COMPUTER CONTROL OF A ROTARY DRYER

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ABSTRACT

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The objective of this project was to adapt a small-scale rotary dryer for electronic data acquisition and computer control, evaluate the dryer performance and incorporate the system into an undergraduate laboratory experiment. The appropriate instrumentation was installed to measure and control the critical process variables, and a suitable electronic interface was designed to link the instrumentation to an Apple II Plus computer. A computer program was written to direct the dryer start-up and subsequent data acquisition and control. Several drying experiments were conducted to evaluate the process and the control system.

It was found that the drying equipment and the process control system are adequate for the intended application. However, dryer capacity is limited by the natural gas supply pressure which is too low to achieve a satisfactory gas flow rate. It is recommended that the supply pressure be increased prior to implementation in the teaching laboratory.

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LIST OF SYMBOLS

A	=	dummy variable used in the rounding function RR(A)
A_i	=	heat capacity constant
$Airflow_c$	=	air flow rate required for complete combustion, lb/min
$Airflow_{db}$	=	dry-basis air flow rate, lb/min
$Airflow_{wb}$	=	wet-basis air flow rate, lb/min
$Airflow_{xs}$	=	air flow rate in excess of amount required for combustion, lb/min
AVE(CH)	=	average a/d converter value for channel CH
$AVE(CH)^s$	=	average a/d converter value at steady state
AVE(CH,s)	=	transform of the response variable AVE(CH)
AVE(CH,t)	=	value of AVE(CH) at time t
AVE'(CH,t)	=	deviation variable for AVE(CH,t)
B_i	=	heat capacity constant
CH	=	a/d or d/a converter channel
C_i	=	heat capacity constant
C_p	=	specific heat of humid air
C_{p_i}	=	heat capacity, cal/gmol/°C
$C_{p,sat}$	=	specific heat of humid air at saturation
DIG(CH)	=	digital value from a/d converter or to d/a converter channel CH
DP_{new}	=	new damper position
DP_{old}	=	previous damper position
E(t)	=	error at time t

Error	=	difference between calculated value of x_{water} and initial guess, x_g
Evap(1)	=	required drying rate, lb water/min
Evap(2)	=	maximum drying rate, lb water/min
F	=	factor defined for simplification purposes
$Feed_{db}$	=	dry-basis feed rate into dryer, lb/min
$Feed_{wb}$	=	wet-basis feed rate into dryer, lb/min
Gas	=	gas flow rate into the dryer, liters/min
Gas^s	=	gas flow rate at steady state, liters/min
Gas_{mass}	=	gas flow rate into the dryer, lb/min
Gas(s)	=	transform of the forcing function Gas(t)
Gas(t)	=	gas flow rate into the dryer at time t, liters/min
Gas'(t)	=	deviation variable for Gas(t)
h	=	heat transfer coefficient, BTU/ft^2/hr/°F
H	=	absolute humidity, lb water/lb dry air
$\bar{H}_{c,i}$	=	molar enthalpy of combustion products at T_i
$\bar{H}_c^o$	=	molar heat of combustion for natural gas, cal/gmol
H_E	=	absolute humidity of exhaust air, lb water/lb dry air
H_R	=	absolute humidity of supply (room) air at temperature T_R, lb water/lb dry air
$\bar{H}_R$	=	enthalpy of air at temperature T_R
H_s	=	saturation humidity, lb water/lb dry air
$\bar{H}_{xs,i}$	=	molar enthalpy of excess air at T_i
H_1	=	lower value of the saturation humidity used for interpolation, lb water/lb dry air
H_2	=	upper value of the saturation humidity used for interpolation, lb water/lb dry air
j_H	=	Colburn analogy heat transfer factor
j_M	=	Colburn analogy mass transfer factor

k_x = mass transfer coefficient, $(ft^2\ hr)^{-1}$

K = Analogic display set-up constant

K_{air} = transfer function for air flow rate

K_{amp} = transfer function of operational amplifier circuit

K_c = controller gain

$K_{d/a}$ = transfer function for d/a conversion

K_{Gas} = sensitivity of gas flow rate measurement

$K_{i,db}$ = sensitivity of inlet temperature measurement

$K_{I/P}$ = transfer function for current to pressure conversion of electro-pneumatic transducer

$K_{o,db}$ = sensitivity of outlet dry-bulb temperature measurement

$K_{o,wb}$ = sensitivity of outlet wet-bulb temperature measurement

K_p = overall transfer function for pneumatic control valve

$K_{V/I}$ = transfer function for internal resistance of electro-pneumatic transducer

