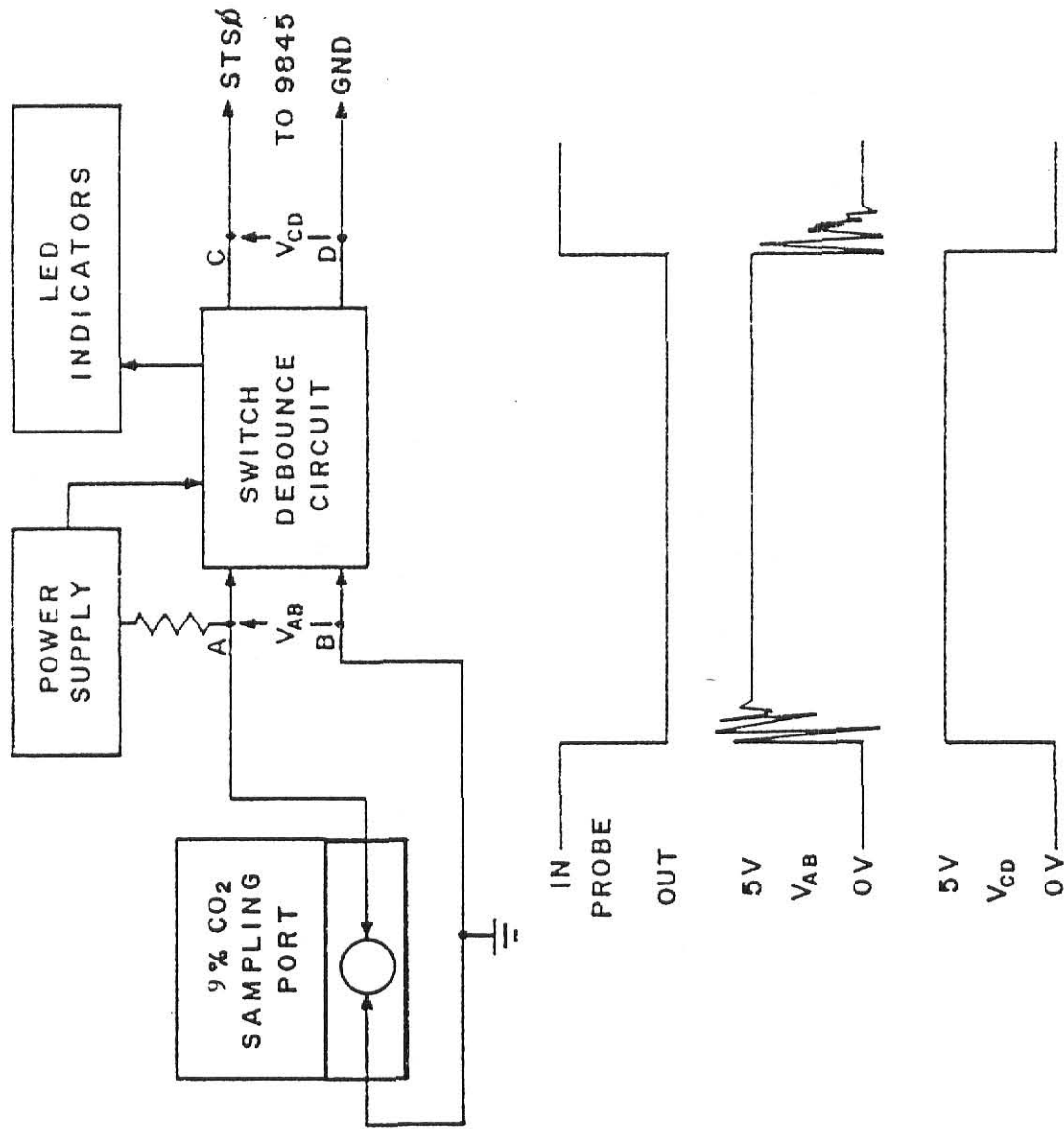


Figure 3.7 Calibration Hardware for Gas Mass Spectrometer (GMS)
Delay Time Determination.

switch opens giving rise to a spurtic voltage waveform (Vab Figure 3.7). Without some form of signal conditioning, additional software would be required to correctly detect probe removals. Potentially this could create timing problems associated with the software execution time. Since timing was critical, the additional hardware to debounce the switch was justified. The effect of the debounce circuit is to provide a single, clean voltage transition to the computer each time the probe is placed in or removed from the 9% CO₂ gas port (Vcd Figure 3.7). Two light emitting diodes (LEDs) were also included in the design of the debounce circuit. A green LED lights when the probe is in the 9% CO₂ port, and a red LED lights when the probe is removed. The complete circuit schematic for the switch debounce circuit and photo electric switch is presented in Figures A3.1 and A3.2 located in Appendix III.

IV. SYSTEM SOFTWARE

A combination BASIC/HP assembly language program was written to handle the tasks of data acquisition, data analysis, data display, and display of calculated results. The system software was organized into a main routine, called the System Controller Routine, and several supporting subroutines that perform specialized system functions. The System Controller Routine serves to allow the system operator versatile access of the system subroutines. Figure 4.1 illustrates all possible paths for the flow of system operation provided by the System Controller Routine. The primary system functions; data acquisition, data analysis and display, and calibration, are highlighted by large boxes. The System Controller Routine

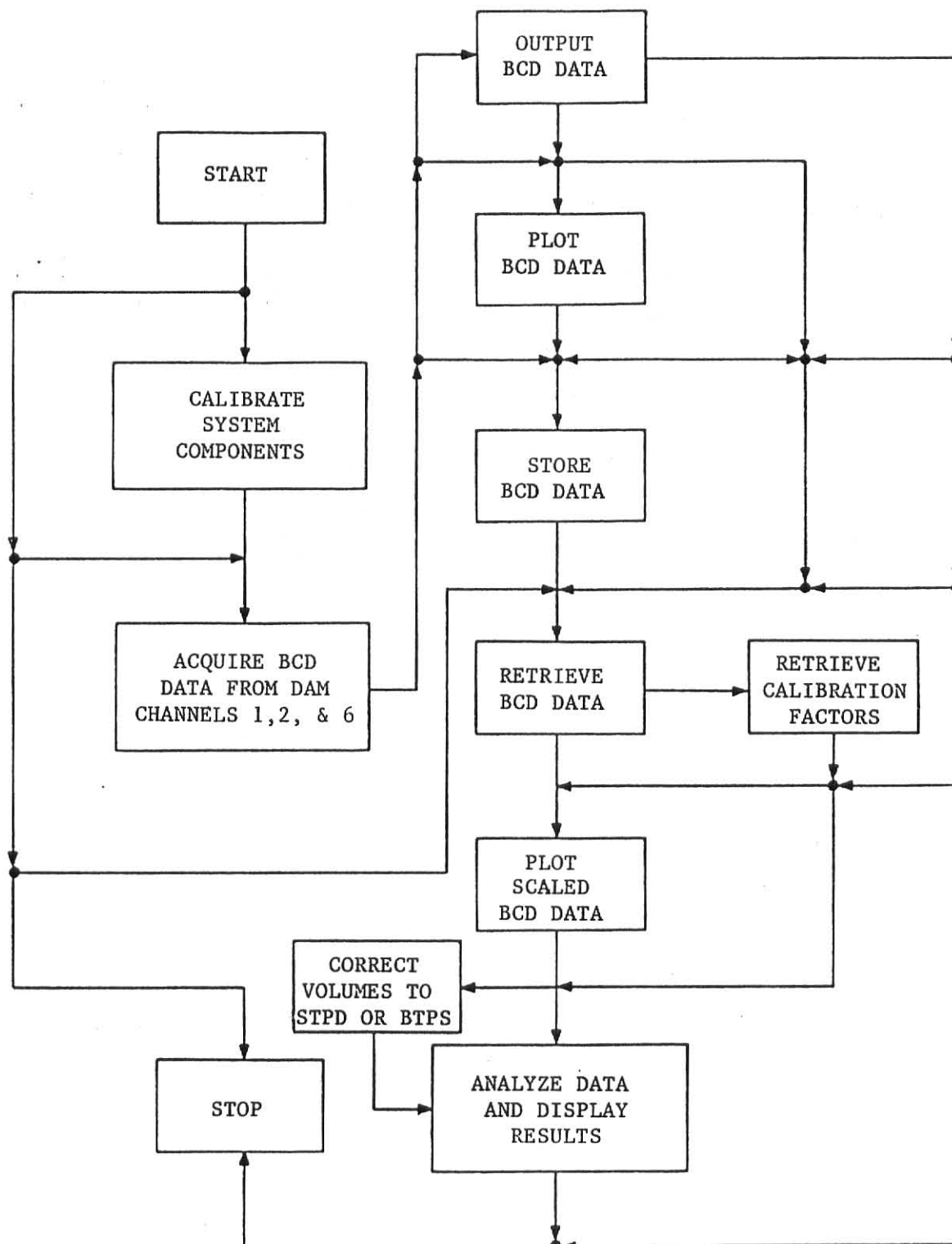


Figure 4.1 Possible Operation Sequences for the System Controller Routine.

was organized to allow the execution of any logical sequence of system subroutines. Additional documentation outlining the program variables, logic flow diagrams, and source listings appears in Appendix II.

From a functional viewpoint the system subroutines fall into one of two categories:

- 1) Software for data acquisition.
- 2) Software for data processing and data display.

The following two sections contain brief explanations of the subroutines which comprise each of these categories.

4.1 Instrumentation Software for Data Acquisition

The software routines to drive the various instrumentation components are a collection of subroutines grouped together in one large program. The individual functions performed by the subroutines may be classified as follows:

- 1) Calibrates and zero dc offsets the hardware components within the DAM.
- 2) Generates appropriate control words for initializing the DAM to sample the input channels at the user selected sampling frequency.
- 3) Generates handshake and control signals for the procurement and transfer of binary data from the DAM to the memory of the computer.

4.1.1 Data Acquisition Module Hardware Calibration

The purpose of this routine is to provide the user with a simple, systematic approach to calibrating the DAM. Basically the user is required to adjust several potentiometers located inside the DAM. The computer program prompts the user at each step of the procedure with specific instructions. At completion, the DAM

is free from large dc offsets in the amplifier components, and the voltage references are set at their correct values. This procedure is only occasionally necessary. Once calibrated, the DAM internal components should remain calibrated for days at a time barring any drastic changes in environmental conditions.

4.1.2 Software Control of the DAM Sampling Frequency

In the design of the DAM, provisions were made to allow software selectable sampling rates of the input channels. This was accomplished using an Intel 8253 programmable interval timer [22] and a small amount of accompanying control logic. The function of the 8253 is that of a general purpose, multi-timing element that can be treated as an array of I/O ports in the system software. A complete hardware schematic is included in Appendix III.

Conceivably, applications might arise where frequent changes in the sampling frequency are desirable or necessary. To facilitate this, the software to initialize the 8253 was organized as a subroutine. An integer value for the desired sampling frequency is the only parameter passed to the subroutine. The subroutine itself consists of a series of BASIC output statements which send the appropriate 8-bit control words over the parallel interface to select the user desired sampling frequency. A commented program listing of this subroutine is included in Appendix II.

4.1.3 Data Acquisition Software

Once the DAM obtains a digital sample it must be transferred to the computer before another digital sample is obtained. Generally, the sampling frequencies are sufficiently high to require that

the software controlling the data acquisition and transfer be relatively fast. In most circumstances, BASIC program statements require too much time for execution to allow high sampling frequencies, so the data acquisition software is written primarily in Hewlett-Packard assembly language code [23]. Figure 4.2 outlines the algorithm for the data acquisition software [16]. The assembly language routine accepts a parameter from the calling program (BASIC) representing the number of points to be collected from the input channels of the DAM. The assembly program generates the control signals to start the A/D converter, and monitors the end-of-convert (EOC) signal generated by the A/D converter. EOC indicates that a sample has been obtained and is ready for transfer. The computer program then generates the handshake signals for retrieving the data from the DAM. Once obtained, the digital data is placed in the computer's memory such that the Data Analysis Subroutine can use it for computing respiratory quantities at a later time. After the desired number of data points have been acquired from each channel, control is transferred back to the BASIC calling routine. Appendix II contains a complete program listing of the Data Acquisition Subroutine.

4.2 Software for Data Processing and Display

The software for data processing and display consists of a group of BASIC subroutines having the following functions:

- 1) Calibrates the analog respiratory signals by establishing set relationships between values of the input signals and associated binary values.
- 2) Calculates the total time associated with the capillary gas transport and GMS response time.

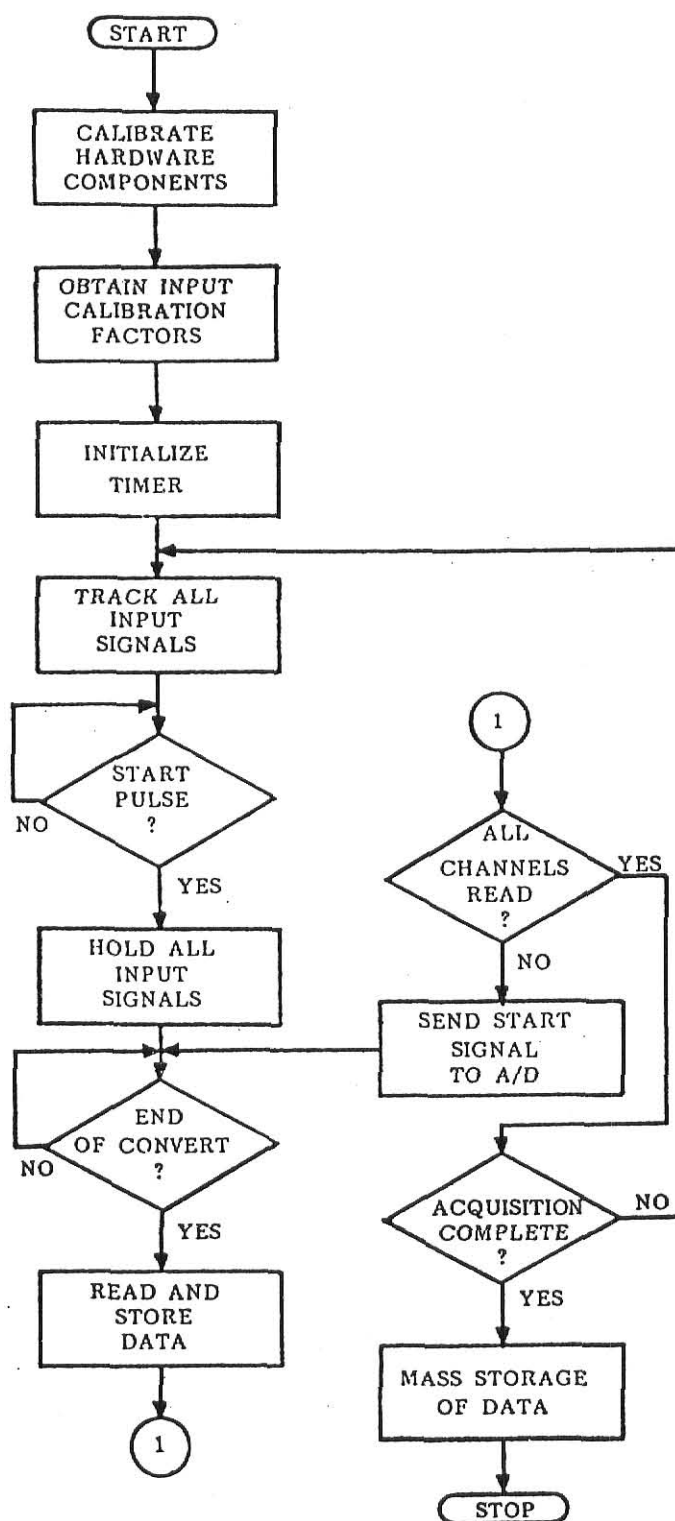


Figure 4.2 Control of the DAM During Data Acquisition.

- 3) Calculates breath-by-breath oxygen consumption and carbon dioxide production using digitized flow and fractional concentration signals in conjunction with the appropriate calibration factors.
- 4) Calculates additional respiratory quantities based on the digitized respiratory signals.
- 5) Calculates and applies correction factors to compensate for temperature and pressure differentials between the subject and the test environment.
- 6) Displays calculated values in a tabular format on a CRT or dot matrix printer.
- 7) Plots out the digitized respiratory signals using the graphics capabilities of the CRT display or optional color pen plotter.

A completely commented listing of each subroutine is included in Appendix II.

4.2.1 Analog Respiratory Signal Calibration

Before the computer can calculate values for the various respiratory parameters in terms of their correct units, calibration factors must be established. The calibration factors are simply numbers used to convert unitless binary data, into data with meaningful units. The binary value associated with a zero analog input is also used in the calculations to account for any dc offsets which might exist in the system.

To determine the dc offset present in each channel, each of the analog transducers are provided a zero level input stimulus. Several binary data samples for each channel are collected and averaged. The averaged binary values represent the binary value associated with a zero analog input stimulus for each respective channel. The binary zero values are subtracted from the binary

data collected from each input channel during an experiment, before the binary data are multiplied by the calibration factors.

Determination of the calibration factor for each channel is a three step procedure. First, an arbitrarily low level input stimulus of known value is applied to the analog transducer, producing an input signal to the DAM. Several corresponding binary data points are obtained and averaged. Second, the level of the input stimulus is increased to some known, arbitrary, higher value. The calibration signal levels are selected so that all anticipated input signals fall within the range of the difference of the calibration signal levels. Again, several corresponding binary values are obtained and averaged. Third, a typical calibration factor is calculated using the relationship:

$$\text{calibration factor} = \frac{\begin{array}{l} \text{known value for} \\ \text{higher level} \\ \text{calibration stimulus} \\ \text{binary value read} \\ \text{for higher level} \\ \text{calibration signal} \end{array}}{\begin{array}{l} \text{known value for} \\ \text{lower level} \\ \text{calibration stimulus} \\ \text{binary value read} \\ \text{for lower level} \\ \text{calibration signal} \end{array}}$$

The calculated calibration factors for the gas fractional concentration signals have units of

$$(\text{fractional concentration}) \cdot (\text{binary increment})^{-1}$$

and the calibration factor for the flow signal has units of

$$(\text{flow in liters/sec}) \cdot (\text{binary increment})^{-1}.$$

The calibration factors are then stored in the computer's memory for subsequent use by the Data Analysis Subroutine.

4.2.2 Determination of Capillary Gas Transport and Mass Spectrometer Response Delay Time

The software required for the task of determining the GMS delay time had two specific functions:

- 1) Rapid collection of binary data from the fractional CO_2 (F_{CO_2}) channel via the DAM.
- 2) Manipulation of the binary data to determine the correct time delay.

Since a rapid sampling rate was desired, the data acquisition software was written in assembly language. This portion of the software was a modification of existing software used to sample the DAM input channels during normal data collection. The modified software was also designed to be compatible with the calibration hardware described in Section 3.2.

The signals involved in the time delay determination are depicted in Figure 4.3. In Figure 4.3.1 t_0 represents the time at which the sampling probe is rapidly removed from the 9% CO_2 mixture to room air. As this occurs, the calibration hardware generates a signal to the computer and sampling of the F_{CO_2} signal begins at a rate of 500 Hz. After 500 samples are acquired (corresponding to 1.0 second of data), data acquisition is complete and the manipulation of the binary data to determine the time delay begins. A plot of the digitized F_{CO_2} data appears in Figure 4.3.3. Note that the digitized F_{CO_2} curve closely resembles the actual analog signal.

The algorithm to determine the total GMS time delay selects the point along the slope of the F_{CO_2} step response curve that yields the most nearly equal areas above and below the point along

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**THE FOLLOWING
DOCUMENT(S) IS OF
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THE ORIGINAL**

**THIS IS THE BEST
COPY AVAILABLE**

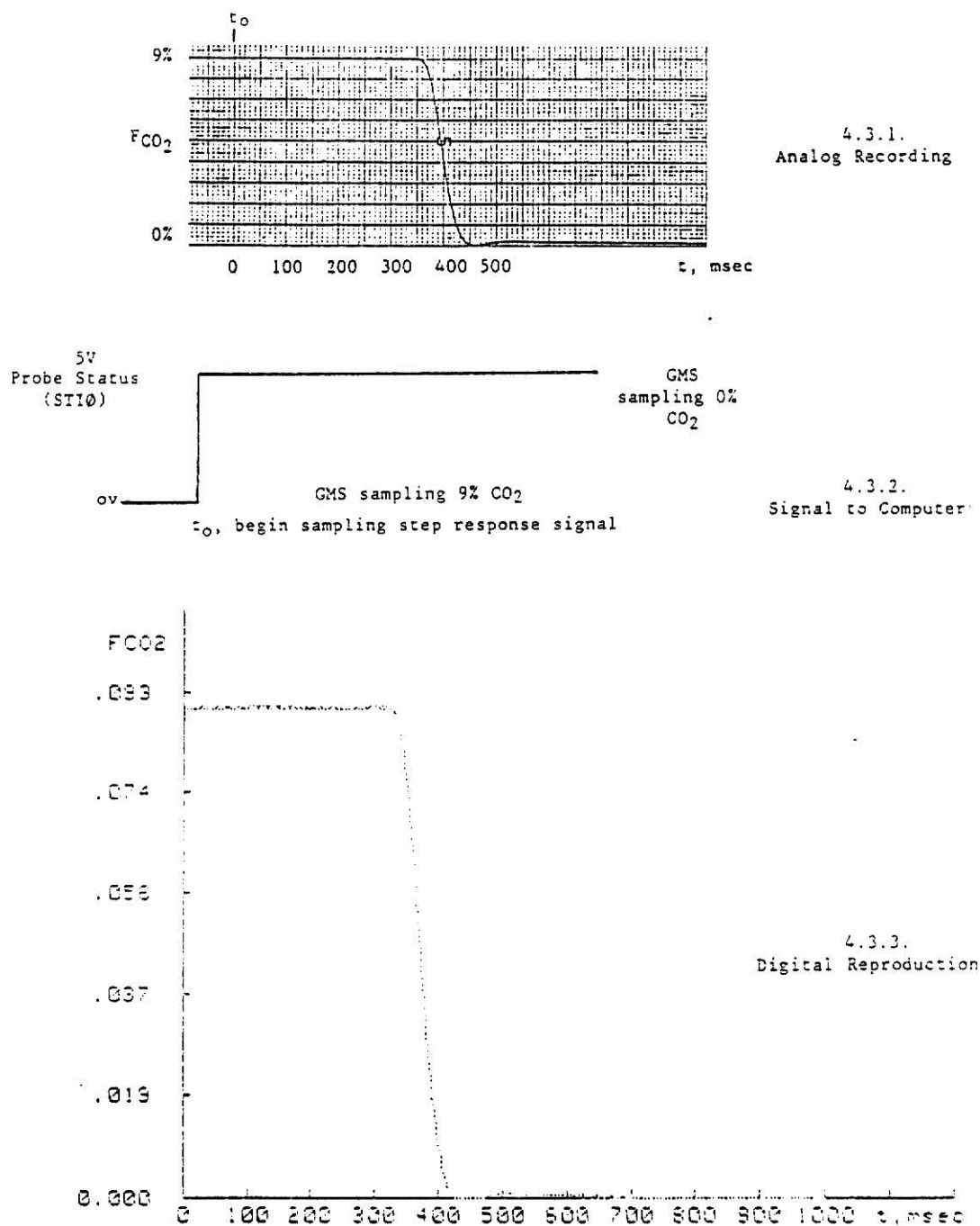


Figure 4.3 Comparison of an Analog and a Digital Recording of the GMS F_{CO_2} Step Response.

the curve. This algorithm which was implemented in BASIC, begins by finding the point along the curve less than or equal to one half of the difference between the binary values corresponding to 9% and 0% CO₂. Computation continues at the point 50 msec previous in time. The areas above and below this point along the F_{CO₂} curve are computed using the Trapezoidal Rule, and then the magnitudes of the areas are compared. The results of the comparison are stored for reference. This procedure is iteratively repeated using the next successive digital datum point in time as the center point for the area calculation, until the digital datum point 50 msec in time past the original center point is reached. Ultimately, the point along the curve where the areas most closely agree is selected as the point in time corresponding to the end of the time delay. Conveniently, this procedure accounts for both the capillary gas transport time and the GMS electrical response time. The equal area approach to determining the GMS time delay (Sue et. al., [12]) was used because it serves to select the point in time which would actually be the end of the time delay if the GMS had an ideal step response. In other words, the time delay algorithm selects the end of the time delay to correspond to the point in time where the output of the GMS would produce a step change, when a step change was applied to the sampling capillary, with the GMS itself having zero response time. A summary of these ideas is depicted in Figure 4.4. Appendix II contains a complete program listing of the Time Delay Determination Subroutine.

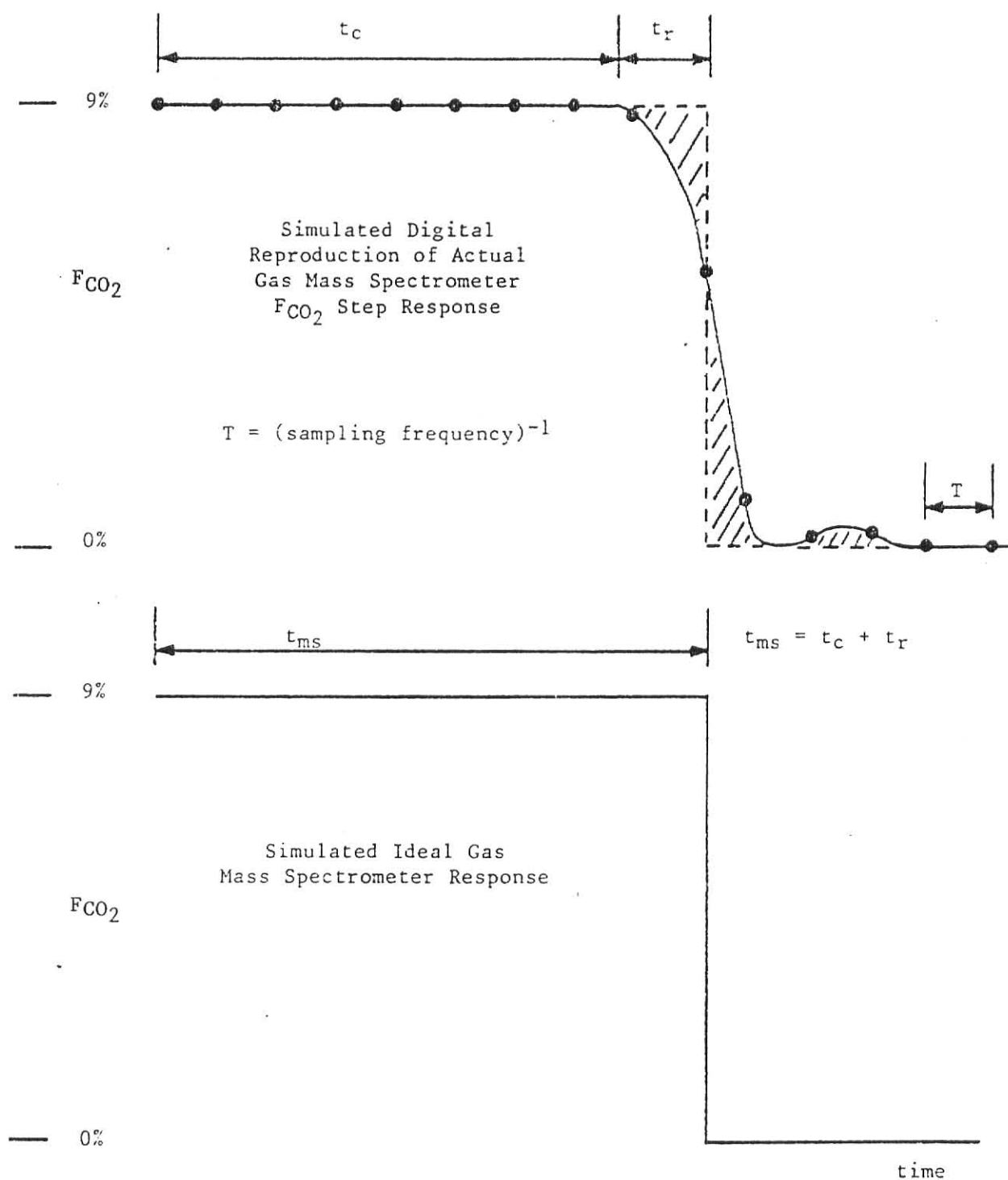


Figure 4.4 Selection of the Terminal End Point for the GMS Delay Time.

Based on the equal area above and below the F_{CO_2} step response curve criterion. t_c is the capillary delay time, t_r is the electrical response time, and t_{ms} represents the total delay time.

4.2.3 Calculation of Breath-by-Breath Respiratory Gas Volumes

In order to calculate breath-by-breath oxygen consumption and carbon dioxide production at the mouth three respiratory signals are required:

- 1) Fractional CO_2 concentration, F_{CO_2} ,
- 2) Fractional O_2 concentration, F_{O_2} ,
- 3) Respiratory Flow, $\dot{V}$.

In addition, several other quantities are required to compute the correction factors necessary to compensate for the differences in humidity and temperature between the subject's body and the test environment. Refer to Table 4.1 for a complete definition of symbols.

Total volumes for gas inspired and expired for a particular breath are given by the integral of the respiratory flow signal.

For inspiration:

$$(V_I)_M = \int_{\text{insp}} \dot{V}_I[\text{BTPS}] dt \quad (4-1)$$

and for expiration:

$$(V_E)_M = \int_{\text{expr}} \dot{V}_E[\text{BTPS}] dt \quad (4-2)$$

To correct the respiratory volumes to the subject's body temperature, the inspiratory and expiratory flow signals measured at the PTM are corrected as follows:

$$\dot{V}_I[\text{BTPS}] = \dot{V}_I \cdot K_I[\text{BTPS}] \quad (4-3)$$

$$\dot{V}_E[\text{BTPS}] = \dot{V}_E \cdot K_E[\text{BTPS}] \quad (4-4)$$

where $K_I[\text{BTPS}]$ and $K_E[\text{BTPS}]$ are defined by Phper et. al., [24]

and shown here:

TABLE 4.1

Definition of Symbols for Computing
Breath-by-Breath Respiratory Volumes

F_{ICO_2} , F_{IO_2}	Dry fractional gas concentrations in the inspire.
F_{ECO_2} , F_{EO_2}	Dry fractional gas concentrations in the expirate.
$K_I[BTPS]$, $K_E[BTPS]$	Factors to correct inspiratory and expiratory flows to BTPS conditions.
$K_I[STPD]$, $K_E[STPD]$	Factors to correct inspiratory and expiratory flows to STPD conditions.
P_B	Barometric pressure (Torr).
$P_{H_2O}[T_I]$, $P_{H_2O}[T_E]$, $P_{H_2O}[T_B]$	Saturated H_2O vapor pressures at the specified temperatures (Torr).
R_H	Atmospheric relative humidity.
T_B	Body temperature of the subject ($^{\circ}C$).
T_I , T_E	Average temperatures for inspiratory and expiratory gas flows. Measured on the subject side of the PTM, close to the location where the flow is measured ($^{\circ}C$).
$(V_{CO_2})_M$, $(V_{O_2})_M$	Total CO_2 and O_2 gas volumes (STPD) exchanged during one breath, measured at the mouth (liters).
V_{IO_2} , V_{ICO_2}	Integrated inspiratory volumes for O_2 and CO_2 . Corrected to STPD conditions (liters).
$\dot{V}_I$, $\dot{V}_E$	Respiratory gas flow during inspiration and expiration as measured using the PTM (liters $\cdot$ sec $^{-1}$).
$\dot{V}_I[BTPS]$, $\dot{V}_E[BTPS]$	Inspiratory and expiratory gas flows corrected to BTPS conditions (liters $\cdot$ sec $^{-1}$).

TABLE 4.1 cont.

$(V_I)_M, (V_E)_M$	Total respiratory lung gas volumes (BTPS) for a particular breath, measured at the mouth (liters).
$\dot{V}_I[\text{STPD}], \dot{V}_E[\text{STPD}]$	Inspiratory and expiratory gas flows corrected to STPD conditions ($\text{liters} \cdot \text{sec}^{-1}$).
V_{EO_2}, V_{ECO_2}	Integrated expiratory volumes for O_2 and CO_2 . Corrected to STPD conditions (liters).

$$K_I[BTPS] = \left[\frac{P_B - R_H \cdot P_{H_2O}[T_I]}{P_B - P_{H_2O}[T_B]} \right] \cdot \left[\frac{273 + T_B}{273 + T_I} \right] \quad (4-5)$$

$$K_E[BTPS] = \left[\frac{P_B - P_{H_2O}[T_E]}{P_B - P_{H_2O}[T_B]} \right] \cdot \left[\frac{273 + T_B}{273 + T_I} \right] \quad (4-6)$$

Note that the expiratory flow is assumed to be 100% saturated with water vapor in the calculation for $K_E[BTPS]$. The relative humidity, R_H , is used to compute $K_I[BTPS]$ since $P_{H_2O}[T_I]$ is a saturated water vapor pressure. Ordinarily the room air in the laboratory which the subject inspires is only 35% to 75% saturated with water vapor.

Total volumes of O_2 and CO_2 exchanged during one breath

((V_{O_2})_M and (V_{CO_2})_M), measured at the mouth, are given by the difference between their inspired and expired volumes [13],

$$(V_{O_2})_M = \int_{\text{insp}} F_{IO_2} \cdot \dot{V}_I[STPD] \cdot dt - \int_{\text{expr}} F_{EO_2} \cdot \dot{V}_E[STPD] \cdot dt \quad (4-7)$$

$$(V_{CO_2})_M = \int_{\text{expr}} F_{ECO_2} \cdot \dot{V}_E[STPD] \cdot dt - \int_{\text{insp}} F_{ICO_2} \cdot \dot{V}_I[STPD] \cdot dt \quad (4-8)$$

The dry fractional gas concentrations are measured by the GMS in the mainstream of the respiratory flow, on the room air side of the PTM. $\dot{V}_I$ and $\dot{V}_E$ are the inspiratory and expiratory gas flows sensed by the PTM near the location where the fractional concentrations are measured. Commonly, the volume of a gas species is always expressed in STPD conditions [25]. $\dot{V}_I$ and $\dot{V}_E$ are scaled to STPD using the relationships:

$$\dot{V}_I[STPD] = \dot{V}_I \cdot K_I[STPD] \quad (4-9)$$

$$\dot{V}_E[STPD] = \dot{V}_E \cdot K_E[STPD] \quad (4-10)$$

where $K_I[STPD]$ and $K_E[STPD]$ are defined by Phper et. al., [24]:

$$K_I[STPD] = \left[\frac{P_B - R_H \cdot P_{H_2O}[T_I]}{760} \right] \cdot \left[\frac{273}{273 + T_I} \right] \quad (4-11)$$

$$K_E[STPD] = \left[\frac{P_B - P_{H_2O}[T_E]}{760} \right] \cdot \left[\frac{273}{273 + T_E} \right] \quad (4-12)$$

In section 3.1 representative signals for an exercising calf were presented. A description of how these signals are used in a digital fashion to implement the integrals for computing the respiratory variables is described in the following paragraphs.

After being digitized by the DAM and passed to the computer, the respiratory signals reside in the computer's memory as three arrays of discrete BCD data points. Initially, the digitized flow signal is not time aligned with the fractional concentration signals. To properly align them, the indicies of the data arrays are shifted by the number of points corresponding to the time delay computed by the GMS Time Delay Determination Subroutine. The actual number of points by which the data arrays are shifted depends on the sampling frequency at which the data points were acquired. Figure 4.5 illustrates how the time aligned digital signals compare with the actual analog respiratory signals.

Once the proper alignment of the digital data sets is achieved, two new data arrays are formed; one, the point-by-point product of the $\dot{V}[STPD]$ and F_{O_2} arrays, the other, the point-by-point product of the $\dot{V}[STPD]$ and F_{CO_2} arrays. These new arrays are digital representations of the flow of CO_2 gas and the flow of O_2 gas with respect to time. Both of the resultant arrays oscillate around

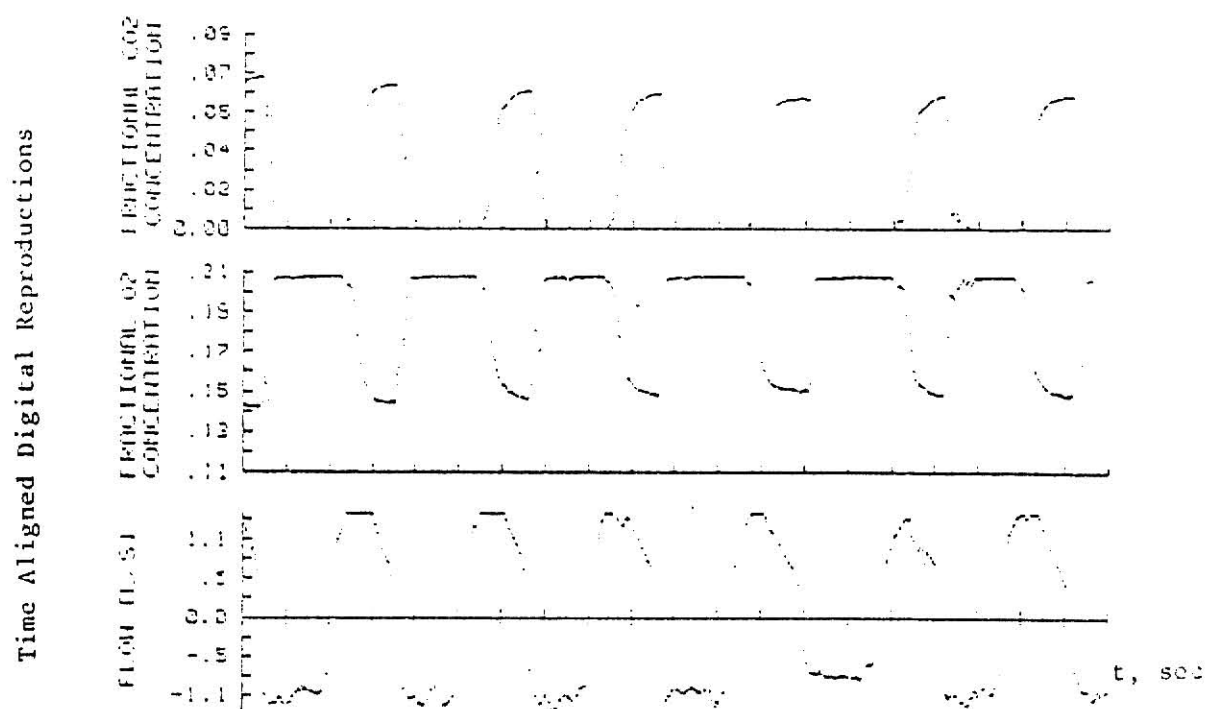
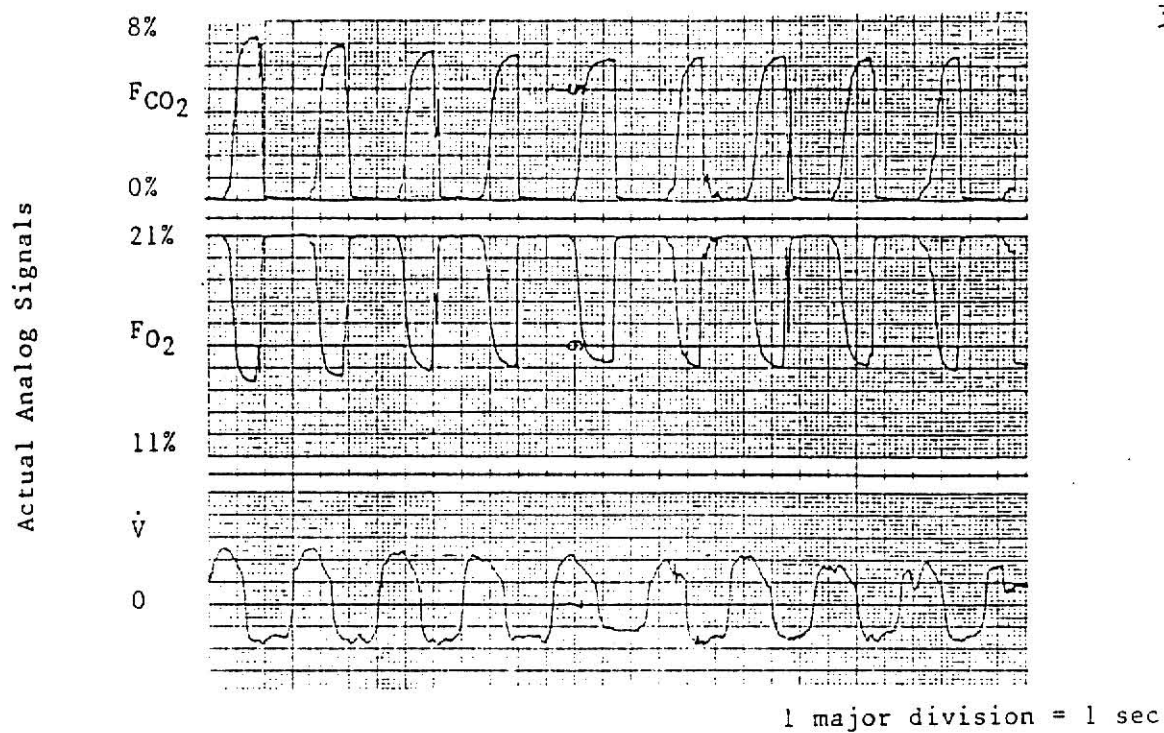


Figure 4.5 Comparison of Actual Analog Respiratory Signals with their Time Aligned Digital Reproductions.

a zero flow base line with the negative regions corresponding to inspiration and the positive regions to expiration. The areas enclosed by the composite flow signals are directly related to the amounts of O_2 and CO_2 present in the inspiratory and expiratory volumes.

The Trapezoidal Rule, a numerical integration technique, is used to compute the volumes of total gas, and O_2 and CO_2 inspired and expired during any given breath. Figure 4.6 illustrates the Trapezoidal Rule technique. Prior to integration, any dc offsets determined during calibration are subtracted from the digital flow signals, and each flow signal is multiplied by the appropriate calibration factors. The relationships used to convert the unitless BCD data into data with meaningful units are:

$$CO_2 \text{ Gas Flow (l/s)} = \text{BCD flow} \times \text{Flow calibration factor} \times$$

$$CO_2 \text{ calibration factor}$$

$$O_2 \text{ Gas Flow (l/s)} = (\text{BCD } O_2 \text{ flow} \times O_2 \text{ calibration factor} + 0.11) \times$$

$$\text{Flow calibration factor.}$$

The 0.11 is included in the O_2 gas flow equation because the GMS is adjusted to zero suppress 11% O_2 , which means that an 11% O_2 gas mixture input to the GMS yields a 0 volt output, resulting in a zero BCD value when sampled by the DAM.