L = stepper motor direction indicator

Le = Lewis number

MW_{air} = molecular weight of dry air

$MW_{dry\ air}$ = molecular weight of dry air

MW_{Gas} = molecular weight of natural gas

MW_{mix} = molecular weight of the humid air

MW_{water} = molecular weight of water

$n_{air,c}$ = molar flow rate of air for combustion, gmol/min

$n_{air,xs}$ = excess air flow rate into the combustion chamber, gmol/min

n_{Gas} = gas flow rate into the dryer, gmol/min

n_i = flow rate of combustion product i, gmol/min

N = cycle number of data acquisition loop

NN = number of a/d conversions to be averaged

Number	=	number of stepper motor steps
N_{water}	=	mass flux of water
O^s	=	steady-state controller output
O(t)	=	controller output signal at time t
P	=	specified number of decimal places for data displays
Pr	=	Prandtl number
Pressure	=	control valve top air pressure, psig
$Product_{db}$	=	dry-basis product flow rate, lb/min
$Product_{wb}$	=	wet-basis product flow rate, lb/min
P_1	=	pressure, atm
R	=	ideal gas constant
R_i	=	resistance of resistor i, ohms
RR(A)	=	function used to round off any calculated variable denoted as A in the function
R_v	=	rangeability of the control valve
Sc	=	Schmidt number
SUM(CH)	=	sum of consecutive a/d conversions for channel, CH
t	=	elapsed time
T	=	temperature
T_{db}	=	dry-bulb temperature
T_i	=	dry-bulb temperature of air downstream of the combustion chamber
$T_{i,db}$	=	dry-bulb temperature of air downstream of the combustion chamber
T_{max}	=	high temperature calibration endpoint for thermocouple
T_{min}	=	low temperature calibration endpoint for thermocouple
$T_{o,db}$	=	dry-bulb temperature at the outlet of the dryer
$T_{o,wb}$	=	wet-bulb temperature at the outlet of the dryer
T_R	=	dry-bulb temperature of the room air

T^s = steady-state temperature

$T(s)$ = transform of the temperature input function

$T(t)$ = temperature at time t

$T'(t)$ = deviation variable of the temperature

T_{wb} = wet-bulb temperature

u_b = velocity of fluid

V = voltage

V_{cc} = electronic circuit supply voltage

V_m = natural gas molar volume, liters/gmol

$V_{offset,i}$ = op-amp circuit offset voltage (i= 1 or 2), volts

V_{output} = thermocouple transmitter output voltage, volts

V_1 = output voltage from Analogic panel meter

V_2 = output voltage from gas flow rate measurement op-amp circuit

V_3 = output voltage from d/a channel 11

V_4 = output voltage from gas flow rate control op-amp circuit

$Water_C$ = rate of water generated by combustion, lb/min

$Water_E$ = rate of water exiting dryer in exhaust air, lb/min

$Water_F$ = rate of water entering dryer in feed, lb/min

$Water_{in}$ = total rate of water entering dryer, lb/min

$Water_{out}$ = total rate of water exiting dryer, lb/min

$Water_P$ = rate of water exiting dryer in product, lb/min

$Water_R$ = rate of water entering dryer in room air, lb/min

x_F = feed moisture content, mass fraction

x_g = initial guess for x_{water} in iteration procedure

x_P = steady-state product moisture content, mass fraction

x_{sp} = controller set-point

x^{*}_{sp}	=	desired controller set-point
x_{water}	=	mole fraction of water in air
$x_{water,s}$	=	mole fraction of water at saturation
x_1	=	guess for x_{water} in iteration procedure
XX	=	numeric value at computer memory location -16384
ΔH_c	=	rate of total heat of combustion, cal/min
ΔH_p	=	rate of enthalpy change of combustion products, cal/min
ΔH_{xs}	=	rate of enthalpy change of excess air, cal/min
Δt	=	sampling interval
λ	=	latent heat of vaporization of water, BTU/lb
ρ	=	density of fluid
$\rho_{F,db}$	=	bulk density of dry feed material, g/ml
$\rho_{F,wb}$	=	bulk density of wet feed material, g/ml
τ_I	=	controller integral time, minutes

LIST OF PROGRAM VARIABLES

AAIR = heat capacity constant for air, equal to 6.90

A = dummy variable used in the rounding function RR(A)

AC = heat capacity constant, equal to 76.6

ADB(N) = dry-basis air flow rate at interval N, lb/min

ANS$ = string variable defined by keyboard input by the operator due to computer prompt

AVE(CH) = average a/d converter value for channel CH

AXS = excess air flow rate into the combustion chamber, gmol/min

AWB = wet-basis air flow rate, lb/min

A1$ = string variable defined by keyboard input by the operator due to computer prompt

A2$ = string variable defined by keyboard input by the operator due to computer prompt