In performing the integration, the data analysis routine searches through the flow data array until a positive-to-negative zero crossing, marking the beginning of the first complete breath is found. The volumes for total gas inspired, V_I ; oxygen inspired, V_{IO_2} ; and carbon dioxide inspired, V_{ICO_2} ; are estimated using the following equations:

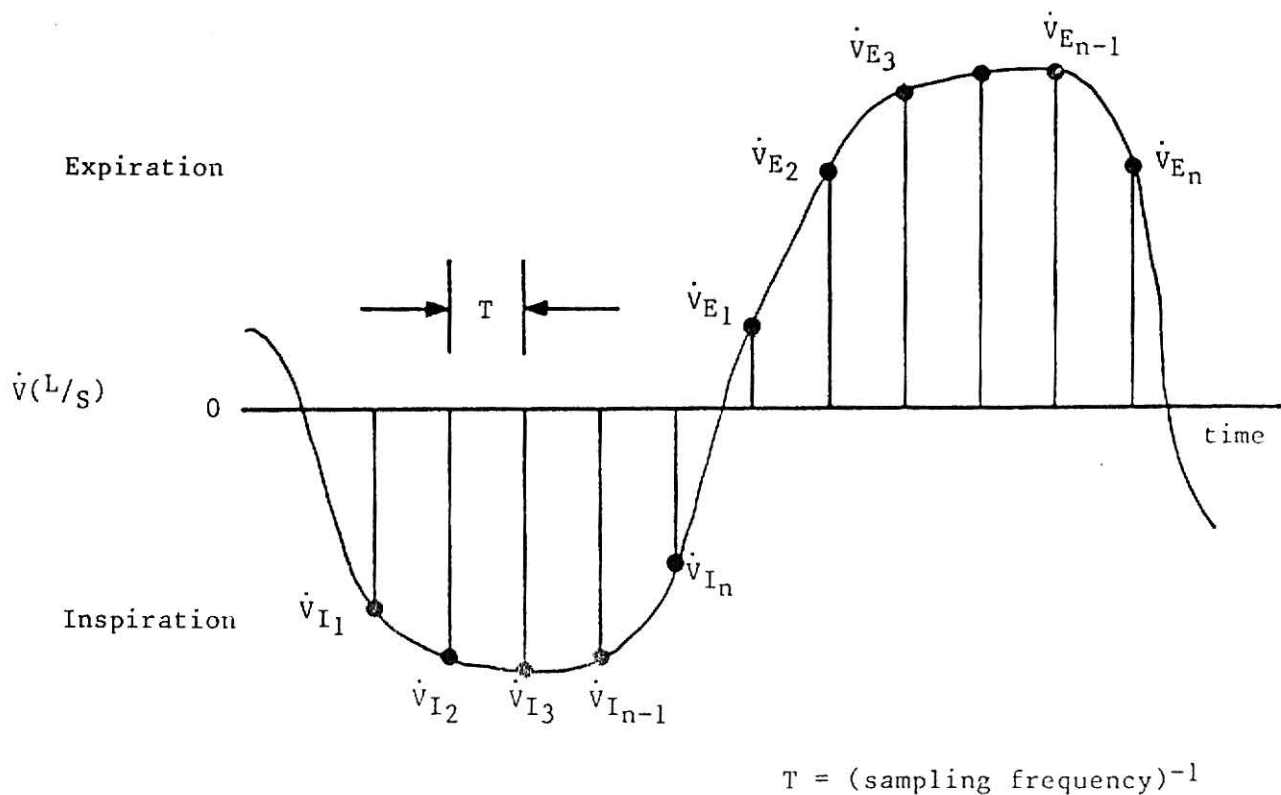


Figure 4.6 Area by Approximation Using the Trapezoidal Rule.

If $\dot{V}_1, \dot{V}_2, \dots, \dot{V}_{n-1}, \dot{V}_n$ are the lengths of a series of n equally spaced chords, and if T is their distance apart, the area enclosed by the flow ($\dot{V}$) curve (corresponding to volume, V) is given approximately by:

$$V = \left(\frac{1}{2} \dot{V}_1 + \sum_{i=2}^{n-1} \dot{V}_i + \frac{1}{2} \dot{V}_n \right) T$$

$$V_I = [0.5 V_{I_1} + [\sum_{i=2}^{n-1} \dot{V}_{I_i}] + 0.5 \dot{V}_{I_n}] \cdot T \quad (4-13)$$

$$V_{ICO_2} = [0.5 V_{I_1}(F_{ICO_2})_1 + [\sum_{i=2}^{n-1} \dot{V}_{I_i}(F_{ICO_2})_i] + 0.5 \dot{V}_{I_n}(F_{ICO_2})_n] \cdot T \quad (4-14)$$

$$V_{IO_2} = [0.5 \dot{V}_{I_1}(F_{IO_2})_1 + [\sum_{i=2}^{n-1} \dot{V}_{I_i}(F_{IO_2})_i] + 0.5 \dot{V}_{I_n}(F_{IO_2})_n] \cdot T \quad (4-15)$$

Likewise, the expiratory volumes for total gas expired, V_E , oxygen expired, V_{EO_2} , and carbon dioxide expired, V_{ECO_2} are estimated using:

$$V_E = [0.5 \dot{V}_{E_1} + [\sum_{i=2}^{n-1} \dot{V}_{E_i}] + 0.5 \dot{V}_{E_n}] \cdot T \quad (4-16)$$

$$V_{ECO_2} = [0.5 \dot{V}_{E_1}(F_{ECO_2})_1 + [\sum_{i=2}^{n-1} \dot{V}_{E_i}(F_{ECO_2})_i] + 0.5 \dot{V}_{E_n}(F_{ECO_2})_n] \cdot T \quad (4-16)$$

$$V_{EO_2} = [0.5 \dot{V}_{E_1}(F_{EO_2})_1 + [\sum_{i=2}^{n-1} \dot{V}_{E_i}(F_{EO_2})_i] + 0.5 \dot{V}_{E_n}(F_{EO_2})_n] \cdot T \quad (4-18)$$

In each of the six equations above, T represents the sampling period and n represents the number of discrete data points for a particular inspiration or expiration. After computing these volumes for the first breath, this procedure repeats for successive breaths until the digital data are exhausted.

After the respiratory volumes for a given breath are computed, the oxygen consumed $(V_{O_2})_M$ and the carbon dioxide produced $(V_{CO_2})_M$ for that breath are calculated as follows:

$$O_2 \text{ Consumed: } (V_{O_2})_M = V_{IO_2} - V_{EO_2}$$

$$CO_2 \text{ Produced: } (V_{CO_2})_M = V_{ECO_2} - V_{ICO_2}$$

Once computed, these values are organized into arrays and preserved for future printout and display.

4.2.4 Calculation of Additional Respiratory Quantities

As the breath-by-breath respiratory volumes are computed, the analysis routine calculates the time associated with each particular inspiration and expiration. Since the BCD data are obtained at discrete, regular time intervals, the respiratory times are simply calculated using the relationships:

$$t_i = (\text{number of inspiratory points}) \cdot T \quad (4-19)$$

$$t_e = (\text{number of expiratory points}) \cdot T \quad (4-20)$$

After the analysis routine concludes calculating the breath-by-breath volumes, several additional average and time dependent quantities are calculated. Following is a summary of the equations programmed into the Data Analysis Routine to perform the additional calculations.

$$\text{Total Inspiratory Time (sec): } t_I = \sum_{i=1}^{B_T} t_i \quad (4-21)$$

$$\text{Total Expiratory Time (sec): } t_E = \sum_{i=1}^{B_T} t_e \quad (4-22)$$

$$\text{Total Respiratory Time (sec): } t_R = t_I + t_E \quad (4-23)$$

$$\text{Inspiratory Minute Volume: } \dot{V}_I = \left[\sum_{i=1}^{B_T} (V_I)_{M_i} \right] \cdot 60 \cdot t_R^{-1} \quad (4-24)$$

(liters·sec⁻¹, BTPS)

$$\text{Expiratory Minute Volume: } \dot{V}_E = \left[\sum_{i=1}^{B_T} (V_E)_{M_i} \right] \cdot 60 \cdot t_R^{-1} \quad (4-25)$$

(liters·sec⁻¹, BTPS)

$$\text{Inspiratory Tidal Volume: } V_{TI} = \left[\sum_{i=1}^{B_T} (V_I)_{M_i} \right] \cdot B_T^{-1} \quad (4-26)$$

(liters, BTPS)

$$\text{Expiratory Tidal Volume: } V_{TE} = \left[\sum_{i=1}^{B_T} (V_E)_{M_i} \right] \cdot B_T^{-1} \quad (4-27)$$

(liters, BTPS)

$$\begin{array}{l} \text{Inspiratory O}_2 \text{ Tidal Volume: } V_{TIO_2} \\ \text{(liters, STPD)} \end{array} = \left[\sum_{i=1}^{B_T} (V_{IO_2})_i \right] \cdot B_T^{-1} \quad (4-28)$$

$$\begin{array}{l} \text{Expiratory O}_2 \text{ Tidal Volume: } V_{TEO_2} \\ \text{(liters, STPD)} \end{array} = \left[\sum_{i=1}^{B_T} (V_{EO_2})_i \right] \cdot B_T^{-1} \quad (4-29)$$

$$\begin{array}{l} \text{Inspiratory CO}_2 \text{ Tidal Volume: } V_{TICO_2} \\ \text{(liters, STPD)} \end{array} = \left[\sum_{i=1}^{B_T} (V_{ICO_2})_i \right] \cdot B_T^{-1} \quad (4-30)$$

$$\begin{array}{l} \text{Expiratory CO}_2 \text{ Tidal Volume: } V_{TECO_2} \\ \text{(liters, STPD)} \end{array} = \left[\sum_{i=1}^{B_T} (V_{ECO_2})_i \right] \cdot B_T^{-1} \quad (4-31)$$

$$\begin{array}{l} \text{Tidal O}_2 \text{ Consumption:} \\ \text{(liters, STPD)} \end{array} \quad V_{TO_2} = V_{TIO_2} - V_{TEO_2} \quad (4-32)$$

$$\begin{array}{l} \text{Tidal CO}_2 \text{ Production:} \\ \text{(liters, STPD)} \end{array} \quad V_{TCO_2} = V_{TECO_2} - V_{TICO_2} \quad (4-33)$$

$$\begin{array}{l} \text{Minute O}_2 \text{ Consumption:} \\ \text{(liters} \cdot \text{min.}^{-1}, \text{ STPD)} \end{array} \quad \dot{V}_{O_2} = V_{TO_2} \cdot 60 \cdot t_R^{-1} \quad (4-34)$$

$$\begin{array}{l} \text{Minute CO}_2 \text{ Production:} \\ \text{(liters} \cdot \text{min.}^{-1}, \text{ STPD)} \end{array} \quad \dot{V}_{CO_2} = V_{TCO_2} \cdot 60 \cdot t_R^{-1} \quad (4-35)$$

$$\text{Respiratory Quotient:} \quad R = \dot{V}_{CO_2} \cdot \dot{V}_{O_2}^{-1} \quad (4-36)$$

In each of the above equations, the subscript i , represents the i^{th} breath, and B_T represents the total number of breaths that occurred during the experiment.

4.2.5 Data Display and Program Output

Prior to the analysis of experimental data, the System Controller Routine provides the system operator the option of generating a plot of the data. The digital data sets for the flow and fractional concentration signals are plotted on the CRT, utilizing the graphics capabilities of the computer. The user controls the number of points to be plotted and the calibration factors used to scale the digital data. If no calibration factors are used, the Data Plotting Subroutine normalizes them to one, in which case the data are plotted in terms of Analog-to-Digital Converter Units, ADUs.

After the plot is completed, the user has the option of dumping the CRT display to an 11" graphics thermal printer for a hard copy record. An example of plotted data was previously given in Figure 4.5. Appendix A2.5 contains additional information regarding the Data Plotting Subroutine.

The organization and presentation of experimental results is a very important aspect of any experiment. The software which handles the task of displaying data and experimental results was written with the following objectives in mind:

- 1) Provide clear, easy to read documents.
- 2) Provide user feedback during inter-breath computations.
- 3) List breath-by-breath volumes for inspiratory and expiratory respiratory volumes of interest.
- 4) List mean values for the breath-by-breath quantities.
- 5) Allow for the option of hard copy of CRT display.
- 6) Be as "user friendly" as possible.

Figures 4.7 and 4.8 are reproductions of hard copy outputs from an experimental run. Analysis routine printout begins with a listing of the breath-by-breath volumes of the respiratory gases, and concludes with a listing of the average respiratory gas volumes and the time dependent respiratory variables. Additional information regarding the calibration factors and temperature correction factors is also provided at the conclusion of the listing of the experimental results. This allows the user to double check the values for the calibration and correction factors used by the Data Analysis Subroutine to generate the experimental results.

SUBJECT IDENTIFIER: CALF 125 EX 12

DATE: 8/17/82

Breath Number	Air Inspired (liters) RIPS	Air Expired (liters) RIPS	O ₂ Inspired (liters) SIPD	O ₂ Expired (liters) SIPD	CO ₂ Inspired (liters) SIPD	CO ₂ Expired (liters) SIPD	O ₂ Consumed (liters) SIPD	CO ₂ Produced (liters) SIPD	Insp Time (sec)	Exp Time (sec)
1	-1.456	1.377	-.248	.284	-.000	.022	-.036	.022	.46	.36
2	-1.821	1.528	-.296	.232	-.003	.030	-.065	.027	.50	.36
3	-2.026	2.182	-.320	.295	-.010	.054	-.025	.044	.60	.54
4	-2.374	2.366	-.392	.303	-.001	.073	-.039	.072	.66	.49
5	-1.478	1.807	-.239	.242	-.003	.046	.003	.043	.60	.42
6	-2.224	2.364	-.355	.303	-.008	.071	-.052	.063	.60	.52
7	-1.168	1.332	-.189	.192	-.002	.022	.004	.020	.34	.32
8	-2.321	2.439	-.382	.327	-.000	.061	-.054	.060	.66	.48
9	-1.554	1.400	-.252	.281	-.003	.024	-.051	.021	.44	.30
10	-2.131	2.178	-.348	.297	-.001	.050	-.051	.049	.60	.44
11	-2.380	2.517	-.390	.336	-.001	.066	-.054	.055	.66	.62
12	-2.678	2.689	-.437	.343	-.000	.074	-.077	.073	.70	.56
13	-1.190	1.037	-.196	.156	-.000	.012	-.040	.012	.36	.28
14	-2.380	2.614	-.389	.346	-.001	.072	-.043	.070	.70	.40
15	-2.290	2.348	-.376	.313	-.000	.062	-.063	.062	.70	.66
16	-2.257	1.999	-.369	.273	-.001	.048	-.076	.047	.62	.42
17	-2.359	2.196	-.388	.295	-.000	.055	-.073	.054	.68	.60
18	-1.978	2.311	-.338	.304	-.001	.062	-.023	.062	.69	.48
17	-2.216	2.143	-.365	.289	-.000	.043	-.076	.053	.62	.52

Figure 4.7 Data Analysis Routine Hard Copy Output for
Breath-by-Breath Respiratory Quantities.


```

Inspiratory minute volume = -114.3 liters per minute      BTPS
Expiratory minute volume = 116.5 liters per minute        BTPS
Inspiratory tidal volume = -2.016 liters                  BTPS
Expiratory tidal volume = 2.046 liters                     BTPS
Respiratory frequency = 56.9 breaths per minute

Mean O2 inspired = -.329 liters      STPD
Mean O2 expired = .276 liters        STPD
Mean CO2 inspired = -.002 liters     STPD
Mean CO2 expired = .050 liters       STPD
Mean O2 consumed per breath = -.053 liters      STPD
Mean CO2 produced per breath = .043 liters      STPD
O2 consumed per minute = -3.004 liters per minute  STPD
CO2 produced per minute = 2.756 liters per minute  STPD
RESPIRATORY QUOTIENT = .917

Total time of inspiration = 11.1 sec
Total time of expiration = 8.9 sec
Total time of respiration = 20.0 sec

Relative Humidity = 61 %

Average Inspiratory Temperature = 31.900
PH2O at 31.900 deg C = 21.632

Average Expiratory Temperature = 34.300
PH2O at 34.300 deg C = 40.570

Calf's Body Temperature = 38.700 deg C
PH2O at 38.700 deg C = 51.601

Barometric Pressure = 736.700

FLOW DC OFFSET = 125.00      CO2 DC OFFSET = 0.00      O2 DC OFFSET = 0.00
CO2 CALIBRATION FACTOR = 3.7000E-04      O2 CALIBRATION FACTOR = 3.9200E-04
INSPIRATORY FLOW CALIBRATION FACTOR = 5.7300E-02      EXPIRATORY FLOW CALIBRATION FACTOR = 5.9100E-02
SAMPLING FREQUENCY = 50
MASS SPECTROMETER TIME DELAY = 376 nsec
FLOW CALIBRATION FILENAME: C817A2

```

Figure 4.8 Data Analysis Routine Hard Copy Output for Average and Time Dependent Respiratory Quantities.

During printout of the interbreath respiratory volumes, the display routine prints out the respiratory volumes for each breath as they are calculated. This serves as feedback to inform the user that the program is functioning correctly and isn't stuck in an endless loop. At the time of printout, the user is questioned by the computer as to whether the printout should be directed to the CRT or the 2631B printer. After the printout is completed, printing control is always returned to the CRT.

V. EXPERIMENTAL METHODS

5.1 Animal Preparation

Hereford steers weighing 300 to 600 pounds were used to evaluate the performance of the computer based data acquisition and analysis system. Prior to conducting any experiments, the Hereford calves were acclimated to the environmental conditions of the laboratory. While in training, the calves had to become accustomed to walking on the slick waxed floors between the holding area and the laboratory; and accustomed to the experience of walking in place on the treadmill. Another obstacle was to get the calves to wear a custom fitted face mask which was necessary for holding the PTM and GMS sampling probe in close proximity to the nostril. Different sizes of masks were constructed to accomodate the changes in the size of the calves' muzzels as they matured. The masks, which served to channel all of the subject's respiratory gases through the PTM were constructed from rubber, marine resin, rubber o-rings, brass rings, PVC pipe, and canvas strappings. The frontispiece illustrates

the calf on the treadmill and the attachment of the PTM and sampling capillary using the mask.

As with humans, the disposition and intelligence varied between calves. Typically, two weeks were required to train the calves to run on the treadmill, and to familiarize them with the laboratory conditions. Throughout the training period, the calves were outfitted with two vital pieces of equipment used for capturing excreted waste materials. A urinal, consisting of a plastic funnel and rubber girdle was strapped around the abdomen with the funnel proximate to the penis. A rubber tube drained the urine out the side of the treadmill into a five gallon bucket. To catch the fecal material, hog rings were attached to the buttocks of each calf about six inches either side of the tail, and about six inches down from the anus. A plastic bag was stretched across the buttocks and tied to the hog rings. The center point on the opposite side of the bag was tied to the tail. With this system, when the calf lifted his tail to defecate, the plastic bag opened and the feces fell in. The equipment to contain the excrement served to keep the laboratory reasonably clean and the experiments running smoothly.

5.2 System Calibration

5.2.1 Fractional Concentration Gas Signal Calibration

Calibration of the gas fractional concentration signals was necessary to establish relationships between known gas concentrations and their corresponding DAM assigned BCD values. These calibration factors were subsequently used by the data analysis routine to

convert fractional concentration BCD data into data with fractional concentration units.

The equipment required to calibrate the fractional concentration signals is schematically illustrated in Figure 5.1. Three gas cylinders, each containing either pure O_2 , CO_2 , or N_2 , and a Digamix Type m/300a gas mixing pump (Calibrated Instruments Inc.) [26] were used to generate the calibration gas mixtures. The mixing pump is an extremely useful device for creating highly accurate gas mixtures of widely varying concentrations of the gas constituents. For this system, the mixing pump was plumbed so that gas mixtures of O_2 , CO_2 , and N_2 could be easily created as described in Table 5.1.

TABLE 5.1

Outline of Calibration Gas Mixture Combinations

Gas Species	% Concentration Range	Variable by % Increments of
Nitrogen (N_2)	0 to 100	10
Oxygen (O_2)	0 to 100	1
Carbon Dioxide (CO_2)	0 to 100	1

The GMS F_{CO_2} analog output was amplified and connected to DAM channel one. Since the GMS CO_2 channel is a zero to ten volt channel, it produces a zero volt output for a zero percent CO_2 input, and a ten volt output for a ten percent CO_2 gas mixture input. Generally, the CO_2 concentration in a calf's respiratory gases fluctuates between zero and eight percent. The amplifier was set to provide a ten volt output for a nine percent CO_2 input, and a zero volt output for a zero percent CO_2 input. This served to protect against random occurrences of transient high level CO_2 concentrations in the calf's respiratory flow.

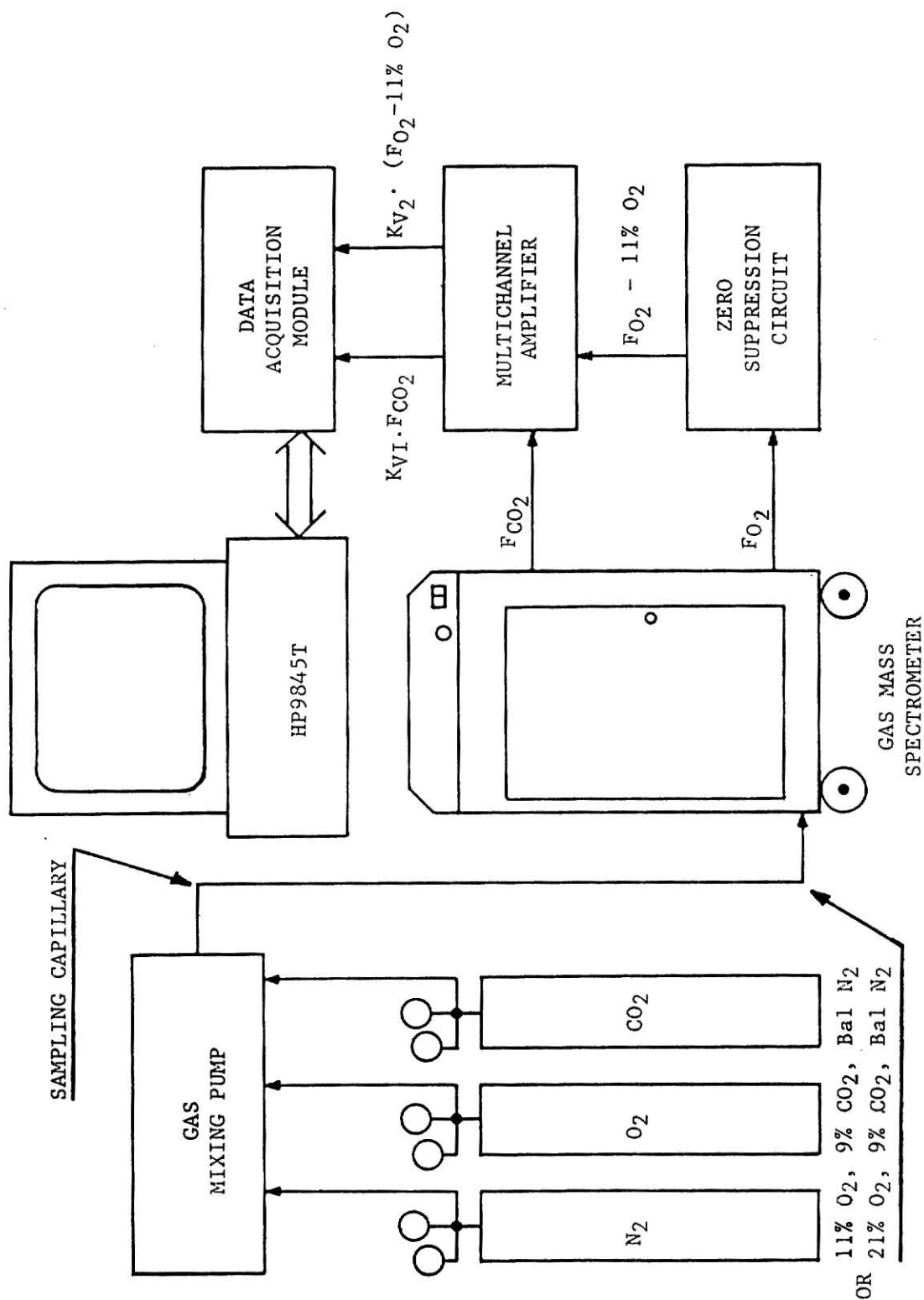


Figure 5.1 Calibration Hardware for Gas Fractional Concentration Signals.

Connection of the F_{O_2} signal to the DAM was somewhat more complicated. The GMS O_2 channel is a 100% channel, meaning that it gives a zero volt output for a zero percent input, and a ten volt output for a 100% O_2 input gas. The O_2 content of a calf's respiratory gases oscillates between 11% and 21%, corresponding to GMS F_{O_2} output voltages of 1.1 and 2.1 volts. If this signal was simply amplified so that a 21% O_2 gas signal input gave a ten volt output, an 11% gas signal input would result in a 5.2 volt output. Consequently, the F_{O_2} signal presented to the DAM would only utilize approximately half of the available zero to ten volt input voltage range, resulting in less than optimal resolution.

To enhance the F_{O_2} signal resolution, the GMS F_{O_2} output was conditioned using a zero suppression circuit. This circuit simply subtracted a dc voltage from the signal present at its input. The zero suppression circuit was set to give a zero volt output when an 11% gas signal input was applied to the GMS. The output of the zero suppression circuit was then amplified and connected to DAM input channel two. The amplification was set so that a 21% O_2 gas mixture resulted in a ten volt input signal to the DAM.

The heart of the DAM is an 8-bit NSC 8016 A/D converter [27] having eight binary outputs. Each output line can be in one of two possible states; a "1" or a "0", corresponding to five volts (or some voltage close to five volts) and zero volts (or something close to zero volts) respectively. With eight output lines, 256 different binary combinations are possible. The DAM electronics are designed such that a zero volt analog input signal produces all zeros (0 BCD) on the binary outputs, and a 10.24 volt input

produces all ones (255 BCD). Since only 256 output combinations are possible, not every analog input voltage has a unique corresponding binary output. In fact, the analog inputs to the DAM are classified by the A/D converter in 40 mV increments resulting in the staircase transfer characteristic depicted in Figure 5.2. Also illustrated are the relationships between the gas fractional concentration signals and the DAM binary outputs. For F_{CO_2} , zero percent CO_2 corresponds to binary zero, and nine percent CO_2 corresponds to binary 255 (or some binary value close to 255, depending on the amplifier setting). For F_{O_2} , 11% O_2 corresponds to binary zero and 21% O_2 corresponds to binary 255 (or something close to 255, again depending on the amplification). After the binary data are passed over the 16-bit parallel interface (using only 8 bits for data transfer, the remaining bits for control) they reside in the computer's random access memory, and are available for computations in a BCD format.

Once the hardware connections were made as described above, calibration of the fractional concentration signals was possible. A software subroutine was written to systematically aid the user in the procurement of the required calibration factors. Besides calculating calibration factors, the BCD equivalents as obtained by the DAM for zero percent CO_2 and 11% O_2 were also stored for use by the Data Analysis Routine. These values represent the BCD equivalents of any dc offset in either of the fractional concentration channels, and were subtracted from data obtained in subsequent experimental runs. A description of the step-by-step procedure used to calibrate the gas fractional concentration signals prior to each experimental run follows.

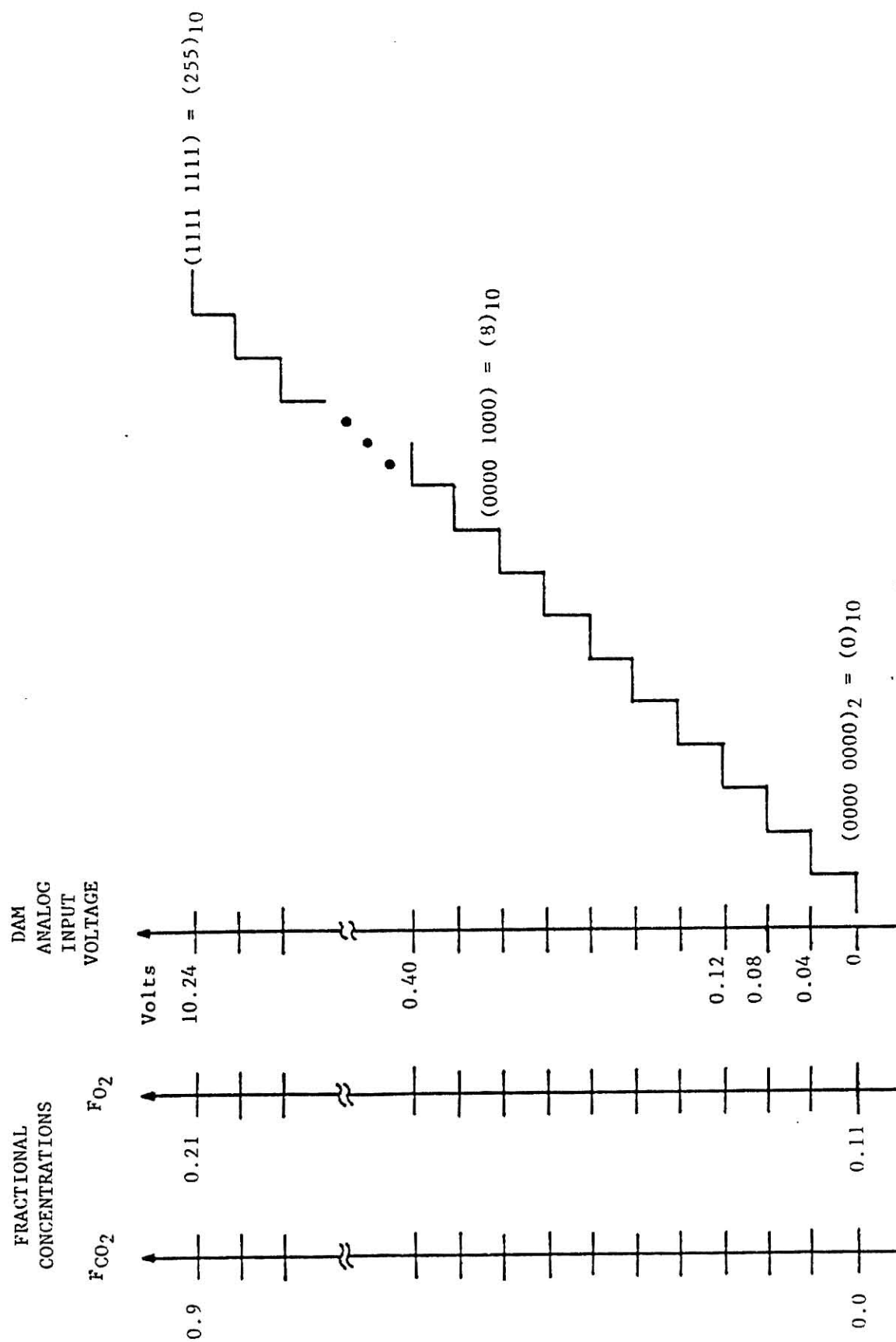


Figure 5.2 Analog-to-Digital Conversion Staircase Transfer Function.

1. The mixing pump was set to deliver a gas mixture of 9% CO_2 , 11% O_2 , and 80% N_2 .
2. The GMS sampling capillary was connected to the gas mixture of Step 1. The GMS gain and dc offset potentiometers were adjusted until the concentrations as displayed by the GMS agreed with the actual input concentrations.
3. The GMS sampling capillary was placed in 100% N_2 . This provided a zero percent CO_2 gas input to the GMS.
4. The F_{CO_2} output was read by the computer via the DAM. One hundred values were read and averaged over a period of one second. The result represented the BCD value for the dc offset in the F_{CO_2} channel (ordinarily zero) and the BCD value for a gas input signal having zero percent CO_2 .
5. The GMS sampling capillary was placed in the gas mixture of Step 1.
6. The actual fractional concentrations of O_2 and CO_2 as displayed by the GMS were entered into the computer.
7. One hundred values were read and averaged from both the F_{O_2} and F_{CO_2} channels, over a period of one second, by the computer, via the DAM. The average for the F_{CO_2} channel represented the BCD equivalent for a gas mixture of 9% CO_2 . The average for the F_{O_2} channel represented both the BCD value for the dc offset in the F_{O_2} channel, and the BCD equivalent of an 11% F_{O_2} gas signal.
8. The mixing pump was set to deliver a gas mixture of 9% CO_2 , 21% O_2 , and 70% N_2 . Time was allowed to let the gas concentrations stabilize.
9. The GMS sampling capillary was placed in the gas mixture of Step 9.
10. The actual fractional concentration of O_2 as displayed by the GMS was entered into the computer.
11. One hundred values from the F_{O_2} channel were read and averaged by the computer via the DAM. The result represented the BCD equivalent for a gas mixture having a 21% O_2 content.
12. F_{O_2} and F_{CO_2} calibration factors were calculated using the relationships:

$$\text{F}_{\text{O}_2} \text{ Calibration Factor } [\text{O}_2_cal] = \frac{\text{Known value for 21\% O}_2}{\text{BCD average value read for 21\% O}_2} - \frac{\text{Known value for 11\% O}_2}{\text{BCD average value read for 11\% O}_2}$$

$$\text{F}_{\text{CO}_2} \text{ Calibration Factor } [\text{Co}_2_cal] = \frac{\text{Known value for 9\% CO}_2}{\text{BCD average value read for 9\% CO}_2} - \frac{\text{Known value for 0\% CO}_2}{\text{BCD average value read for 0\% CO}_2}$$

13. The F_{O_2} and F_{CO_2} calibration factors and corresponding BCD dc offset equivalents were stored on magnetic tape.

In Step 12, O_2_cal and Co_2_cal are the program variable names for the F_{O_2} and F_{CO_2} calibration factors. Appendix II contains further information regarding the Fractional Gas Signal Calibration Subroutine.

5.2.2 Flow Signal Calibration

The flow signal ($\dot{V}$) was calibrated using a Harvard small animal respirator, the Fleisch PTM, the Godart PTG, the DAM, a variable non-inverting amplifier, and the HP9845T desktop computer. Figure 5.3 illustrates the flow signal calibration system interconnections.

In calibrating the flow signal, there were actually three quantities necessary. First, there was the inspiratory and expiratory calibration factors, which were used to scale the discrete BCD flow data; and secondly, there was the BCD value associated with zero flow through the PTM. This value was used to distinguish each BCD flow data point as belonging to either inspiratory or expiratory flow. Turney et. al., [28] recommended the use of distinct calibration factors for inspiratory and expiratory flow. Separate calibration factors help to compensate for any PTM asymmetry which may exist, and also help to compensate for the limited DAM

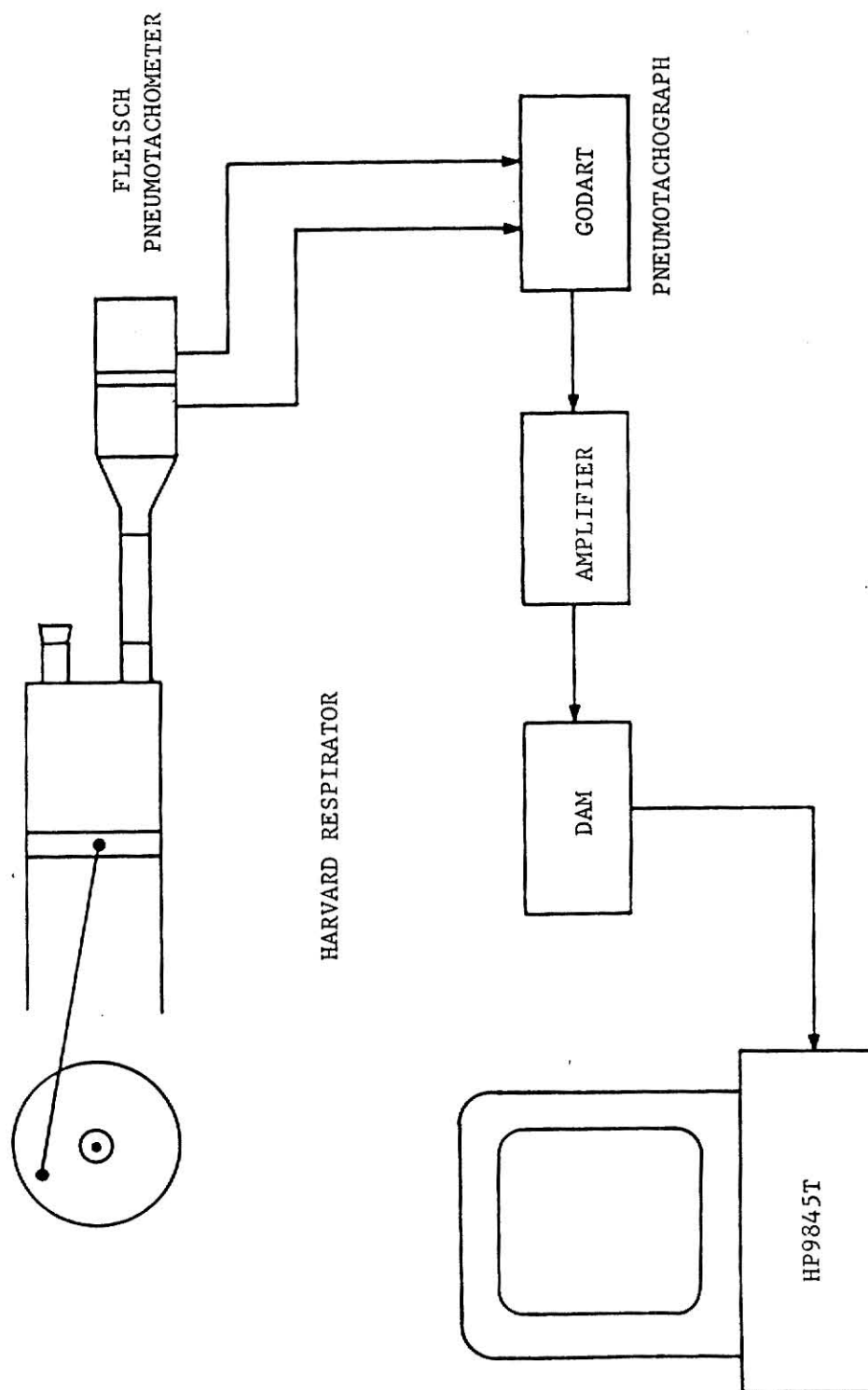


Figure 5.3 Flow Signal Calibration Instrumentation.

A/D converter resolution. A computer program (Flow Signal Calibration Subroutine, Appendix A2.2.2) was written to accomplish the flow signal calibration.

The respirator was adjusted to deliver maximum stroke volume (763 ml) and connected to force room air through the PTM bidirectionally. Since the respirator stroke volume was constant, equal volumes of air were moved through the PTM in alternate directions. The resultant flow gave rise to a proportional differential pressure in the PTM which was converted to an electrical analog (continuous) signal by the PTG. The PTG output signal was such that a negative output voltage corresponded to inspiratory flow (if connected to a subject) and a positive output voltage represented an expiratory flow. After being amplified to fall within a ± 5 volt range, the analog flow signal was connected to DAM input channel six (one of the three DAM channels with bipolar capability). The bipolar channels of the DAM were designed to yield zero BCD outputs for -5.12 volt inputs; approximately $(126)_{10}$ BCD outputs for zero volt inputs; and $(255)_{10}$ BCD outputs for 5.12 volt inputs. During calibration the BCD value corresponding to zero flow was obtained by averaging several values read over a two second interval. This value was subtracted from the BCD flow data obtained from an experimental run to distinguish between inspiration and expiration.

Since the expiratory cycle on the respirator was longer than the inspiratory cycle the resulting flow signal wasn't perfectly symmetric; however, the areas enclosed by the respiratory flow signal (corresponding to inspiratory and expiratory stroke volume)

were observed to be equal. The exact stroke volume of the respirator was experimentally determined to be 763 ml. Appendix II, Section A2.2.2 outlines the experimental protocol for determining the stroke volume.

To obtain the flow calibration factors and the BCD zero flow equivalent the following procedure was used each time prior to the collection of experimental data.

1. The PTG was zeroed as outlined in the Godart operation manual [14].
2. The PTM was connected to the subject, the PTM to the PTG, and the output of the PTG to a non-inverting amplifier whose output was fed to DAM input channel six.
3. Next the Data Acquisition Subroutine was run and the flow BCD data observed using the System Controller Routine.
4. The gain of the flow signal was adjusted such that the peak flow fell well within the limits of the BCD scale. This helped to insure that an occasional deep breath by the subject didn't saturate the flow channel.
5. Steps 3 and 4 were repeated until the objective of Step 4 was satisfied.
6. The Harvard respirator was adjusted to deliver a peak flow rate comparable to, but within the BCD limits of the DAM. At this point, the actual calibration factors were ready to be obtained using the Flow Signal Calibration Subroutine.
7. The input differential pressure valve on the PTG was closed. This provided a dc PTG signal output for zero flow.
8. The zero flow signal was sampled 200 times at a sampling frequency of 100 Hz using the Data Acquisition Subroutine. The average of these values was the BCD value used to distinguish inspiratory and expiratory flow.
9. The input differential pressure valve on the PTG was opened and the respirator turned on.
10. A three minute waiting period was executed to allow the temperature and pressure of the respirator gas to equilibrate.

11. Next, 1200 BCD samples were collected from the flow channel at a rate of 100 Hz. Depending on the exact respirator setting, 8 to 25 respirator cycles of BCD data were acquired.
12. The Data Analysis Routine was used to integrate the BCD flow data. For this, the BCD value for zero flow obtained in Step 8 was used, and the flow calibration factors were normalized to one.
13. The average values for the inspiratory and expiratory areas enclosed by the respirator flow signal (unscaled) were used to compute two separate flow calibration factors - one for inspiration, the other for expiration. Using the known volume of the respirator cyclinder, the flow calibration factors were calculated as follows:

$$\begin{array}{lcl} \text{Inspiratory Flow} & & 0.763 \quad (\text{liter}) \\ \text{Calibration Factor} & = & \frac{\text{av. Inspired Stroke Volume}}{\text{[Insp_flow_cal]}} \quad (\text{ADU} \cdot \text{sec}) \end{array}$$

$$\begin{array}{lcl} \text{Expiratory Flow} & & 0.763 \quad (\text{liter}) \\ \text{Calibration Factor} & = & \frac{\text{Av. Expired Stroke Volume}}{\text{[Expr_flow_cal]}} \quad (\text{ADU} \cdot \text{sec}) \end{array}$$

14. The zero flow BCD value and the calibration factors for respiratory flow were stored on tape in the calibration file for use in subsequent data analysis runs.

Insp_flow_cal and Expr_flow_cal are the program variable names for the respective calibration factors. Appendix 2.2.2 contains additional information regarding the details of operation of the Flow Signal Calibration Subroutine.

5.2.3 Mass Spectrometer Delay Time Estimation

Accurate determination of the GMS time delay is essential for computing breath-by-breath respiratory quantities. A complete discussion of this very important point was presented in Section 4.2.2. Determination of the time delay was performed prior to the collection of experimental data using the system illustrated in Figure 5.4, and the Time Delay Determination Subroutine which

is documented in Appendix A2.2.3. Calibration of each of the instruments depicted in Figure 5.4 was thoroughly discussed in Sections 5.2.1 and 5.2.2.

Simply stated, the software routine computes the GMS time delay to be the point along the F_{CO_2} step response curve where the areas above and below the curve are most nearly equal. Following is the step-by-step procedure which the GMS Time Delay Determination Subroutine controlled and executed prior to the collection of experimental data.

1. The DAM sampling frequency was set at 500 Hz using the sampling frequency selection subroutine.
2. The GMS sampling capillary was placed in the 9% CO_2 and 21% O_2 mixture used to determine the fractional concentration signal calibration factors.
3. Five hundred digital samples were read and averaged from the CO_2 channel using the computer and DAM.
4. The GMS sampling capillary was placed in room air.
5. Five hundred digital samples were read and averaged from the CO_2 channel using the computer and DAM.
6. The sampling capillary was once again placed in the 9% CO_2 mixture, making sure that the switch debounce LED indicator for "probe in" was illuminated.
7. The GMS Time Delay Determination Subroutine signaled the user to extract the sampling capillary from the 9% CO_2 mixture to room air as rapidly as possible.
8. The GMS time delay was calculated using the methods described in Section 4.2.2.
9. Steps 6, 7, and 8 were repeated two additional times to give a total of three trials.
10. The results of the three trials were averaged. The average value was displayed (in msec) and made available for storage on tape in the calibration file.