BAIR = heat capacity constant for air, equal to 0.92×10^{-3}

BC = heat capacity constant, equal to 1.38×10^{-2}

CAIR = heat capacity constant for air, equal to -0.18×10^{-5}

CC = heat capacity constant, equal to -2.96×10^{-5}

CH = a/d or d/a converter channel

CHR$(13) = ASCII code that indicates that the <RETURN> key has been depressed

CHR$(27) = ASCII code that indicates that the <ESC> key has been depressed

CP = specific heat of humid air

DAMPER = damper position

DD	=	difference between the required damper position and the existing damper position
DH(1)	=	rate of total heat of combustion
DH(2)	=	rate of enthalpy change of combustion products
DH(3)	=	rate of enthalpy change of excess air
DIG(CH)	=	digital value sent to or from d/a or a/d converter channel CH
DIR$	=	user-specified direction for stepper motor movement
DP	=	new, required damper position
DRYAIR	=	dry-basis air flow rate, lb/min
DRYAIR(I)	=	dry-basis air flow rate at i^{th} interval, lb/min
E(N)	=	difference between process set-point and measured value of product moisture content at interval N
EVAP(1)	=	required drying rate, lb water/min
EVAP(2)	=	maximum drying rate, lb water/min
E1	=	difference between calculated value of x_{water} and initial guess, x_g
F	=	factor defined for simplification purposes
FEED(0,1)	=	initial dry-basis feed rate into dryer, lb/min
FEED(1,1)	=	previous dry-basis feed rate into dryer, lb/min
GAIN(1)	=	controller gain
GAIN(2)	=	controller integral time, minutes
GAS(I)	=	gas flow rate into the dryer at i^{th} interval, liters/min
GASFLOW	=	gas flow rate into the dryer, liters/min
GG	=	controller output signal to d/a converter
G1	=	gas flow rate into the dryer, gmol/min
G2	=	gas flow rate into the dryer, lb/min
H	=	absolute humidity, lb water/lb dry air
H(I)	=	absolute humidity of exhaust air at i^{th} interval, lb water/lb dry air

HC	=	molar heat of combustion for natural gas, -191,160 cal/gmol
HS	=	saturation humidity, lb water/lb dry air
H1	=	lower value of the saturation humidity used for interpolation, lb water/lb dry air
H2	=	upper value of the saturation humidity used for interpolation, lb water/lb dry air
H2O(1)	=	rate of water entering dryer in feed, lb/min
H2O(2)	=	rate of water entering dryer in room air, lb/min
H2O(3)	=	rate of water generation due to combustion, lb/min
H2O(4)	=	total rate of water entering dryer, lb/min
H2O(5)	=	rate of water exiting dryer in exhaust air, lb/min
H2O(6)	=	rate of water exiting dryer in product, lb/min
I	=	index counter
II(N)	=	value of controller error integral at interval N
J	=	index counter
JJ	=	index counter
L	=	stepper motor direction indicator
LAMBDA	=	latent heat of vaporization of water, BTU/lb
LEWIS	=	Lewis number
MAIR	=	molecular weight of dry air
MH2O	=	molecular weight of water
MMIX	=	molecular weight of the humid air
N	=	cycle number of data acquisition loop
NN	=	number of a/d conversions to be averaged
NPR	=	Prandtl number
NUMBER	=	number of stepper motor steps
O(N)	=	controller output at interval N
P	=	specified number of decimal places for data displays

PILOT = gas flow rate of the pilot stream, liters/min

PILOT$ = string variable used to identify whether or not the gas pilot is burning

ROOM(1) = dry-bulb temperature of the room air

ROOM(2) = wet-bulb temperature of the room air

ROOM(3) = mole fraction of water in the supply air

ROOM(4) = absolute humidity of supply (room) air at temperature T_R, lb water/lb dry air

ROOM(5) = molecular weight of the supply air

RR(A) = function used to round off a calculated variable, A

SCHMIDT = Schmidt number

SUM(CH) = sum of consecutive a/d conversions for channel CH

T(i,j) = temperature for thermocouple i and interval j

TDB = dry-bulb temperature at the outlet of the dryer

TIN = dry-bulb temperature of air downstream of the combustion chamber

TWB = wet-bulb temperature at the outlet of the dryer

T1 = dry-bulb temperature of the room air, in K

T2 = dry-bulb temperature of air downstream of the combustion chamber, in K

V1 = output voltage from Analogic panel meter, volts

V2 = output voltage from gas flow rate measurement op-amp circuit, volts

WARNING$ = string variable used to indicate excessive voltage from thermocouple transmitters