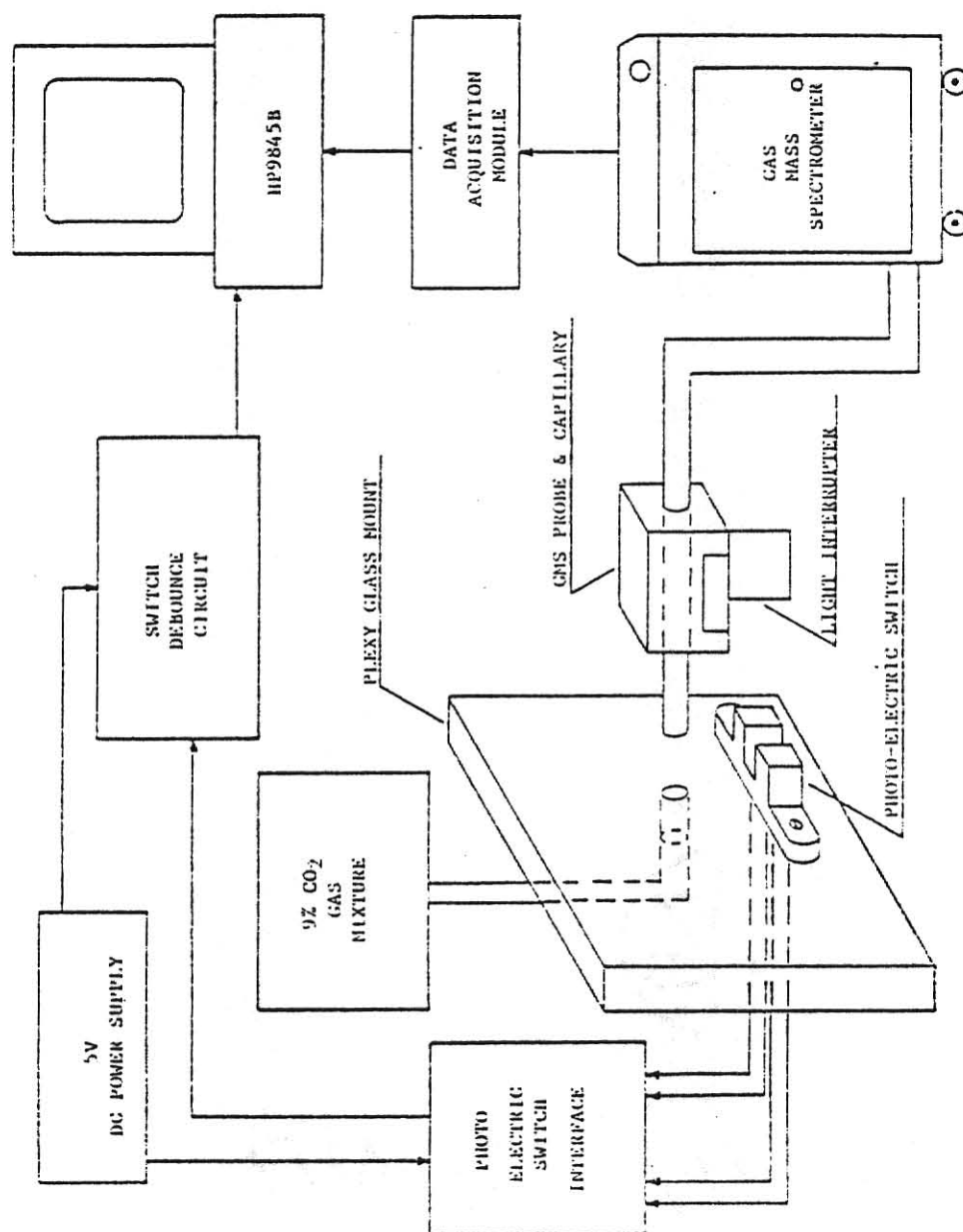


Figure 5.4 Instrumentation for GMS Time Delay Determination.

11. A plot of the CO₂ step response was generated on the CRT of the computer, then dumped to the thermal printer for a hard copy record.

Once the GMS time delay was determined it was assumed to remain constant throughout data collection. A study of the prudence of this procedure was conducted. Ultimately, it was determined that variations in the GMS time delay of less than 10 msec had no significant impact on the experimental data analysis. Documentation for this study is included in Appendix A2.2.3. This appendix also contains information about the GMS Time Delay Subroutine operation and program variables.

Once all of the calibration factors were obtained, the system operator had the option of storing them on tape. This allowed the use of the same calibration factors on multiple experimental runs. The data and sampling frequency for data acquisition were entered and stored along with the other calibration factors.

5.2.4 Temperature Calibrations

Calibration of the thermistor and tele-thermometer components used to monitor the subject's body temperature and respiratory flow temperature was performed without the aid of the DAM or the computer. Each of the tele-thermometers was calibrated to read correctly using their own particular thermistor, following the manufacturer's guidelines. This was considered a drastic type calibration which was only occasionally required. This calibration was performed using water baths of specific temperatures obtained using an adjustable heated water bath and a standard thermometer accurate to within ± 0.05 °C. At the conclusion of this calibration, the tele-thermometers closely agreed.

Since the tele-thermometers were battery operated, their baseline temperature readings drifted as the batteries ran down. This was periodically corrected for using a potentiometer to align the meter movement with a front panel indicator mark. Once correctly positioned, the tele-thermometer baseline remained stable for several hours.

The respiratory flow temperature was monitored using an analog chart recorder. To utilize the information from this recording some type of calibration was required to establish a relationship between the analog recorder pen deflection and the respiratory flow temperature. Figure 5.5 illustrates the equipment for calibrating the respiratory flow temperature signal. The vertical deflection on the recorder was divided into 50, 1.0 mm increments. Generally the system was calibrated so that 27 °C corresponded to a near zero pen deflection (i.e. just a few millimeters of pen deflection), and 37 °C corresponded to nearly 50 mm of pen deflection. A description of the step-by-step procedure employed to obtain such an arrangement is described below.

1. The tele-thermometer was adjusted to red-line using the positioning potentiometer.
2. Using the standard thermometer; and hot and cold tap water, a 27 °C water mixture was generated in a beaker.
3. The thermistor was connected to the tele-thermometer and placed in the 27 °C water bath.
4. The pen deflection was adjusted close to zero.
5. The thermistor was transferred to the heated water bath, set at 36 °C.
6. The gain on the chart recorder amplifier was adjusted until the pen deflection registered close to full scale on the chart.

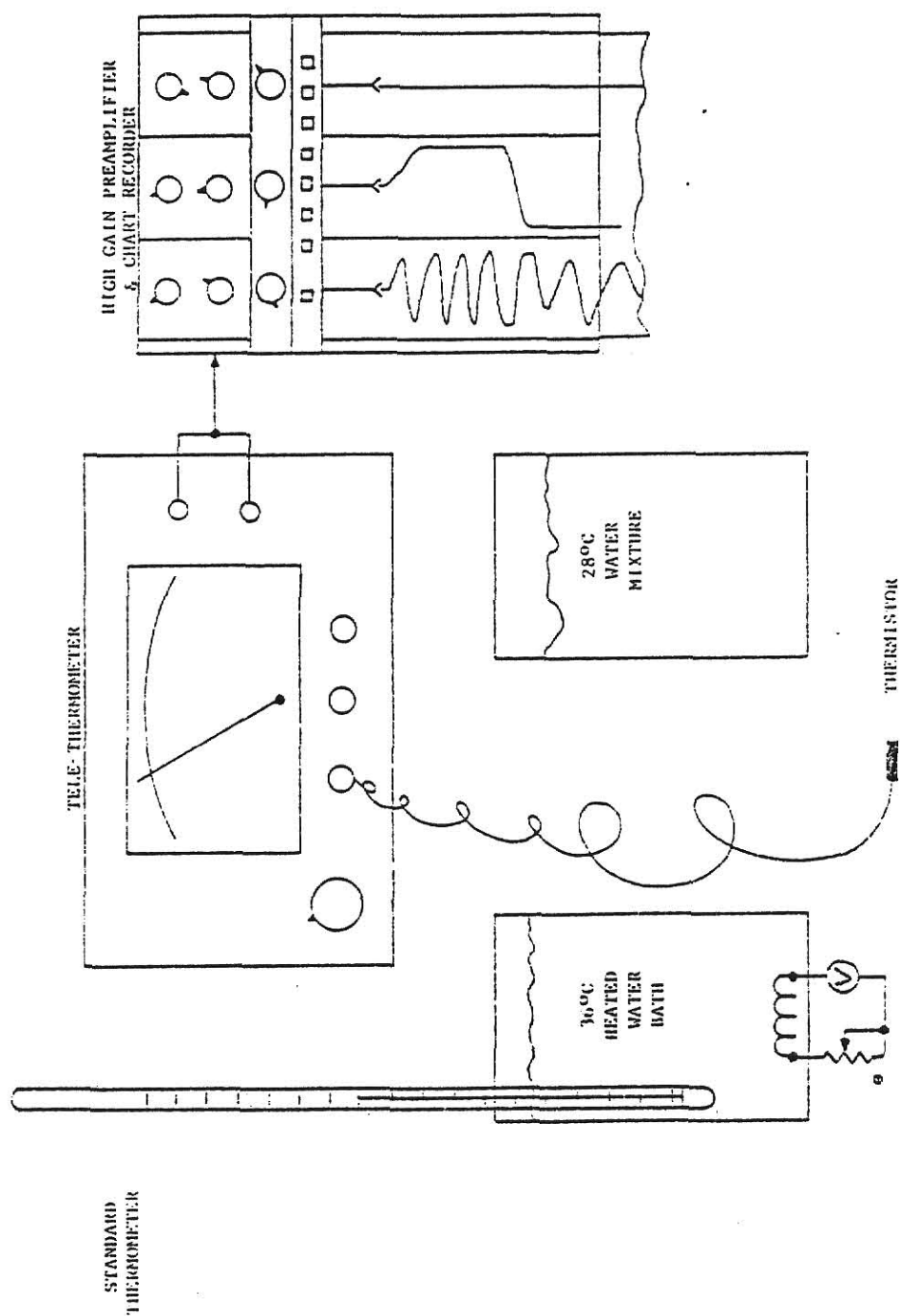


Figure 5.5 Instrumentation for Temperature Calibration.

7. The thermistor was transferred back to the 27 °C water bath.
8. Steps 4-7 were repeated until no further adjustments were required.
9. The actual temperature for the 27 °C water bath, as measured using the standard thermometer, was recorded directly on the chart near the actual mark corresponding to a 27 °C pen deflection.
10. The actual temperature for the 36 °C water bath, as measured using the standard thermometer, was recorded directly on the chart near the actual mark corresponding to a 36 °C pen deflection.
11. The number of degrees Centigrade per millimeter was calculated as follows:

$$\text{Temperature Factor} \quad (\text{°C} \cdot \text{mm}^{-1}) = \frac{\text{High Temperature near 36 °C} - \text{Low Temperature near 27 °C}}{\text{Pen Deflection for 36 °C} - \text{Pen Deflection for 27 °C}}$$

This temperature factor was then used for data analysis to compute the average inspiratory and expiratory flow temperature. Section 5.3.2 contains a description of how the average inspiratory and expiratory flow temperatures were determined.

5.3 Experimental Measurements

5.3.1 Data Collection

Once the system components were completely calibrated, data collection was possible. The System Controller Routine was set up to allow data collection of up to 15,000 data samples per DAM input channel, at a variable sampling frequency. Generally a sampling frequency of 50 Hz was used to collect either 15,000 or 7500 data samples from each channel. This translated into experimental run times of 5.0 and 2.5 minutes respectively.

During the course of data collection the instrumentation system ran itself, sampling the calf's respiratory flow and fractional concentration signals in the user prescribed manner. The system operator was required to record the calf's body temperature, the barometric pressure, and the atmospheric relative humidity as the instrumentation system collected data. These values were used during data analysis to correct the calculated respiratory volumes to BTPS and STPD conditions. The barometric pressure was read from a barometer accurate to within ± 0.05 Torr. Relative humidity was obtained using a wet bulb / dry bulb thermometer. Body temperature was read from a tele-thermometer connected to a thermistor positioned to sense the calf's rectal temperature.

Two calves were used to evaluate the performance of the experimental instrumentation system. At the time the experiments were conducted, calves #25 and #67 weighed approximately 500 and 400 pounds respectively. Each calf had resting tidal volumes between 1.0 and 1.5 liters. Three studies were conducted using the two calves.

In the first study, data were collected from calf #25 at rest. For the second study, rest data were collected from calf #67. In the third and final study, exercise data were taken from calf #25 at a treadmill speed of 1.0 meter per second. In each study, at least five trials were conducted, each on separate days.

For system verification purposes, emphasis was placed on the data from the first two resting studies. The results from these studies were compared with the results from an end-expired bag

collection system, as a basis for ascertaining the instrumentation system accuracy [29]. The bag collection system consisted of a two-way non-rebreathing valve and a meteorological balloon. Using the valve, the subject's respiratory gas was channeled into the bag during the experiment. Later, the volume of gas in the bag was measured using a tissot spirometer. While dumping the gas from the bag into the spirometer, the O_2 and CO_2 concentrations of the mixed expired respiratory gas were measured. Using the elapsed experimental time and the values mentioned above, several respiratory quantities could be computed. Results from bagged samples of mixed expired respiratory gas are a commonly accepted means of evaluating the accuracy of other types of respiratory measurement systems [5,6,12,13].

Since data from the instrumentation system and data from the bag system couldn't be acquired simultaneously, data for comparison purposes were collected from each system as closely together in time as possible. Rest data as opposed to exercise data were compared between the two systems because the calf's physiology could logically be assumed to be relatively consistent over a time interval of 10 to 20 minutes. This was the length of time required to collect data from both systems. In all runs, the instrumentation system data were obtained prior to the bag data.

5.3.2 Data Analysis

Once the experimental data were collected and stored in the computer, the Data Analysis Subroutine was employed to generate the experimental results. Although user interaction at this point

was minimal, the user was required to input the following values obtained during the course of the experiment. These values were used for temperature and water vapor corrections.

- 1) Relative Humidity.
- 2) Average inspiratory flow temperature, °C.
- 3) Average expiratory flow temperature, °C.
- 4) Barometric pressure, Torr.
- 5) Calf's body temperature, °C.

Water vapor pressure values corresponding to each of the input temperatures were acquired by accessing tabulated water vapor pressures stored on magnetic tape. Tabulated values from 25 to 40 °C by 0.1 °C increments were available, providing a sufficiently wide range and resolution. Collectively, the temperature and water vapor pressure values were manipulated by the system software to generate factors for scaling the respiratory flow data to either BTPS or STPD conditions. Details of these calculations were presented in Section 4.2.3.

The average inspiratory and expiratory flow temperatures were determined at the conclusion of each experiment utilizing information from the temperature tracing, and the temperature calibration factor (see Section 5.2.4). Roughly, the temperature tracing was observed to be sinusoidal in shape, fluctuating around a baseline temperature (refer to Figure 3.3). The baseline temperature and average peak deflections were estimated by sight, and the average inspiratory and expiratory flow temperatures were calculated by adding and subtracting 0.64 multiplied by the peak deflection (mm), and by the temperature calibration factor (°C/mm). The 0.64 factor represents the 1/2 cycle average of a sinusoidal waveform. Obviously, the values used for the average inspiratory and expiratory flow

were at best, good approximations. The value for the subject's body temperature was obtained directly from the tele-thermometer at the conclusion of an experimental run.

After procurement of the last of the necessary pieces of information for data processing, the analysis routine proceeded to generate the experimental results and program output as previously described.

VI. EXPERIMENTAL RESULTS

6.1 Presentation of the Experimental Results

Although breath-by-breath respiratory quantities are useful and desirable to obtain, they don't contribute much to the task of system verification. This is especially true when the system standard is only capable of providing average respiratory measurements as was the case in these experiments. To logically compare the resting results for the calves at rest, between the instrumentation system and the bag collection system, required that breath-by-breath data be averaged over all breaths and time scaled whenever appropriate. Since the analysis routine was already set up to generate this information, comparison of the average respiratory quantities between systems was convenient.

Unfortunately, not all of the computed quantities provided by the instrumentation system were obtainable from the bag system. The common variables between systems are presented in Tables 6.1 and 6.3. Table 6.4 compares the means and standard deviations over all experimental trails for each of the common variables, on both calves. Resting results provided only by the instrumentation

TABLE 6.1

Summary of Computerized Instrumentation System (CIS) and Expired Bag Collection System (BAG)
Results for Resting Minute Volumes, Tidal Volumes, and Respiratory Frequency.

Calf #	Trial #	Inspiratory Minute Volume (liters/min)		Exp. Minute Volume (liters/min)		Inspiratory Tidal Volume (liters)		Exp. Tidal Volume (liters)		Respiratory Frequency (min ⁻¹)	
		CIS	BAG	CIS	BAG	CIS	BAG	CIS	BAG	CIS	BAG
Calf #67	1	31.1	34	31.7	34	1.336	1.362	1.362	1.17	23.2	21
	2	34.0	31	34.1	31	1.330	1.333	1.333	1.08	25.6	29
	3	44.6	43	45.3	43	1.469	1.492	1.492	1.30	30.4	33
	4	33.0	33	32.6	33	1.528	1.511	1.511	1.17	21.6	28
	5	34.5	33	34.8	33	1.429	1.440	1.440	1.26	24.2	26
Calf #25	1	40.5	39	40.5	39	1.518	1.516	1.516	1.45	26.7	27
	2	36.6	42	38.0	42	1.736	1.761	1.761	1.95	21.6	22
	3	41.6	43	41.2	43	1.687	1.674	1.674	1.83	24.6	24
	4	42.9	44	42.9	44	1.650	1.651	1.651	1.59	26.0	28
	5	40.6	36	40.6	36	1.377	1.375	1.375	1.50	29.5	24

TABLE 6.2

Summary of CIS Results for Resting Tidal Volumes of: O₂ Inspired and Expired;
CO₂ Inspired and Expired; O₂ Consumed and CO₂ Produced.

MEAN O ₂ INSPIRED	MEAN O ₂ EXPIRED	MEAN CO ₂ INSPIRED	MEAN CO ₂ EXPIRED	MEAN O ₂ CONSUMED	MEAN CO ₂ PRODUCED
VTIO ₂ (liter)	VTEO ₂ (liter)	VTICO ₂ (liter)	VTECO ₂ (liter)	VTIO ₂ (liter)	VTCO ₂ (liter)

Calf #67

TRIAL #	CIS	CIS	CIS	CIS	CIS
1	0.215	0.191	0.003	0.029	0.024
2	0.215	0.184	0.003	0.031	0.030
3	0.235	0.207	0.004	0.037	0.028
4	0.244	0.205	0.005	0.041	0.038
5	0.226	0.195	0.005	0.035	0.032

Calf #25

TRIAL #	CIS	CIS	CIS	CIS	CIS
1	0.242	0.214	0.005	0.032	0.028
2	0.279	0.242	0.003	0.042	0.037
3	0.272	0.234	0.003	0.039	0.038
4	0.267	0.233	0.003	0.039	0.035
5	0.221	0.196	0.004	0.027	0.025

TABLE 6.3

Summary of CIS and Bag Resting Results for Minute O₂ Consumption, Minute CO₂ Production, Respiratory Quotient, and Associated Respiratory Times.

Calf #	Trial #	O ₂ Consumed per minute $\dot{V}O_2$ (liter/min)		CO ₂ Produced per minute $\dot{V}CO_2$ (liter/min)		Respiratory Quotient R		Total Time Insp (sec)		Total Time Exp (sec)		Total Time Respiration (sec)	
		CIS	BAG	CIS	BAG	CIS	BAG	CIS	BAG	CIS	BAG	CIS	BAG
Calf #67	1	0.557	0.67	0.593	0.65	1.065	0.972	65.8	68.2	134.0			
	2	0.779	0.67	0.723	0.64	0.929	0.967	42.5	34.9	77.4			
	3	0.854	0.80	0.988	0.84	1.156	1.050	38.3	30.9	69.1			
	4	0.828	0.67	0.766	0.67	0.925	1.004	60.9	50.3	111.2			
	5	0.764	0.71	0.724	0.70	0.948	0.989	63.9	47.9	111.7			
Calf #25	1	0.752	0.78	0.707	0.74	0.939	0.941	63.8	73.1	137.0			
	2	0.781	0.88	0.830	0.88	1.060	1.000	65.0	62.9	127.9			
	3	0.938	0.90	0.887	0.91	0.945	1.007	62.9	68.6	131.5			
	4	0.901	0.83	0.931	0.85	1.033	1.021	61.2	68.0	129.2			
	5	0.751	0.75	0.675	0.67	0.899	0.897	31.3	35.8	67.1			

TABLE 6.4

Comparison of Means and Standard Deviations Between Common Variables Measured
Using CIS and BAG Techniques.

VARIABLE	Calf #67		Calf #25	
	CIS MEAN $\pm$ S.D.	BAG EXPIRATE MEAN $\pm$ S.D.	CIS MEAN $\pm$ S.D.	BAG EXPIRATE MEAN $\pm$ S.D.
EXPIRATORY TIDAL VOLUME	1.428 $\pm$ 0.078	1.196 $\pm$ 0.086	1.595 $\pm$ 0.151	1.664 $\pm$ 0.217
VTE (liters) BTPS				
RESPIRATORY FREQUENCY	25.0 $\pm$ 3.4	27.4 $\pm$ 4.4	25.7 $\pm$ 2.9	25.0 $\pm$ 2.5
f (min ⁻¹)				
EXPIRATORY MINUTE VOLUME	35.7 $\pm$ 5.5	32.8 $\pm$ 6.8	40.6 $\pm$ 1.8	40.8 $\pm$ 3.3
$\dot{V}_E$ (liters/min) BTPS				
MINUTE O ₂ CONSUMPTION	0.756 $\pm$ 0.117	0.704 $\pm$ 0.056	0.825 $\pm$ 0.088	0.828 $\pm$ 0.064
$\dot{V}O_2$ (liter/min) STPD				
MINUTE CO ₂ PRODUCTION	0.759 $\pm$ 0.144	0.700 $\pm$ 0.082	0.860 $\pm$ 0.112	0.810 $\pm$ 0.101
$\dot{V}CO_2$ (liter/min) STPD				
RESPIRATORY QUOTIENT	1.005 $\pm$ 0.102	0.996 $\pm$ 0.033	0.975 $\pm$ 0.068	0.973 $\pm$ 0.052
R				

system are included in Table 6.2 for comparison with the corresponding exercise results.

Values for calf #25's average exercising respiratory parameters are presented in Tables 6.5, 6.6, and 6.7. Since experimental data couldn't be acquired from the instrumentation system and the bag collection system simultaneously, no bag data were collected during the exercise studies. Had bag data been acquired, no meaningful comparisons would have been possible because there was no way to insure that the subject's physiology remained the same throughout the time required to switch between the two measurement systems. The main purpose of the exercise experiments was to demonstrate that the instrumentation system was capable of generating reasonable results from measurements made on an exercising subject.

VII. DISCUSSION OF RESULTS

7.1 Comparison of Resting Results Between the Instrumentation System (CIS) and the Bag Collection System (BAG)

Under resting conditions the mammalian cardiopulmonary control system functions to maintain constant alveolar ventilation. If airway resistance changes, the respiratory frequency, and/or the respiratory tidal volume will change. The directions and magnitudes of these changes are difficult to specify since any two subjects are likely to respond differently to the same change in airway resistance. This suggests that meaningful comparisons between experimental results generated using two different measurement systems can only be made on ventilatory parameters. This is especially true if the airway resistance imposed on the subject by the respective systems is grossly different. Since no evaluation was performed to ascertain the resistance

TABLE 6.5

Summary of CIS Results for Exercising Minute Volumes,
Tidal Volumes, and Respiratory Frequency.

TRIAL #	INSPIRATORY MINUTE VOLUME $\dot{V}_I$ (liters/min)	EXPIRATORY MINUTE VOLUME $\dot{V}_E$ (liters/min)	INSPIRATORY TIDAL VOLUME VTI (liters)	EXPIRATORY TIDAL VOLUME VTE (liters)	RESPIRATORY FREQUENCY f (min ⁻¹)
1	141.0	140.9	1.808	1.807	78.0
2	135.0	138.7	1.623	1.667	83.2
3	114.9	115.7	1.708	1.719	67.3
4	116.8	116.8	2.186	2.187	53.4
5	131.7	129.8	1.953	1.925	67.4
6	136.6	133.1	2.139	2.084	63.9
7	141.2	141.4	2.090	2.093	67.6
8	130.2	131.5	1.976	1.997	65.9
9	128.2	127.7	2.147	2.139	59.7

TABLE 6.6

Summary of CIS Results for Exercising Tidal Volumes of: O₂ Inspired and Expired;
CO₂ Inspired and Expired; O₂ Consumed and CO₂ Produced.

TRIAL #	MEAN O ₂ INSPIRED VTIO ₂ (liter)	MEAN O ₂ EXPIRED VTEO ₂ (liter)	MEAN CO ₂ INSPIRED VTICO ₂ (liter)	MEAN CO ₂ EXPIRED VTECO ₂ (liter)	MEAN O ₂ CONSUMED VTO ₂ (liter)	MEAN CO ₂ PRODUCED VTCO ₂ (liter)
1	0.295	0.249	0.001	0.042	0.046	0.041
2	0.265	0.233	0.001	0.035	0.033	0.034
3	0.279	0.237	0.001	0.040	0.042	0.039
4	0.357	0.292	0.002	0.061	0.066	0.059
5	0.320	0.269	0.001	0.042	0.050	0.041
6	0.350	0.288	0.002	0.052	0.063	0.050
7	0.337	0.285	0.001	0.048	0.051	0.046
8	0.317	0.270	0.002	0.045	0.047	0.042
9	0.348	0.298	0.001	0.043	0.050	0.042

TABLE 6.7

Summary of CIS Results for Exercising O₂ Consumption,
Minute CO₂ Production, Respiratory Quotient, and Associated Respiratory Times.

TRIAL #	O ₂ CONSUMED per MINUTE $\dot{V}O_2$ (liter/min)	CO ₂ PRODUCED per MINUTE $\dot{V}CO_2$ (liter/min)	RESPIRATORY QUOTIENT R	TOTAL TIME		TOTAL TIME RESPIRATION
				INSP (sec)	EXPR (sec)	
1	3.560	3.210	0.902	84.3	71.7	155.4
2	2.720	2.840	1.044	108.8	92.3	201.2
3	2.843	2.591	0.911	98.9	90.2	189.1
4	3.506	3.129	0.892	85.3	75.3	160.6
5	3.402	2.749	0.808	98.5	79.5	178.0
6	3.997	3.215	0.804	77.2	63.7	140.9
7	3.474	3.134	0.902	96.8	77.3	174.1
8	3.071	2.798	0.911	59.1	47.4	106.6
9	2.983	2.487	0.834	51.1	41.3	92.4

of the PTM and the 3-way non-rebreathing valve, direct comparison of tidal volumes and respiratory frequencies measured using the two different systems will be made with caution.

Table 6.1 illustrates the experimental results obtained for $\dot{V}_I$, $\dot{V}_E$, V_{TI} , V_{TE} , and f . It is quite apparent that the values for $\dot{V}_E$ obtained using the CIS and the BAG system agree favorably. The average of $\dot{V}_E$ over five trials for one system, is within one standard deviation of the average using the other system (see Table 6.4). Also, the intra-trial agreement of $\dot{V}_E$ values is much better for calf #25 than for calf #67. This phenomenon also occurs on other variables and is difficult to classify quantitatively. It's worthwhile noting however, that calf #25 was somewhat older, bigger, and more accustomed to the experimental protocol at the time the studies were conducted. Perhaps #25 had a more stable metabolism than #67 - or perhaps this indicates a difference in each calf's response to the CIS and BAG system. In comparing these systems one should be aware that they both involve experimental procedures. Neither system may be legitimately considered as the standard.

Under resting conditions, values of $\dot{V}_I$ and $\dot{V}_E$ should be close to the same value. Table 6.1 illustrates that the CIS $\dot{V}_E$ values do indeed agree quite closely with the BAG $\dot{V}_E$ values. With the exception of one trial (involving calf #67) $\dot{V}_E$ measured using the CIS and BAG agree to within one liter per minute, and often to within 0.5 liter per minute. This is a gratifying observation. Unfortunately, $\dot{V}_I$ cannot be measured easily nor accurately using

the bag system, so it is unavailable for comparison with the CIS $\dot{V}_I$ values.

The CIS inspiratory and expiratory tidal volumes in Table 6.1 agree to within 0.05 liters in each trial. This is an impressive result. Although a result of this type is highly desirable, and probably represents the physiology accurately, one would not expect apriori to obtain such good agreement with a system having so many variables.

The CIS V_{TE} and BAG V_{TE} values are substantially different; but, this is one of those comparisons previously eluded to which must be made with caution. Here it is possible that the subject altered his breathing mechanism differently while attempting to maintain constant ventilation when connected to each of the respective systems. Any breathing pattern alterations would appear most significantly in the tidal volume and respiratory frequency parameters. The average and standard deviations listed in Table 6.4 for V_{TE} and f indicate that calf #25 maintained a fairly constant tidal volume and respiratory frequency between systems; whereas calf #67 lowered his tidal volume and increased his respiratory frequency when connected to the BAG system. Predictably, the two subjects didn't respond the same to the two different systems.

Table 6.2 contains a summary of the mean per breath gas species volumetric quantities. Each of these quantities was produced by the CIS system. No similar results for comparison were conveniently available from the BAG system. Certainly, the trends of the data in Table 6.2 are reasonable. In each trial, the average inspiratory

O_2 is larger than the expiratory O_2 . Inspired CO_2 is nearly zero, whereas expired CO_2 has a nominal value in the range of 2.5% to 3% of the total expired volume. Finally, the resting tidal volumes for breath-by-breath O_2 consumed are very close to the resting volumes of CO_2 produced. For resting subjects these results are anticipated since the ratio V_{CO_2}/V_{O_2} , (R) is typically close to 1.0 for resting subjects.

Table 6.3 contains two key comparisons between the BAG and CIS systems; namely, $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$. Note that these two variables are ventilatory parameters and are expected to remain relatively constant, independent of the subject's changes in breathing mechanics due to changes in airway resistance. Comparing CIS and BAG $\dot{V}_I$ values down the line for calf #67, it is questionable as to how close they actually agree. However, the means for the CIS and BAG $\dot{V}_I$ presented in Table 6.4 are well within one standard deviation of each other - lying this concern to rest. Additionally, there is even better agreement for the CIS and BAG $\dot{V}_I$ means for calf #25; once again suggesting that this calf was either more physiologically stable, or else, was better able to compensate for differences in the airway resistance of the measurement systems. It's also possible that the resolution of the CIS was insufficient to accurately measure such small volumes of O_2 and CO_2 .

Similar comments are appropriate regarding the agreement of CIS and BAG $\dot{V}_E$ values, however, for this variable, the difference in CIS and BAG mean values is about the same for both subjects.

This would seem to suggest that the CIS's measurement of $\dot{V}_E$ was reasonably consistent and accurate throughout the studies.

The values for the respiratory quotients listed in Table 6.2 were computed using the ratio of $\dot{V}_{CO_2}$ to $\dot{V}_{O_2}$, and consequently, are very sensitive to any combined experimental error involved with $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$. Generally, the trial values for R obtained using the CIS and BAG system compare closely, and in all cases are within one standard deviation of the average. Considering all the variables in the CIS which had an indirect influence on R, it's satisfying to observe such agreement between systems. Overall, the average values obtained for R were closer for calf #25 than for #67. Apparently, this is another example of how the CIS produced more reasonable looking results when used on calf #25 than when used on #67.

Table 6.3 also contains the CIS trial values for the total times of inspiration, expiration, and respiration. These are included to emphasize the fact that the CIS offers a wide variety of possible computations for time dependent respiratory variables. Each of the tabulated experimental times represent a fraction of a 2.5 minute trial. The total times for respiration never reached 150 s because the analysis routine was designed to ignore "glitches" in the digitized flow signal.

Table 6.4 is a compilation of the means and standard deviations for the common variables measured with the CIS and BAG system. Values for each calf are presented side-by-side for comparison. The values in Table 6.4 are averages of respiratory variables over a period of several days. It's worthwhile to note that almost

universally, the standard deviations are small compared to the mean values - suggesting that the CIS performance and the subject's physiology remained relatively consistent throughout the studies.

7.2 Discussion of Exercise Results

Calf #25 was exercised at a treadmill speed of 1.0 m/s, and a treadmill incline of 3° during each trial. This work load was selected because it was one that the calf could handle easily without exceeding the limitations of the instrumentation system components. Table 6.5 indicates a significant elevation in exercising minute ventilation from the resting values. The $\dot{V}_I$ and $\dot{V}_E$ are roughly three times larger than the resting values. This correlates with the fact that there is a substantial increase in ventilation in response to exercise. Although $\dot{V}_I$ and $\dot{V}_E$ have increased, they remain comparable in magnitude. The tabulated values for $\dot{V}_I$ and $\dot{V}_E$ often fall within 0.5 liter per minute of being the same.

The effect of added work load on tidal volume and respiratory frequency is also illustrated in Table 6.5. Interestingly, tidal volume really didn't change much from the resting values. The average resting V_{TI} increased from 1.595 liters at rest, to an exercising value of 1.959 liters (a net increase of 360 ml), and the average V_{TE} increased from 1.593 liters to an exercise value of 1.958 (also about a 360 ml increase). Both inspiratory and expiratory tidal volume increased by approximately the same amount.

By contrast, the respiratory frequency increased dramatically during exercise. Exercise values for f are roughly three times the magnitudes of the resting values. This reveals that the dominant

factor contributing to increased minute ventilation during exercise as being the respiratory frequency, and not tidal volume.

Table 6.6 summarizes the exercising values for inspiratory and expiratory tidal volumes of O_2 and CO_2 . The net impact of exercise on O_2 consumed and CO_2 produced is summarized in the last two columns which list values for V_{TO_2} and V_{TCO_2} . These values indicate an approximate 38% increase in exercising mean O_2 consumption and CO_2 production (per breath) from their resting values. On the average, V_{TO_2} and V_{TCO_2} both increase by a similar amount (12 ml). V_{TO_2} and V_{TCO_2} agree closely in each trial, often to within 5.0 ml. Some differences in V_{TO_2} and V_{TCO_2} are to be logically anticipated during exercise.

Trial values for minute O_2 and minute CO_2 ventilation are listed in Table 6.7. On the average, $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are not grossly different (3.284 l/min for $\dot{V}_{O_2}$, 2.906 l/min for $\dot{V}_{CO_2}$), but are far enough apart (380 ml/min) to indicate that the subject was involved in some activity other than peaceful rest. More than likely the values for $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ contain a certain amount of error, probably due to a combination of experimental error in calibration and a lack of overall system resolution. It is true that even though $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ may be somewhat in error, the values of R which they yield are entirely reasonable, and within the realm of possibilities. Consequently, it's difficult to judge from the results themselves as to the overall system accuracy. It is possible indeed that the CIS produced reasonably accurate values for all the exercise respiratory parameters.

The associated respiratory times for each exercise trial also appear in Table 6.7. The total respiratory time is the time occupied by the portions of the discrete time flow signal which the analysis routine used to generate the experimental results.

VIII. EXPERIMENTAL ERROR ANALYSIS

8.1 Description of the Primary System Errors

Accurate estimation of the total experimental error is no trivial task. The potential for errors in the experimental measurements is great, simply due to the complexity of the system. Although the various aspects of the experimental errors are numerous, the components of the total error related to gas volume measurements and their associated correction factors are of primary concern.

In considering gas volume error estimates, three subdivisions are of significance:

- 1) Errors associated with total gas volume measurements.
- 2) Errors associated with the measurement of individual gas species volumes.
- 3) Errors associated with the correction of gas volumes to STPD and BTPS conditions.

The errors of the first category are a subset of the errors comprising the second category. To obtain volumes of the O_2 and CO_2 gas constituents requires all the same system components and calculations used to determine the total gas volumes. An additional compound error dimension is introduced into the gas species volume determinations by the errors associated with the measurement of the fractional gas concentrations. The error involved with the correction of

the gas volumes to BTPS and STPD must also be considered, and adds to each of the errors mentioned above.

8.1.1 Total Gas Volume Measurement Errors

The primary errors involved in the measurement of the total gas volumes for inspiration and expiration are several:

- 1) A/D conversion amplitude quantizing errors.
- 2) Sampling errors.
- 3) Errors due to assymetry and drift in the flow transducer.
- 4) Flow signal calibration errors.
- 5) Numerical integration errors.

A brief discussion of each of these various types of errors follows.

Amplitude Quantizing Errors

When an A/D converter is used to sample a continuous time signal, round off occurs due to the limited resolution of the A/D converter. This error can be minimized using A/D converters with a large number of output bits. Ordinarily, the amplitude quantizing error is considered to be $1/2$ of the least significant bit (lsb). For an 8-bit converter this corresponds to an error of 0.195% for each binary number generated. Additional A/D conversion errors are also present. Collectively, the total A/D conversion error is given by a quantity called the absolute error. For the ADC0816, the absolute error is ± 1 lsb [30]. This represents a 0.39% error in each binary value generated.

Sampling Errors

Sampling errors occur when a band limited signal isn't sampled at a sufficiently high frequency. The sampling theorem states

that in order to obtain a unique set of binary data representing the band limited continuous time (analog) signal, the binary data must be acquired at a sampling frequency of at least twice the frequency of the highest order harmonic. This is roughly equivalent to requiring that the intra-sample interval be less than one half of the fastest rise time of the sampled signal. The fastest rise times observed for the exercising respiratory $\dot{V}$ signal was in the neighborhood of 40 to 50 msec. A sampling frequency of 50 Hz (20 msec period), for the most part, satisfied the sampling theorem and kept the sampling error small.

Flow Transducer Errors Due to Drift and Assymetry

The PTM and PTG collectively comprise the flow transducer. Yeh et. al., [31] have demonstrated that the flow conductivity of a PTM is dependent on the direction and composition of the flow through it. Compensating for this unfortunate phenomenon is a difficult, but necessary task. Potentially, these assymetries could perpetuate experimental errors as large as 5%. Another 1 to 5% error is possible due to drift in the electronics of the PTG. This problem is extremely difficult to deal with and necessitates having a flow transducer exhibiting low drift over a period of time long enough to conduct an experiment. The stability of the Godart flow transducer zero baseline was investigated. Results of this effort appear in Appendix II Section A2.2.2. It was determined that the Godart's baseline was sufficiently stable. Previously a different flow transducer was tried and abandoned due to unacceptable zero baseline drift.

Flow Signal Calibration Errors

Since the computer and DAM were used to calibrate the flow signal, errors were inevitable. The chance for errors to creep in was also increased because the determination of the flow calibration factors was based on an experimentally determined constant. Estimation of the magnitude of these combined errors is difficult. They are however, potentially significant.

Numerical Integration Errors

These types of errors occurred because the signals being integrated were broken into a finite number of points prior to integration. This means that not all of the signal information was present due to the digitizing process. This error is minimized if the sampling frequency is made sufficiently high. Theoretically, a numerical integration procedure becomes exact as the number of points representing the curve becomes infinite. The effect of the numerical integration errors was compounded because the procedure was used for both determining the flow calibration factors, and then again for the actual data analysis. Here again, the true value representing the magnitudes of these combined errors is difficult to estimate analytically.

8.1.2 O₂ and CO₂ Gas Volume Measurement Errors

In addition to all of the possible errors described above, O₂ and CO₂ gas volume measurements are subject to the following errors:

- 1) Errors in calibration of the fractional O₂ and CO₂ concentration signals.
- 2) Improper time alignment of the gas fractional concentration signals with the respiratory flow signal.

Errors in O₂ and CO₂ Concentration Signal Calibration

As with the flow calibration factor, these calibrations were performed with the computer and a variety of other instruments. Most of the significant errors developed due to GMS zero baseline drift and gas mixing pump instability. These errors were particularly significant because the actual volumes of O₂ and CO₂ were small compared to the total respiratory tidal volumes. Typically, the volumes of O₂ consumed and CO₂ produced for a particular breath were an order of magnitude less than the total respiratory tidal volume.

Errors Due to Improper Time Alignment of Signals

It was observed during system development that the gas volume calculations for O₂ and CO₂ were somewhat sensitive to small changes in the exact time alignment of the flow signal with the fractional concentration signals. To gain a better appreciation of the magnitude of this effect, an investigation was performed where the alignment was artificially varied. The results of this effort suggest that variations of the time alignment within ± 10 msec of the correct alignment do not produce large errors. Complete documentation of this study appears in Appendix II Section 2.2.3.

8.1.3 Errors in Determining Scaling Factors for Correcting Gas Volumes to STPD and BTPS Conditions

There are three types of potentially significant errors associated with the determination of the factors used for scaling the respiratory gas volumes to BTPS and STPD conditions.

- 1) Temperature signal calibration errors.
- 2) Errors in the interpretation of the midline and peak respiratory flow temperatures.

- 3) Inherent error of the technique of using average value correction factors.

Items 1 and 2 above are involved primarily with instrumentation and experimental errors, whereas Item 3 suggests the possibility of a fundamental problem with the experimental procedure. A short elaboration on each item follows.

Temperature Signal Calibration Errors

Errors in determining the temperature signal calibration factor are attributable to: inaccurate measurement of calibration water bath temperatures (± 0.1 °C possible error), and inaccurate determination of chart recorder pen deflections corresponding to the respective water bath calibration temperatures (± 1 mm out of 50 mm possible error). Roughly, this represents a possible combined temperature calibration factor error of approximately 3%.

Errors in Midline and Peak Temperature Determinations

Recall that in the average inspiratory and expiratory flow temperature estimations that the average peak temperatures are estimated by sight and then the point midway between the peaks was taken to be the midline temperature. Most temperature signal tracings obtained during experimentation exhibited peak-to-peak differences of about 20 mm. Realistically, the error in these determinations may be as much as ± 2 mm. This translates into a possible 10% error. When this error is combined with the maximum possible error in the temperature calibration factor established above, the total error in the values used to represent the average inspiratory and expiratory temperatures may be as high as 13%. It doesn't require a vivid imagination to see that these errors are of significance.

Clearly, the errors associated with the average respiratory temperatures are the most significant encountered so far.

Inherent Error of the Technique

Use of the average inspiratory and expiratory temperature values was an unavoidable compromise. This technique contains obvious limitations. The flow rate during any particular breath takes on a very wide range of values. By using average temperatures to compute scaling factors, some of the flow signal is weighted inappropriately high, and some of it is weighted low. Using the average temperatures would actually only be accurate if the flow signal was a symmetric square wave. It's not obvious what the magnitude of this error would be. Determination would require an involved analytical analysis, or experimental procedure.

8.2 Estimation of the Total Error in the Total Gas Volume Measurements

8.2.1 Error in the Uncorrected Total Gas Volume Measurements

As previously mentioned, analytic determination of the error associated with the composite uncorrected volume measurements is difficult, tedious, and of questionable accuracy. To avoid these difficulties, a direct estimation approach was employed to evaluate the experimental error. A description of the direct estimation procedure follows.

- 1) The Godart PTG was turned on and allowed sufficient time to warm up.
- 2) The valve on the input differential pressure port was closed and the PTG baseline was adjusted to zero.
- 3) The calibration routine was run to determine flow calibration factors (see Section 5.2.2 for details).

- 4) Using the data acquisition routine, digital data for 20 cycles of the respirator were obtained.
- 5) The data analysis routine was used to compute the stroke volume of the pump during each cycle, and the average stroke volume for the 20 cycles.
- 6) Steps 2-5 above were repeated until five trials were completed.

The stroke volume of the respirator was set the same (763 ml) for both calibration and data acquisition. In a system void of errors, the average inspiratory and expiratory stroke volumes would both be exactly 763 ml. Table 8.1 summarizes the results of the five trials. V_{TI} and V_{TE} represent the average inspiratory and expiratory stroke volumes respectively. The error values represent the deviation of the computed tidal volumes from the actual value of 763 ml.

TABLE 8.1

Estimations of % Errors in Inspiratory and
Expiratory Tidal Volume Calculations

Trial #	V_{TI} (ml)	V_{TI} % Error	V_{TE} (ml)	V_{TE} % Error	Total Error
1	762	0.13	757	0.79	0.92
2	760	0.39	761	0.26	0.65
3	759	0.52	763	0.00	0.52
4	760	0.39	759	0.52	0.91
5	761	0.26	761	0.26	0.52

For all trials listed in Table 8.1 the percent error is acceptably small. In all cases the total error was below 1.0%. This suggests that there is actually very small error in the volume measurements. The beauty of these results

is that they represent the combined total of all of the possible individual system errors which were described in Section 8.1.1. The only factor unaccounted for by this estimation technique is the possible error which might evolve because of using room air to simulate both inspiratory and expiratory flow during calibration. In an experimental situation, the subject inspires room air, but the expirate is at a temperature above ambient and is saturated with water vapor. An ideal calibration gas would be one that possessed these same characteristics. Undoubtedly slight changes in the calibration gas will alter the expiratory flow calibration factor, which in turn would produce slightly different calculated volumes and percent error estimations.

8.2.2 Error in the Total Gas Volumes Corrected to BTPS Conditions

The error involved with the corrected total gas volume measurements is primarily due to the large potential error involved with establishing the BTPS scaling factors. As previously discussed in Section 8.1.3 this error may be as large as 10%. Hopefully it never actually gets this high, but unfortunately, no easy means of controlling this error exists. Obviously this error is large compared to the total error in the unscaled volume measurements, and as such, represents the maximum possible error in the gas volumes scaled to BTPS conditions.

8.3 Estimation of the Total Error in Measurement of the Individual Gas Species Volumes

8.3.1 Error in the Uncorrected Gas Species Volume Measurements

The net error in the uncorrected gas species volume measurements will primarily consist of the sum of the following errors:

- 1) Error in determining the total unscaled respiratory volumes.
- 2) Error in determining the fractional gas signal calibration factors.
- 3) Error in the time alignment of the flow and fractional concentration digital data sets.

Since the gas species volumes of interest are differences between inspired and expired volumes, the "Total Error" column of Table 8.1 must be considered for estimating the error involved with determining the unscaled gas species volumes. This error component is below 1% for each of the five trials listed in Table 8.1. Clearly, this error is insignificant.

No actual quantitative analysis was performed to estimate the magnitude of the error in Items 2 and 3 listed above. It is reasonable to assume however, that the magnitude of the total gas volume measurement errors will be fairly representative of the magnitude of the gas species volume measurement error. The gas species volume measurement error will in fact be somewhat larger because the calculations for the gas species volumes involve the same variables as used in the total gas volume calculations, plus a few additional errors associated with determining the fractional gas signal calibration factors and GMS time delay. The error involved with the time alignment of the signals is less than 2%. Refer to Appendix II Section A2.2.3 for additional details.

Even if the additional error contributed by Items 2 and 3 is double that of the total volume measurement errors, the total error in the gas species volume calculations would be 2% at the most. This is quite acceptable experimental error and is

definitely small compared to the errors introduced by the uncertainty in the STPD scaling factors.

8.3.2 Errors in the Volume Measurements of Gas Species Corrected to STPD Conditions

Although the calculated volumes of O_2 and CO_2 contain some error due to the various sources described in Section 8.3.1, the primary errors are introduced when the unscaled volumes are multiplied by the STPD scaling factors. As discussed in Section 8.1.3 the total error in determining the scaling factors can be as high as 10%. Since the unscaled O_2 and CO_2 volumes are directly multiplied by the scaling factors, the scaled volumes which result will also contain a potential 13% error. This by far is the dominant error in the gas species volume calculations.

IX. CONCLUSIONS

From the endeavors of system design, development, analysis, and operation of the computerized instrumentation system, several conclusions have been reached.

1. Stable, quality transducers are required to generate accurate analog signals useful for computing breath-by-breath respiratory quantities. In addition, it is essential that the transducers exhibit linear operating characteristics over the full range of possible input signals. If these requirements are not satisfied the computed respiratory quantities will be overtly subject to errors, especially those quantities which are generated by multiplying two or more of the signals together.

2. Alignment of the digitized $\dot{V}$ signal with the F_{O_2} and F_{CO_2} signals to within ± 20 msec of their real time alignments is sufficient for calculating respiratory gas volumes with acceptable experimental error. For sampling frequencies of 50 Hz or greater this restriction allows misalignment of the digital signals by a maximum of one datum sample. In practice, a quality gas analyzer with a rapid response time is essential for keeping the error in the signal time alignments minimized.
3. Computer controlled system calibration must be simple, orderly, and repeatable to obtain valid experimental results. In the early stages of system development this point became painfully obvious each time something avoidable went wrong during the course of system calibration. As the system evolved, the calibration procedure was revised several times until a reasonably simple, straightforward technique was obtained. Maintaining a simple calibration procedure helps to enhance the accuracy of the experimental results.
4. A 50 Hz sampling frequency is sufficiently high to allow accurate gas volume calculations using the Trapezoidal Rule numerical integration technique. By comparing plotted digital data with the corresponding analog strip chart recordings it was apparent that the digital waveforms were quality reproductions of the original signals. A 50 Hz sampling frequency is

fast enough to catch the majority of the sharp peaks and valleys which randomly appear in the calf's respiratory flow signal. Sampling at the lowest reasonable frequency has the advantage that it conserves computer memory, enabling longer experimental run times. The sampling frequency should always be selected so that a majority of the original signal information is retained, without "over sampling" the signal.

5. Computed BTPS and STPD respiratory gas volumes are subject to large experimental errors due to the uncertainty in the determination of the BTPS and STPD scaling factors. This in turn generates large errors in the time dependent respiratory variables $\dot{V}_I$, $\dot{V}_E$, $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$. The results of the error analysis indicate that if the errors generated when correcting gas volumes to STPD and BTPS can be eliminated, then the sum of the total system errors can be maintained below 5%. Elimination of the errors caused by the scaling factors will require additional computerized instrumentation to account for instantaneous changes in temperature of the respiratory flow signal. Prior to integration, the flow signal should be corrected on a point-by-point basis. Using this system all components of the flow signal receive appropriate weightings. In the current system all points comprising the flow signal are weighted using average temperature values.

6. Calculation of average and time dependent respiratory quantities are simple extensions of the breath-by-breath computations and are useful for system verification purposes. Breath-by-breath quantities are of use for determining dynamic trends of a particular respiratory variable, but they are not particularly useful for system verification purposes. Also, the experimentalist conducting the exercise study often desires average and time dependent information simply because others before him have conducted their studies and based their conclusions on these types of variables.
7. If higher treadmill speeds are to be used on calves weighing in excess of 400 pounds, a respirator with a larger stroke volume, and a PTM with a larger bore will be required. Subjects of this size simply have larger minute volumes than the current system can handle. The respirator in use now can generate peak flow rates of about 5 l/s. A 400 pound calf subjected to heavy work loads can easily generate peak flow rates of 10 l/s and occasionally as high as 15 l/s. To calibrate the flow signal over this range using the current respirator necessitates large extrapolations. Also, the current PTM in use is only specified to be linear for flow rates up to 10 l/s. However, some independent tests were performed that indicated

the PTM was acceptably linear up to 15 l/s. Regardless of the PTM linearity, a larger bore PTM is necessary to insure that the instrumentation system does not appreciably affect the subject's natural breathing mechanics.

8. The results of this work suggest, that contrary to the opinion of others within the scientific community [32], given sufficient time, money, and resources, it is indeed possible to accurately measure breath-by-breath respiratory quantities at the mouth of an exercising subject.

X. SUGGESTED AREAS FOR ADDITIONAL RESEARCH AND SYSTEM IMPROVEMENTS

Frequently during the course of system operation the instrumentation system generated experimental results which were clearly nonrealistic. Before the system can be used on an everyday basis by non-technical personnel, additional work will be required to eliminate the primary causes of system inaccuracies. Some thoughts on how the system could be improved and better utilized follow.

10.1 Additional System Error Analysis

Although some experimental error analysis has already been performed, there is a need for further investigation.

- 1) A quantitative relationship between the magnitude of flow and fractional concentration signal misalignment and the magnitude of the resulting experimental error needs to be established. At this point it appears that the exact alignment is not critical as long as the signals are sampled at 50 Hz or faster.

- 2) The sensitivity of the experimental results to errors in the temperature correction factors needs further consideration. From the frequent occurrence of valid experimental results it seems unlikely that the results always contain the maximum possible error of 13%. A known relationship between average temperature value errors and total experimental error would be useful.
- 3) Classification of the sensitivity of the total experimental error to PTM nonlinearities and asymmetries would be useful. Many investigators have verified that the PTM is not a perfectly linear device [6,28,31]. It would be useful to know if the magnitudes of the PTM's undesirable characteristics substantially affect the system operation, and if so, to quantify these effects.

To investigate each of the items listed above would require additional software analysis routines. The general scheme would be to work with a constant set of experimental data and have the analysis routine artificially vary the parameter(s) of interest. This would enable classification of the system errors.

10.2 Calibration Modifications

If it is determined that the PTM operational characteristics are significantly adverse, a new calibration technique will be required. Yeh et. al., [31] have suggested a calibration procedure based on the conductive properties of the PTM. Their claim is that the PTM exhibits a different conductivity depending on the rate and composition of the respiratory flow. Their solution is to obtain a set of flow calibration factors so that each digital flow data point can be given the appropriate weighting. This approach seems reasonable and warrants further investigation.

10.3 Additional Instrumentation

The DAM presently has five unused inputs to which additional transduced physiological signals could be connected. Among the

additional signals of interest are: respiratory flow temperature, body temperature, heart rate, and arterial and venous blood pressure. The advantage of having all of these signals is that it would enable calculation of a wider variety of cardiopulmonary variables.

For the immediate future, use of a respiratory temperature signal is highly recommended. This signal should be digitized along with the $\dot{V}$, F_{CO_2} and F_{O_2} signals and then used to correct the flow signal on a point-by-point basis. This should serve to eliminate the majority of the system error associated with temperature corrections.

A rapidly responding hypodermic thermocouple will be necessary to transduce the flow temperature signal. The thermocouple must have an extremely small diameter so it can reside in close proximity to the location within the PTM where the flow is sensed. The thermocouple must also have the fastest possible time constant so it can accurately follow rapid changes in the flow temperature.

The possibility of developing a feedback control system to maintain the PTM case temperature close to the subject's body temperature should also be considered. This would help to reduce the condensation of water vapor inside the PTM and also the inspiratory and expiratory peak temperature differentials. Excessive condensation may potentially alter the PTM operating characteristics. Maintaining small temperature fluctuations between inspiration and expiration would help to curb the experimental error.

10.4 Software Enhancement

There are two main categories of interest with regard to software enhancement.

- 1) Modifications of existing software to obtain additional respiratory quantities of interest.
- 2) Development of new software for display of respiratory and cardiopulmonary quantities.

Software for Additional Respiratory Quantities

Beaver et. al., [13] have recently outlined equations which allow determination of alveolar O_2 and CO_2 gas exchange volumes using gas fractional concentrations measured at the mouth. They have also presented equations for evaluating inter-breath changes in the FRC (Functional Residual Capacity). This information may provide more meaningful insight into the physiology of an exercising subject than similar quantities determined at the mouth.

Software for Display

A wide variety of software routines could easily be written to display the dynamic trends of various respiratory variables.

Potential candidates for display are:

- 1) $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ vs. elapsed experimental time.
- 2) Respiratory frequency vs. elapsed experimental time.
- 3) $\dot{V}_{O_2}$ vs. various treadmill speeds.
- 4) $\dot{V}_{O_2}$ vs. heart rate.
- 5) Body temperature vs. elapsed experimental time.

The graphics capabilities of the computer system are well suited for these kinds of applications.

10.5 System Applications

It would be very interesting to test the system on a variety of different subjects and particularly humans. The system could be easily adapted to function on any animal, provided a face mask could be constructed to channel all of the subject's respiratory gases through the PTM. Undoubtedly, the system as it currently stands, is much better suited for operation with subjects having lower minute ventilations than do 400 pound steers.

Conceivably, the system software could be adapted to a smaller, less expensive dedicated computer system. This would substantially reduce the cost of the overall system, perhaps making it affordable for physicians in diagnostic settings who deal with patients having respiratory diseases.

BIBLIOGRAPHY

- [1] H.A. DeVries, "Exercise metabolism", in Physiology of Exercise for Physical Education and Athletics, 3rd ed., Dubuque, Iowa: Wm. C. Brown, 1980, ch. 10.
- [2] D.H. Paterson, D.A. Cunningham, and A. Donner, "The effect of different treadmill speeds on the variability of $\dot{V}O_2$ max in children", Eur. J. Appl. Physiol., Springer-Verlag, vol. 47, pp. 113-122, 1981.
- [3] R.L. Hughson and J.M. Kowalchuk, "Influence of diet on CO_2 production and ventilation in constant-load exercise", Respiration Physiology, vol. 46, pp. 149-160, Elsevier/North-Holland Biomedical Press, 1981.
- [4] E.E. Creel, R.R. Gallagher, and W.D. Kuhlmann, "Analysis of respiratory gases on a breath-by-breath basis", Proc. 35th ACEMB, p. 260.
- [5] W.L. Beaver, K. Wasserman, and B.J. Whipp, "On-line computer analysis and breath-by-breath graphical display of exercise function tests", J. Appl. Physiol., vol. 34(1), pp. 128-132, 1973.
- [6] S.Z. Turney and W. Blumenfeld, "On-line respiratory-waveform analysis using a digital desk calculator", Medical and Biol. Engr., pp. 275-285, May, 1973.
- [7] G.P. Herr, S.F. Sullivan, H.J. Khambatta, and R. Crane, "On-line acquisition of pulmonary gas exchange data", IEEE Trans. on Biomed. Engr., vol. BME-25(1), pp. 83-87, 1978.
- [8] J.H. Wilmore, J.A. Davis, and A.C. Norton, "An automated system for assessing metabolic and respiratory function during exercise", J. Appl. Physiol., vol. 40(4), pp. 619-624, 1976.
- [9] D.H. Pearce, H.T. Milhorn, G.H. Holloman, and W.J. Reynolds, "Computer-based system for analysis of respiratory responses to exercise", J. Appl. Physiol., vol. 42(6), pp. 968-975, 1977.
- [10] T.E. Bernard, "Aspects of on-line digital integration of pulmonary gas transfer", J. Appl. Physiol., vol. 43(2), pp. 375-378, 1977.
- [11] S. Damato, "The breath-by-breath analysis of alveolar ventilation", J. Mass Spectrom. in Biochem. Med. and Environ. Research, vol. 1(3), pp. 185-189, 1980.

- [12] D.Y. Sue, J.E. Hansen, M. Blais, and K. Wasserman, "Measurement and analysis of gas exchange during exercise using a programmable calculator", J. Appl. Physiol., vol. 49(3), pp. 456-461, 1980.
- [13] W.L. Beaver, N. Lamarra, and K. Wasserman, "Breath-by-breath measurement of true alveolar gas exchange", J. Appl. Physiol., vol. 51(6), pp. 1662-1675, 1981.
- [14] Godart Pneumotachograph Provisional Instruction Manual, Godart-Statham B.V., Jan van Eycklaan 2, Bilthoven 2660, Holland.
- [15] Perkin-Elmer MGA-1100 Medical Gas Analyzer Operations and Maintenance Manual, Perkin-Elmer Medical Instruments, 2771 N. Garey Avenue, Pomona, California, 91767.
- [16] E. Creel, D. Gallagher, and R. Gallagher, "Design considerations for a general purpose, multichannel data acquisition module", Proc. 3rd EMBS, pp. 429-434.
- [17] Hewlett-Packard 98032A 16-Bit Interface Installation and Service Manual, Hewlett-Packard Desktop Computer Division, 3404 East Harmony Road, Fort Collins, Colorado 80525.
- [18] Hewlett-Packard 2631B Printer Installation and Service Manual, Hewlett-Packard Desktop Computer Division, 3404 East Harmony Road, Fort Collins, Colorado 80525.
- [19] Hewlett-Packard 98034A HP-IB Interface Installation and Service Manual, Hewlett-Packard Desktop Computer Division, 3404 East Harmony Road, Fort Collins, Colorado 80525.
- [20] Operating and Programming, HP System 45 Desktop Computer, Hewlett-Packard Desktop Computer Division, 3404 East Harmony Road, Fort Collins, Colorado 80525.
- [21] P. Horowitz and W. Hill, "Digital meets analog", in The Art of Electronics, New York: Cambridge Press, 1980, ch. 9.
- [22] Intel Component Data Catalog 1980, Intel Corporation, 3065 Bowers Avenue, Santa Clara, California 95051, pp. 8-50.
- [23] Assembly Development and Assembly Execution ROMS, HP9845 Desktop Computer, Hewlett-Packard Desktop Computer Division, 3404 East Harmony Road, Fort Collins, Colorado 80525.
- [24] J. Phper, P. Dejours', P. Haab, and H. Rahn, "Concepts and basic quantities in gas exchange physiology", Respiration Physiology, vol. 13, pp. 292-304: North-Holland Publishing Company, Amsterdam, 1971.

- [25] J.H. Comroe, R.E. Forster, A.B. Dubois, W.A. Briscoe, and E. Carsen, "Examples of use of the gas laws", in The Lung-Clinical Physiology and Pulmonary Function Tests, 2nd ed., Chicago, Illinois: Year Book Medical Publishers, 1974, Appendix C.
- [26] Digamix Gas Mixing Pump Type M/300a Operating Manual, Calibrated Instruments Inc., 731 Saw Mill River Road, Ardsley, New York 10502.
- [27] National Semiconductor CMOS Databook 1978, National Semiconductor Corporation, 2900 Semiconductor Drive, Santa Clara, California 95051, pp. 1-184 to 1-193.
- [28] S.Z. Turney and W. Blumenfeld, "Heated Fleisch pneumotachometer: a calibration procedure", J. Appl. Physiol., vol. 34(1), pp. 117-121, 1973.
- [29] W.D. Kulhmann, and M.R. Fedde, "Cardiopulmonary changes during acute exercise-stress in hereford calves", The Physiologist, vol. 25(4) p. 198, August 1982.
- [30] National Semiconductor Data Acquisition Handbook 1978, National Semiconductor Corporation, 2900 Semiconductor Drive, Santa Clara, California 95051, p. 2-30.
- [31] M.P. Yeh, R.M. Gardner, T.D. Adams, and F.G. Yanowitz, "Computerized determination of pneumotachometer characteristics using a calibrated syringe", Am. Physiol. Soc., vol. 53(1), pp. 280-285, 1982.
- [32] Darryl Y. Sue, personal communication.
- [33] Graphics ROM Manual, HP9845 Desktop Computer, Hewlett-Packard Desktop Computer Division, 3404 East Harmony Road, Fort Collins, Colorado 80525.

ACKNOWLEDGMENTS

Certainly, if left to my own means, this thesis would have never reached completion. I would like to thank my committee members Dr. Michael Lucas and Dr. Roger Fedde for their help and suggestions. A special thanks goes to my Major Professor Dr. Richard Gallagher for his ideas and guidance throughout the course of research and thesis preparation.

Although many individuals contributed to the success of this research, none more so than Mr. Wade Kuhlmann, I deeply appreciate the help and advice he gave during system development, verification, and experimentation.

My parents deserve mention for all the emotional and financial support they provided throughout my college career. I would also like to thank the Departments of Electrical Engineering and Anatomy and Physiology, for their unusually generous financial support throughout my graduate studies.

I dedicate this work to my wife Estella and daughter Kandace who provided the love, encouragement and ears of sympathy which made it all possible.

APPENDIX I

DEFINITIONS OF ACRONYMS

A/D Converter	<u>A</u> nalog-to- <u>D</u> igital Converter - an electronic integrated circuit which measures the instantaneous voltage at its input, and after a short delay (10-100 μ s typical) generates an associated binary number on the output lines.
ADU	<u>A</u> nalog-to- <u>D</u> igital <u>U</u> nit - equivalent to one analog-to-digital converter binary increment.
BAG	<u>B</u> AGged expireate collection system - the system used to verify the validity of resting respiratory data obtained using the computerized instrumentation system.
BCD	<u>B</u> inary <u>C</u> oded <u>D</u> ecimal - the base 10 (decimal) equivalent of a binary number.
BTPS	<u>B</u> ody <u>T</u> emperature and <u>P</u> ressure <u>S</u> aturated
CIS	<u>C</u> omputerized <u>I</u> nstrumentation <u>S</u> ystem - The system described in this thesis used for measuring breath-by-breath respiratory quantities.
DAM	<u>D</u> ata <u>A</u> cquisition <u>M</u> odule - a device used to interface analog signals to a digital computer.
FRC	<u>F</u> unctional <u>R</u> esidual <u>C</u> apacity - the volume of gas in the lung after a normal expiration.
GMS	<u>G</u> as <u>M</u> ass <u>S</u> pectrometer - an instrument which measures either the partial pressure or the fractional concentrations of various gases (O_2 , N_2 , CO_2 , etc.) in a given gas sample.
GPIO	<u>G</u> eneral <u>P</u> urpose <u>I</u> nput/ <u>O</u> utput.
HPIB	<u>H</u> ewlett- <u>P</u> ackard <u>I</u> nterface <u>B</u> us.
LED	<u>L</u> ight <u>E</u> mitting <u>D</u> iode - a semiconductor device which illuminates when an appropriate potential is applied.
lsb	<u>l</u> east <u>s</u> ignificant <u>b</u> it - the digit with the lowest weighting in a binary number.

PTG	<u>P</u> neumotachograph - an electronic instrument which produces a continuous electrical signal proportional to a differential pressure signal input.
PTM	<u>P</u> neumotachometer - a device used to transduce respiratory flow. Generates a differential pressure proportional to the flow of gas through it.
S/H Amplifier	<u>S</u> ample/ <u>H</u> old Amplifier - a special purpose device used for maintaining (or "holding") a particular voltage for short periods of time.
STPD	<u>S</u> tandard <u>T</u> emperature and <u>P</u> ressure, <u>D</u> ry - 273 °C, 760 Torr, and no water vapor.

APPENDIX II

SYSTEM SUBROUTINE LISTINGS, DOCUMENTATION AND VERIFICATION

This appendix is intended to provide additional details of interest regarding the System Controller Routine and each of the system subroutines, not included in the main text. Each section of this appendix is organized as follows:

- 1) A brief functional description.
- 2) A listing and description of each subroutine variable.
- 3) A high level flowchart illustrating the subroutine logic.
- 4) A listing of the BASIC and/or assembly language code.
- 5) Any verification or test results pertaining to subroutine operation.

In Item 2, the variable listing and description also includes the variable type, which can be one of four kinds: integer, short precision, real, or string. Table A2.1 describes each variable type [20]. Although all numerical variables could have been declared real (the default type), in many instances it was more appropriate to use integer or short precision variables. Generally, these types of variables were involved with data transfer between the DAM and computer; or used to transfer discrete data from the computer's memory to the mass storage device. Integer and short precision variables conserve valuable memory. They require fewer bytes than do real variables for internal and mass storage binary representation.

TABLE A2.1
Description of Variable Types

Variable Type	Description	<u>Bytes Required</u>	
		Storage in Memory	Mass Storage
Full precision numeric (real)	Represented internally with 12 significant digits and an exponent in the range of -99 through 99.	10	8
Short precision numeric	Represented internally with 6 significant digits and an exponent in the range of -63 through 63.	6	4
Integer precision numeric	Have no digits following the decimal point. Possible range of values is -32768 through 32767.	4	4
String	Represent strings of characters may have maximum length of 32767.	6 + length	4 + length

A2.1 System Controller Routine

Overview

The System Controller Routine allows the user to execute any logical sequence or combination of the following system functions:

- 1) Calibration of system components.
- 2) Collection of $\dot{V}$, F_{CO_2} , and F_{O_2} digital data.
- 3) Mass storage of system calibration factors.
- 4) Mass storage of digital data.
- 5) Display of digital data sets.
- 6) Analysis of digital data sets.
- 7) Display of analysis results.
- 8) Correction of digital data for temperature and humidity differentials between the subject's body and the environment.
- 9) Retrieval of digital data from mass storage.

Chapter IV describes the functional details of each of the system functions. Figure 4.1 illustrates all of the possible operation sequences of the System Controller Routine.

System Controller Routine Variables

<u>Name</u>	<u>Type</u>	<u>Description</u>
Beep	real	Loop counter used to output 10 successive "beeps", 100 msec apart, signaling the completion of data collection.
Bin_zero_flow	real	See Section A2.2.1
C\$	string	User specified filename for the F_{CO_2} digital data.
Cal\$	string	User specified filename for the system calibration factors.
Co2_cal	short precision	See Section A2.2.1.
Co2_dc_offset	short precision	See Section A2.2.1.
Date\$	string	The date (Day/Month/Year) for a particular experimental run, stored along with system calibration factors.
Expr_flow_cal	real	See Section A2.2.2.
F\$	string	User specified filename for the $\dot{V}$ digital data.
I	integer	Loop counter. Used for the iterative display of the digital data sets.
Insp_flow_cal	real	See Section A2.2.2.
Line1 (*)	integer array	Holds BCD F_{CO_2} data collected by the DAM.
Line2 (*)	integer array	Holds BCD F_{O_2} data collected by the DAM.
Line6 (*)	integer array	Holds BCD $\dot{V}$ data collected by the DAM.
Name\$	string	User specified title of a particular experimental run. 25 characters maximum.

<u>Name</u>	<u>Type</u>	<u>Description</u>
No_points	integer	The total number of points collected from each channel of the DAM during the data acquisition stage of an experiment.
O\$	string	User specified filename for the FCO ₂ digital data set. 6 characters maximum.
O2_cal	short precision	See Section A2.2.1.
O2_dc_offset	short precision	See Section A2.2.1.
Q\$	string	Input variable for numerous yes/no user queries. Allows conditional branching so the user can execute the various system functions in any logical order.
S	integer	The sampling frequency used for data acquisition.
Time_delay	real	See Section A2.2.3.

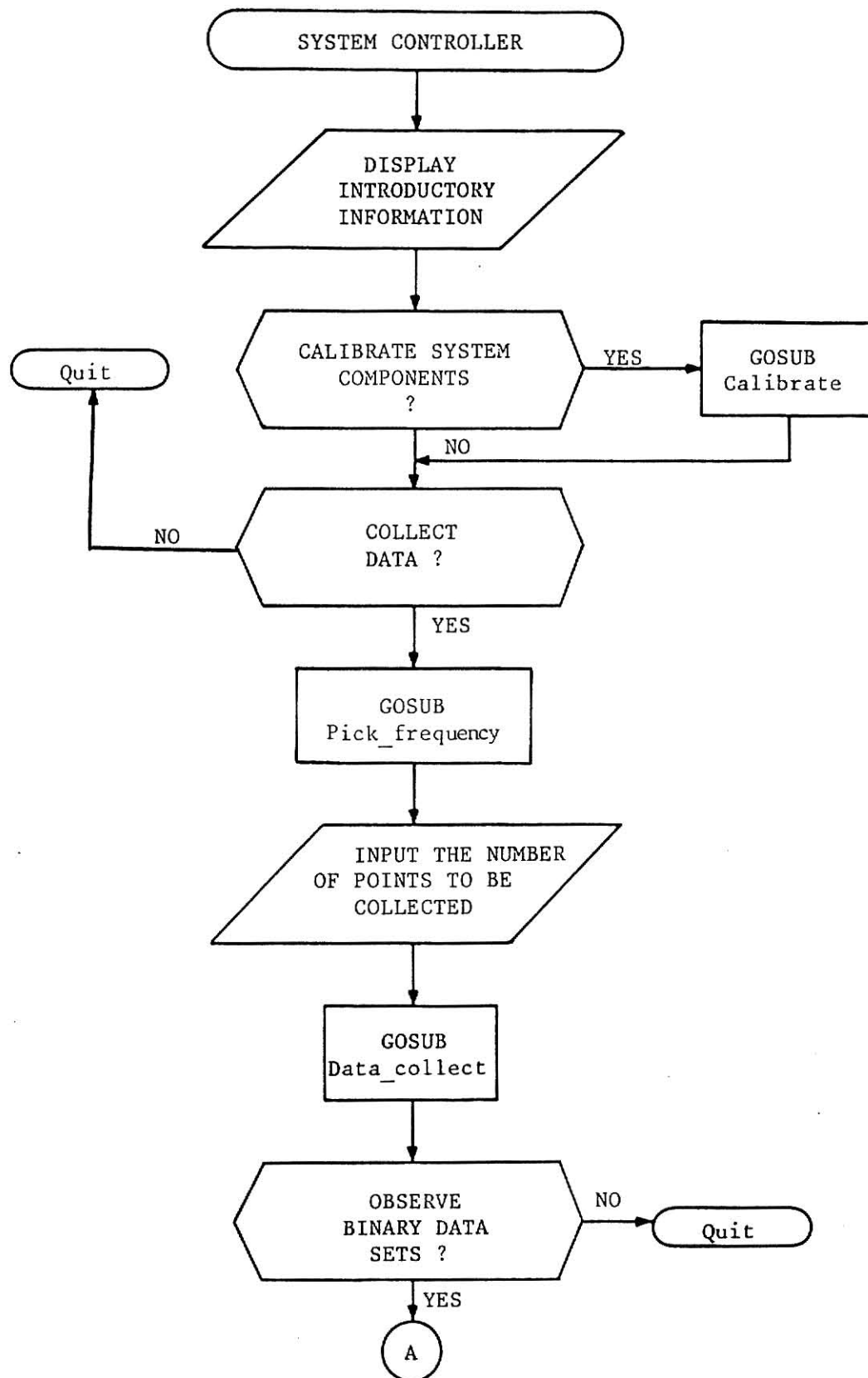
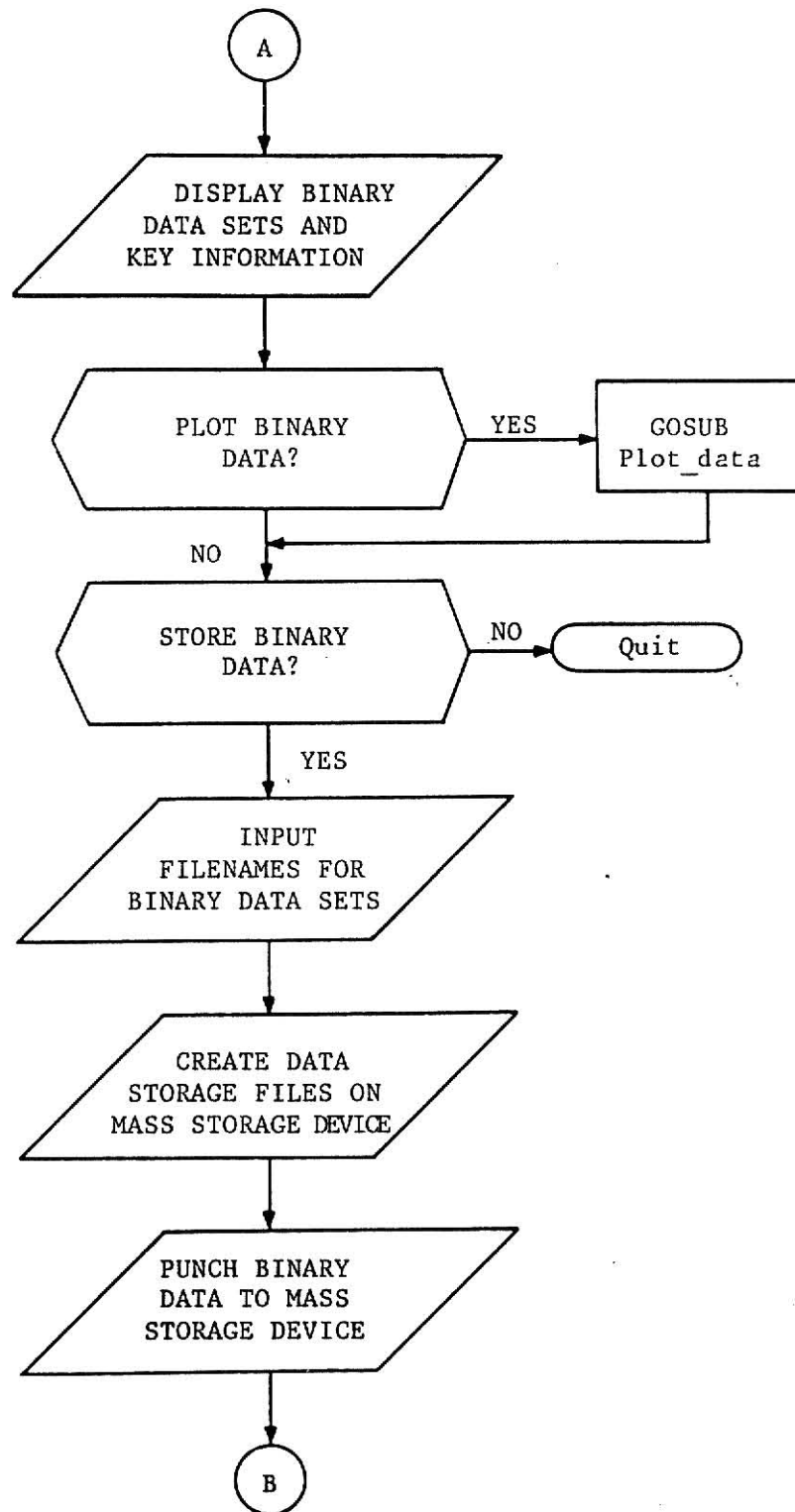
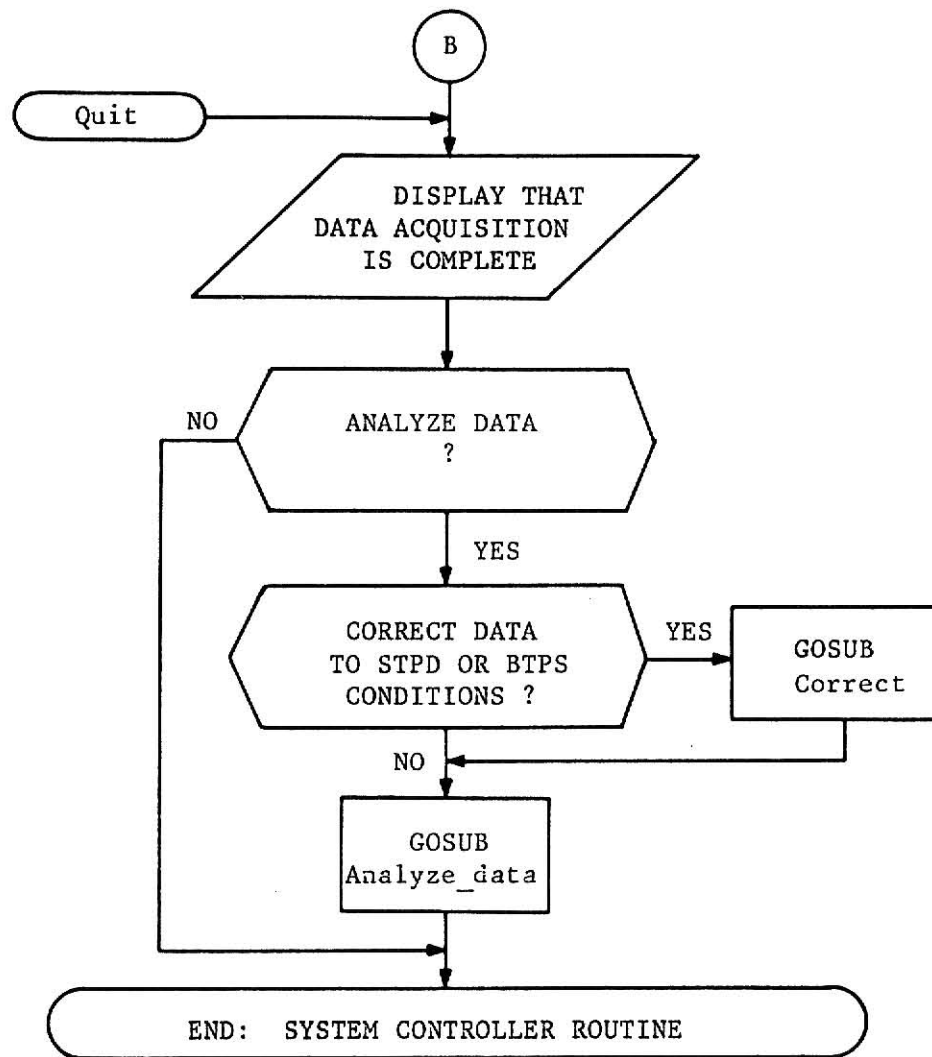


Figure A2.1 System Controller Routine Flowchart.





```

10  ! Program for collecting data to measure breath-by-breath oxygen consump-
20  ! tion and carbon dioxide production in exercising calves.
30  !
40  ! Programmed by Earl Creel Version 6.0, July 1982
50  !
60  ! The program assumes the following connections to the DAM:
70  !
90  !             Channel 1: Fractional O2 concentration
90  !             Channel 2: Fractional CO2 concentration
100  !             Channel 3: Flow
110  !
120  ! Inputs to channels 1 & 2 must be unipolar signals, 0 to 10 volts.
130  !
140  ! Input to channel 3 must be bipolar, -5 to 5 volts.
150  !
160  SERIAL
170  OPTION BASE 1
180  INTEGER No_points,S ! No_points is the number of points to be collected
190  ! S is the sampling frequency for data acquisition
200  INTEGER Line1(20000),Line2(20000),Line3(20000)
210  DIM Dates(25),Name$(25)
220  ! Set aside memory for the assembly language routine and assemble.
230  ICOM 750
240  IASSEMBLE
250  LOAD KEY "B45C45"
260  ON KEY #0 GOTO 620
270  ON KEY #1 GOTO 670
280  ON KEY #2 GOTO 720
290  !
300  ! Get ready to print introductory marquee.....
310  !
320  PRINT PAGE;TAB(20);"PROGRAM NAME:  COWCOR ";LIN(2)
330  PRINT "This is a BASIC/Assembly language program which collects data from"
340  PRINT "channels 1,2 and 3 of the A/D converter module. The user is free to"
350  PRINT "select sampling frequency and the number of data points collected"
360  PRINT "per channel."
370  PRINT LIN(3)
380  DISP "DO YOU WANT TO CALIBRATE THE SYSTEM? (Y/N)";
390  INPUT Q$
400  IF Q$="Y" THEN GOSUB Calibrate
410  DISP "DO YOU WANT TO COLLECT DATA ? (Y/N)";
420  INPUT Q$
430  IF Q$<>"Y" THEN Quit
440  GOSUB Pick_frequency
450  INPUT "HOW MANY POINTS TO BE ACQUIRED FROM EACH CHANNEL ?";No_points
460  GOSUB Data_collect
470  FOR Beep=1 TO 10
480  BEEP
490  WAIT 100
500  NEXT Beep
510  IF No_points>=20000 THEN 530
520  REDIM Line1(No_points),Line2(No_points),Line3(No_points)
530  DISP ""
540  INPUT "WOULD YOU LIKE TO OBSERVE THE BINARY DATA SETS ?(Y/N)";Q$
550  IF Q$<>"Y" THEN Store
560  FIXED 3
570  DISP "PRESS (K0) TO TERMINATE DISPLAY"

```



```

580 PRINT LIN(3);CHR$(133);"CHANNEL1 (CO2 CONCENTRATION)";CHR$(128)
590 FOR I=1 TO No_points
600 PRINT Line1(I);
610 NEXT I
620 DISP "PRESS (K1) TO TERMINATE DISPLAY"
630 PRINT LIN(3);CHR$(133);"CHANNEL2 (O2 CONCENTRATION)";CHR$(128)
640 FOR I=1 TO No_points
650 PRINT Line2(I);
660 NEXT I
670 DISP "PRESS (K2) TO TERMINATE DISPLAY"
680 PRINT LIN(3);CHR$(133);"CHANNEL6 (FLOW)";CHR$(128)
690 FOR I=1 TO No_points
700 PRINT Line6(I);
710 NEXT I
720 Store: MASS STORAGE IS ":T14"
730 INPUT "DO YOU WANT A PLOT OF THE BINARY DATA SETS ? (Y/N)",Q$
740 IF Q$<>"Y" THEN GOTO Save
750 INPUT "DO CALIBRATION FACTORS NEED TO BE LOADED FROM TAPE (Y/N) ?",Q$
760 IF Q$<>"Y" THEN 810
770 INPUT "ENTER CALIBRATION FILE FILENAME",Cal$
780 ASSIGN #1 TO Cal$
790 ON END #1 GOTO 810
800 READ #1;Co2_dc_offset,O2_dc_offset,Bin_zero_flow,Co2_cal,O2_cal,Insp_flow_c
al,Exp_flow_cal,Time_delay,S,Date$
810 GOSUB Plot_data
820 Save: INPUT "DO YOU WISH TO SAVE THE DATA(Y/N)",Q$
830 IF Q$<>"Y" THEN Quit
840 INPUT "ENTER THE CO2 SIGNAL FILE NAME",C$
850 INPUT "ENTER THE O2 SIGNAL FILE NAME",O$
860 INPUT "ENTER THE FLOW SIGNAL FILE NAME",F$
870 CREATE C$,1,No_points*4
880 CREATE O$,1,No_points*4
890 CREATE F$,1,No_points*4
900 ASSIGN #1 TO C$
910 ASSIGN #2 TO O$
920 ASSIGN #6 TO F$
930 ON END #1 GOTO 980
940 ON END #2 GOTO 1000
950 ON END #6 GOTO Quit
960 READ #1,1
970 PRINT #1;Line1(*)
980 READ #2,1
990 PRINT #2;Line2(*)
1000 READ #6,1
1010 PRINT #1;Line6(*)
1020 MASS STORAGE IS ":T14"
1030 Quit: PRINT LIN(3);"DATA ACQUISITION COMPLETE"
1040 INPUT "WOULD YOU LIKE TO ANALYZE DATA ? (Y/N)",Q$
1050 IF Q$="Y" THEN GOSUB Analyze_data
1060 PRINTER IS 16
1070 DISP "PROGRAM RUN COMPLETE"
1080 BEEP
1090 MASS STORAGE IS ":T15"
1100 END
1110 ! *****
1120 ! ***** END OF THE SYSTEM CONTROLLER ROUTINE *****
1130 ! *****

```

A2.2 Calibration Subroutine

A2.2.1 Gas Signal Calibration Subroutine

Gas Signal Calibration Subroutine Variables

<u>Name</u>	<u>Type</u>	<u>Description</u>
Avco2h	short precision	The average BCD value of 100 samples obtained from the F_{CO_2} channel (channel 1, DAM) with the mass spectrometer probe connected to 9% CO_2 .
Avco2l	short precision	The average BCD value of 100 samples obtained from the F_{CO_2} channel with the mass spectrometer probe connected to 100% N_2 .
Avo2h	short precision	The average BCD value of 100 samples obtained from the F_{O_2} channel (channel 2, DAM) with the mass spectrometer probe connected to 11% O_2 .
Avo2l	short precision	The average BCD value of 100 samples obtained from the F_{O_2} channel with the mass spectrometer probe connected to 21% O_2 .
Ch	short precision	The actual value for CO_2 displayed by the mass spectrometer with the sampling probe connected to 9% CO_2 .
Cl	short precision	The actual value for CO_2 displayed by the mass spectrometer with the sampling probe connected to 100% N_2 .
Co2_cal	short precision	The calibration factor for the F_{CO} channel (channel 1, DAM). Multiplying digital F_{CO_2} data by this factor yields data with fractional concentration unit
Co2_dc_offset	short precision	Same as Avco2l.
I	integer	Loop counter. Used for totalizing arrays when determining average values for calibration signals.

<u>Name</u>	<u>Type</u>	<u>Description</u>
Line1(*)	integer array	Holds BCD data obtained from the F_{CO_2} channel (channel 1, DAM).
Line2(*)	integer array	Holds BCD data obtained from the F_{O_2} channel (channel 2, DAM).
No_points	integer	A parameter passed to the data acquisition subroutine which determines the number of points to be collected from DAM input channels 1, 2, and 6.
0h	short precision	The actual value for O_2 displayed by the mass spectrometer with the sampling probe connected to 21% O_2 .
0l	short precision	The actual value for O_2 displayed by the mass spectrometer with the sampling probe connected to 11% O_2 .
02_cal	short precision	The calibration factor for the F_{O_2} signal. Multiplying data obtained from the F_{O_2} channel (channel 2, DAM) by this calibration factor yields discrete F_{O_2} data with fractional concentration units.
02_dc_offset	short precision	Same as Avo2l.
Q\$	string	Input variable for numerous yes/no user queries. Allows for conditional branching around the gas signal calibration routine and/or to the flow signal calibration routine.
S	integer	A parameter passed to the timer initialization subroutine. Determines the sampling frequency for channels 1, 2, and 6 of the DAM.