X = mole fraction of water in air

XDESIRED = desired controller set-point

XDESIRED(0) = previous desired controller set-point

XDESIRED(1) = desired controller set-point

XFEED = feed moisture content, mass fraction

XG	=	initial guess for x_{water} in iteration procedure
XPRODUCT	=	steady-state product moisture content, mass fraction
XPRODUCT(N)	=	steady-state product moisture content at interval N
XS	=	mole fraction of water at saturation
XX	=	numeric value at computer memory location -16384
X1	=	subsequent guess for x_{water} in iteration procedure

I. Introduction

A small-scale gas-fired rotary dryer that is useful for running many and varied experiments is located in the Department of Chemical Engineering's unit operations laboratory. The dryer system may be used to study the fundamentals of the drying process and to test the application of a basic process control system. For a specific drying application one may identify, optimize and attempt to control the process parameters that affect the product moisture content. The critical process variables may include the feed material flow rate and residence time and the drying air flow rate and temperature.

The dryer and its original instrumentation were installed approximately twenty years ago and the system was interfaced at that time with a small computer for electronic data acquisition and control. However, some of the hardware was subsequently damaged or removed and the dryer has not been used for several years. This project was initiated to revitalize the dryer system and to incorporate its use into a suitable unit operations laboratory course project. The scope of this project is defined below:

- Install the additional instrumentation needed to measure and control the critical process variables

- Calibrate the existing thermocouple transmitters and the electro-pneumatic transducer for the appropriate ranges

- Design and construct an electronic interface between the instrumentation and a personal computer

- Develop the relationship between the controlled and measured process variables

- Develop a control algorithm for a specific application

- Develop software for data acquisition and computer control and write a user-friendly computer program to incorporate the dryer into a laboratory experiment

- Evaluate the dryer performance and provide suitable recommendations for its experimental operation

II. Equipment Description

The rotary dryer (manufactured by Bartlett-Snow) has a six-inch diameter three-foot long cylinder and can be operated with cocurrent or countercurrent flow. For this project the dryer has been equipped for countercurrent flow (the heated gases and feed material travel in opposite directions), and the dryer system is portrayed in Figure 1. The energy source for the dryer is obtained from the building natural gas supply. There are two manual shutoff valves in the gas line and a pneumatic control valve that controls the flow rate of gas to the combustion chamber. The recommended operating range of gas pressure is 5 to 30 psig, and the maximum operating temperature of the inlet gases is 1000°F due to the design specifications of the fan bearings [1].

The velocity of the heated gases passing through the dryer cylinder is controlled by the blower, duct and damper arrangement downstream of the combustion chamber. Under normal operating conditions the gas velocity should be sufficiently high to optimize drying efficiency, but it must be limited to that which will create a minimum entrainment of material in the gas exhaust stream. The exhaust stream is drawn by an exhaust blower and is vented to the outdoors.

A variable frequency vibratory feeder delivers the wet feed material from the storage hopper above the dryer to a chute in the feed breeching. The