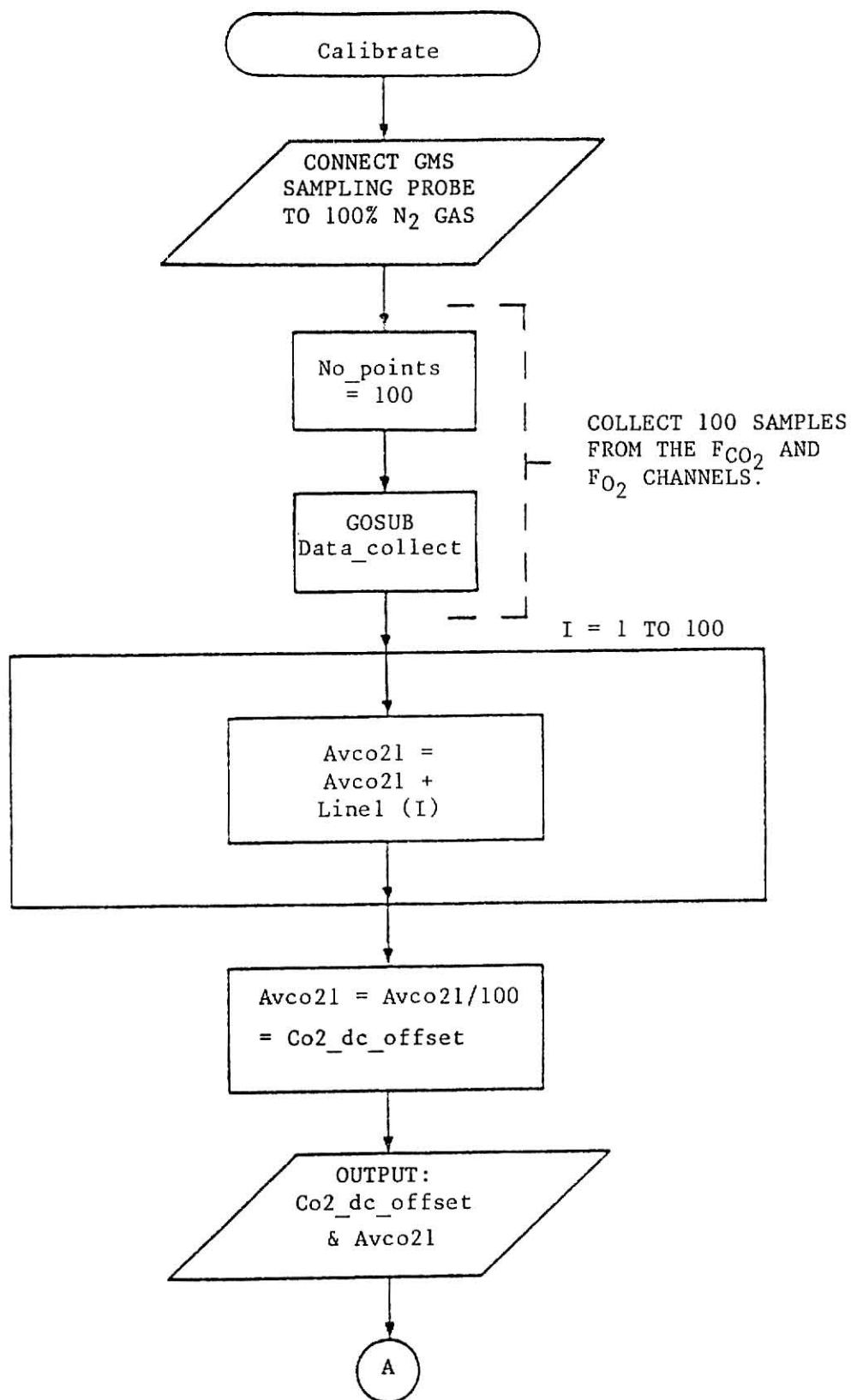
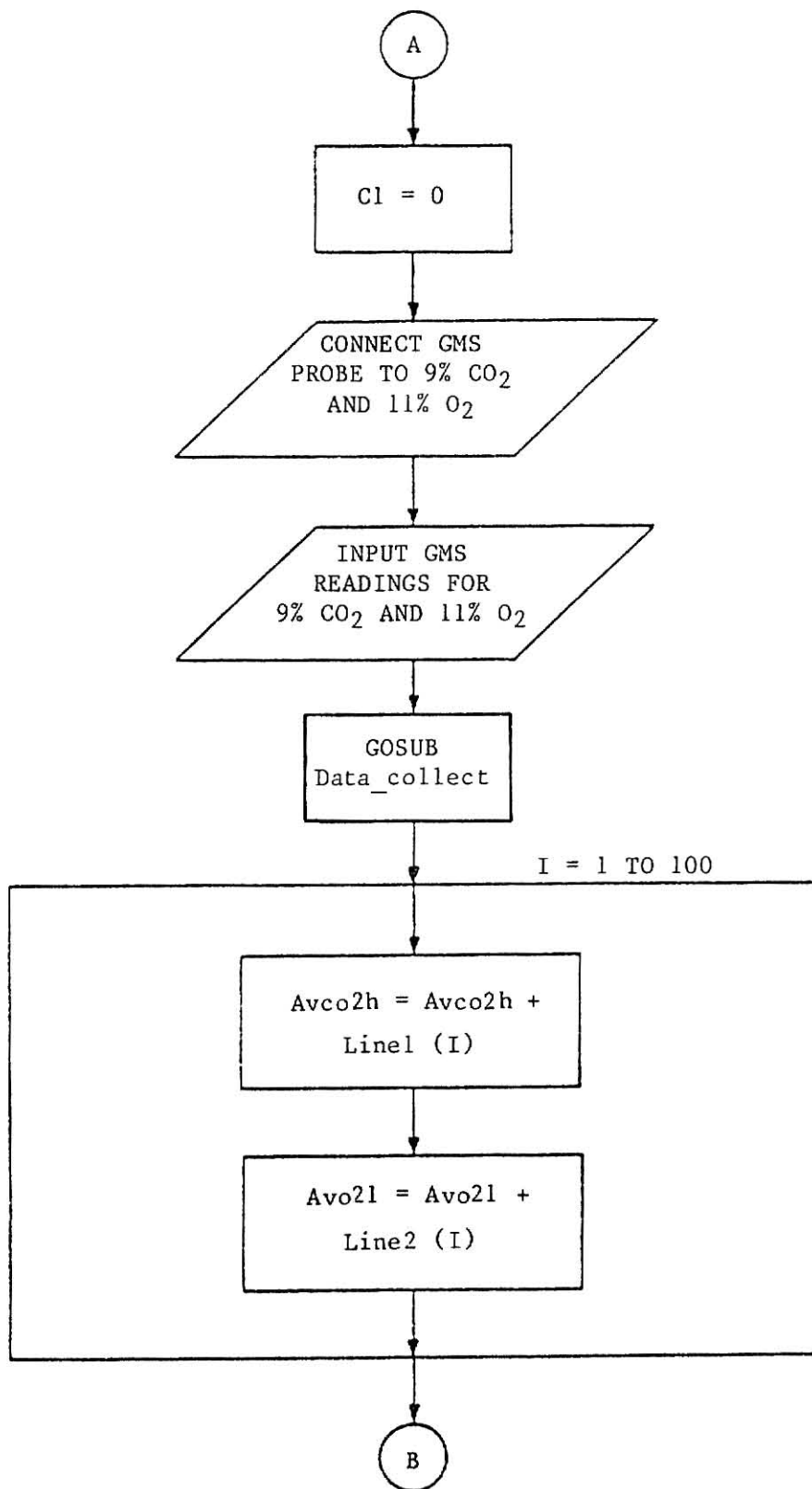
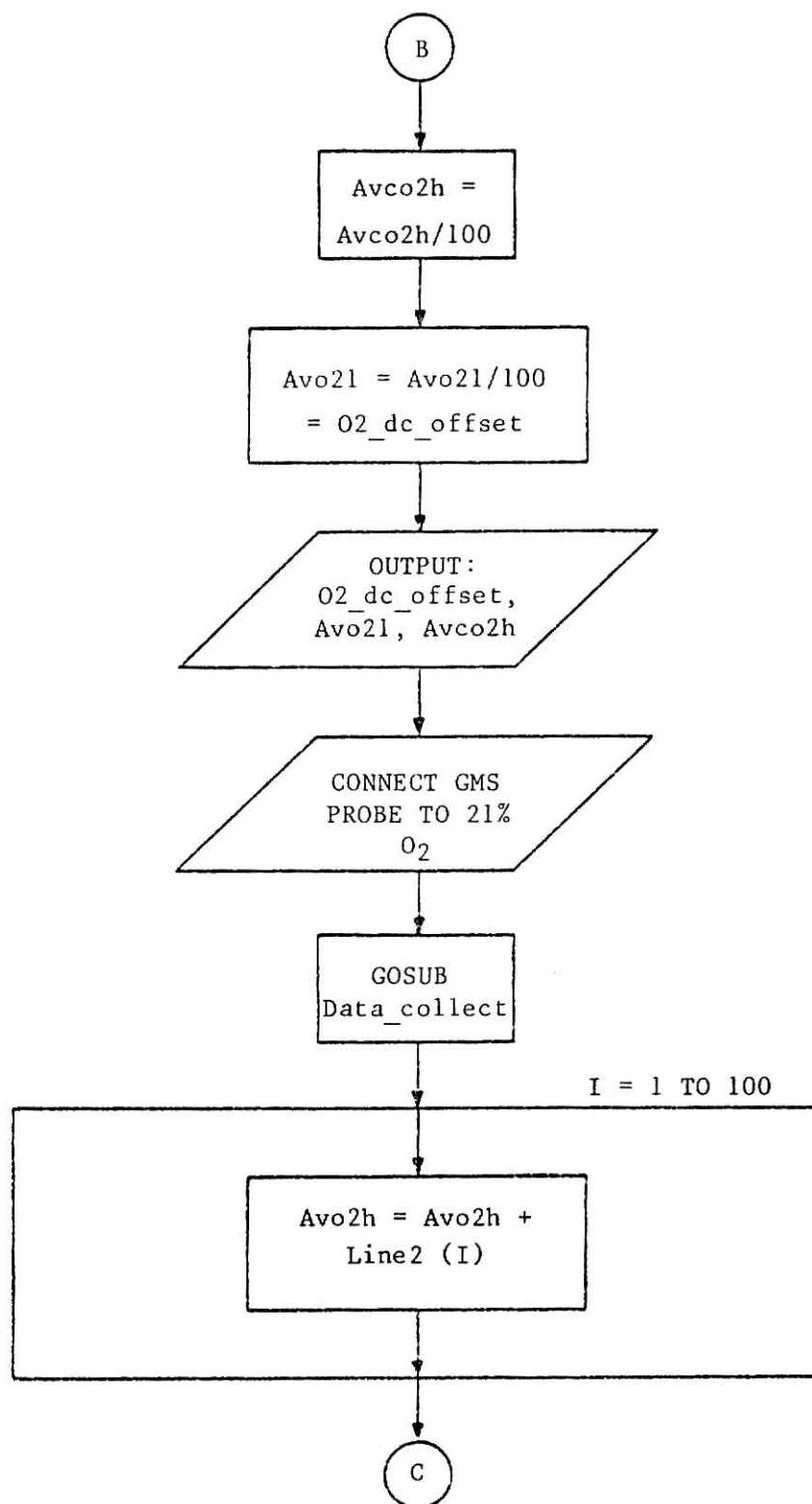
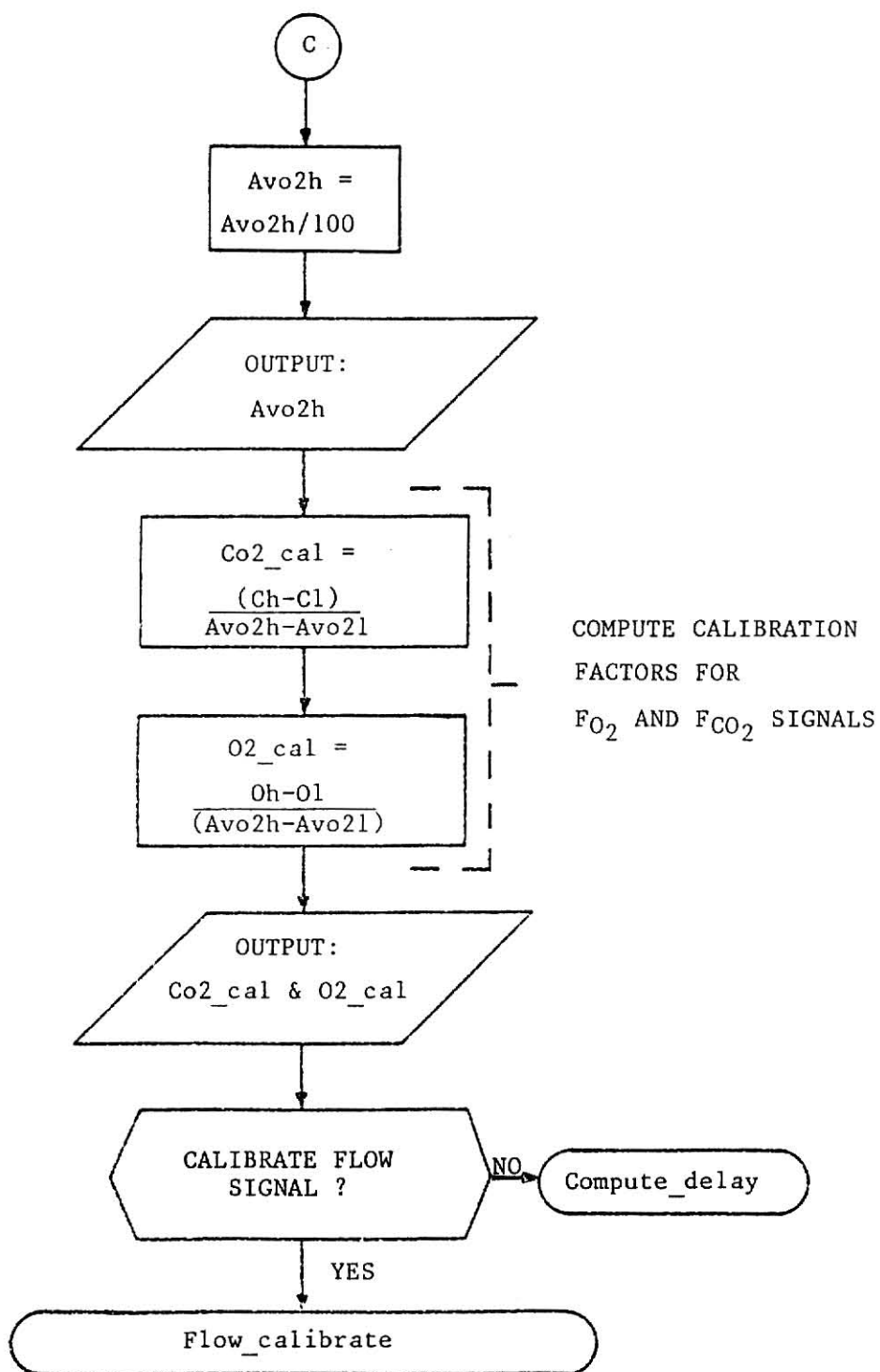


Figure A2.2 Gas Signal Calibration Subroutine Flowchart.







```

1550 !
1560 Calibrate: Subalgorithm to calibrate system components.
1570 !
1580 PRINT PAGE;"          GAS SIGNAL CALIBRATION ROUTINE"
1590 STANDARD
1600 SHORT Co2_dc_offset,O2_dc_offset,Co2_cal,O2_cal,Oh,O1,Ch,C1
1610 SHORT Av_co2l,Av_co2h,Av_o2h,Av_o2l
1620 S=100 ! For calibration, sampling frequency is 100
1630 GOSUB Pick_freq_ms ! jump to timer initialization routine
1640 INPUT "DO YOU WANT TO OBTAIN MASS SPEC CALIBRATION FACTORS ?(Y/N)",Qs
1650 IF Qs="N" THEN Flow_query
1660 PRINT LIN(2);" CONNECT THE MASS SPECTROMETER PROBE TO 100% N2 "
1670 DISP "PRESS <CONT> WHEN THE CONNECTION IS COMPLETED"
1680 PAUSE
1690 No_points=100
1700 DISP ""
1710 GOSUB Data_collect ! go get 100 points from the Fco2 and Fo2 channels
1720 FOR I=1 TO 100
1730 Avco2l=Avco2l+Line1(I)
1740 NEXT I ! Loop until all Fco2 data points are summed
1750 Avco2l=Co2_dc_offset=PROUND(Avco2l/100,0) ! Average of Fco2 data
1760 PRINT LIN(1);"CO2 DC OFFSET =";Co2_dc_offset
1770 PRINT LIN(1);"Average value read for 0% CO2 was....";Avco2l
1780 C1=0
1790 PRINT LIN(2);" CONNECT THE MASS SPECTROMETER PROBE TO 9% CO2 AND 11% O2
"
1800 INPUT "ENTER THE ACTUAL VALUE FOR THE CO2 CONCENTRATION",Ch
1810 INPUT "ENTER THE ACTUAL VALUE FOR THE O2 CONCENTRATION",O1
1820 GOSUB Data_collect
1830 FOR I=1 TO 100
1840 Avco2h=Avco2h+Line1(I)
1850 Avco2l=Avco2l+Line2(I)
1860 NEXT I
1870 Avco2h=PROUND(Avco2h/100,0)
1880 Avco2l=O2_dc_offset=PROUND(Avco2l/100,0)
1890 PRINT LIN(1);"O2 DC OFFSET =";O2_dc_offset
1900 PRINT LIN(1);"Average value read for 9% CO2 was....";Avco2h
1910 PRINT LIN(1);"Average value read for 11% O2 was....";Avco2l
1920 PRINT LIN(2);" CHANGE #: MIXING PUMP TO 9% CO2, 21% O2, 70% N2 "
1930 DISP "PRESS <CONT> AFTER PUMP CONCENTRATIONS STABILIZE"
1940 PAUSE
1950 PRINT LIN(2);" CONNECT MASS SPECTROMETER PROBE TO 9% CO2, 21% O2 "
1960 INPUT "ENTER ACTUAL O2 CONCENTRATION",Oh
1970 GOSUB Data_collect
1980 FOR I=1 TO 100
1990 Avco2h=Avco2h+Line2(I)
2000 NEXT I
2010 Avco2h=PROUND(Avco2h/100,0)
2020 PRINT LIN(1);"Average value read for 21% O2 was....";Avco2h;LIN(2)
2030 Co2_cal=PROUND((Ch-C1)/(Avco2h-Avco2l),-6) ! CO2 CALIBRATION FACTOR
2040 O2_cal=PROUND((Oh-O1)/(Avco2h-Avco2l),-6) ! O2 CALIBRATION FACTOR
2050 PRINT LIN(1);"CO2 CALIBRATION FACTOR =";Co2_cal
2060 PRINT LIN(1);"O2 CALIBRATION FACTOR =";O2_cal;LIN(1)
2070 !
2080 ! ***** END THE GAS SIGNAL CALIBRATION ROUTINE *****
2090 !

```


Gas Signal Calibration Subroutine Verification

To verify that this subroutine worked as intended the values for the following program variables were hand calculated and compared with the computer generated values for a single calibration run:

- 1) Avco2l - Average BCD value for 0% CO₂.
- 2) Avco2h - Average BCD value for 9% CO₂.
- 3) Avo2l - Average BCD value for 11% O₂.
- 4) Avo2h - Average BCD value for 21% O₂.
- 5) Co2_cal - F_{CO₂} calibration factor.
- 6) O2_cal - F_{O₂} calibration factor.

Table A2.2 summarizes the results. The hand calculated values were obtained using a listing of the contents of the fractional concentration data arrays. Clearly, the calibration factors for the fractional concentration signals were calculated correctly by the gas signal calibration subroutine.

TABLE A2.2

Verification Data for the Gas Signal
Calibration Subroutine

		Computer Generated Value	Hand Calculated Value
Avco2l	(BCD equivalent)	0	0
Avco2h	(BCD equivalent)	243	243
Avo2l	(BCD equivalent)	0	0
Avo2h	(BCD equivalent)	248	248
Co2_cal	(Frac. Conc. x ADU ⁻¹)	0.000370	0.000370
O2_cal	(Frac. Conc. x ADU ⁻¹)	0.000401	0.000401

The stability of the gas calibration subroutine as a function of time was also investigated. The subroutine was run five times, 30 minutes apart, on two successive days.

Table A2.3 summarizes the results of the stability study. The values listed in Table A2.3 suggest that the gas calibration factors were stable over a period of a few hours, and virtually constant from day-to-day.

TABLE A2.3

Results of the Gas Signal Calibration
Subroutine Stability Study

Trial #	Day 1		Day 2	
	Calibration Factor		Calibration Factor	
	CO ₂ 10 ⁻⁴ · (BCD Equivalent) ⁻¹	O ₂ 10 ⁻⁴ · (BCD Equivalent) ⁻¹	CO ₂ 10 ⁻⁴ · (BCD Equivalent) ⁻¹	O ₂ 10 ⁻⁴ · (BCD Equivalent) ⁻¹
1	3.70	4.01	3.72	4.00
2	3.71	4.00	3.72	4.02
3	3.71	4.02	3.71	4.00
4	3.70	4.00	3.70	4.01
5	3.72	4.01	3.72	4.02

The slight differences observed in the calibration factors were generated by slight changes in the gas concentrations delivered by the gas mixing pumps; and/or drift in the GMS electronics. The calibration factors were rounded to three significant digits, because at best, only three significant digits could be read from the output display of the GMS.

Results of the gas signal calibration factor stability study indicate that frequent gas signal calibration is unnecessary.

A2.2.2 Flow Signal Calibration Subroutine

Flow Signal Calibration Subroutine Variables

<u>Name</u>	<u>Type</u>	<u>Description</u>
Avole	real	The average unscaled BCD value representing the expiratory stroke volume.
Avoli	real	The average unscaled BCD value representing the inspiratory stroke volume.
Bin_zero_flow	real	The average of 200 BCD values read from the DAM V channel with a zero flow connected to the PTM.
Cal_flag	real	Serves to distinguish between a data analysis subroutine call made by either the System Controller Subroutine or the Flow Signal Calibration Subroutine.
Expr_flow_cal	real	This value is multiplied by each of the expiratory V digital data points to convert them from discrete values with ADUs to discrete values with units of l/s. One of the three calibration factors generated by the Flow Calibration Subroutine.
Flow_cal	real	During calibration assumes a value of 1 so that the integrated values for inspiratory and expiratory areas will consist of raw sums of BCD data only.
I	integer	Loop counter used for totalizing the data array holding the 200 BCD values read for zero flow.

<u>Name</u>	<u>Type</u>	<u>Description</u>
Insp_flow_cal	real	This value is multiplied by each of the inspiratory $\dot{V}$ digital data points to convert them from discrete values with ADUs to discrete values with units of l/s. One of the three calibration factors generated by the Flow Calibration Subroutine.
No_points	integer	A parameter passed to the data acquisition subroutine which determines the number of points to be collected from DAM input channels 1, 2, and 6.
S	integer	A parameter passed to the timer initialization subroutine. Determines the sampling frequency for channels 1, 2, and 6 of the DAM.
Tot_zero	real	The sum of the 200 BCD values collected from the $\dot{V}$ channel of the DAM with zero flow connected.
U	integer	Loop counter, used for creating a three minute delay between the time the calibration signal is switched on and the time at which the calibration data is obtained. During this time thermal stability is achieved.

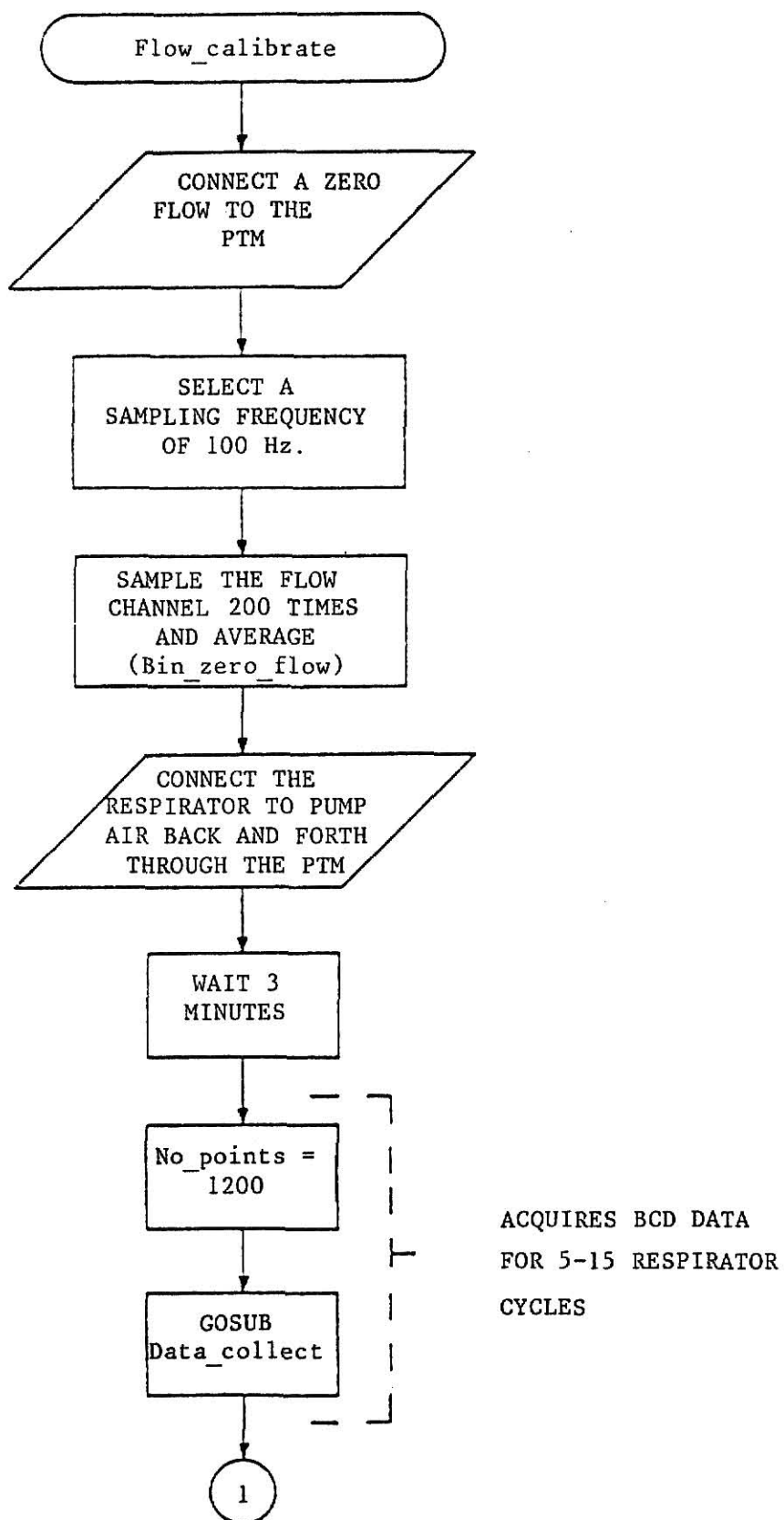
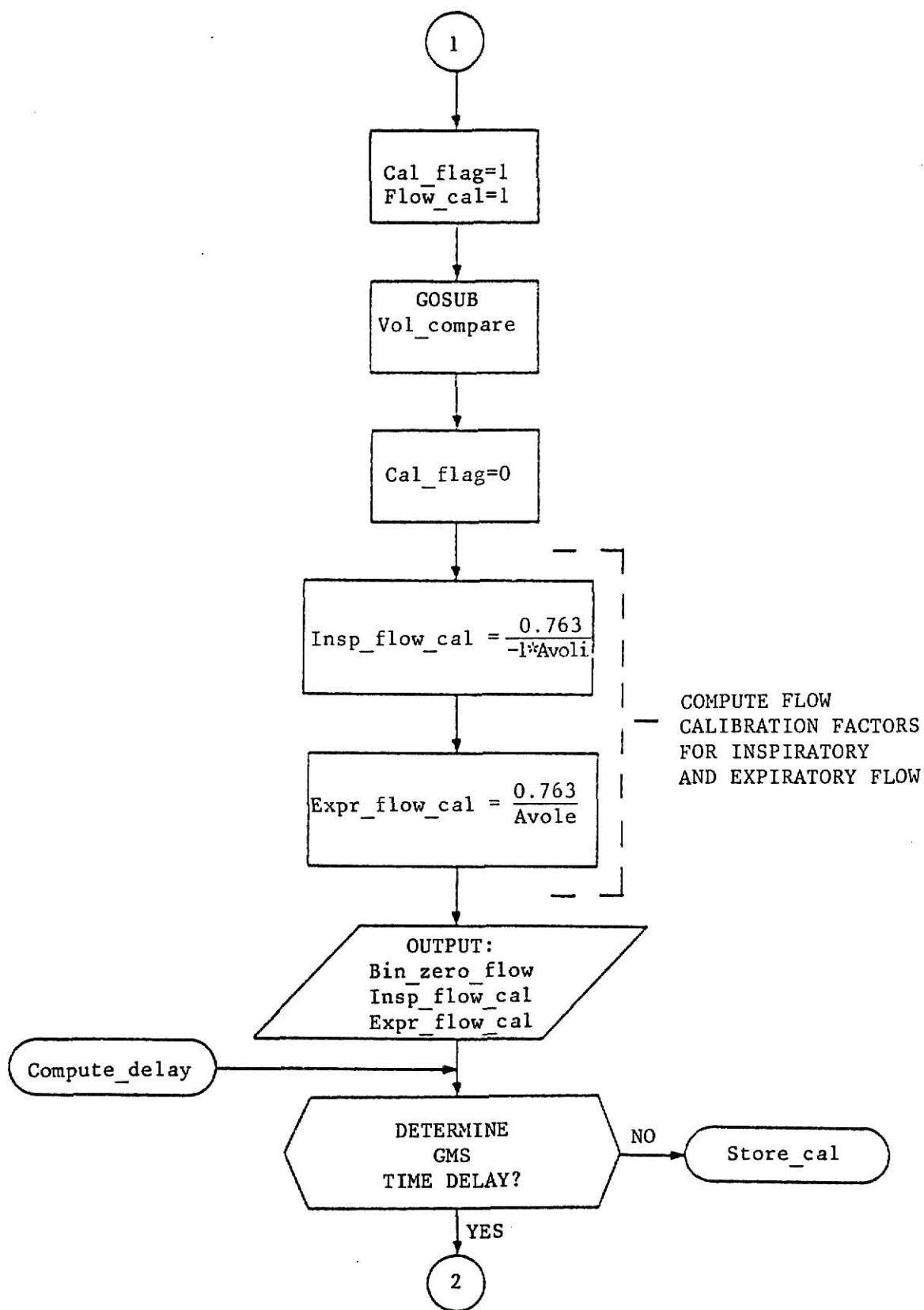
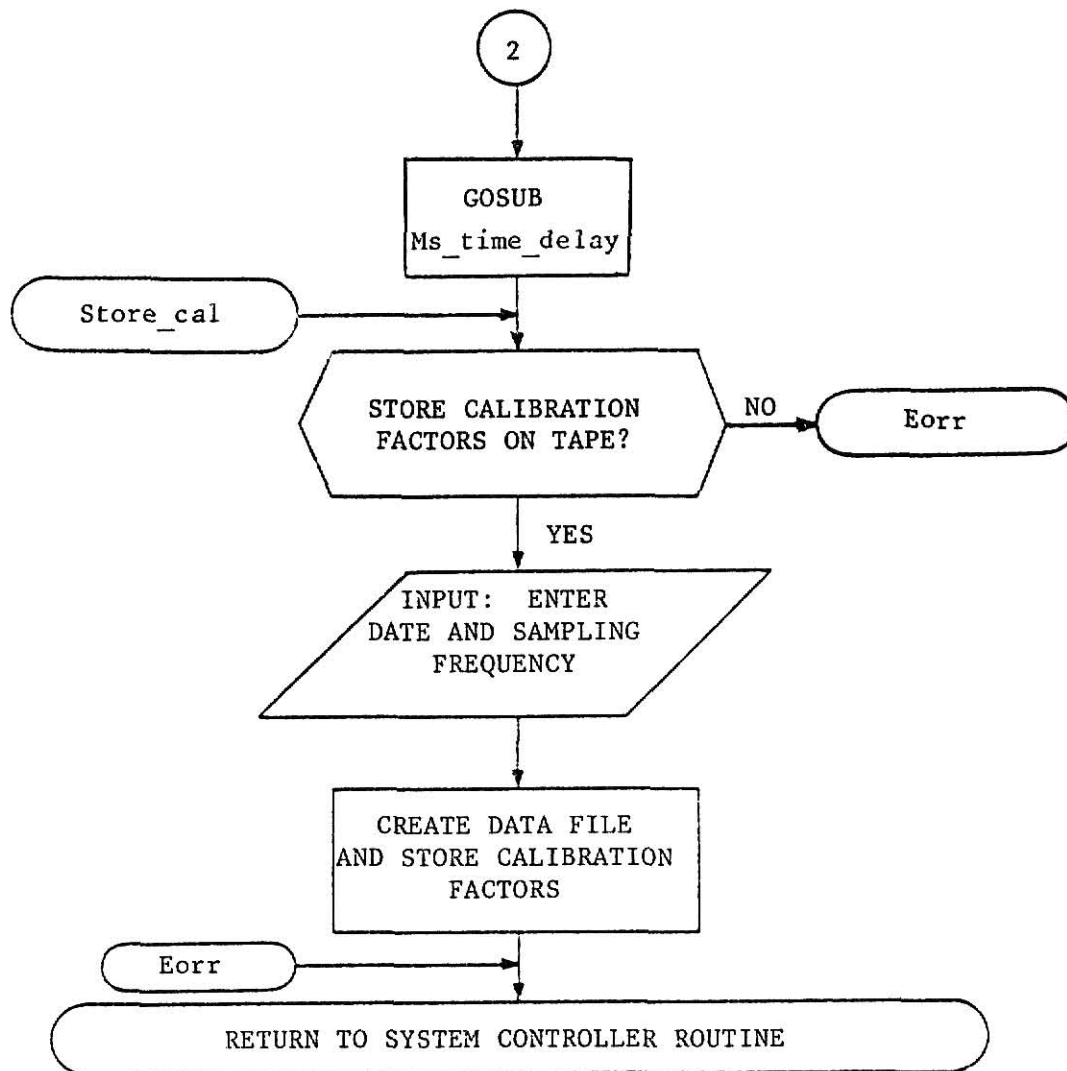


Figure A2.3 Flow Signal Calibration Subroutine Flowchart.





```

2100 Flow_query: INPUT "DO YOU WANT TO CALIBRATE THE FLOW SIGNAL (Y/N) ?";Q$
2110 IF (Q$<>"Y") AND (Q$<>"N") THEN 2100
2120 IF Q$="N" THEN Compute_delay
2130 Flow_calibrate:PRINT PAGE;"                                FLOW SIGNAL CALIBRATION ROUTINE
"
2140 SHORT Bin_zero_flow,Flow_cal
2150 PRINT LIN(2);"      The purpose of this routine is to determine a calibration factor"
2160 PRINT "for the gas flow signal."
2170 DISP "PRESS CONT AFTER CONNECTING ZERO FLOW TO THE PNEUMOTACHOMETER"
2180 PAUSE
2190 DISP ""
2200 No_points=200
2210 S=100
2220 GOSUB Pick_freq_ms
2230 GOSUB Data_collect
2240 FOR I=1 TO No_points
2250 Tot_zero=Tot_zero+Line6(I)
2260 NEXT I
2270 Bin_zero_flow=PROUND(Tot_zero/200,0)
2280 PRINT LIN(2);"Average binary value read for zero flow =";Bin_zero_flow
2290 DISP "PRESS CONT AFTER CONNECTING THE PUMP FLOW TO THE PNEUMOTACHOGRAPH"
2300 PAUSE
2310 FOR U=180 TO 1 STEP -1
2320 DISP "  WAITING FOR SYSTEM EQUILIBRATION  -  TIME TILL DATA COLLECTION:";
U;"sec"
2330 WAIT 900
2340 NEXT U
2350 No_points=2400
2360 DISP "  NOW COLLECTING DATA  ....please wait patiently !"
2370 GOSUB Data_collect
2380 REDIM Line6(No_points)
2390 DISP "  DATA COLLECTION COMPLETE  ....you may now turn off the pump."
2400 WAIT 2000
2410 DISP "  Now calculating ....best binary zero and flow calibration factor"
2420 Cal_flag=1
2430 Flow_cal=Expr_flow_cal=Insp_flow_cal=1
2440 GOSUB Vol_compare
2450 Insp_flow_cal=PROUND(.763/(-1*Avoli),-4)
2460 Expr_flow_cal=PROUND(.763/Avole,-4)
2470 PRINT LIN(2);"BINARY ZERO FLOW  =";Bin_zero_flow
2480 PRINT LIN(2);"INSPIRATORY FLOW CALIBRATION FACTOR  =";Insp_flow_cal
2490 PRINT LIN(2);"EXPIRATORY FLOW CALIBRATION FACTOR  =";Expr_flow_cal
2500 Cal_flag=0
2510 ! *****
2520 ! *****  END OF FLOW SIGNAL CALIBRATION SUBROUTINE *****
2530 ! *****
2540 Compute_delay: INPUT "DO YOU WANT TO DETERMINE THE TIME DELAY THROUGH THE M
ASS SPEC ? (Y/N)";Q$
2550 IF Q$="N" THEN Store_cal
2560 !
2570 ! Routine to determine mass spectrometer time delay
2580 ! includes capillary transport time and instrument response time
2590 !
2600 GOSUB Ms_time_delay
2610 !
2620 ! Now that we have the calibration factors, lets put them on tape

```



```

2630 !
2640 Store_cal: INPUT "DO YOU WANT TO STORE THE CALIBRATION FACTORS ON TAPE ?(Y
/N)",Q$
2650 IF Q$="N" THEN Errr
2660 INPUT "ENTER THE FREQUENCY FOR DATA ACQUISITION",S
2670 INPUT "ENTER THE FILE NAME FOR THE CALIBRATION FACTORS",Cal$
2680 INPUT "ENTER TODAY'S DATE, FORMAT: Month / Day / Year",Dates
2690 MASS STORAGE IS ":T14"
2700 CREATE Cal$,1,260
2710 ASSIGN #8 TO Cal$
2720 ON END #3 GOTO Errr
2730 !
2740 ! THE CALIBRATION FACTORS ARE STORED AS FOLLOWS:
2750 !      Co2_dc_offset: dc offset in the co2 channel
2760 !      O2_dc_offset: dc offset in the o2 channel
2770 !      Bin_zero_flow: binary value associated with zero flow
2780 !      Co2_cal: co2 calibration factor
2790 !      O2_cal: o2 calibration factor
2800 !      Flow_cal: flow calibration factor
2810 !      Time_delay: time delay through the mass spec in msec
2820 !      S: sampling frequency
2830 PRINT #8;Co2_dc_offset,O2_dc_offset,Bin_zero_flow,Co2_cal,O2_cal,Insp_flow_
cal,Exor_flow_cal,Time_delay,S,Dates
2840 Errr: MASS STORAGE IS ":T15"
2850 RETURN !Return to the main routine

```

Harvard Respirator Stroke Volume Determination

The stroke volume of the Harvard respirator was measured using a Collins 9 liter spirometer and a vernier caliper. A great deal of thought and effort went into making this measurement because the Harvard respirator was used to calibrate the flow signal during experiments. Consequently, every ventilatory quantity calculated by the analysis routine was directly dependent on the value used for the volume displacement of the respirator.

A relatively simple procedure was used to determine the stroke volume. The spirometer pen was positioned mid way on the chart paper. Both the spirometer and respirator have two ports serving as inlets and/or outlets. All one-way valves were removed from the ports to allow bidirectional gas flow through any particular port. One port of the spirometer was connected to one port of the respirator. The remaining ports were sealed using rubber stoppers. A very slow frequency of five breaths per minute was selected to eliminate any mechanical overshoot problems associated with the spirometer bell. For thirty minutes the respirator pumped air to and from the spirometer. This was done to allow temperature and volume equilibration. At the end of thirty minutes several stroke volumes were recorded on Collins authorized 9 liter spirometer chart paper. Figure A2.4 is a representative reproduction of such a recording. A vernier caliper was used to measure the distance on the chart paper corresponding to a one liter spirometer volume to within ± 0.0125 in. A value of 1.900 in. was read. Next a peak-to-peak difference on the chart paper was measured, again using the caliper.

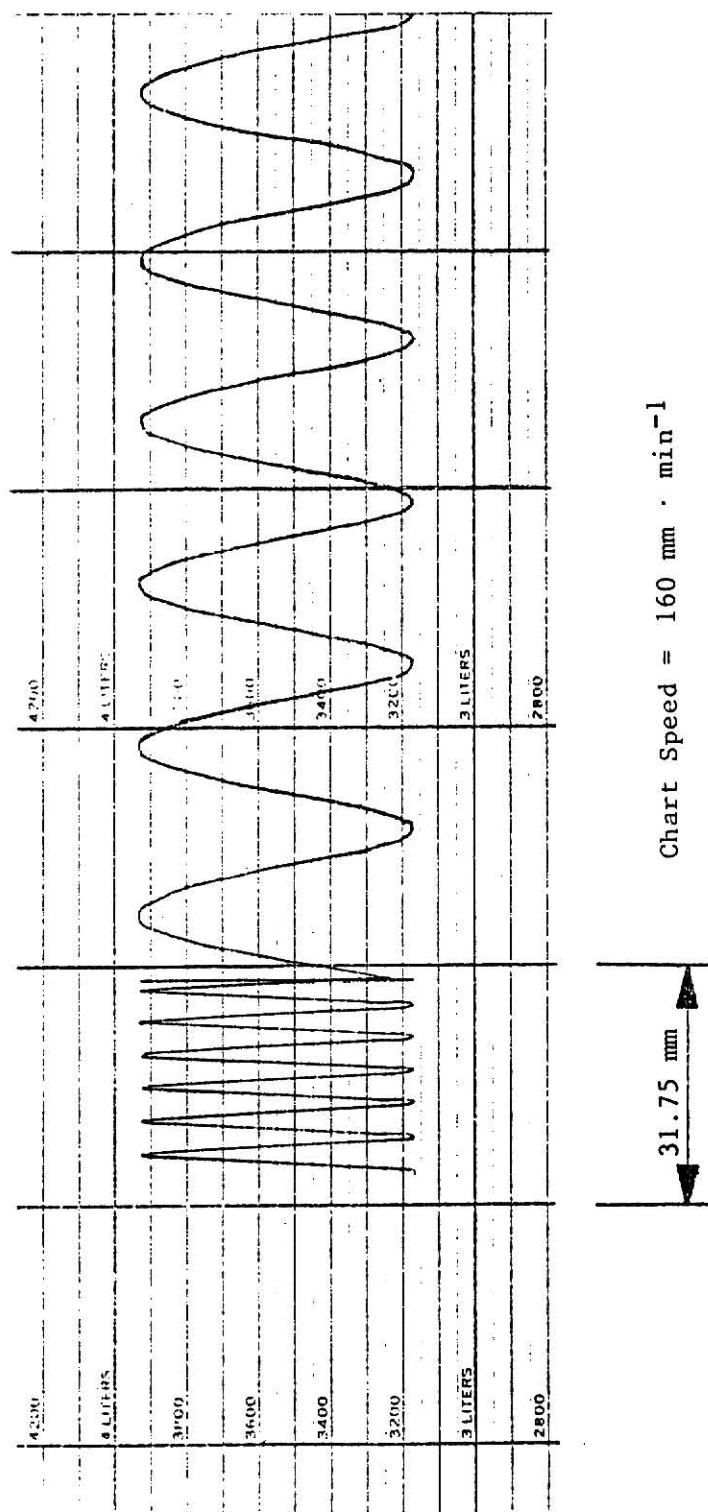


Figure A2.4 Respirator Stroke Volume Spirometer Tracing.

This value corresponded to the stroke volume of the respirator. To convert this value into a stroke volume, the factor obtained for a one liter volume was multiplied by the peak-to-peak difference as follows:

$$\text{Stroke Volume (liter)} = \frac{1}{1.900} \left(\frac{\text{liter}}{\text{inches}} \right) \times \frac{\text{Peak-to-Peak (inches)}}{\text{Difference}}$$

This procedure was repeated twice a day on four successive days to insure that the stroke volume remained constant. Table A2.4 summarizes the results of the eight trials.

TABLE A2.4

Data for Harvard Respirator Stroke
Volume Determination

Day	Trail #	1 Liter Factor (inches)	Peak-to-Peak Difference (inches)	Stroke Volume (liter)
1	1	1.900	1.450	0.763
	2	1.900	1.450	0.763
2	3	1.900	1.450	0.763
	4	1.900	1.4625	0.770
3	5	1.900	1.450	0.763
	6	1.900	1.450	0.763
4	7	1.900	1.450	0.763
	8	1.900	1.450	0.763

Based on the repeatability of the results, 0.763 was selected as the value representing the volume displacement of the Harvard respirator.