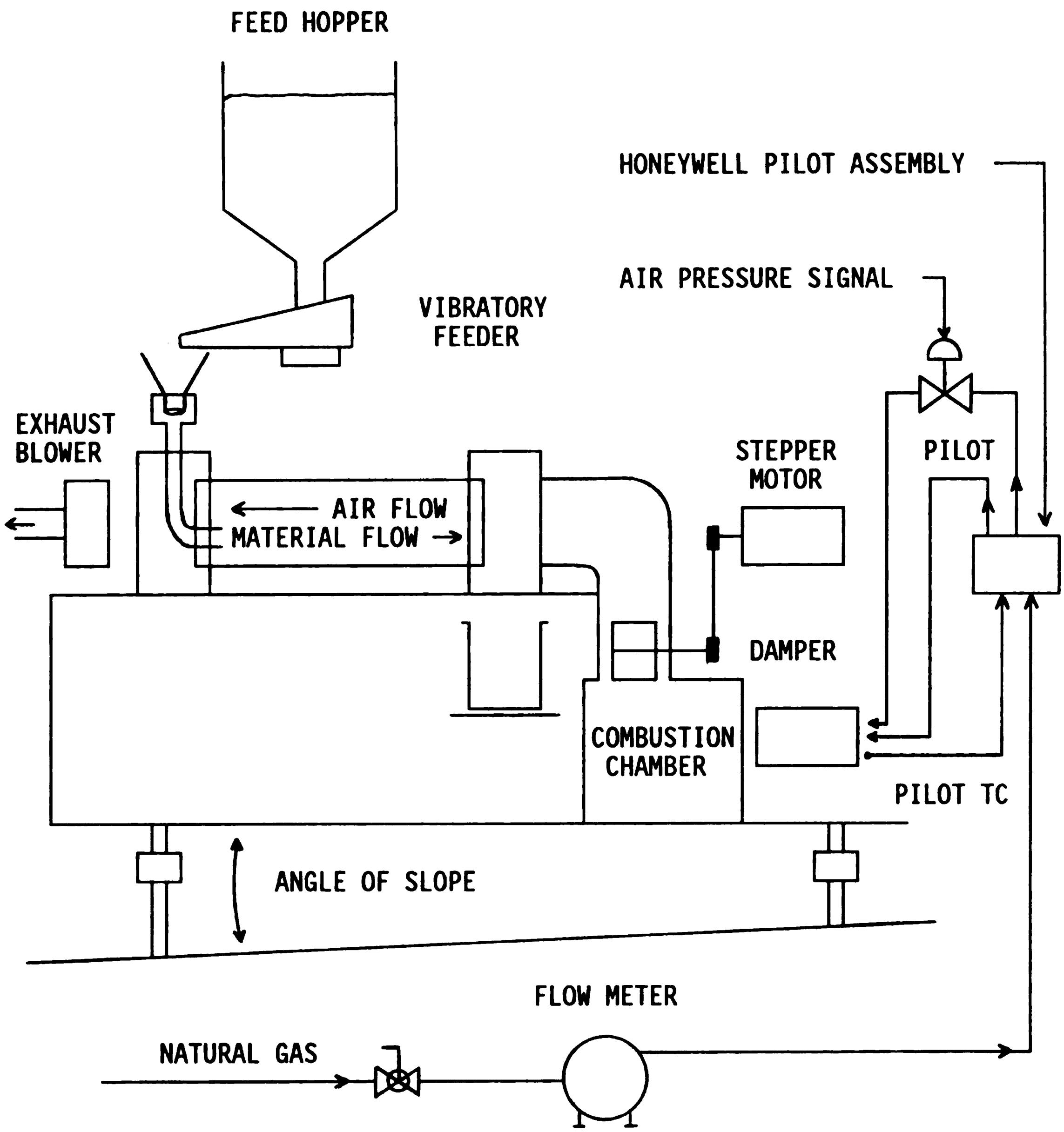


Figure 1. Diagram of Rotary Dryer System

interior of the dryer cylinder is fitted with spiral flights at the feed end to quickly move the material into the active section of the cylinder, where longitudinal, parallel lifting flights pick up the material and cascade it in sheets to facilitate drying. From the feed end, the material gradually progresses downhill to the hoppered bottom of the discharge breeching and into an insulated receptacle. The dryer retention period must allow the material to be sufficiently dried under the given conditions.

The retention period is controlled by the slope and rotational speed of the cylinder and the air velocity through the cylinder. For the laboratory dryer, the cylinder slope has been set at approximately one-eighth inch per foot. The cylinder is rotated by means of a sprocket and gear reducer connected to a Minarik variable speed, 1/4 HP electric motor. For the countercurrent flow system, the motor is run in the forward direction and the rotational speed should be set between three and ten revolutions per minute (rpm) to achieve a satisfactory sheeting action of the material. The rotational speed is maintained at a constant rate throughout an experiment.

III. Instrumentation and Interfacing

The dryer system has been equipped with the instrumentation necessary to directly measure and control several process variables, including inlet and outlet temperatures, natural gas flow rate and air flow rate, and to indirectly measure and control the product moisture content. The instrumentation has been interfaced with an Apple II Plus microcomputer as required for data acquisition and computer control.

3.1. Apple II Plus Microcomputer

The Apple II Plus microcomputer has 48 kilobytes (48K) of memory and operates with a single "floppy" disk drive unit. An attractive feature of the Apple II is the ease with which it can be interfaced. This is especially due to the eight peripheral card slots (numbered 0 to 7) and the game input/output (i/o) connector that are located on the Apple II system board. Seven of the eight card slots can accommodate any of the peripheral cards that are designed specifically for the Apple (slot 0 is reserved for special applications) [2].

3.2. Analog-to-Digital + Digital-to-Analog Converter Board

A Mountain Computer analog-to-digital (a/d) and digital-to-analog (d/a) converter board has been placed in slot 1 of the Apple. This board provides 16 channels for analog input to the computer and 16 channels for analog output from it. Each of the 16 channels of each converter has a unique address that is dependent on the slot location and is defined by the expression

$$\text{Address} = 49280 + 16\,(\text{slot number}) + \text{channel} \tag{1}$$

where the slot number must be an integer from 1 to 7 and the channel must be an integer from 0 to 15 [3]. With the board in slot 1, the address for each respective channel is listed in Table 1.