A2.2.3 GMS Time Delay Estimation Subroutine

GMS Time Delay Subroutine Variables

<u>Name</u>	<u>Type</u>	<u>Description</u>
A1	real	Temporary storage locations for the last four above curve area-to-below curve area ratios. Iteration continues until all four variables are equal whereupon program execution skips to the CO ₂ step response plotting routine.
A2		
A3		
A4		
Area_ratio	real	The absolute value of one minus the ratio of the computed values for the areas above and below the CO ₂ step response curve. Area_ratio equals zero when the area above exactly equals the area below the curve.
B_area	real	An estimation of the area below the CO ₂ step response curve as computed using the Trapezoidal Rule numerical integration technique.
Best_match	real	The best above curve to below curve area ratio computed during the iterative adjustment of integration center points.
Best_time	real	The time in milliseconds at which the best above curve to below curve area ratio occurs.
Co2_dc_offset	short precision	The average BCD value of 100 samples obtained from the FCO ₂ channel (channel 1, DAM) with the mass spectrometer probe connected to room air.
Co2_high	real	The average BCD value of 100 samples obtained from the FCO ₂ channel (channel 1, DAM) with the mass spectrometer probe connected to 9% CO ₂ .
Co2_low	short precision	Same as Co2_dc_offset.

<u>Name</u>	<u>Type</u>	<u>Description</u>
I	Integer	Loop counter. Used for totalizing arrays in computing required average values.
Line1 (*)	integer array	Holds BCD data obtained from the FCO ₂ channel (channel 1, DAM).
Mass_f	integer	The user selected sampling frequency for acquiring BCD data from the FCO ₂ channel for estimating the mass spectrometer time delay.
Mid_co2	integer	The first BCD data point in discrete time less than or equal to 50% of the average BCD value computed for the 9% CO ₂ concentration.
No_points	integer	A parameter passed to the CO ₂ step response data acquisition subroutine which determines the number of points to be collected from DAM input channel 1. Equals Mass_f in absolute value (i.e. 1 second is collected at a rate of Mass_f points per second).
Q	integer	Used to index the FCO ₂ BCD data array during computation of the areas above and below the CO ₂ step response curve.
Qf	integer	The index corresponding to the last integration center point.
Q_mid	integer	The index corresponding to the Mid_co2 data point. Used in establishing the range of integration center points.
Qs	integer	The index corresponding to the first integration center point.

<u>Name</u>	<u>Type</u>	<u>Description</u>
T_area	real	An estimation of the area above the CO ₂ step response curve as computed using the Trapezoidal Rule numerical integration technique.
Time_delay	real	The mass spectrometer time delay (capillary transit time + response time) in milliseconds.

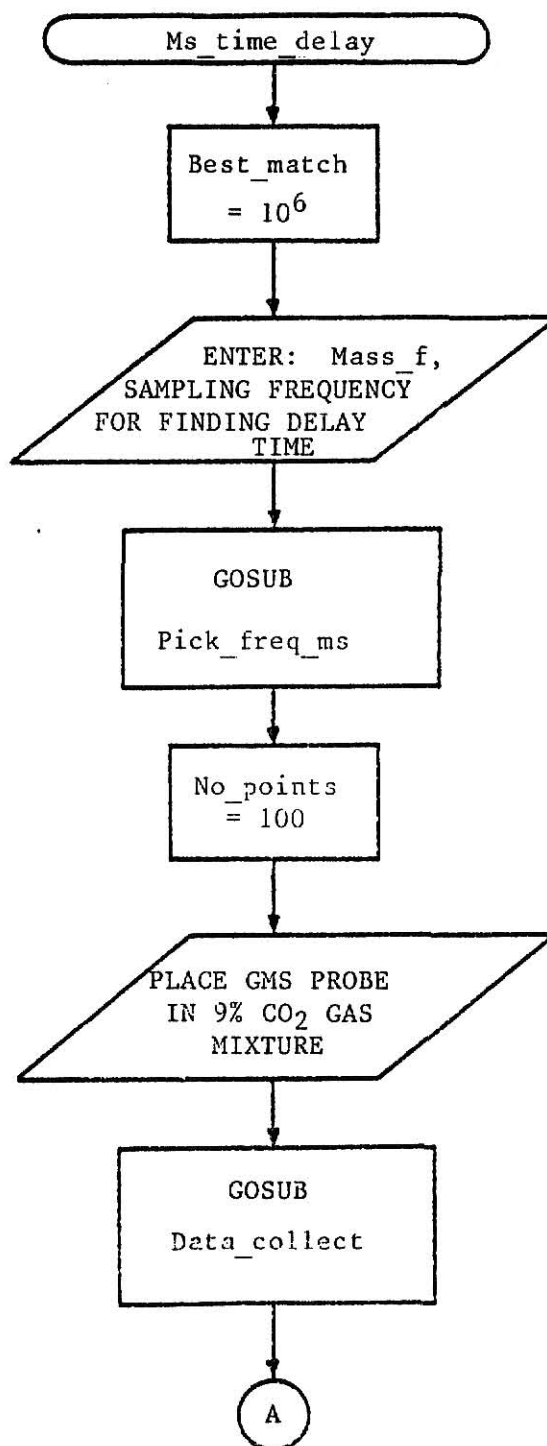
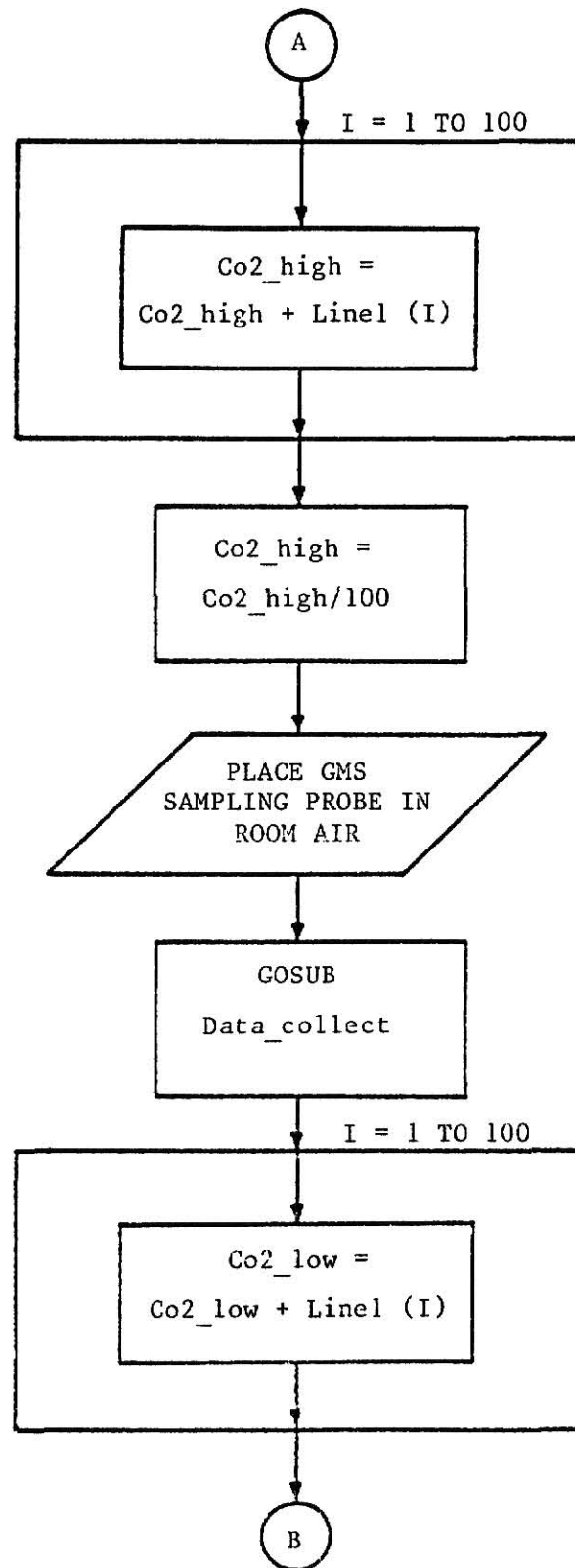
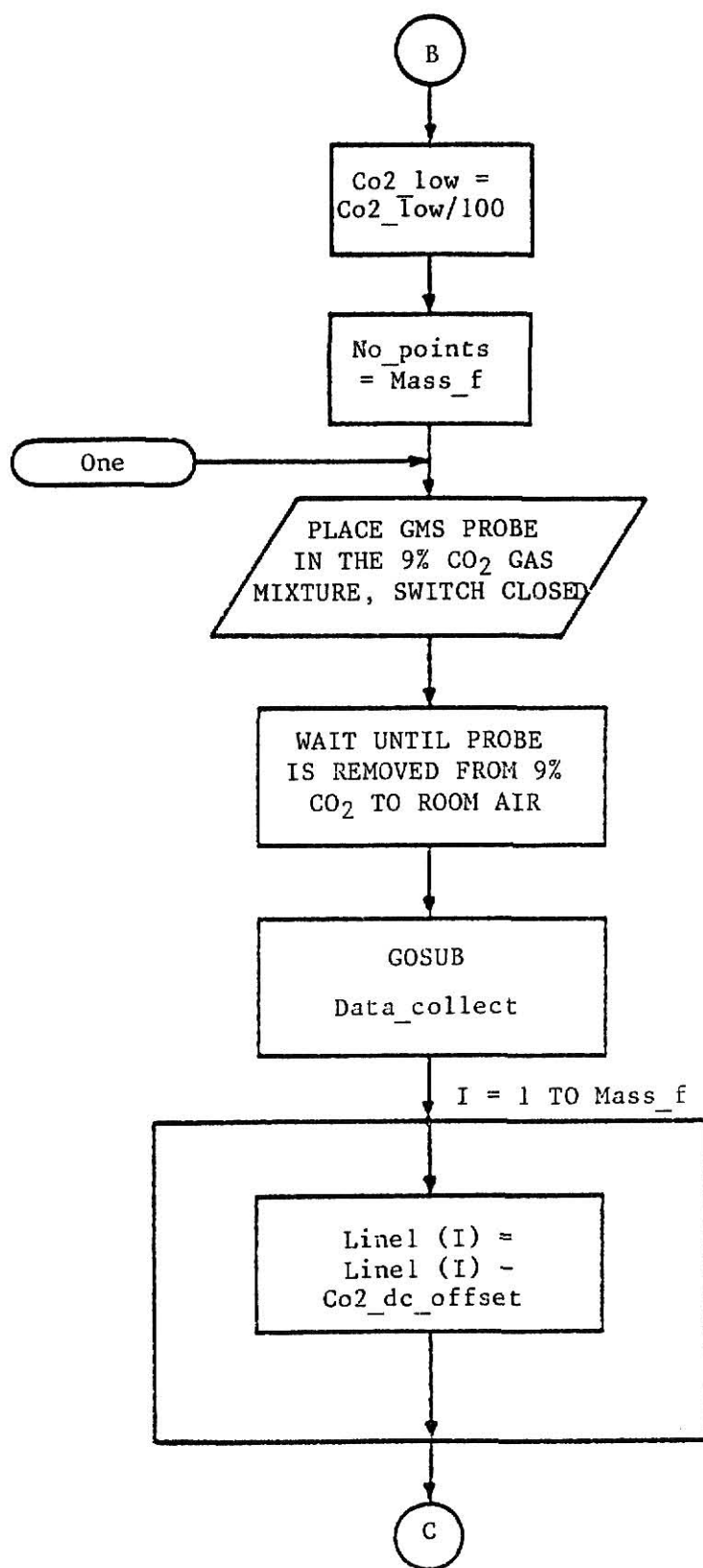
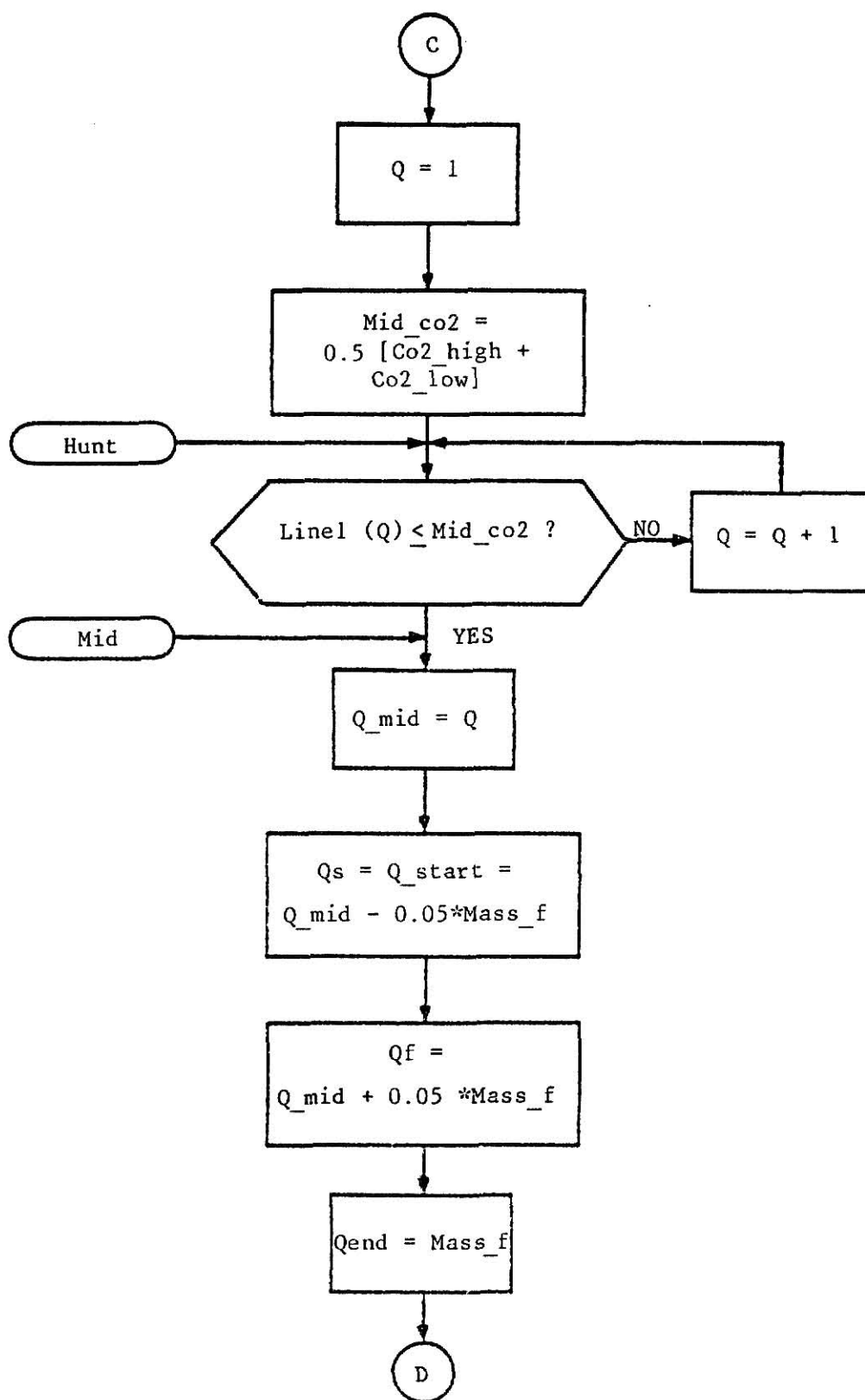
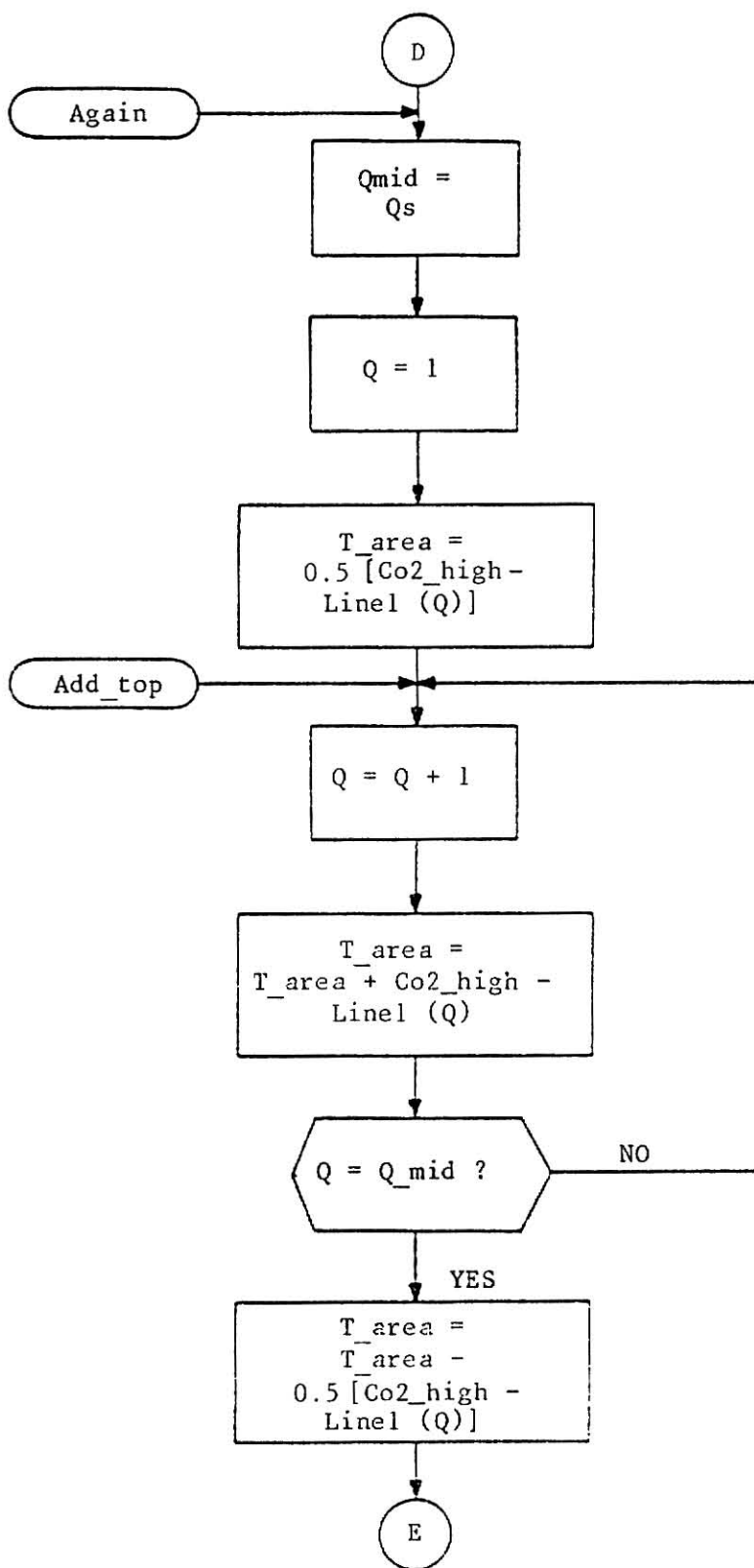


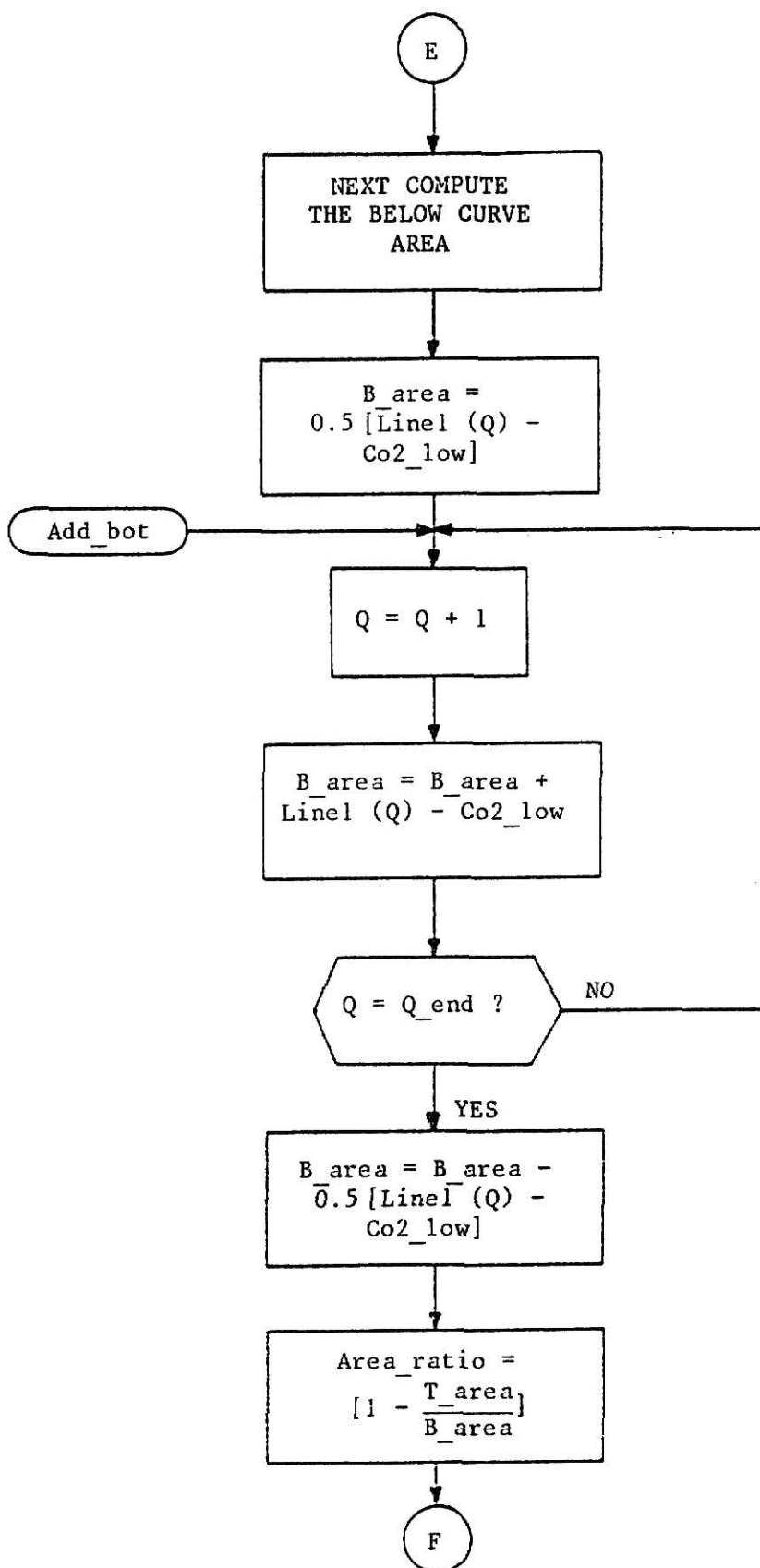
Figure A2.5 GMS Time Delay Estimation Subroutine Flowchart.

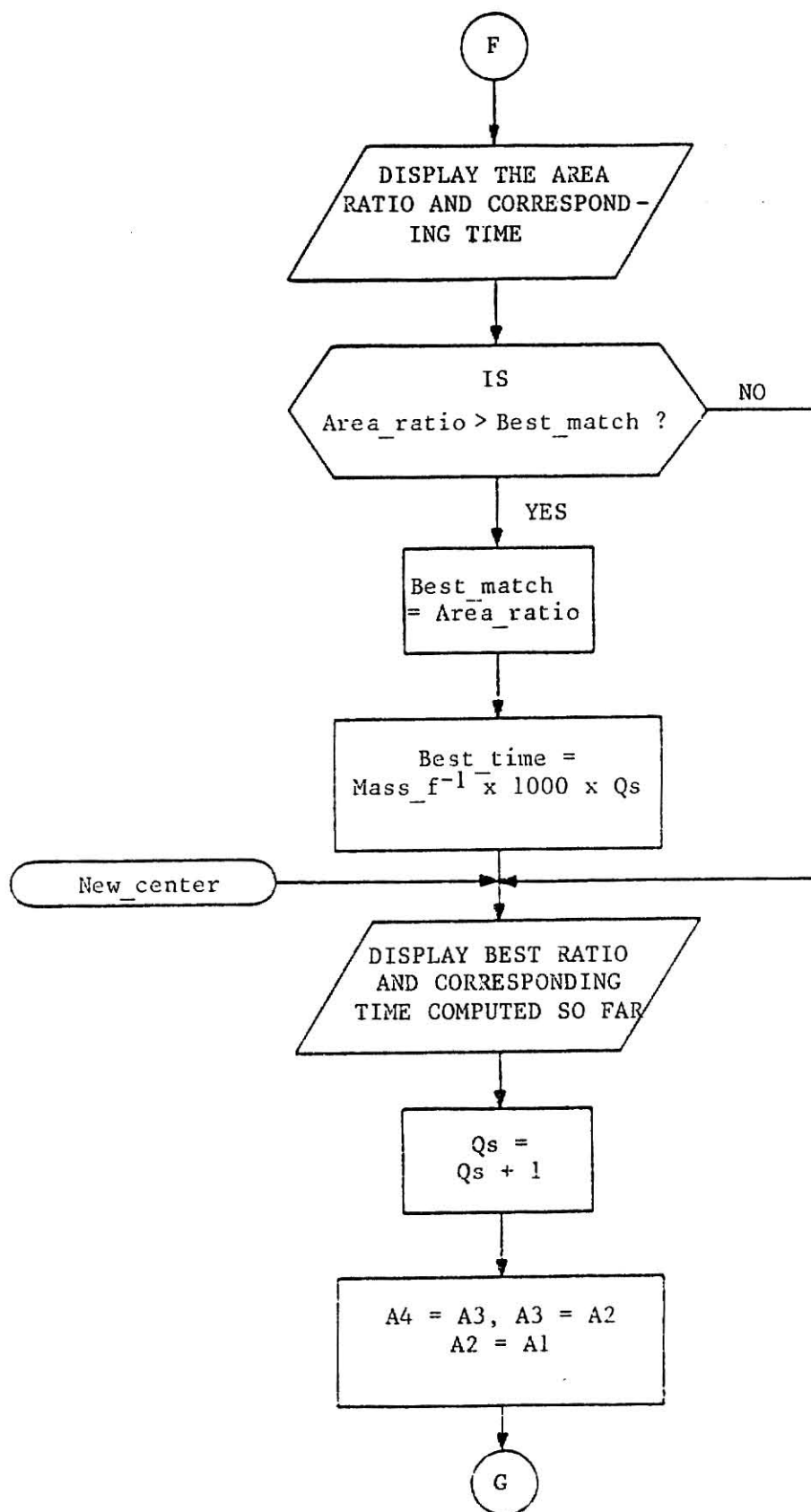


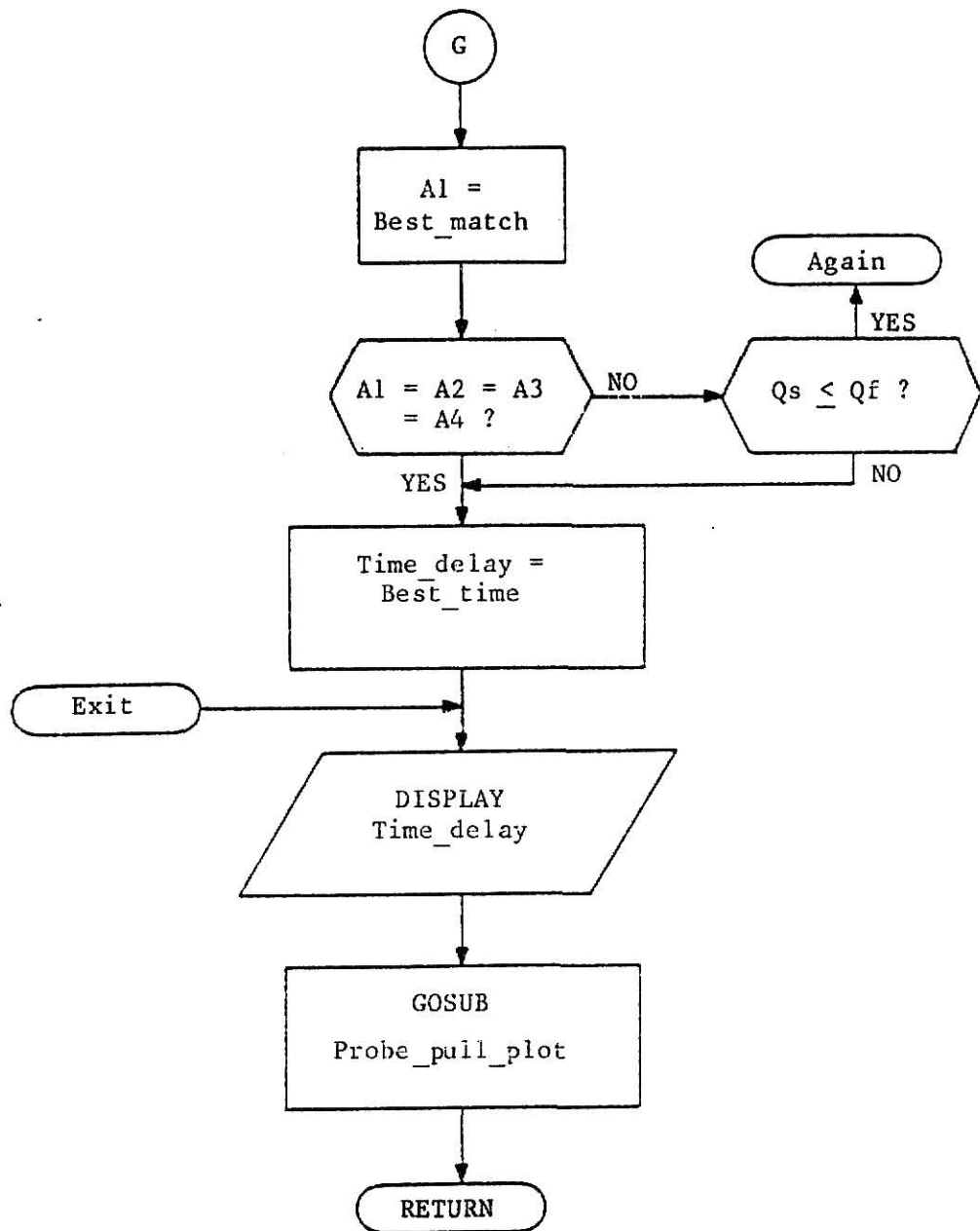












```

6790 Ms_time_delay: ! SUBROUTINE TO DETERMINE MASS SPECTROMETER TIME DELAY
6800 No_areas=0
6810 Best_match=1E6
6820 INPUT "ENTER SAMPLING FREQUENCY FOR MASS SPECTROMETER TIME DELAY",Mass_f
6830 S=Mass_f
6840 DISP "PLACE MASS SPECTROMETER PROBE IN THE 9% CO2 MIXTURE"
6850 PAUSE
6860 DISP
6870 GOSUB Pick_freq_ms
6880 No_points=100
6890 GOSUB Data_collect
6900 FOR I=1 TO 100
6910 Co2_total=Co2_total+Line1(I)
6920 NEXT I
6930 Co2_high=Co2_total/100
6940 PRINT LIN(1);"Average value read for 9% CO2 was...";Co2_high
6950 DISP "PLACE MASS SPECTROMETER PROBE IN ROOM AIR"
6960 PAUSE
6970 DISP
6980 GOSUB Data_collect
6990 Co2_total=0
7000 FOR I=1 TO 100
7010 Co2_total=Co2_total+Line1(I)
7020 NEXT I
7030 Co2_low=Co2_total/100
7040 PRINT LIN(1);"Average value read for room air CO2 was...";Co2_low;LIN(2)
7050 No_points=Mass_f !Get ready to collect one second of data
7060 PRINTER IS 0
7070 PRINT LIN(5);"TRIAL #";TAB(13);"TIME DELAY (msec)"
7080 PRINTER IS 16
7090 FOR T=1 TO 3
7100 One:DISP "PLACE MASS SPECTROMETER PROBE IN THE SAMPLING FIXTURE"
7110 PAUSE
7120 DISP "READY TO SAMPLE TIME DELAY, Pull the Plug "
7130 !CALL Time_delay(No_points,Line1(*))
7140 DISP "DATA COLLECTION COMPLETE, NOW COMPUTING TIME DELAY"
7150 FOR I=1 TO Mass_f
7160 Line1(I)=Line1(I)-Co2_cc_offset
7170 NEXT I
7180 Q=1
7190 Mid_co2=.5*(Co2_high+Co2_low)
7200 Hunt:IF Line1(Q)<=Mid_co2 THEN Mid
7210 Q=Q+1
7220 IF Q<=Mass_f THEN Hunt
7230 GOTO One
7240 Mid:Q_mid=Q
7250 Qs=Q_mid-.05*Mass_f
7260 Q_start=Qs
7270 Qf=Q_mid+.05*Mass_f
7280 Q_end=Mass_f
7290 Again:Q_mid=Qs
7300 Q=1
7310 T_area=.5*(Co2_high-Line1(Q))
7320 Add_top:Q=Q+1
7330 T_area=T_area+Co2_high-Line1(Q)
7340 IF Q>Q_mid THEN Add_top
7350 T_area=T_area-.5*(Co2_high-Line1(Q))

```



```

7360 B_area=.5*(Line1(Q)-Co2_low)
7370 Add_bot:Q=Q+1
7380 B_area=B_area+Line1(Q)-Co2_low
7390 IF Q(>)Mass_f THEN Add_bot
7400 B_area=B_area-.5*(Line1(Q)-Co2_low)
7410 Area_ratio=ABS(1-T_area/B_area)
7420 PRINT "AREA RATIO AT";1/Mass_f*Qs*1000;"msec CENTER POINT =";Area_ratio
7430 IF Area_ratio<Best_match THEN New_center
7440 Best_match=Area_ratio
7450 Best_time=1/Mass_f*1000*Qs
7460 New_center: PRINT "BEST RATIO SO FAR IS";Best_match,"AT";Best_time;"msec",L
IN(2)
7470 Q=1
7480 Qs=Qs+1
7490 A4=A3
7500 A3=A2
7510 A2=A1
7520 A1=Best_match
7530 IF (A1=A2) AND (A2=A3) AND (A3=A4) AND (Best_time>360) THEN Exit
7540 IF Qs<=Qf THEN Again
7550 Exit:Time_delay=Best_time
7560 PRINTER IS 0
7570 PRINT LIN(1);T,TAB(20);Time_delay
7580 PRINTER IS 16
7590 Tot_delay=Tot_delay+Time_delay
7600 Best_match=1E6
7610 NEXT T
7620 Time_delay=INT(Tot_delay/3)
7630 BEEP
7640 PRINTER IS 0
7650 PRINT LIN(2);"MASS SPECTROMETER TIME DELAY =";Time_delay;"msec";LIN(5)
7660 PRINTER IS 16
7670 WAIT 2000
7680 ! Time delay calculation complete
7690 GOSUB Probe_pull_plot
7700 RETURN
7710 ! *****
7720 ! ***** END OF MASS SPEC DELAY TIME ROUTINE *****
7730 ! *****

```

```

9230 ISOURCE NAM Capillary_delay
9240 ISOURCE EXT Get_value,Put_value,Get_info,Put_element
9250 ISOURCE Pass0:BSS 2
9260 ISOURCE Pass1:BSS 2
9270 ISOURCE Counter:BSS 2
9280 ISOURCE Array_info:BSS 30
9290 ISOURCE Element:EQU Array_info+16
9300 ISOURCE SUB
9310 ISOURCE Val0:INT
9320 ISOURCE Val1:INT (*)
9330 ISOURCE Time_delay:LDA #2
9340 ISOURCE STA Pa ! SELECT 16 BIT PARALLEL INTERFACE
9350 ISOURCE LDB #1
9360 ISOURCE Check_probe_in:LDA R5
9370 ISOURCE AND B !MASK OFF ALL BUT LEAST SIGNIFICANT BITS
9380 ISOURCE SZA Check_probe_in
9390 ISOURCE Check_probe_out:LDA R5 !READ THE R5 REGISTER
9400 ISOURCE AND B ! MASK OFF ALL BUT LEAST SIGNIFICANT BITS
9410 ISOURCE RZA Check_probe_out !GO BACK AND READ R5 AGAIN IF A REGISTER "1"
9420 ISOURCE LDA #Pass0
9430 ISOURCE LDB #Val0
9440 ISOURCE JSM Get_value ! GET THE NUMBER OF POINTS TO BE COLLECTED FROM BASIC
9450 ISOURCE LDA #0
9460 ISOURCE STA Counter ! SET UP MATRIX POINTER TO POINT AT THE FIRST ELEMENT
9470 ISOURCE LDA #-32734 ! 0101 1000
9480 ISOURCE STA R6 ! CH1, INT TRIG, DIS 8253 BUS, DIS START, EDC, DIS INT TRIG
9490 ISOURCE LDA #-30976 ! 0111 1000
9500 ISOURCE STA R6 ! ENABLE THE START LINE
9510 ISOURCE Next_data: LDA #1792 ! 1111 1000
9520 ISOURCE STA R6 ! ENABLE INTERNAL TRIGGER, SELECT EDC
9530 ISOURCE G1: LDA R4 ! GET EDC DATA FROM ADC
9540 ISOURCE CMA ! COMPLEMENT THE DATA TO NEGATE INPUT LOGIC INVERSION
9550 ISOURCE RLA G1 ! SKIP TO GOLOW IF b0<>0 (EDC NOT LOW)
9560 ISOURCE GH:LDA R4 ! GET EDC DATA FROM THE ADC
9570 ISOURCE RLA GH ! SKIP TO GOHIGH IF b0<>0 (EDC NOT HIGH)
9580 ISOURCE LDA #19176 ! 1011 1000 SELECT DATA LINES
9590 ISOURCE STA R6
9600 ISOURCE LDA #Array_info
9610 ISOURCE LDB #Val1
9620 ISOURCE JSM Get_info
9630 ISOURCE LDA Counter
9640 ISOURCE STA Element
9650 ISOURCE LDA R4 ! READ THE DATA FROM THE ADC
9660 ISOURCE LDB #255 ! INITIALIZE MASK WORD TO 0000 0000 1111 1111
9670 ISOURCE CMA ! COMPLEMENT ADC DATA TO NEGATE INPUT LOGIC INVERSION
9680 ISOURCE AND B ! MASK OFF UPPER 8 BITS OF REGISTER A
9690 ISOURCE STA Pass1 ! BEGIN UTILITY TO PASS DATA TO BASIC
9700 ISOURCE LDA #Pass1
9710 ISOURCE LDB #Array_info
9720 ISOURCE JSM Put_element ! PASS THE ADC DATA TO THE BASIC ARRAY (Line1111)
9730 ISOURCE LDA #-14592! 0011 1000
9740 ISOURCE STA R6 ! SELECT b0,b1,b2/b1 line LOW, CH.1
9750 ISOURCE ISZ Counter ! INCREMENT THE COUNTER
9760 ISOURCE DBZ Pass0 ! DECREMENT Pass0
9770 ISOURCE JMP Next_data !IF COUNTER<>0 THEN BRANCH & READ EACH CHANNEL AGAIN
9780 ISOURCE Hal:RET ! ! ALL DATA POINTS HAVE BEEN OBTAINED, RETURN TO BASIC
9790 ISOURCE END Capillary_delay
9800 ! ***** END PROBE PULL ROUTINE *****

```

GMS Time Delay Estimation Subroutine Verification.

In order to investigate the stability of the GMS time delay, the subroutine for estimating the delay was run once a day, on nine different days. The GMS time delay obtained on each particular day is listed in Table A2.5. Also, the mechanics of the subroutine were checked using hand calculated results generated from a set of fabricated data. This was done to insure that non-identical time delays were due to factors other than the subroutine itself.

TABLE A2.5

Data for GMS Time Delay Stability Study

Day	Time Delay (msec)
1	387.6
2	393.2
3	374.8
4	373.2
5	377.2
6	374.4
7	371.2
8	371.0
9	<u>373.8</u>

Average 377.4

Each of the above time delays was calculated based on a sampling frequency of 500 Hz. It was observed that the time delay associated with the GMS's electrical response time was constant. This meant that the variability present was primarily due to the gas transport (capillary) delay. A full scale investigation was launched to determine a possible explanation for the observed variability. Two different types of variance were discovered. The first type can best be described as small changes (10 to 20 msec) in the average

value of the time delay. The average value was obtained by performing five or ten successive time delay runs and averaging the results. The average would remain relatively constant over a period of a few hours, but was observed to fluctuate unpredictably from day-to-day. The most probable cause for this type of delay would be the presence of a minute particle of foreign matter lodged somewhere inside the capillary. Perhaps also there might be small day-to-day fluctuations in the vacume which draws the gas sample through the capillary. Realistically, only a small change in vacume would be necessary to create a ten or twenty millisecond difference in the transport delay time.

The second type of variability manifested itself as moderate fluctuations (2-20 msec) about the average values. These differences were determined to be due to subtle differences (human factors) in the manner in which the capillary probe was withdrawn from the 9% CO₂ sampling port to room air. Since no convenient technique for controlling either of the sources of variability existed, the next step was to investigate the effect of the capillary delay variability on the analysis routine results.

The system was calibrated using the system calibration routine. Next, 20 breaths of respiratory data from a calf were collected at a sampling frequency of 50 Hz. The digital data was stored on magnetic tape, and then analyzed using the original delay time of 394.6 msec. Next, the time delay was artificially manipulated in 5 msec increments about the original time delay value, and the analysis routine run using each time delay.

Although each of the computed respiratory quantities are affected by changes in the GMS delay time, the respiratory quotient, R, is most sensitive. A listing of the R values obtained for the various time delay values is given in Table A2.6.

TABLE A2.6

Variations in R Due to Changes in the GMS Delay Time

Time Delay (msec)	R	% Deviation from Original R Value
350	0.992	2.72
360	0.992	2.72
370	1.007	1.18
380	1.007	1.18
385	1.007	1.18
390	1.019	0.00
** 394	1.019	0.00
400	1.019	0.00
405	1.019	0.00
410	1.028	0.88
420	1.028	0.88
430	1.035	1.57

**Original computed values.

The results in Table A2.7 indicate that variations in the GMS delay time of less than 10 msec do not significantly alter the computed experimental results.

A2.2.4 CO₂ Step Response Plotting Subroutine

The CO₂ Step Response Plotting Subroutine plots out the digital FCO₂ signal obtained during the third step of the GMS time delay determination procedure. During the third step, one second of digital FCO₂ data is recorded at a high sampling frequency (500 Hz typically). Recording begins the instant the GMS sampling probe is removed from a 9% CO₂ gas mixture to room air. A representative plot illustrating the GMS gas transport delay and electrical response time was previously given in Figure 4.3.3. This figure was produced using the plotting subroutine.

Although a FCO₂ step response plot is nonessential to system calibration, it is useful from the standpoint that it provides a document illustrating the response curve for each experiment. This serves to inform the user if any significant changes occur from day-to-day.

All variables used in the plotting subroutine have been previously defined, hence, no variable list is included. The program structure is sufficiently simple that no flowchart is required. A program listing which features Hewlett-Packard Enhanced BASIC graphics statements [33] is included.

```

9440
9450 Probe_pull_plot: ! Plotting routine to plot out Mass spec CO2 step response
9460
9470 PLOTTER IS "GRAPHICS"
9480 GRAPHICS
9490 STANDARD
9500 LOCATE 20,120,10,90
9510 SCALE 0,Mass_f+Mass_f/5,0,300
9520 AXES Mass_f/10,50
9530 LINE TYPE 3
9540 FOR I=1 TO Mass_f
9550 PLOT I,Line1(I)
9560 NEXT I
9570 LINE TYPE 1
9580 LORG 5
9590 FOR I=0 TO Mass_f STEP Mass_f/10
9600 MOVE I,-5
9610 LABEL I*1000/Mass_f
9620 NEXT I
9630 MOVE Mass_f+1.5*Mass_f/10,-5
9640 LABEL "t,msec"
9650 LORG 8
9660 FOR I=0 TO 250 STEP 50
9670 MOVE -3,I
9680 FIXED 3
9690 LABEL I*Co2_cal:" "
9700 NEXT I
9710 MOVE -3,275
9720 LABEL "FCO2";" "
9730 LORG 2
9740 MOVE 50,275
9750 LABEL "MASS SPECTROMETER CO2 STEP INPUT RESPONSE"
9760 WAIT 3000
9770 DUMP GRAPHICS
9780 EXIT GRAPHICS
9790 RETURN
9800 ! *****
9810 ! ***** END PROBE PULL PLOT ROUTINE *****
9820 ! *****

```

A2.3 Data Acquisition Module Sampling Frequency Subroutine

This subroutine initializes the DAM sampling frequency. The BASIC variable S determines the sampling frequency and must be in the range of 10 Hz to 1 KHz.