Table 1. Addresses For A/D and D/A Converter Channels

A/D or D/A Channel	Decimal Address	A/D or D/A Channel	Decimal Address
00	49296	08	49304
01	49297	09	49305
02	49298	10	49306
03	49299	11	49307
04	49300	12	49308
05	49301	13	49309
06	49302	14	49310
07	49303	15	49311

3.2.1. Analog-to-Digital Conversion

Analog conversion is performed by an eight-bit successive approximation register. Each a/d channel will accept input voltages in the range of -5 to +5 volts and the a/d converter will convert the input voltage to a digital value (proportional to the input) ranging from 0 to 255 in 9 microseconds. The number of possible digital output values (256 or 2^8) is characteristic of the eight-bit converter. The computer output is defined by the expression

$$\text{Digital Output} = 255\ \frac{\text{Input Voltage} - (-5\ \text{volts})}{5\ \text{volts} - (-5\ \text{volts})} \tag{2}$$

For the specified input voltage range, the resolution of the converter is approximately 39 millivolts, calculated by dividing the voltage range (10 volts) by the digital output range (255). The absolute accuracy of the a/d converter is specified as $\pm$ 3% Full Scale Resolution (FSR), and the relative accuracy is specified as $\pm$ 1 Least Significant Bit (LSB) [3]. Therefore, the allowable absolute error in digital output is eight (3% of 255), and the allowable total error is nine digits.

The BASIC command,

PEEK (address)

"reads" the result of the previous a/d conversion (regardless of the address of the previous conversion), and initiates a new a/d conversion at the specified address. Therefore, the PEEK command must be used twice to retrieve the current value from the desired address.

For improved accuracy in analog measurements, several consecutive a/d conversions should be made, and the digital values from the second through the last conversions should be averaged. A subroutine has been written to perform the a/d data acquisition and averaging. The converter channel and the number of conversions to be averaged are input to the subroutine and the subroutine returns the average value of the conversions. A flowchart of the subroutine is shown in Figure 2, and the subroutine program steps are shown in Figure A1.

3.2.2. Digital-to-Analog Conversion

Digital-to-analog conversion is performed by an eight-bit converter that will accept digital input values in the range of 0 to 255, and will produce an output voltage (proportional to the input) in the range of -5 to +5 volts in 16 microseconds. The converter output voltage is defined by the expression

$$\text{Output Voltage} = 10\,\frac{\text{Digital Input} - 128}{255} \tag{3}$$

The resolution of the d/a converter is also approximately 39 mv, and the allowable error is $\pm$ 3% FSR (absolute) and $\pm$ 1 LSB (relative). Therefore the total allowable error is approximately 339 mv (3% of the 10 volt range plus 39 mv in the LSB).

The BASIC command

```
POKE address, Digital Input
```

initiates the conversion and outputs the resulting voltage to the specified slot-dependent address. The maximum output current is 2 milliamps (ma) (source or sink) [3].