Conceptually, initialization of the 8253 programmable timer is simple. The 8253 is connected to a 1 MHz clock. Using two 16-bit counters in cascade, the 1 MHz clock frequency is divided down to obtain the desired sampling frequency. The cascaded counters are initialized through an 8-bit parallel data path using the DAM Sampling Frequency Subroutine Software. The output from the second counter stage is gated together with other DAM control signals to produce the A/D start pulse.

A flowchart illustrating the timer initialization procedure does not contain significantly more information than the BASIC program listing, and thus, was omitted. However, a well commented program listing illustrating the necessary control works for timer initialization, is included. The variable types and functions are evident from the program listing.


```

1140
1150 Pick_frequency: SUBALGORITHM TO INITIALIZE 9253 TIMER
1160
1170 INPUT "ENTER SAMPLING FREQUENCY (10 TO 500 Hz)",S
1180 Pick_freq_ms:X=INT(500000/S) ! X is a constant fed to the 9253 for setting
1190 ! up the sampling frequency
1200 IF X<256 THEN 1250 ! X has a different flavor if the sampling
1210 ! frequency is less than 256
1220 Fm=INT(X/256) ! Fm is the msb of the sampling control word sent
1230 F1=X-256*Fm ! to the 9253
1240 GOTO 1270
1250 Fm=0
1260 F1=X
1270 WRITE IO 2,6;2048 ! 11110111 MODE CONTROL WORD
1280 WRITE IO 2,4;201 ! 00110110 CONTROL WORD FOR COUNTER 0
1290 WRITE IO 2,6;6144 ! 11100111 WRITE MODE WORD INTO CONTROL WORD REGISTER
1300 WRITE IO 2,6;2048 ! 11110111 DISABLE CHIP SELECT
1310 WRITE IO 2,4;137 ! 01110100 MODE CONTROL WORD FOR COUNTER 1
1320 WRITE IO 2,6;6144 ! 11100111 WRITE MODE WORD INTO CONTROL WORD REGISTER
1330 WRITE IO 2,6;2048 ! 11110111 DISABLE CHIP SELECT
1340 WRITE IO 2,6;2816 ! 11110100 PREPARE TO LOAD COUNTER 0
1350 WRITE IO 2,4;253 ! 00000010 LSByte FOR COUNTER 0
1360 WRITE IO 2,6;4864 ! 11101100 LOAD LSByte INTO COUNTER 0
1370 WRITE IO 2,6;768 ! 11111100 DISABLE CHIP SELECT
1380 WRITE IO 2,4;255 ! 00000000 MSByte FOR COUNTER 0
1390 WRITE IO 2,6;4864 ! 11101100 LOAD MSByte INTO COUNTER 0
1400 WRITE IO 2,6;768 ! 11111100 DISABLE CHIP SELECT
1410 WRITE IO 2,6;2560 ! 11110101 SELECT COUNTER 1
1420 F1=256-(1+F1) ! ONES COMPLEMENT OF F1
1430 WRITE IO 2,4;F1 ! LSByte FOR COUNTER 1
1440 WRITE IO 2,6;6656 ! 11100101 LOAD LSByte INTO COUNTER 1
1450 WRITE IO 2,6;2560 ! 11110101 DISABLE CHIP SELECT
1460 Fm=256-(Fm+1) ! ONES COMPLEMENT OF Fm
1470 WRITE IO 2,4;Fm ! MSByte FOR COUNTER 1
1480 WRITE IO 2,6;6656 ! 11100101 LOAD MSByte INTO COUNTER 1
1490 WRITE IO 2,6;2560 ! 11110101 DISABLE CHIP SELECT
1500 WRITE IO 2,6;-28738 ! 01110000 SAMPLE ALL CHANNELS
1510 RETURN
1520 ! *****
1530 ! ***** END OF TIMER INITIALIZATION ROUTINE *****
1540 ! *****

```

A2.4 Data Acquisition Subroutine

The Data Acquisition Subroutine is a combination BASIC/HP assembly language program which acquires digital data from DAM channels one, two, and six. The BASIC portion of the subroutine serves only to invoke the assembly routine; which systematically sends and receives information over the 16-bit parallel interface during the course of data acquisition. The assembly language routine was required because a comparable BASIC program would execute too slowly to enable rapid sampling of multiple analog input signals.

The data acquisition software is extremely dependent on the operational characteristics of the DAM. Documentation for this software is long and tedious; and most probably not of general interest. For the interested reader, complete documentation for this subroutine is available through Dr. Richard Gallagher, Department of Electrical Engineering, Kansas State University, 66502. A complete, well commented version of the Data Acquisition Subroutine follows.

```

6050
6060 Data_collect: ! This subroutine actually performs the task of data
6070 ! acquisition. The assembly routine is called from BASIC.
6080 ! the data is obtained and then control is passed back
6090 ! to BASIC.
6100 !
6110 ! Following is an assembly routine which collects data from channels
6120 ! 1,2, and 6 at the user selected sampling frequency.
6130 ! At completion, data obtained from channels 1, 2, & 6 reside in
6131 ! BASIC arrays Line1(*), Line2(*), and Line6(*) respectively.
6140 DISP " NOW COLLECTING DATA .....Sit Back, Relax, and Wait for the beep!"
6150 ICALL Output(No_points,Line1(*),Line2(*),Line6(*))
6160 DISP
6170 BEEP
6180 RETURN
6190 ISOURCE NAM A_to_d
6200 ISOURCE EXT Get_value,Put_value,Get_info,Put_element
6210 ISOURCE Pass0:BSS 2
6220 ISOURCE Pass1:BSS 2
6230 ISOURCE Pass2:BSS 2
6240 ISOURCE Pass3:BSS 2
6250 ISOURCE Pass6:BSS 2
6260 ISOURCE Counter:BSS 2
6270 ISOURCE Array_info:BSS 30
6280 ISOURCE Array_info2:BSS 30
6290 ISOURCE Array_info3:BSS 30
6300 ISOURCE Array_info6:BSS 30
6310 ISOURCE Element:EQU Array_info+16
6320 ISOURCE Element2:EQU Array_info2+16
6330 ISOURCE Element6:EQU Array_info6+16
6340 ISOURCE SUB
6350 ISOURCE Val0:INT
6360 ISOURCE Val1:INT (* )
6370 ISOURCE Val2:INT (* )
6380 ISOURCE Val6:INT (* )
6390 ISOURCE Output:LDA #2
6400 ISOURCE STA Pa ! SELECT 16 BIT PARALLEL INTERFACE
6410 ISOURCE LDA #Pass0
6420 ISOURCE LDB #Val0
6430 ISOURCE JSH Get_value ! GET THE NUMBER OF POINTS TO BE COLLECTED FROM BASIC
6440 ISOURCE LDA #0
6450 ISOURCE STA Counter ! GET UP MATRIX POINTER TO POINT AT THE FIRST ELEMENT
6460 ISOURCE LDA #-22784 ! 0101 1000
6470 ISOURCE STA R6 ! CH1, INT TRIG, DIS 9253 BUS, DIS START, EOC, DIS INT TRIG
6480 ISOURCE LDA #-30976 ! 0111 1000
6490 ISOURCE STA R6 ! ENABLE THE START LINE
6500 ISOURCE Next_loop: LDA #1792 ! 1111 1000
6510 ISOURCE STA R6 ! ENABLE INTERNAL TRIGGER, SELECT EOC
6520 ISOURCE Golow: LDA R4 ! GET EOC DATA FROM ADC
6530 ISOURCE CMA ! COMPLEMENT THE DATA TO NEGATE INPUT LOGIC INVERSION
6540 ISOURCE RLA Golow ! SKIP TO GOLOW IF 60<>0 (EOC NOT LOW)
6550 ISOURCE Gohigh:LDA R4 ! GET EOC DATA FROM THE ADC
6560 ISOURCE RLA Gohigh ! SKIP TO GOHIGH IF 60<>0 (EOC NOT HIGH)
6570 ISOURCE LDA #19176 ! 1011 1000 SELECT DATA LINES
6580 ISOURCE STA R6

```

```

6590 ISOURCE LDA =Array_info
6600 ISOURCE LDB =Val1
6610 ISOURCE JSM Get_info
6620 ISOURCE LDA Counter
6630 ISOURCE STA Element
6640 ISOURCE LDA R4 ! READ THE DATA FROM THE ADC
6650 ISOURCE LDB =255 ! INITIALIZE MASK WORD TO 0000 0000 1111 1111
6660 ISOURCE CMA ! COMPLEMENT ADC DATA TO NEGATE INPUT LOGIC INVERSION
6670 ISOURCE AND B ! MASK OFF UPPER 8 BITS OF REGISTER A
6680 ISOURCE STA Pass1 ! BEGIN UTILITY TO PASS DATA TO BASIC
6690 ISOURCE LDA =Pass1
6700 ISOURCE LDB =Array_info
6710 ISOURCE JSM Put_element ! PASS THE ADC DATA TO THE BASIC ARRAY (Line100)
6720 ISOURCE LDA =1536 ! 1111 1001
6730 ISOURCE STA R6 ! SELECT CH2, AND EOC
6740 ISOURCE LDA =9728 ! 1101 1001
6750 ISOURCE STA R6 ! LOWER CS TO INITIATE A NEW START PULSE
6760 ISOURCE LDA =1536 ! 1101 1001
6770 ISOURCE STA R6 ! BRING CS BACK HIGH TO COMPLETE START PULSE
6780 ISOURCE Low2:LDA R4 ! READ EOC DATA FROM ADC
6790 ISOURCE CMA ! COMPLEMENT A REGISTER
6800 ISOURCE RLA Low2 ! SKIP TO Low2 IF b0<>0 (EOC NOT LOW)
6810 ISOURCE High2:LDA R4 ! READ EOC DATA FROM ADC
6820 ISOURCE RLA High2 ! SKIP TO High2 IF b0<>0 (EOC NOT HIGH)
6830 ISOURCE LDA =17920 ! 1011 1001 SELECT DATA LINES
6840 ISOURCE STA R6
6850 ISOURCE LDA =Array_info2
6860 ISOURCE LDB =Val2
6870 ISOURCE JSM Get_info
6880 ISOURCE LDA Counter
6890 ISOURCE STA Element2
6900 ISOURCE LDA R4 ! READ THE DIGITAL DATA FROM THE ADC
6910 ISOURCE LDB =255 ! INITIALIZE MASK WORD TO 0000 0000 1111 1111
6920 ISOURCE CMA ! COMPLEMENT THE DATA TO NEGATE INPUT LOGIC INVERSION
6930 ISOURCE AND B ! MASK OFF THE UPPER 8 BITS OF THE A REGISTER
6940 ISOURCE STA Pass2 ! CALL UTILITY TO PASS DATA TO BASIC
6950 ISOURCE LDA =Pass2
6960 ISOURCE LDB =Array_info2
6970 ISOURCE JSM Put_element ! PASS THE DATA TO BASIC ARRAY (Line200)
6980 ISOURCE LDA =512 ! 1111 1101
6990 ISOURCE STA R6 ! SELECT CHANNEL 5,EOC
7000 ISOURCE LDA =8704 ! 1101 1101
7010 ISOURCE STA R6 ! BRING CS LOW TO INITIATE START PULSE
7020 ISOURCE LDA =512 ! 1111 1101
7030 ISOURCE STA R6 ! BRING CS BACK HIGH TO COMPLETE START PULSE
7040 ISOURCE Low6:LDA R4 ! GET EOC DATA FROM THE ADC
7050 ISOURCE CMA
7060 ISOURCE RLA Low6 ! SKIP TO Low6 IF b0<>0 (EOC NOT LOW)
7070 ISOURCE High6:LDA R4 ! GET EOC DATA FROM THE ADC
7080 ISOURCE RLA High6 ! SKIP TO High6 IF b0<>0 (EOC NOT HIGH)
7090 ISOURCE LDA =-14592 ! 0011 1000
7100 ISOURCE STA R6 ! SELECT b7, b1, 5/4 LINE LOW
7110 ISOURCE LDA =Array_info6
7120 ISOURCE LDB =Val6
7130 ISOURCE JSM Get_info
7140 ISOURCE LDA Counter
7150 ISOURCE STA Elements

```

```

7160 ISOURCE LDA R4 ! READ THE DATA FROM THE ADC
7170 ISOURCE LDB #255 ! INITIALIZE THE MASK WORD TO 0000 0000 1111 1111
7180 ISOURCE CMA ! COMPLEMENT THE DATA TO NEGATE THE INPUT LOGIC INVERSION
7190 ISOURCE AND B ! MASK OFF THE UPPER 16 BITS OF REGISTER A
7200 ISOURCE STA Pass6 ! CALL UTILITY TO PASS DATA TO BASIC
7210 ISOURCE LDA #Pass6
7220 ISOURCE LDB #Array_in*06
7230 ISOURCE JSH Put_element ! PASS DATA TO BASIC ARRAY (Line6(*))
7240 ISOURCE ISZ Counter ! INCREMENT THE COUNTER
7250 ISOURCE DSZ Pass0 ! DECREMENT Pass0
7260 ISOURCE JMP Next_loop ! IF COUNTER < 0 THEN BRANCH BACK AND READ EACH CHA
NNEL AGAIN
7270 ISOURCE Quit:RET 1 ! ALL DATA POINTS HAVE BEEN OBTAINED, RETURN TO BASIC
7280 ISOURCE END A_to_d
7290 ! *****
7300 ! ***** END OF ASSEMBLY DATA ACQUISITION SUBROUTINE *****
7310 ! *****

```

A2.5 Data Plotting Subroutine

The Data Plotting Subroutine enables the system user to create digital reconstructions of the analog respiratory signals. Many times it is useful to be able to observe the shapes, durations, and inter-relationships of the digital signals used to generate the experimental results. Plotting may be performed on the CRT of the 9845; or, an HP9836 color pen plotter may also be used.

Organization of the plotting software is relatively simple. The plotting area is divided into three regions; one region for each of the respiratory signals. Each of the regions is scaled 0 to 255 on the vertical axis; and 0 to however many points the user specifies, on the horizontal axis. The digital data is then plotted in the appropriate region and the axes are labeled with magnitudes and labels. Figure 3.2 was generated using this subroutine.

Each of the variables in the Data Plotting Subroutine has been previously identified and so a variable listing is not included. Since a subroutine flowchart would strongly resemble the BASIC program listing, it too has been omitted. A BASIC program listing of the Data Plotting Subroutine, is included.

```

8290      !
8290      Plot_data: ! Subalgorithm to plot out binary data sets
8300      !
8310      INPUT "HOW MANY POINTS WOULD YOU LIKE PLOTTED",P
8320      Offset=INT(Time_delay/1000*S) ! FIND DATA ARRAY SHIFT FACTOR
8330      !
8340      ! SELECT PLOTTER DEVICE
8350      !
8360      INPUT "OUTPUT ON CRT OR PLOTTER ? (CRT/PLOTTER)",Q$
8370      IF Q$="PLOTTER" THEN 8400
8380      PLOTTER IS "GRAPHICS"
8390      GOTO 8410
8400      PLOTTER IS "9872A"
8410      GRAPHICS
8420      DEG
8430      LOCATE 15,120,5,30 ! SPECIFY PLOTTING REGION FOR FLOW SIGNAL
8440      SCALE 0,P,0,255
8450      LINE TYPE 1
8460      CSIZE 3
8470      AXES S,25,0,Bin_zero_flow
8480      LORG 8
8490      FIXED 1
8500      Flow_cal=(Insp_flow_cal+Expr_flow_cal)/2 ! USE AVERAGE FLOW CAL FACTOR
8510      FOR I=Bin_zero_flow TO 255 STEP 50
8520      MOVE -2,I
8530      LABEL (I-Bin_zero_flow)*Flow_cal ! LABEL THE FLOW AXIS
8540      NEXT I
8550      FOR I=Bin_zero_flow-50 TO 0 STEP -50
8560      MOVE -1,I
8570      LABEL (I-Bin_zero_flow)*Flow_cal
8580      NEXT I
8590      LDIR 0
8600      CSIZE 3.3
8610      LINE TYPE 2
8620      FOR I=1 TO P ! PLOT OUT THE FLOW SIGNAL
8630      PLOT I,Line6(I),2
8640      NEXT I
8650      LINE TYPE 1
8660      IF P/S>7 THEN No_one_sec
8670      !
8680      ! SHOW 1 SECOND ON TIME AXIS IF SCALE LARGE ENOUGH
8690      !
8700      MOVE S,25
8710      DRAW S,0
8720      MOVE 2*S,25
8730      DRAW 2*S,0
8740      MOVE S,5
8750      DRAW 2*S,5
8760      LORG 4
8770      MOVE 1.5*S,14
8780      LABEL "1 sec"
8790      No_one_sec:CSIZE 3.3

```

```

8800 LOCATE 0,120,5,30
8810 SCALE 0,125,5,30
8820 MOVE 1,18
8830 LORG 5
8840 LDIR 90
8850 LABEL "FLOW [L/S]"
8860 LOCATE 15,120,35,60 ! SPECIFY THE PLOTTING REGION FOR THE F02 SIGNAL
8870 SCALE 0,P,0,255
8880 AXES S,25
8890 LDIR 0
8900 CSIZE 3
8910 LORG 8
8920 FIXED 2
8930 FOR I=0 TO 255 STEP 50 ! PLOT OUT THE F02 SIGNAL
8940 MOVE -1,I
8950 LABEL I*O2_cal+.11 ! PUT UNITS ON AXIS
8960 NEXT I
8970 LDIR 90
8980 CSIZE 3.3
8990 LINE TYPE 2
9000 FOR I=1 TO P-Offset
9010 PLOT I,Line2(I+Offset)-O2_dc_offset,2
9020 NEXT I
9030 LINE TYPE 1
9040 LOCATE 0,120,35,60
9050 SCALE 0,125,35,60
9060 MOVE 1,47
9070 LORG 5
9080 LABEL "FRACTIONAL O2" ! LABEL AXIS
9090 MOVE 4,47
9100 LABEL "CONCENTRATION"
9110 LOCATE 15,120,65,90 ! SPECIFY F02 PLOTTING REGION
9120 SCALE 0,P,0,255
9130 AXES S,25
9140 LDIR 0
9150 CSIZE 3
9160 LORG 8
9170 FOR I=0 TO 255 STEP 50 ! PLOT OUT F02 SIGNAL
9180 MOVE -1,I
9190 LABEL I*CO2_cal ! PUT UNITS ON F02 AXIS
9200 NEXT I
9210 CSIZE 3.3
9220 LDIR 90
9230 LINE TYPE 2
9240 FOR I=1 TO P-Offset
9250 PLOT I,Line1(I+Offset)-CO2_dc_offset,2
9260 NEXT I
9270 LOCATE 0,120,65,90
9280 SCALE 0,125,65,90
9290 LINE TYPE 1
9300 LORG 5
9310 MOVE 1,78
9320 LABEL "FRACTIONAL CO2" ! LABEL F02 AXIS
9330 MOVE 4,78
9340 LABEL "CONCENTRATION"

```



```
9350 PEN 0 ! PUT PLOTTER PEN IN STABLE
9360 INPUT "DUMP GRAPHICS ? (Y/N)",Q$
9370 IF Q$="Y" THEN DUMP GRAPHICS
9380 WAIT 2000
9390 EXIT GRAPHICS
9400 RETURN ! Plot complete, return to main routine
9410 ! *****
9420 ! ***** END OF DATA PLOTTING ROUTINE *****
9430 ! *****
```

A2.6 Data Analysis Subroutine

The Data Analysis Subroutine utilizes digital respiratory data in combination with correction and calibration factors to calculate breath-by-breath respiratory gas volumes for total air, and O₂ and CO₂. The volumes and associated times are printed out as they are calculated. When the data is exhausted, average and time dependent respiratory volumes are calculated and displayed. The subroutine concludes by displaying pertinent calibration and correction factor information.

The flow chart to follow outlines the functional blocks which comprise the Data Analysis Subroutine. Extreme detail in the flow chart was purposely avoided to provide brevity and clarity. The accompanying program is sufficiently documented so that the interested reader can easily relate program variables to program function.

Data Analysis Subroutine Variables

<u>Name</u>	<u>Type</u>	<u>Description</u>
A\$, B\$, C\$, D\$, E\$, F\$, G\$, H\$	string	Unique string variables which collectively make up the output display table heading.
A	real	Index for the $\dot{V}$ signal data array.
Aire	real	The expiratory volume for a particular breath, in liters.
Airi	real	The inspiratory volume for a particular breath, in liters.
Avco2prod	real	The average volume of CO ₂ produced per breath, liter.
Avo2cons	real	The average volume of O ₂ consumed per breath, liter.
Avole	real	The average total expiratory volume, in liters.
Avoli	real	The average total inspiratory volume, in liters.
B	real	Same as Bin_zero_flow.
Bin_zero_flow	real	See Section A2.2.2.
Body_temp	real	Subject's body temperature during experimental data collection, in °C.
Cal\$	string	Filename for the calibration factors.
Cal_flag	real	See Section A2.2.2.
Co2_cal	short precision	See Section A2.2.1.
Co2_dc_offset	short precision	See Section A2.2.1.
Co2e	real	The volume of CO ₂ expired for a particular breath, liter.
Co2i	real	The volume of CO ₂ inspired for a particular breath, liter.

Data Analysis Subroutine Variables

<u>Name</u>	<u>Type</u>	<u>Description</u>
A\$, B\$, C\$, D\$, E\$, F\$, G\$, H\$	string	Unique string variables which collectively make up the output display table heading.
A	real	Index for the V signal data array.
Aire	real	The expiratory volume for a particular breath, in liters.
Airi	real	The inspiratory volume for a particular breath, in liters.
Airi	real	The inspiratory volume for a particular breath, in liters.
Avco2prod	real	The average volume of CO ₂ produced per breath, liter.
Avo2cons	real	The average volume of O ₂ consumed per breath, liter.
Avole	real	The average total expiratory volume, in liters.
Avoli	real	The average total inspiratory volume, in liters.
B	real	Same as Bin_zero_flow.
Bin_zero_flow	real	See Section A2.2.2.
Body_temp	real	Subject's body temperature during experimental data collection, in °C.
Cal\$	string	Filename for the calibration factors.
Cal_flag	real	See Section A2.2.2.
Co2_cal	short precision	See Section A2.2.1.
Co2_dc_offset	short precision	See Section A2.2.1.
Co2e	real	The volume of CO ₂ expired for a particular breath, liter.
Co2i	real	The volume of CO ₂ inspired for a particular breath, liter.

<u>Name</u>	<u>Type</u>	<u>Description</u>
Co2prod	real	The net volume of CO ₂ produced for a particular breath, liter.
Co2e_tidal	real	The average volume of CO ₂ expired per breath, liter.
Co2i_tidal	real	The average volume of CO ₂ inspired per breath, liter.
Date\$	string	The date (MO/DAY/YR) the experiment was performed.
Exp_count	real	The number of data points associated with a particular expiration.
Expr_btps	real	Used to scale expiratory total gas volumes to BTPS conditions.
Expr_flow_cal	real	See Section A2.2.2.
Expr_stpd	real	Used to scale expiratory O ₂ and CO ₂ gas volumes to STPD conditions.
Expr_time	real	The time in seconds associated with a particular expiration.
Flow_cal	real	See Section A2.2.2.
Insp_btps	real	Used to scale inspiratory total gas volumes to BTPS conditions.
Insp_count	real	The number of data points associated with a particular inspiration.
Insp_flow_cal	real	See Section A2.2.2.
Insp_stpd	real	Used to scale inspiratory O ₂ and CO ₂ gas volumes to STPD conditions.
Insp_time	real	The time in seconds associated with a particular inspiration.
Line1 (*), Line2 (*), integer arrays Line6 (*)		Holds F _{CO₂} , F _{O₂} , and $\dot{V}$ BCD data collected by the DAM.
Minvole	real	Expiratory minute volume, $\dot{V}_E$, in liters per minute.

<u>Name</u>	<u>Type</u>	<u>Description</u>
Minvoli	real	Inspiratory minute volume, V_I , in liters per minute.
Name\$	string	Subject's name.
NoBreaths	real	Represents the current breath number as the gas volumes for that particular breath are calculated. At the conclusion of data analysis, represents the total number of breaths which occurred during the experiment.
NoPoints	integer	The number of data points obtained for each respiratory signal during an experiment.
O2Cons	real	The volume of O_2 consumed during a particular breath, liter.
O2DcOffset	short precision	See Section A2.2.1.
O2e	real	The volume of O_2 expired during a particular breath, liter.
O2eTidal	real	The average volume of O_2 expired per breath, liter.
O2i	real	The volume of O_2 inspired during a particular breath, liter.
O2iTidal	real	The average volume of O_2 inspired per breath, liter.
Pb	real	Barometric pressure, Torr.
Ph2oBody	real	The partial pressure of H_2O at the subject's body temperature, in Torr.
Ph2oExpr	real	The partial pressure of H_2O at the average expiratory flow temperature, in Torr.
Ph2oInsp	real	The partial pressure of H_2O at the average inspiratory flow temperature, in Torr.

<u>Name</u>	<u>Type</u>	<u>Description</u>
Q\$	string	String input variable for various user input queries.
R	real	The respiratory quotient. $R = \dot{V}_{CO_2} / \dot{V}_{O_2}$.
Respf	real	The respiratory frequency, in breaths per minute.
S	integer	The sampling frequency for data acquisition, in samples per second.
T	real	The sampling period, S^{-1} , in seconds.
T_expr	real	The average expiratory flow temperature, in $^{\circ}C$.
Time_delay	real	The composite GMS time delay, in msec.
T_insp	real	The average inspiratory flow temperature, in $^{\circ}C$.
Tot_expr_points	real	Represents the total number of data points used for calculating expiratory volumes.
Tot_insp_points	real	Represents the total number of data points used for calculating inspiratory volumes.
Tot_co2_exp	real	The total volume of CO_2 expired during the experimental run, in liters.
Tot_co2_insp	real	The total volume of CO_2 inspired during the experimental run, in liters.
Tot_co2_prod	real	The total volume of CO_2 produced by the subject during the experiment, in liters.
Tot_o2_cons	real	The total volume of O_2 consumed by the subject during the experiment, in liters.

<u>Name</u>	<u>Type</u>	<u>Description</u>
Tot_o2_expr	real	The total volume of O ₂ expired during the experimental run, in liters.
Tot_o2_insp	real	The total volume of O ₂ inspired during the experimental run, in liters.
Tot_time_exp	real	The total time of expiration, in seconds.
Tot_time_insp	real	The total time of inspiration, in seconds.
Tot_time_resp	real	The total time of respiration, in seconds.
Tot_vol_exp	real	The total volume of gas expired by the subject during the experiment, in liters.
Tot_vol_insp	real	The total volume of gas inspired by the subject during the experiment, in liters.
V_dot_co2	real	Minute CO ₂ production, in liters per minute.
V_dot_o2	real	Minute O ₂ consumption, in liters per minute.
X	real	Used to select printer or CRT for display device.
Z	real	Index for the FCO ₂ and FO ₂ data arrays.

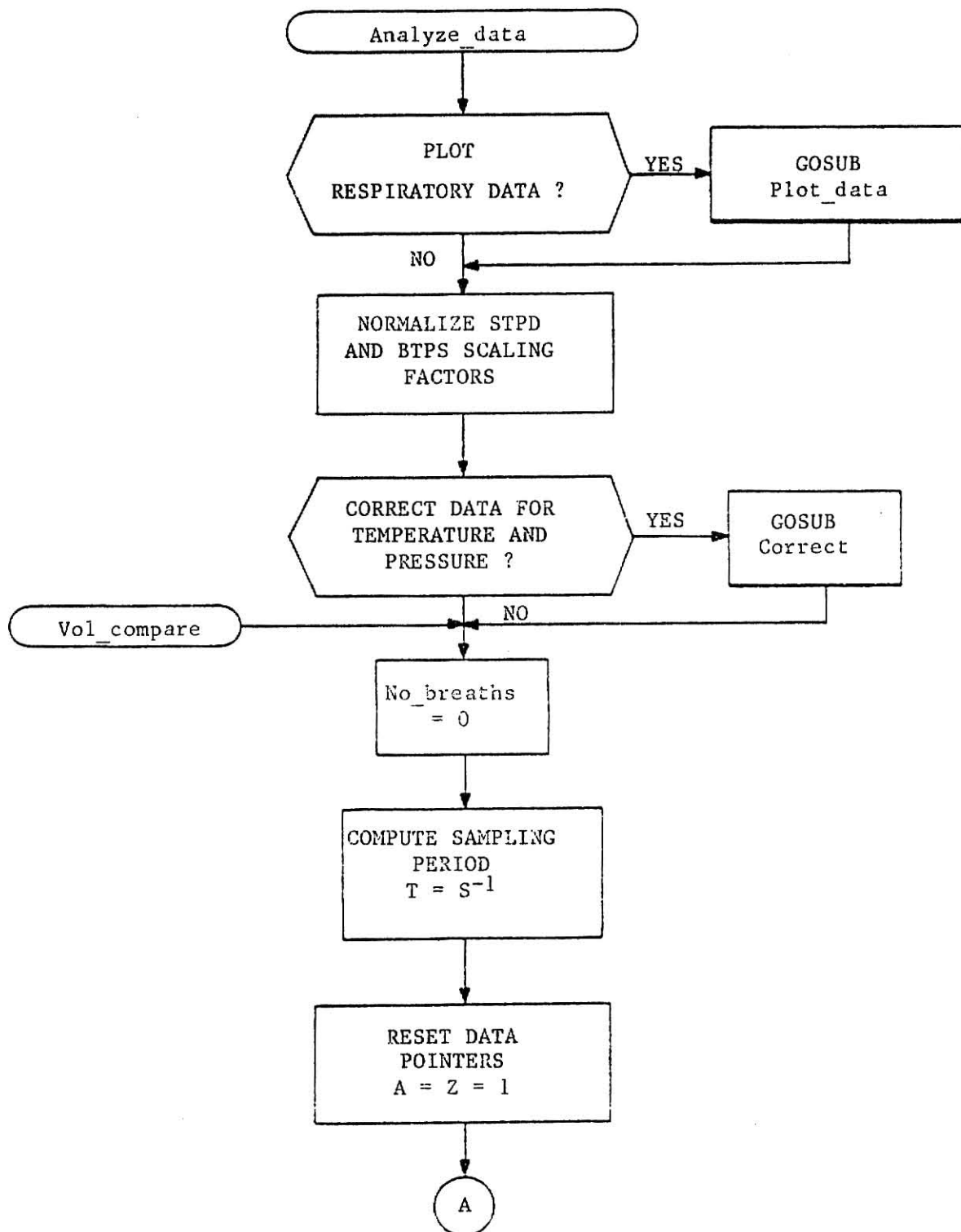
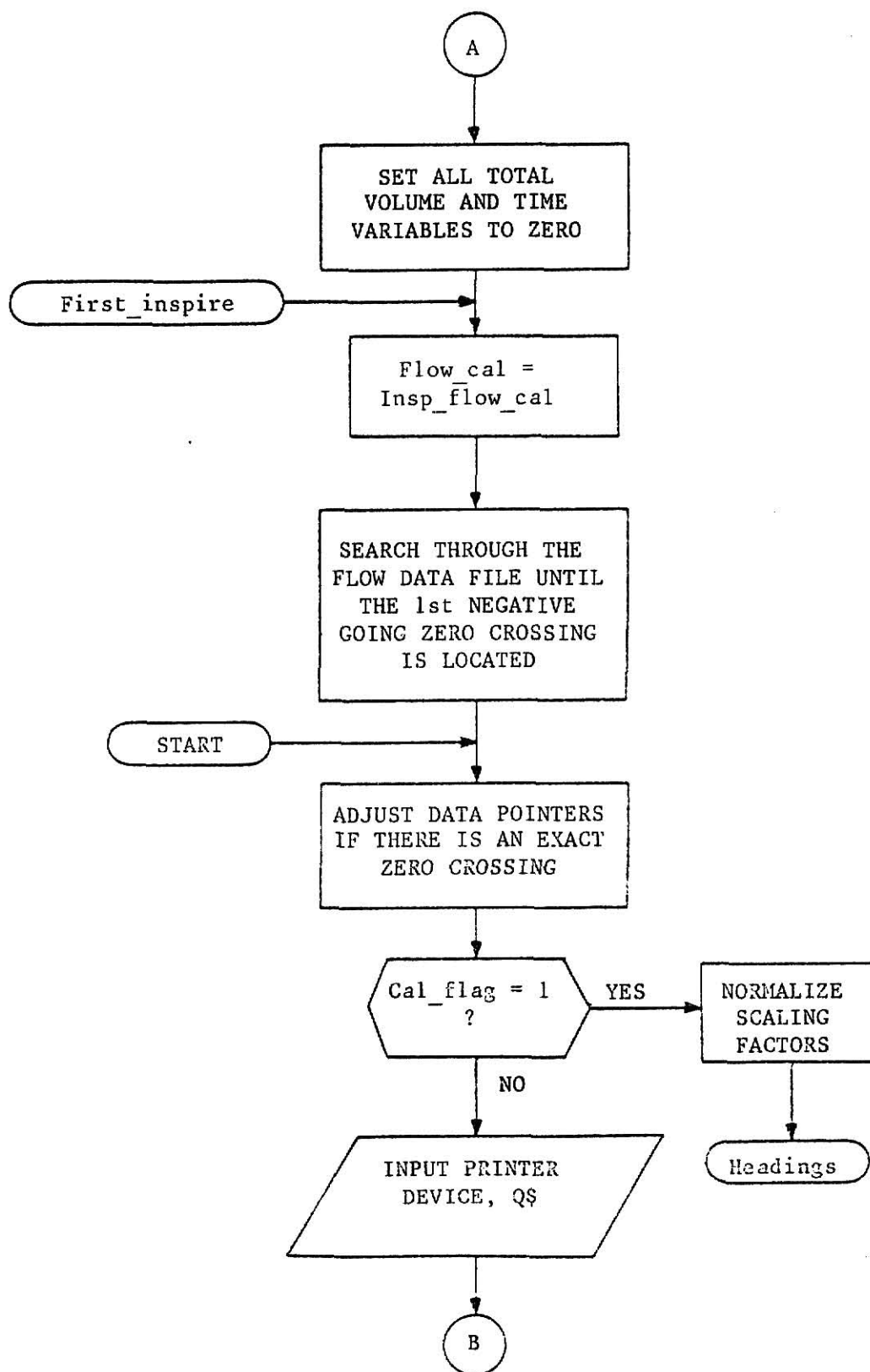
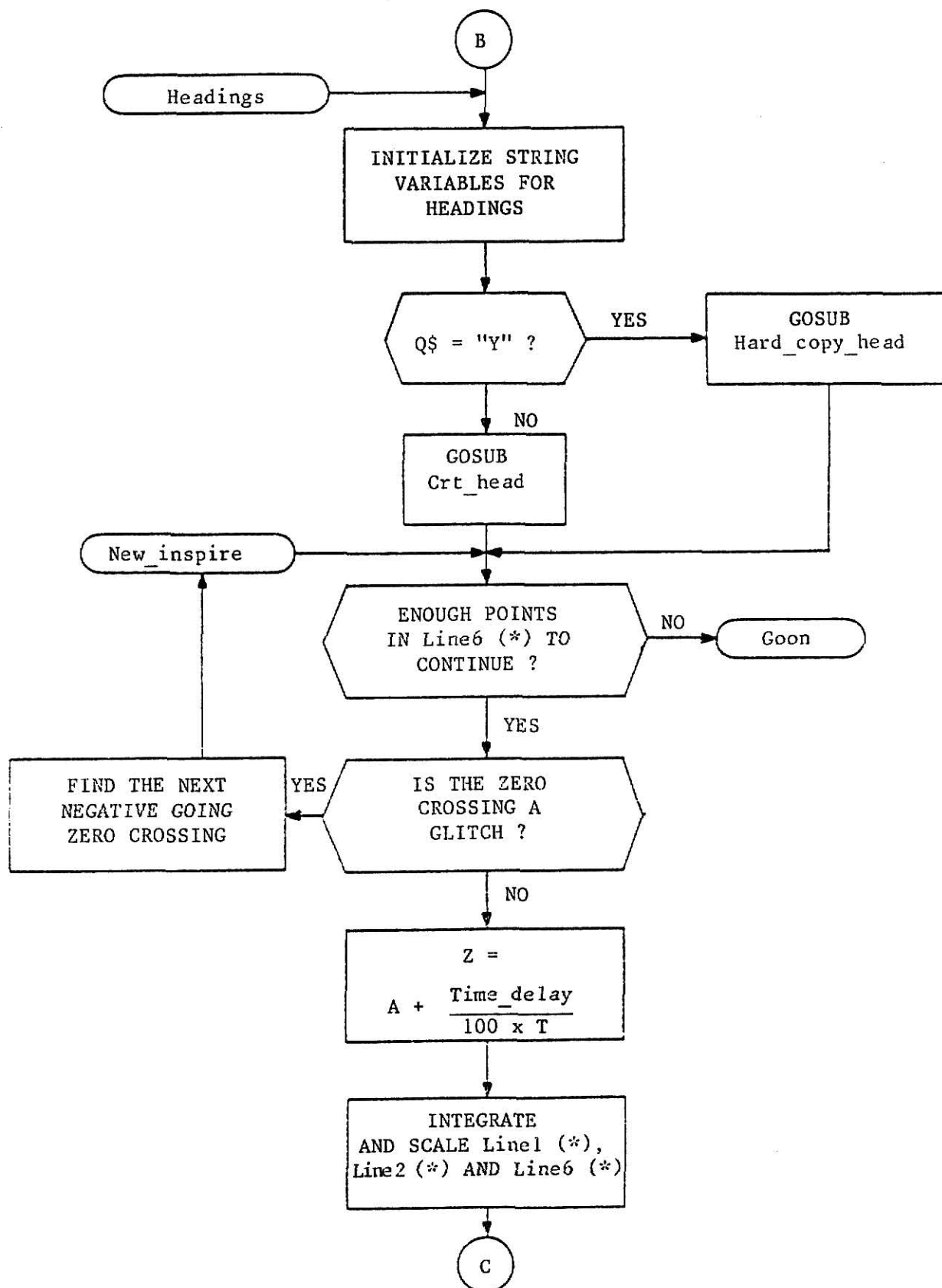
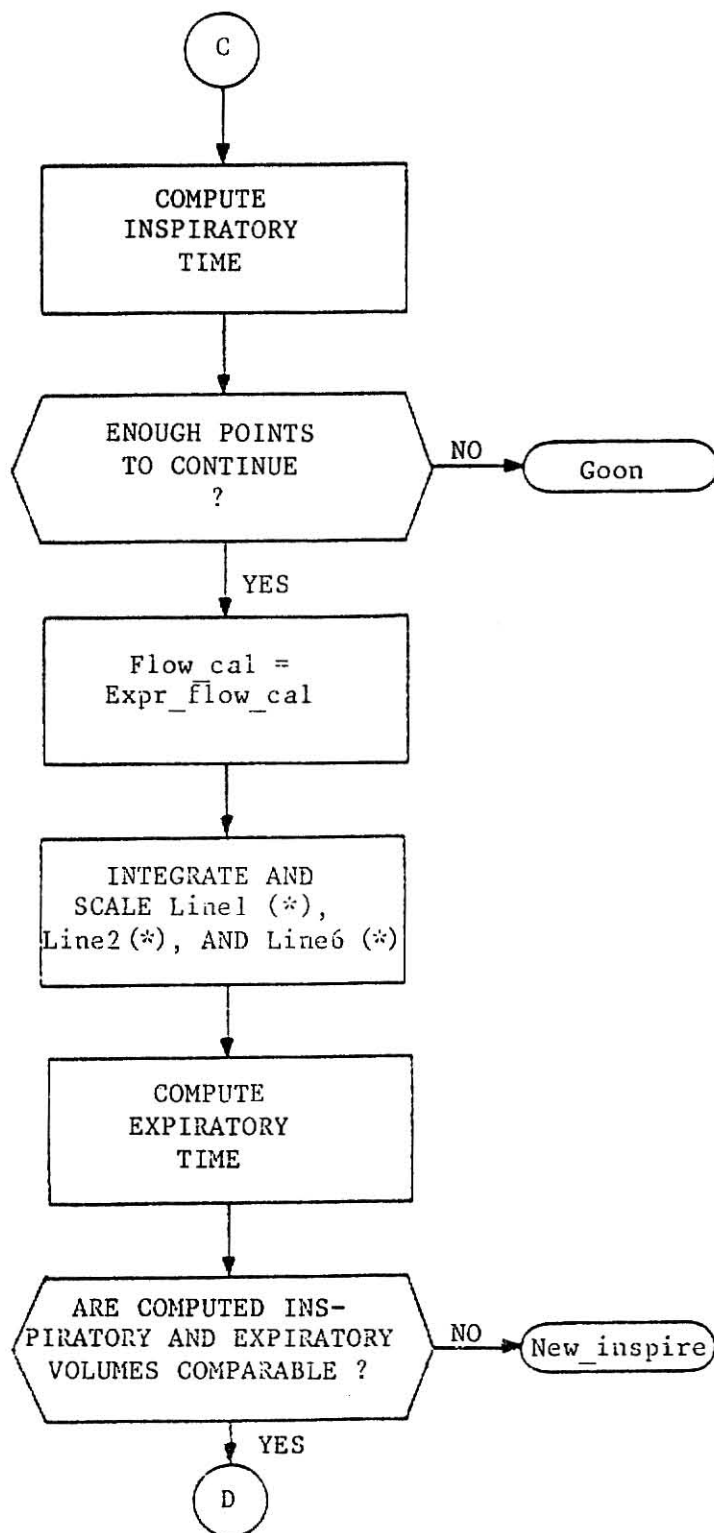
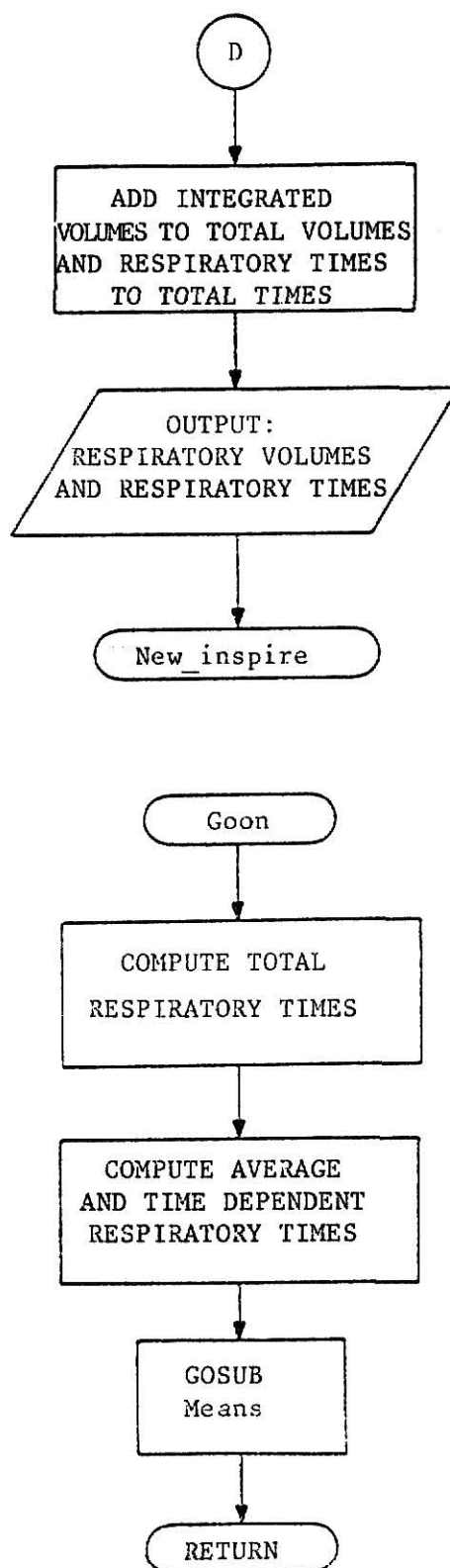


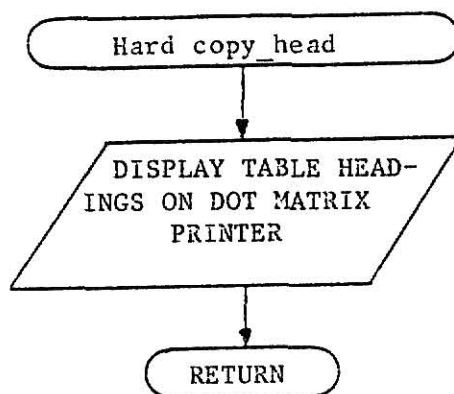
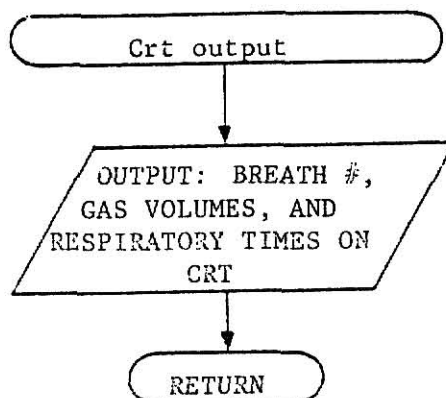
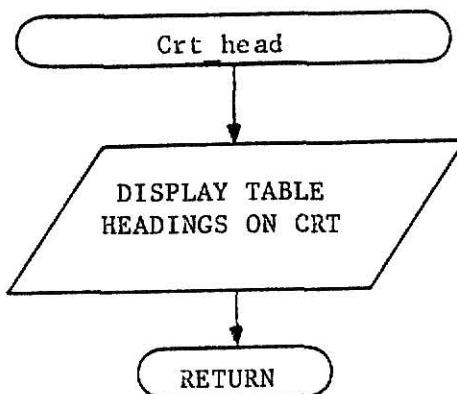
Figure A2.6 Data Analysis Subroutine Flowchart.