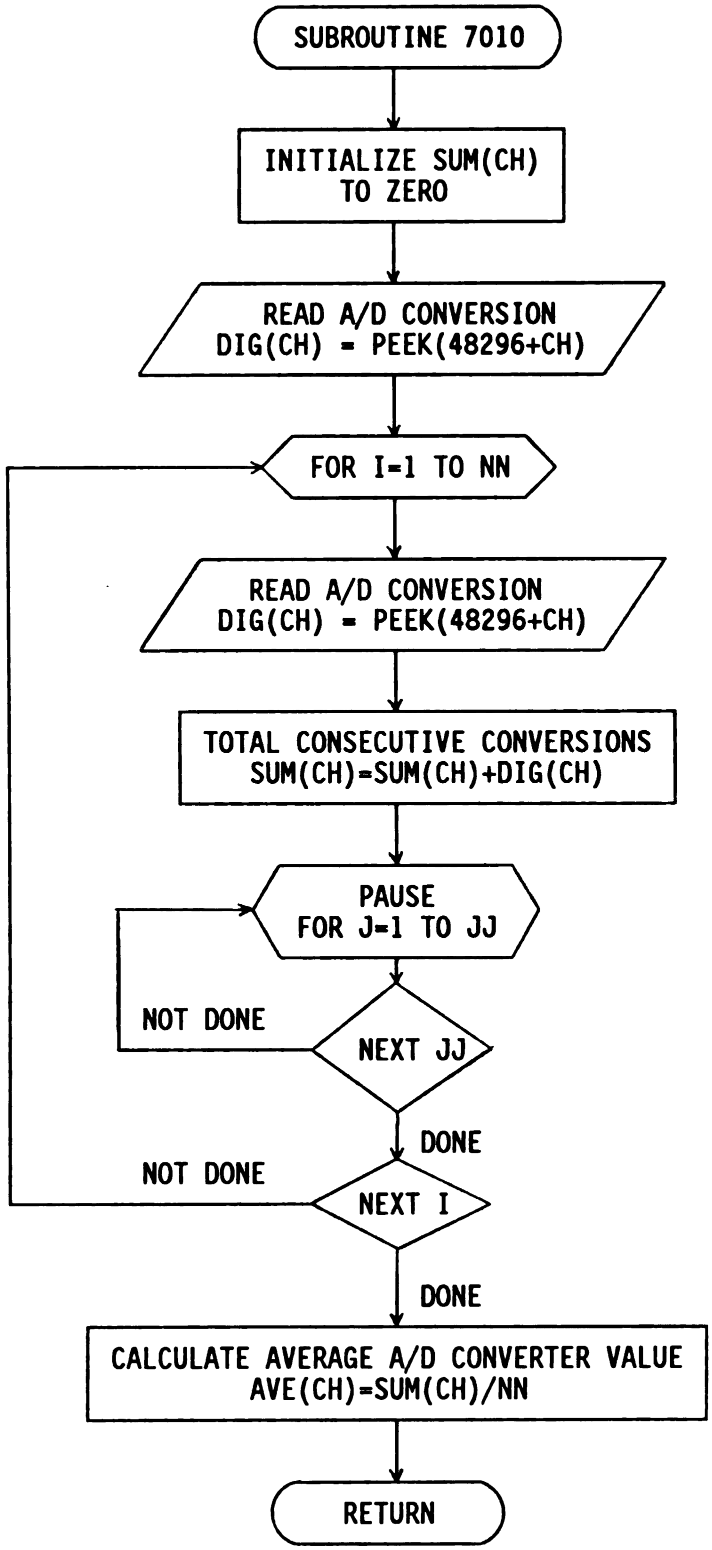


Figure 2. Data Acquisition Subroutine (7010) Flowchart

3.2.3. Converter Board Cable Access

The Mountain Computer board is interfaced through two 26-pin connectors (labeled J1 and J2) located at the top edge of the board. The d/a and a/d converters are accessed through connectors J1 and J2, respectively, and the connector pinouts are identified in Figure B1. Two flat ribbon cables have been fitted on one end with appropriate connectors that plug into J1 and J2. The other ends of the cables have mating DB-25 connectors with pin contacts (male) or socket contacts (female). The DB-25 connectors and the pinouts are shown in Figure B2, and the relationships between the connector pins and the converter signals are outlined in Table C1 [3].

The DB-25 connectors on the cables plug into mating connectors with solderable leads that have been permanently mounted in specially-built boxes. Jumper wires are soldered to each connector pin and are attached to screw terminals that are mounted in the back of the boxes. Therefore, with the ribbon cables in place, all analog input and output to and from the Mountain Computer board may be accessed through the screw terminal blocks.

3.3. Vector Electronics Circuit Board

To accommodate the additional circuitry necessary to interface the game i/o connector and the process instrumentation described in Sections 3.4 and 3.5, a Vector Electronics 4609 Plugboard is utilized and has been placed in peripheral card slot number 5. A pinout diagram of the card slot is shown in Figure B3, and a description of the power and ground pins utilized in the circuitry is given in Table C2 [4].

Input and output signals to and from the Vector board circuits are made via two 15-conductor ribbon cables. Each cable has a 16-pin dual in-line package (DIP) plug on one end that plugs into a mating DIP socket mounted on the Vector board. One cable transmits signals from the game i/o connector and is further described in Section 3.4.

The second cable is fitted on its other end with a male DB-15 connector that plugs into a mating (female) connector with solderable leads that has been mounted in a specially-built auxiliary i/o box. The pinout diagrams for the Vector board socket and the DB-15 connectors are shown in Figures B4 and B5, respectively, and the signal description for each pin is listed in Table C3. Jumper wires are soldered to each connector pin and are attached to screw terminals that are mounted in the back of the auxiliary i/o box.

3.4. Game Input/Output Connector

The game i/o connector is a 16-pin (DIP) socket at the right-rear of the Apple II. A pinout diagram of the connector is shown in Figure B6 (pin 1 is the right-front pin on the socket as one faces the keyboard), and the signal descriptions for several pins are listed in Table C4 [5]. The 5 volt supply, the system ground and two annunciator outputs are utilized in the circuitry described in Section 3.5. The game i/o connector is accessed with a 16-pin DIP jumper, that consists of a 15-conductor ribbon cable and a 16-pin DIP plug on each end. One connector plugs into the game i/o DIP socket and the other plugs into a DIP socket that is mounted on the Vector Electronics 4609 Plugboard as described in Section 3.3. The corresponding pinout diagram of the DIP socket on the Vector board is shown in Figure B7.