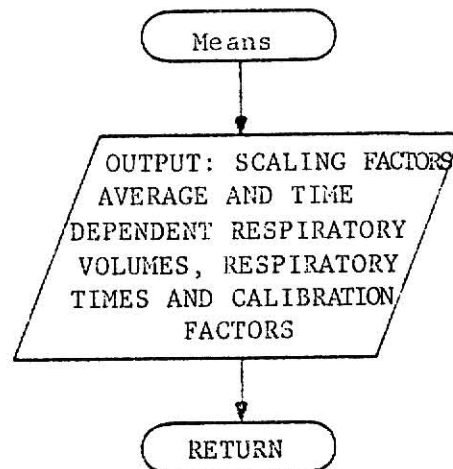
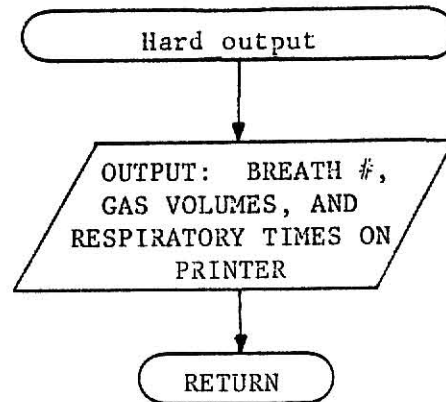












```

2990 Analyze_data: ! Beginning of the analysis routine
2990 !
2910 ! This subprogram accepts 3 arrays of respiratory data (data acquired from
2920 ! a separate routine); total airflow (liters/sec), CO2 and O2 fractional con-
2930 ! centration. The time delay of the CO2 and O2 data is removed so that all
2940 ! three data coincide along the time axis. Once this is achieved numerous
2950 ! features of the respiratory cycle are calculated on a breath by breath
2960 ! basis.
2970 !
2980 INPUT "ENTER THE TOTAL NUMBER OF POINTS TO BE ANALYZED",No_points
2990 REDIM Line1(No_points),Line2(No_points),Line6(No_points)
3000 MASS STORAGE IS ":T14"
3010 OVERLAP
3020 INPUT "ENTER THE SUBJECT'S NAME OR IDENTIFIER",Name$
3030 INPUT "DO CALIBRATION FACTORS NEED TO BE LOADED FROM TAPE ? (Y/N)",Q$
3040 IF Q$(">")"Y" THEN 3090
3050 INPUT "ENTER FILENAME FOR CALIBRATION FACTORS",Cal$
3060 ASSIGN #8 TO Cal$
3070 ON END #8 GOTO 3090
3090 READ #8;Co2_dc_offset,O2_dc_offset,Bin_zero_flow,Co2_cal,O2_cal,Insp_flow_
cal,Expr_flow_cal,Time_delay,S,Data$
3090 INPUT "DO YOU WANT TO USE CURRENT DATA OR LOAD DATA FROM TAPE ? (C/T)",Q$
3100 IF Q$="C" THEN Analyze
3110 IF (Q$(">")"C") AND (Q$(">")"T") THEN 3090
3120 INPUT "ENTER THE CO2 SIGNAL FILE NAME",C$
3130 INPUT "ENTER THE O2 SIGNAL FILE NAME",O$
3140 INPUT "ENTER THE FLOW SIGNAL FILE NAME",F$
3150 ON END #2 GOTO 3230
3160 ON END #3 GOTO 3240
3170 ON END #4 GOTO 3250
3180 ASSIGN #2 TO F$
3190 ASSIGN #3 TO O$
3200 ASSIGN #4 TO C$
3210 ! NOW - GET READY TO READ DATA OFF TAPE (T14)
3220 READ #2;Line6(*)
3230 READ #3;Line2(*)
3240 READ #4;Line1(*)
3250 Analyze: ! Jump to here if current data is to be used
3260 INPUT "WOULD YOU LIKE A PLOT OF THE BINARY DATA ? (Y/N)",Q$
3270 IF Q$="Y" THEN GOSUB Plot_data
3280 Insp_btps=Expr_btps=Insp_stpd=Expr_stpd=1
3290 INPUT "DO YOU WISH TO CORRECT THE VOLUMES FOR TEMPERATURE AND PRESSURE ? (
Y/N)",Correct$
3300 IF Correct$="Y" THEN GOSUB Correct
3310 Vol_compare: ! CONTROL TRANSFERRED HERE FROM FLOW CAL ROUTINE
3320 NoBreaths=0
3330 T=1/S
3340 A=T=1
3350 Tot_vol_insp=Tot_vol_exp=0
3360 Tot_o2_insp=Tot_co2_insp=0
3370 Tot_o2_exp=Tot_co2_exp=0
3380 Tot_o2_cons=Tot_co2_prod=0
3390 Tot_insp_points=Tot_exp_points=0
3400 !
3410 ! THE NEXT FEW LINES OF CODE FINDS THE FIRST (NEXT) INSPIRATION
3420 !

```



```

3430 First_inspire: Flow_cal=Insp_flow_cal
3440 B=Bin_zero_flow
3450 IF (Line6(A)-B<0) AND (Line6(A+1)-B<0) AND (Line6(A+2)-B<0) AND (Line6(A+3)-
-B<0) AND (Line6(A+4)-B<0) THEN Start
3460 IF (Line6(A)-B=0) AND (Line6(A+1)-B<0) AND (Line6(A+2)-B<0) AND (Line6(A+3)-
-B<0) AND (Line6(A+4)-B<0) THEN Start
3470 A=A+1
3480 GOTO First_inspire
3490 Start: IF Line6(A)-Bin_zero_flow<0 THEN A=A+1
3500 Z=A+Time_delay/1000*S ! CALCULATE DATA ARRAY SHIFT INDEX
3510 !
3520 ! IF CONTROL GOT TO HERE VIA Flow_cal THEN NORMALIZE SCALE FACTORS TO :
3530 !
3540 IF Cal_flag=1 THEN X=1
3550 IF Cal_flag=1 THEN Insp_btps=Expr_btps=Insp_stpd=Expr_stpd=1
3560 IF Cal_flag=1 THEN Headings
3570 INPUT "DO YOU WANT HARD COPY OF THE RESULTS ? (Y/N)",Q$
3580 X=1
3590 IF Q$="Y" THEN X=2
3600 !
3610 ! STRING VARIABLE ASSIGNMENTS TO EASE THE PAIN OF GENERATING TABLE TITLE
3620 !
3630 Headings: A$="Air"
3640 B$="O2"
3650 C$="CO2"
3660 D$="Inspired"
3670 E$="Expired"
3680 F$="(liters)"
3690 G$="BTPS"
3700 H$="STPD"
3710 ON X GOSUB Crt_head,Hard_copy_head
3720 New_inspire: ! Check first for glitches
3730 IF A>No_points-5 THEN Goto
3740 IF (Line6(A)-B<0) AND (Line6(A+1)-B<0) AND (Line6(A+2)-B<0) AND (Line6(A+3)-
-B<0) AND (Line6(A+4)-B<0) AND (Line6(A+5)-B<0) THEN E
3750 A=A+1
3760 Z=Z+1
3770 GOTO New_inspire ! IF ZERO CROSSING A GLITCH - GO FIND THE NEXT ONE
3780 !
3790 ! BEGIN INSPIRATORY VOLUME INTEGRATION
3800 !
3810 E:Insp_count=A
3820 Flow_cal=Insp_flow_cal
3830 Airi=.5*(Line6(A)-Bin_zero_flow)*Flow_cal
3840 Co2i=Airi*(Line1(Z)-Co2_dc_offset)*Co2_cal
3850 O2i=Airi*((Line2(Z)-O2_dc_offset)*O2_cal+.11)
3860 A_label: A=A+1
3870 Z=Z+1
3880 IF Z>No_points THEN Goto
3890 IF Line6(A)-Bin_zero_flow=0 THEN B
3900 IF Line6(A)-Bin_zero_flow>0 THEN Decr1
3910 Airi=Airi+(Line6(A)-Bin_zero_flow)*Flow_cal
3920 Co2i=Co2i+(Line1(Z)-Co2_dc_offset)*(Line6(A)-Bin_zero_flow)*Flow_cal
3930 O2i=O2i+(Line2(Z)-O2_dc_offset)*O2_cal+.11*(Line6(A)-Bin_zero_flow)*Flow_cal

```

```

3940 GOTO A_label
3950 Decr1: A=A-1
3960 Z=Z-1
3970 Airi=Air1-.5*(Line6(A)-Bin_zero_flow)*Flow_cal
3980 Co2i=Co21-.5*(Line6(A)-Bin_zero_flow)*(Line1(Z)-Co2_dc_offset)*Flow_cal*Co
2_cal
3990 O2i=O21-.5*(Line6(A)-Bin_zero_flow)*Flow_cal*((Line2(Z)-O2_dc_offset)*O2_c
al+.11)
4000 !
4010 ! INSPIRATORY VOLUME INTEGRATION COMPLETE - NOW EXPIRATORY INTEGRATION
4020 !
4030 A=A+1
4040 Z=Z+1
4050 B:Insp_time=(A-Insp_count)*T!Time of inspiration in seconds
4060 IF A>No_points-10 THEN Goon
4070 ! CHECK TO SEE IF SUBJECT HELD HIS BREATH
4080 IF (Line6(A)-B)=0) AND (Line6(A+1)-B>0) AND (Line6(A+2)-B>0) AND (Line6(A+
3)-B>0) AND (Line6(A+4)-B>0) AND (Line6(A+5)-B>0) THEN New_expire
4090 A=A+1
4100 Z=Z+1
4110 GOTO 4080
4120 New_expire:Flow_cal=Expr_flow_cal
4130 Exp_count=A
4140 Aire=.5*(Line6(A)-Bin_zero_flow)*Flow_cal
4150 Co2e=Aire*(Line1(Z)-Co2_dc_offset)*Co2_cal
4160 O2e=Aire*((Line2(Z)-O2_dc_offset)*O2_cal+.11)
4170 F: A=A+1
4180 Z=Z+1
4190 IF Z>No_points THEN Goon
4200 IF Line6(A)-Bin_zero_flow=0 THEN C
4210 IF Line6(A)-Bin_zero_flow<0 THEN Decr1
4220 Aire=Aire+(Line6(A)-Bin_zero_flow)*Flow_cal
4230 Co2e=Co2e+(Line6(A)-Bin_zero_flow)*(Line1(Z)-Co2_dc_offset)*Flow_cal*Co2_c
al
4240 O2e=O2e+(Line6(A)-Bin_zero_flow)*Flow_cal*((Line2(Z)-O2_dc_offset)*O2_cal+
.11)
4250 GOTO F
4260 Decr1: A=A-1
4270 Z=Z-1
4280 Aire=Aire-.5*(Line6(A)-Bin_zero_flow)*Flow_cal
4290 Co2e=Co2e-.5*(Line6(A)-Bin_zero_flow)*(Line1(Z)-Co2_dc_offset)*Flow_cal*Co
2_cal
4300 O2e=O2e-.5*(Line6(A)-Bin_zero_flow)*Flow_cal*((Line2(Z)-O2_dc_offset)*O2_c
al+.11)
4310 !
4320 ! EXPIRATORY VOLUME INTEGRATION COMPLETE
4330 !
4340 A=A+1
4350 Z=Z+1
4360 !
4370 ! SCALE VOLUMES TO STPD AND BTPS
4380 !
4390 C: Air1=Air1*T*Insp_btps
4400 Co21=Co21*T*Insp_stpd
4410 O21=O21*T*Insp_stpd
4420 Aire=Aire*T*Exp_btps
4430 IF Cal_Flag=1 THEN 4500

```

```

4440 !
4450 ! IF INSPIRATORY AND EXPIRATORY VOLUMES ARE GROSSLY DIFFERENT,
4460 ! THROW THEM OUT AND GO TO THE NEXT BREATH
4470 !
4480 IF (ABS(Airi)<1) OR (ABS(Aire)<1) THEN GOTO E
4490 IF ABS(Airi+Aire)>.6 THEN E
4500 Co2e=Co2e*T*Expr_stpd
4510 O2e=O2e*T*Expr_stpd
4520 O2cons=O2i+O2e
4530 Co2prod=Co2i+Co2e
4540 IF Cal_flag=1 THEN 4560
4550 IF ABS(Co2prod+O2cons)>.05 THEN E
4560 Exp_time=(A-Exp_count)*T
4570 No_breaths=No_breaths+1
4580 !
4590 ! PRINT OUT RESULTS FOR THE CURRENT BREATH
4600 !
4610 ON X GOSUB Cnt_output,Hard_output
4620 !
4630 ! ADD CURRENT BREATH VOLUMES TO TOTALS
4640 !
4650 Tot_vol_insp=Tot_vol_insp+Airi
4660 Tot_vol_exp=Tot_vol_exp+Aire
4670 Tot_o2_insp=Tot_o2_insp+O2i
4680 Tot_o2_exp=Tot_o2_exp+O2e
4690 Tot_co2_insp=Tot_co2_insp+Co2i
4700 Tot_co2_exp=Tot_co2_exp+Co2e
4710 Tot_o2_cons=Tot_o2_cons+O2cons
4720 Tot_co2_prod=Tot_co2_prod+Co2prod
4730 Tot_insp_points=Tot_insp_points+Insp_time/T
4740 Tot_exp_points=Tot_exp_points+(A-Exp_count)
4750 !
4760 ! IF THERE'S STILL DATA LEFT, GO TO THE NEXT BREATH
4770 !
4780 GOTO New_inspire
4790 !
4800 ! OUT OF DATA, COMMENCE AVERAGE AND TIME DEPENDENT CALCULATIONS
4810 !
4820 Goon:Tot_time_insp=Tot_insp_points*T
4830 Tot_time_exp=Tot_exp_points*T
4840 Tot_time_resp=Tot_time_insp+Tot_time_exp
4850 Minvoli=Tot_vol_insp*60/Tot_time_resp
4860 Minvole=Tot_vol_exp*60/Tot_time_resp
4870 Avoli=Tot_vol_insp/No_breaths
4880 Avole=Tot_vol_exp/No_breaths
4890 Respfr=No_breaths*60/Tot_time_resp
4900 O2i_tidal=Tot_o2_insp/No_breaths
4910 O2e_tidal=Tot_o2_exp/No_breaths
4920 Co2i_tidal=Tot_co2_insp/No_breaths
4930 Co2e_tidal=Tot_co2_exp/No_breaths
4940 Avg2cons=Tot_o2_cons/No_breaths
4950 Avg2prod=Tot_co2_prod/No_breaths
4960 V_dot_o2=Tot_o2_cons/Tot_time_resp*60
4970 V_dot_co2=Tot_co2_prod/Tot_time_resp*60
4980 R=ABS(V_dot_co2/V_dot_o2)

```

```

4990 !
5000 ! GO PRINT OUT AVERAGE AND AND TIME DEPENDENT VALUES
5010 !
5020 GOSUB Means
5030 RETURN ! Branch back to the main routine
5040 !
5050 ! HEADING SUBROUTINE FOR CRT OUTPUT
5060 !
5070 Crt_head: PRINTER IS 16,WIDTH(30)
5080 PRINT LIN(2);"SUBJECT IDENTIFIER: ";Name$
5090 PRINT LIN(1);"DATE: ";Date$;LIN(2)
5100 PRINT TAB(1);"Breath";TAB(11);A$;TAB(20);A$;TAB(29);B$;TAB(38);B$;
5110 PRINT TAB(47);C$;TAB(56);C$;TAB(65);B$;TAB(74);C$
5120 PRINT TAB(1);"NUMBER";TAB(8);D$;TAB(18);E$;TAB(26);D$;
5130 PRINT TAB(36);E$;TAB(44);D$;TAB(54);E$;TAB(62);"Consumed";TAB(71);"Produce
d"
5140 PRINT TAB(8);F$;TAB(17);F$;TAB(26);F$;TAB(35);F$;TAB(44);F$;
5150 PRINT TAB(53);F$;TAB(62);F$;TAB(71);F$
5160 PRINT LIN(2);"-----"
5170 RETURN
5180 !
5190 ! SUBROUTINE FOR CRT RESULTS OUTPUT
5200 !
5210 Crt_output: FIXED 0
5220 PRINT TAB(1);No_breaths;
5230 FIXED 3
5240 PRINT TAB(9);Ain1;TAB(18);Aine;TAB(27);O2i;TAB(36);O2e;
5250 PRINT TAB(45);Co2i;TAB(54);Co2e;TAB(63);O2cons;TAB(72);Co2prod
5260 RETURN
5270 !
5280 ! SUBROUTINE FOR HARD COPY TABLE HEADING
5290 !
5300 Hard_copy_head: PRINTER IS 7,1,WIDTH(190)
5310 PRINT LIN(2);"SUBJECT IDENTIFIER: ";Name$
5320 PRINT LIN(1);"DATE: ";Date$;LIN(2)
5330 PRINT TAB(1);"Breath";TAB(20);A$;TAB(38);A$;TAB(56);B$;TAB(74);B$;TAB(92);
C$;
5340 PRINT TAB(110);C$;TAB(128);F$;TAB(146);C$;TAB(164);"Insp";TAB(173);"Expr"
5350 PRINT TAB(1);"Number";TAB(17);D$;TAB(36);E$;TAB(53);D$;TAB(72);E$;
5360 PRINT TAB(89);D$;TAB(108);E$;TAB(125);"Consumed";TAB(143);"Produced";TAB(1
61);"Time";TAB(175);"Time"
5370 PRINT TAB(17);F$;TAB(35);F$;TAB(53);F$;TAB(71);F$;TAB(89);F$;
5380 PRINT TAB(107);F$;TAB(125);F$;TAB(143);F$;TAB(161);" (sec)";TAB(175);" (sec)
"
5390 IF Correct$(Y) THEN 5420
5400 PRINT TAB(19);G$;TAB(37);G$;TAB(55);H$;TAB(73);H$;TAB(91);H$;
5410 PRINT TAB(109);H$;TAB(127);H$;TAB(145);H$
5420 PRINT LIN(1);"-----"
5430 PRINT "-----"
5440 RETURN
5450 !
5460 ! SUBROUTINE FOR HARD COPY RESULTS OUTPUT
5470 !
5480 Hard_output: FIXED 0
5490 PRINT LIN(1);TAB(1);No_breaths;

```

```

5500  FIXED 3
5510  PRINT TAB(18);Airi;TAB(36);Aire;TAB(54);O2i;TAB(72);O2e;
5520  PRINT TAB(90);Co2i;TAB(108);Co2e;TAB(126);O2cons;TAB(144);Co2prod;TAB(159);
5530  FIXED 2
5540  PRINT Insp_time;TAB(173);Exp_time
5550  RETURN
5560  Means: FIXED 1
5570  IF Correct%<>"Y" THEN H$=G$=""
5580  PRINT LIN(2);"Inspiratory minute volume = ";Minvoli;"liters per minute",G$
5590  PRINT LIN(1);"Expiratory minute volume = ";Minvole;"liters per minute",G$
5600  FIXED 3
5610  PRINT LIN(1);"Inspiratory tidal volume = ";Avoli;"liters  ",G$
5620  PRINT LIN(1);"Expiratory tidal volume = ";Avole;"liters  ",G$
5630  FIXED 1
5640  PRINT LIN(1);"Respiratory frequency = ";Respf;" breaths per minute"
5650  FIXED 3
5660  PRINT LIN(1);"Mean O2 inspired = ";O2i_tidal;"liters",H$
5670  PRINT LIN(1);"Mean O2 expired = ";O2e_tidal;"liters",H$
5680  PRINT LIN(1);"Mean CO2 inspired = ";Co2i_tidal;"liters",H$
5690  PRINT LIN(1);"Mean CO2 expired = ";Co2e_tidal;"liters",H$
5700  PRINT LIN(1);"Mean O2 consumed per breath = ";Avco2cons;"liters",H$
5710  PRINT LIN(1);"Mean CO2 produced per breath = ";Avco2prod;"liters",H$
5720  PRINT LIN(1);"O2 consumed per minute = ";V_dot_o2;"liters per minute",H$
5730  PRINT LIN(1);"CO2 produced per minute = ";V_dot_co2;"liters per minute",H$
5740  PRINT LIN(1);"RESPIRATORY QUOTIENT = ";R
5750  FIXED 1
5760  PRINT LIN(1);"Total time of inspiration = ";Tot_time_insp;"sec"
5770  PRINT LIN(1);"Total time of expiration = ";Tot_time_exp;"sec"
5780  PRINT LIN(1);"Total time of respiration = ";Tot_time_resp;"sec"
5790  IF Correct%<>"Y" THEN 5920
5800  STANDARD
5810  PRINT LIN(1);"Relative Humidity=";Rel_humid;"%"
5820  FIXED 3
5830  PRINT LIN(1);"Average Inspiratory Temperature = ";T_insp
5840  PRINT LIN(1);"PH2O at";T_insp;"deg C = ";Ph2o_insp
5850  PRINT LIN(1);"Average Expiratory Temperature = ";T_expr
5860  PRINT LIN(1);"PH2O at";T_expr;"deg C = ";Ph2o_expr
5870  PRINT LIN(1);"Calf's Body Temperature = ";Body_temp;"deg C"
5880  PRINT LIN(1);"PH2O at";Body_temp;"deg C = ";Ph2o_body
5890  PRINT LIN(1);"Barometric Pressure = ";Pb
5900  FIXED 2
5910  PRINT LIN(1);"FLOW DC OFFSET=";Bin_zero_flow;SPA(5);"CO2 DC OFFSET =";Co2_
dc_offset;SPA(5);"O2 DC OFFSET =";O2_dc_offset
5920  FLOAT 4
5930  PRINT LIN(1);"CO2 CALIBRATION FACTOR =";Co2_cal;"O2 CALIBRATION FACTOR =";O
2_cal
5940  PRINT LIN(1);"INSPIRATORY FLOW CALIBRATION FACTOR =";Insp_flow_cal;"EXPIRA
TORY FLOW CALIBRATION FACTOR =";Expr_flow_cal
5950  STANDARD
5960  PRINT LIN(1);"SAMPLING FREQUENCY =";S
5970  PRINT LIN(1);"MASS SPECTROMETER TIME DELAY =";Time_delay;"msec"
5980  PRINT LIN(1);"FLOW CALIBRATION FILENAME: ";CalF
5990  PRINTER IS 15
6000  STANDARD
6010  RETURN

```

A2.7 Correction Factor Subroutine

The purpose of the Correction Factor Subroutine is to generate scaling factors for the following:

- 1) Inspiratory total gas volumes (BTPS).
- 2) Expiratory total gas volumes (BTPS).
- 3) Inspiratory fractional gas volumes (STPD).
- 4) Expiratory fractional gas volumes (STPD).

A complete discussion regarding these scaling factors was presented in Section 4.2.3.

The documentation which follows includes a list and description of the subroutine variables; and a listing of the BASIC code.

The program structure is straightforward and does not warrant a flow chart.

Correction Factor Subroutine Variables

<u>Name</u>	<u>Type</u>	<u>Description</u>
Body_temp	real	The subject's body temperature, in °C.
Expr_btps	real	Scale factor for correcting expiratory total gas volumes to BTPS conditions.
Expr_stpd	real	Scale factor for correcting expiratory fractional gas volumes to STPD conditions.
Insp_btps	real	Scale factor for correcting inspiratory total gas volumes to BTPS conditions.
Insp_stpd	real	Scale factor for correcting inspiratory fractional gas volumes to STPD conditions.
Pb	real	The barometric pressure, in Torr.
Ph2o_body	real	The partial pressure of H ₂ O at the subject's body temperature, in Torr.
Ph2o_expr	real	The partial pressure of H ₂ O at the average expiratory flow temperature, in Torr.
Ph2o_insp	real	The partial pressure of H ₂ O at the average inspiratory flow temperature, in Torr.
Rel_humid	real	The relative humidity in the laboratory during the experiment.
T_expr	real	The average expiratory flow temperature, in °C.
T_insp	real	The average inspiratory flow temperature, in °C.

<u>Name</u>	<u>Type</u>	<u>Description</u>
VAP	string	The filename for the table of H ₂ O vapors which is stored on magnetic tape.
Vap (*)	short precision array	Contains H ₂ O vapor pressures (saturated) in 0.1 temperature increments over a range of 25 to 45 °C. This array is initialized by reading data from file VAP.


```

10410 Correct!! Subroutine to calculate correction factors to convert
10420      ! integrated volumes to STPD AND BTPS
10430 MASS STORAGE IS ":T15"
10440 ASSIGN #7 TO "VAP"
10450 ON END #7 GOTO 10480
10460 SHORT Vap(1,250)
10470 READ #7;Vap(*) ! READ WATER VAPOR PRESSURE VALUES FROM TAPE INTO VAP
10480 INPUT "ENTER THE RELATIVE HUMIDITY (in %)",Rel_humid
10490 INPUT "ENTER THE INSPIRATORY PTM TEMPERATURE (deg C)",T_insp
10500 Ph2o_insp=Vap(1,(T_insp-20)*10+1)*Rel_humid/100
10510 INPUT "ENTER THE EXPIRATORY PTM TEMPERATURE ( deg C)",T_expr
10520 Ph2o_expr=Vap(1,(T_expr-20)*10+1)
10530 INPUT "ENTER THE BAROMETRIC PRESSURE (Torr)",Pb
10540 INPUT "ENTER THE CALF'S BODY TEMPERATURE (deg C)",Body_temp
10550 Ph2o_body=Vap(1,(Body_temp-20)*10+1)
10560 Expr_btcs=(Pb-Ph2o_expr)/(Pb-Ph2o_body)*((273+Body_temp)/(273+T_expr))
10570 Insp_btcs=(Pb-Ph2o_insp)/(Pb-Ph2o_body)*((273+Body_temp)/(273+T_insp))
10580 Insp_stpd=(Pb-Ph2o_insp)/760*(273/(273+T_insp))
10590 Expr_stpd=(Pb-Ph2o_expr)/760*(273/(273+T_expr))
10600 MASS STORAGE IS ":T14"
10610 RETURN

```

APPENDIX III

SYSTEM HARDWARE SCHEMATICS

This Appendix contains circuit schematics for the custom built instrumentation and interface circuits described in Chapter III.

The following schematics are included:

- 1) Switch Debounce Circuit Schematic
- 2) Photo-electric Switch Circuit Schematic
- 3) DAM Circuit Schematic
- 4) DAM Power Supplies Schematic.

Circuit schematics for the other CIS instruments are available through their corresponding operating manuals.

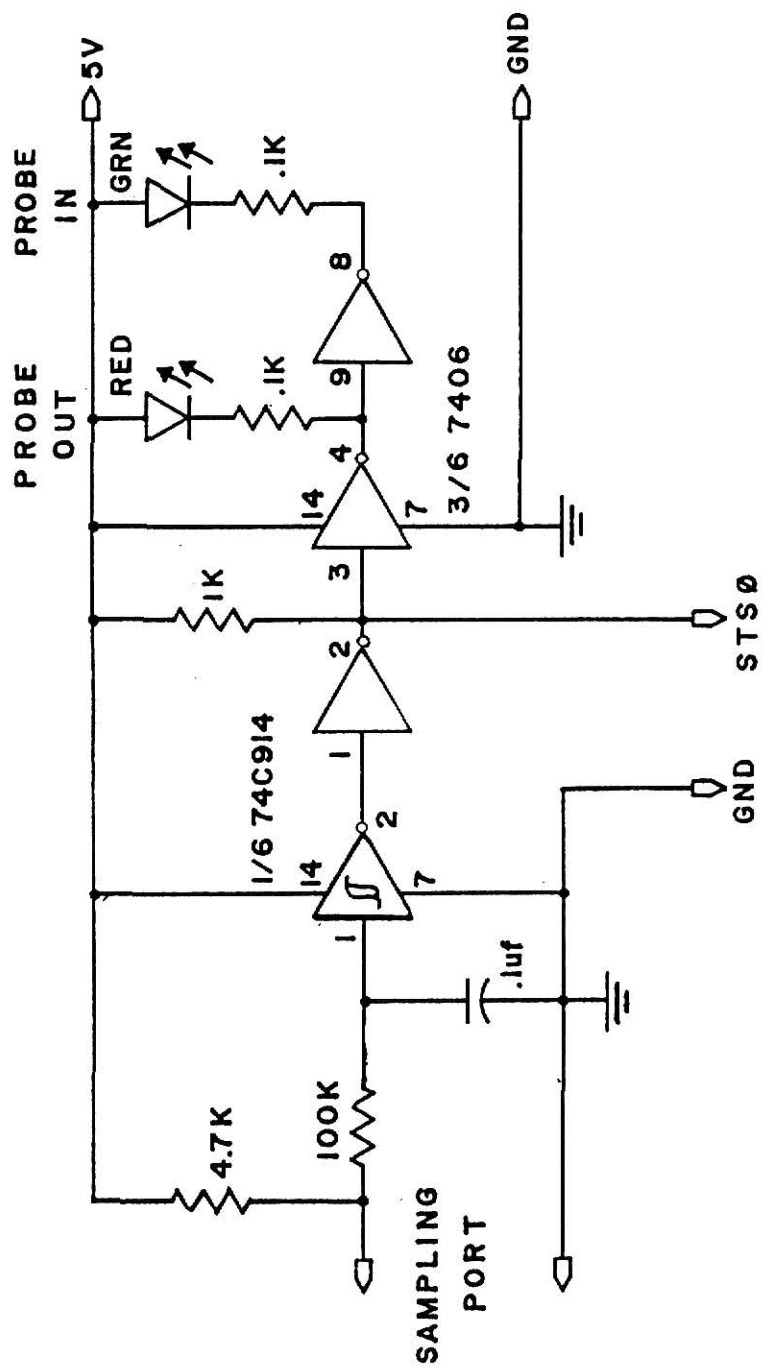


Figure A3.1 Switch Debounce Circuit Schematic.

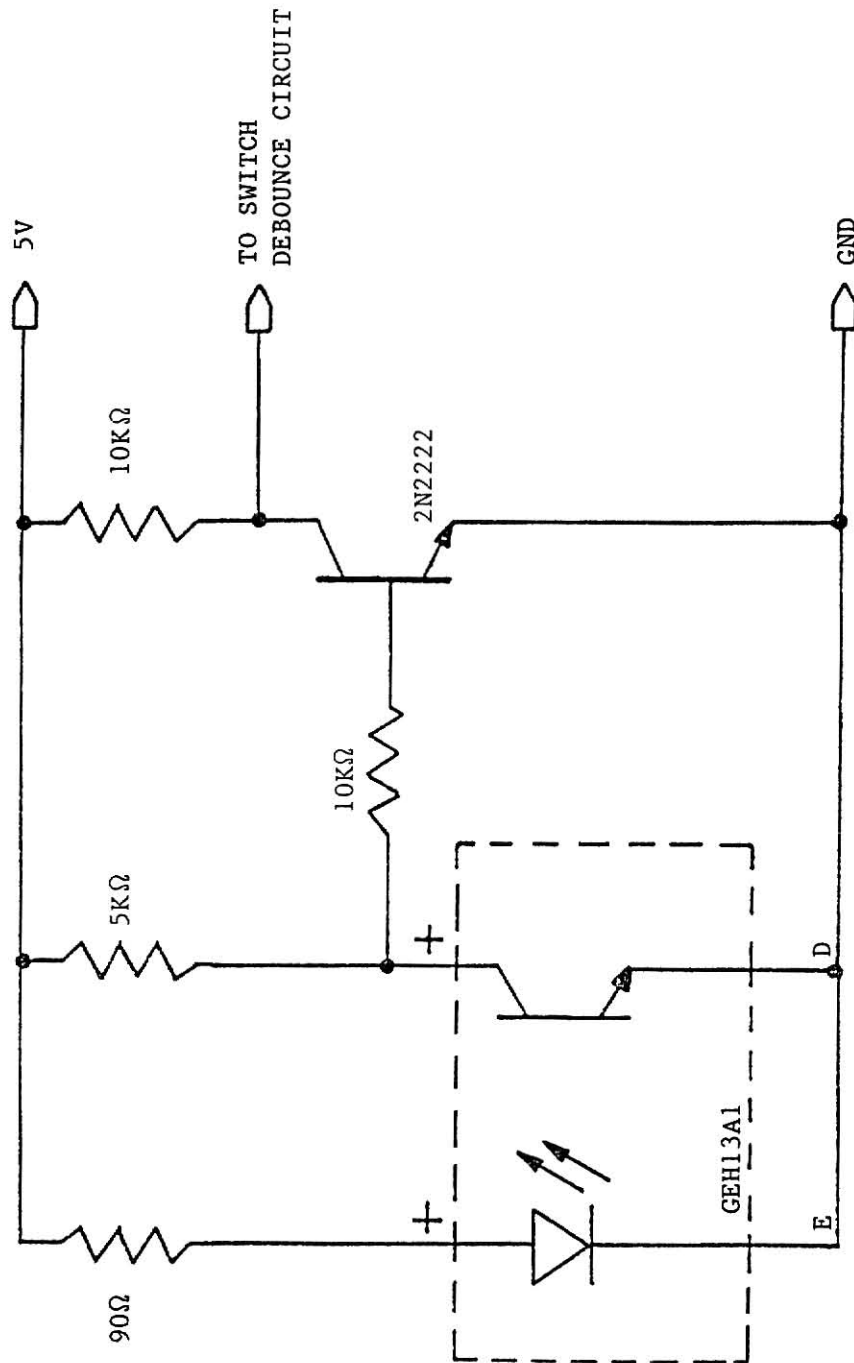


Figure A3.2 Photo-Electric Switch Circuit Schematic.

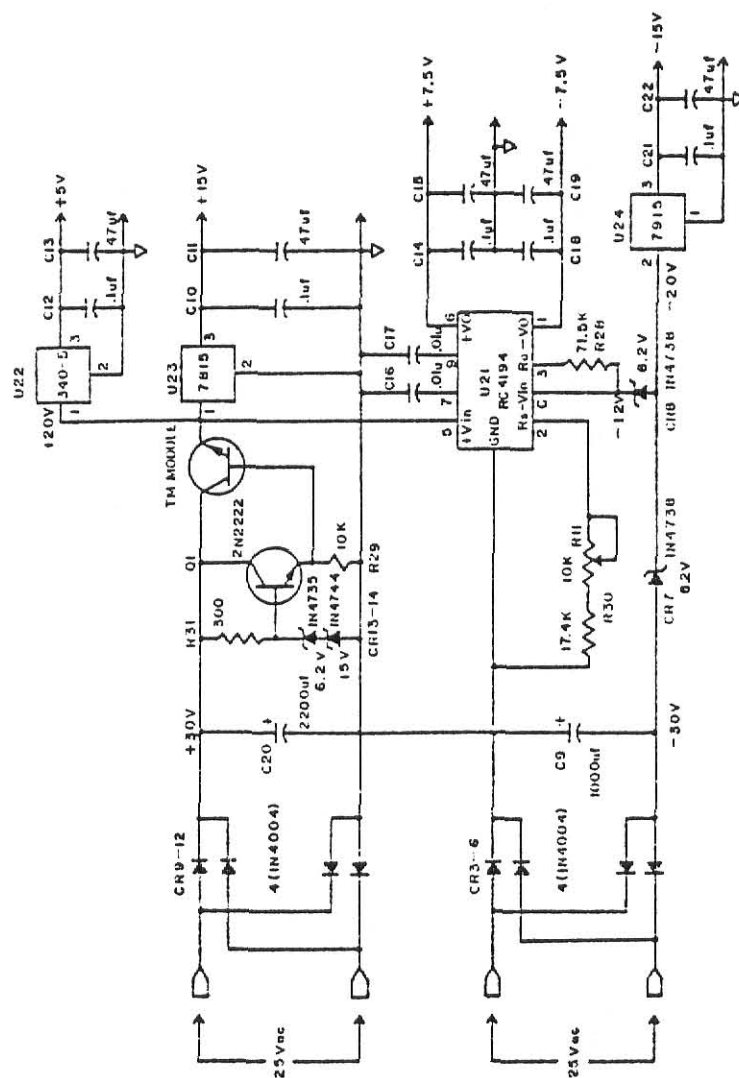


Figure A3.4 Data Acquisition Module Power Supplies Schematic.

APPENDIX IV
SYSTEM OPERATION-COLLECTION AND ANALYSIS OF
BREATH-BY-BREATH RESPIRATORY DATA

To clarify the operation of the system, the following step-by-step procedure is presented.

1. Connect the DAM to the HP9845 computer through the 16-bit parallel interface and the 50-pin-to-25 pin adapter. (The interface select code should be set on 2).
2. Connect the photo-electric switch to the switch debounce circuit. All connections are clearly marked to eliminate confusion.
3. Connect the switch debounce circuit to the auxillary connector on the 16-bit parallel interface. Both ends of this connection involve connectors with eight contacts apiece. The appropriate cable has been fabricated, tested, and is available for use.
4. Connect the GMS F_{CO_2} output to the input (channel 1) of the non-inverting amplifier.
5. Connect the GMS F_{O_2} output to the input of the zero suppression circuit. Connect the output of the zero suppression circuit to the input (channel 2) of the amplifier.
6. Connect the PTG $\dot{V}$ output to the input of the amplifier (channel 3).
7. Connect amplifier outputs 1, 2, and 3, to DAM inputs 1, 2, and 6 respectively.
8. Turn on the gas mixing pump and allow it to warm up for at least 15 minutes.
9. Dial in a 80% N_2 , 9% CO_2 , and 11% O_2 gas mixture on the mixing pump. Wait four minutes for stabilization.
10. Turn the gain controls on the amplifier down as far as possible.
11. Take the GMS off standby, place the sampling probe in 100% N_2 . Zero the GMS as outlined in the operating manual.

12. Place the GMS sampling probe in the gas mixture from the mixing pump. Calibrate the GMS following the operating manual procedure.
13. Adjust the output of the zero suppression circuit so that it reads exactly zero volts using a 3 1/2 digit volt meter.
14. Turn on the computer and wait until it displays "HP9845 READY FOR USE". Turn on the printer and select a print pitch of 16 cpi.
15. Load the tape labeled "EEC3" into the right hand tape drive (T15).
16. Load an initialized tape with sufficient unused storage space into the left hand tape drive (T14).
17. Type the following sequence on the computer keyboard:
 GET "COWCOR"
 then press the key labeled EXECUTE. This loads the system software into the computer's memory. Wait until a flashing cursor reappears on the screen before proceeding.
18. Turn on the amplifier and DAM.
19. Dial in a mixture of 70% N₂, 9% CO₂, and 21% O₂ on the gas mixing pump. Wait for stabilization of the gas concentrations.
20. Place GMS sampling probe in the gas mixture of Step 19.
21. Run the system software. Get in the data acquisition mode. Collect 100 samples at 50 Hz from DAM channels 1, 2, and 6.
22. Observe the BCD data obtained in Step 21. Increase the gain on channels 1 and 2.
23. Repeat steps 20-22 until the average BCD value obtained from channels 1 and 2 is close to, but not equal to 255₁₀.
24. Zero the PTG as outlined in the operating manual.
25. Connect the PTM to the PTG making certain that the pressure lines are free of moisture and other contaminants.
26. Connect the PTM to the Harvard respirator.
27. Adjust the respirator frequency as high as possible.
28. Run the system software. Get in the data acquisition mode. Collect 500 samples at 100 Hz.

29. Observe the BCD data obtained in Step 28 for the flow signal. Adjust the gain.
30. Repeat Steps 28 and 29 until the minimum BCD value obtained is in the range of 60; and maximum value obtained in the range of 190.
31. Connect the thermistor for sensing respiratory flow to the tele-thermometer.
32. Connect the output of the tele-thermometer to the chart recorder pre-amplifier.
33. Using water baths of 38 °C and 28 °C, alternate the thermistor between the water baths, and adjust the chart recorder amplification and positioning controls until the corresponding pen deflections occupy a majority of the available scale.
34. Using a standard thermometer, measure the temperatures of the water baths, and record these values on the strip chart recordings near by their corresponding pen deflections.
35. Position the subject on the treadmill and outfit with environmental protection devices.
36. Place the appropriate face mask on the subject and insert the rectal temperature probe.
37. Dial in 80% N₂, 9% CO₂ and 11% O₂ on the mixing pump.
38. Run the system software and enter the calibration mode.
39. Proceed with calibration under computer control.
40. At the conclusion of calibration the system software will provide the opportunity for data acquisition. Before proceeding, connect the PTM to the subject's face mask. Place the thermistor and GMS sampling probes in the appropriate locations on the PTM.
41. Proceed with data collection under computer control.
42. Record the subject's body temperature, the relative humidity, and the barometric pressure.
43. At the conclusion of data acquisition, compute temperature calibration factors as outlined in Chapter 5.
44. Enter the data analysis mode. Respond to all computer queries, then wait. The computer will start to print out breath-by-breath data momentarily.

45. At the conclusion of data analysis the experiment is complete.
46. Thank the subject for his cooperation with a generous helping of alfalfa hay.

MEASUREMENT OF BREATH-BY-BREATH OXYGEN CONSUMPTION
AND CARBON DIOXIDE PRODUCTION IN EXERCISING CALVES

by

Earl E. Creel

B.S., Kansas State University, 1980

AN ABSTRACT OF A MASTER'S THESIS
submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

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Manhattan, Kansas

1982

ABSTRACT

A growing need exists in the scientific community for automated cardiopulmonary diagnostic tools. Through automation, the dynamic trends in a subject's cardiac or respiratory activity may be recorded. Measurements such as these are of widespread interest because of the wealth of diagnostic information they contain.

A computer based instrumentation system has been developed to accurately measure breath-by-breath oxygen consumption and carbon dioxide production in exercising calves. During an experiment a calf is positioned on the treadmill and outfitted with transducers for monitoring three physiological signals. These signals: respiratory flow, $\dot{V}$; fractional CO_2 , F_{CO_2} ; and fractional O_2 , F_{O_2} , are generated by a Fleisch pneumotachometer, and a Perkin-Elmer Medical Gas Analyzer. The signals are converted from analog to digital signals using a custom electronic instrument, then passed onto and stored in the memory of a digital computer. Prior to data collection, each of the system's instruments is calibrated under computer control, utilizing special calibration software written especially for this system. At the completion of data collection, a numerical integration technique is employed to calculate the volumes of air, O_2 , and CO_2 inspired and expired during each breath.

The calf's body temperature and the average inspiratory and expiratory flow temperature are monitored using rapidly responding thermistors. These variables along with humidity and barometric pressure data are used by the analysis routine to scale computed respiratory volumes to either BTPS or STPD conditions.

Display of analyzed results is organized in a tabular format consisting of a single row of program output for each breath, listing values for all of the calculated gas volumes and associated times. Several average and time dependent quantities are also displayed: namely, O_2 consumption, $\dot{V}_{O_2}$; CO_2 production, $\dot{V}_{CO_2}$; respiratory minute volumes, $\dot{V}_I$ and $\dot{V}_E$; respiratory frequency, total times for inspiration and expiration, and the respiratory quotient, R .

Although this system was developed for calves, it is equally well suited for use with other mammals, and could be easily adapted for use with humans. Overall cost and system complexity could be reduced by the incorporation of a less elaborate dedicated computer system.

Future considerations should concentrate on improving system accuracy through the use of different alternatives for transducing respiratory flow and instantaneous respiratory flow temperature.