3.5. Process Instrumentation

The appropriate instrumentation has been installed and calibrated to measure three process temperatures, to measure and control the natural gas flow rate and to control the drying air flow rate. The instrumentation has been interfaced with the Apple computer through specially constructed electronic circuitry, and is accessed through specific software commands. The instrumentation and its interfacing are described in sections 3.5.1. through 3.5.4.

3.5.1. Temperature Measurement

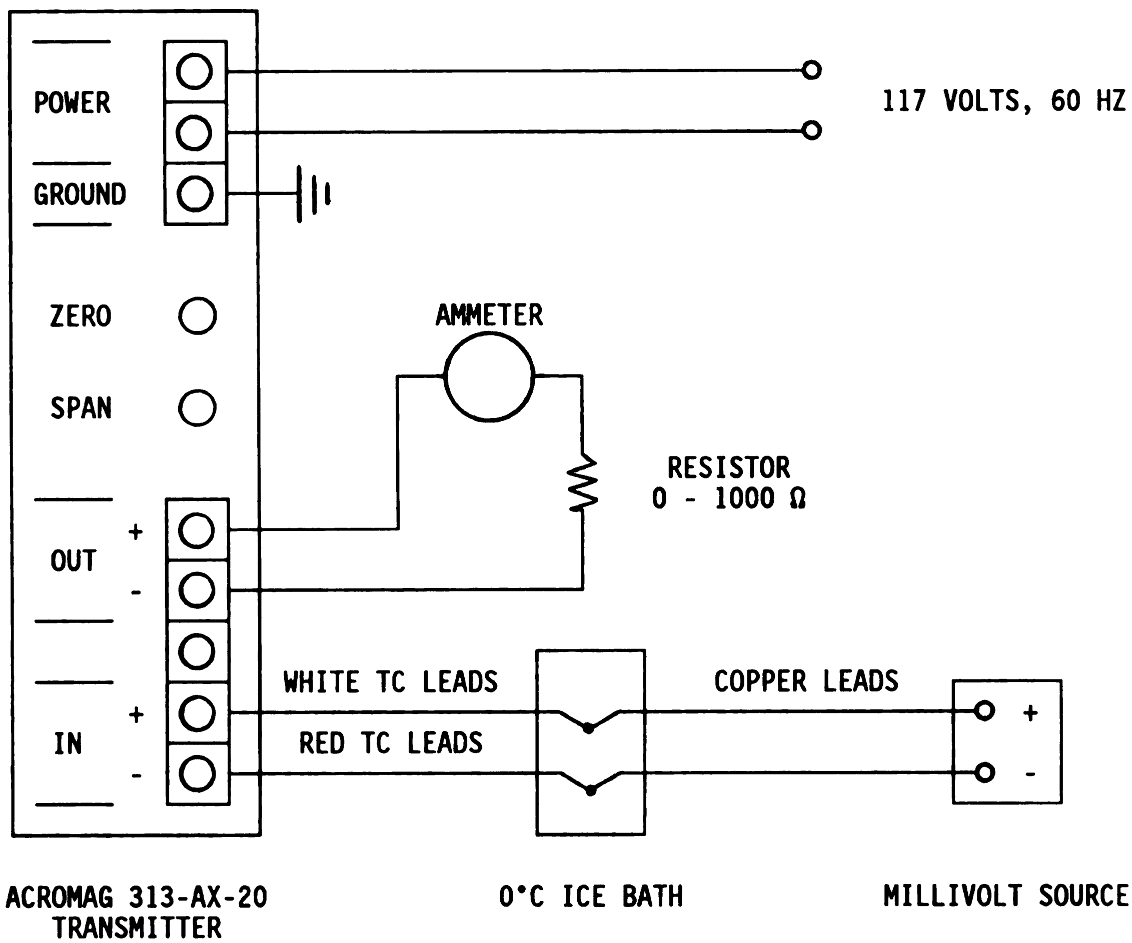
Iron Constantan (Type J) thermocouples are inserted in wells in the feed and discharge breechings of the dryer, to measure the inlet and outlet dry-bulb temperatures ($T_{i,db}$ and $T_{o,db}$, respectively) and the outlet wet-bulb temperature ($T_{o,wb}$) of the gas stream inside the dryer. Each thermocouple (TC) is contained in a protective metal sheath that is partially wrapped with teflon tape to prevent direct contact with the metal well and support. Wrapping the sheath in this manner prevents the occurrence of grounding loops between the thermocouples and the dryer.

Each TC is connected to an Acromag 313-AX-20 transmitter, which accepts a TC input signal and delivers a 4 to 20 ma signal to any external load between 0 and 1000 ohms. For calibrating, each transmitter has two 20-turn infinite resolution potentiometers built-in. The potentiometer labeled ZERO is used to adjust the minimum output current (4 ma) to correspond with the minimum input signal, and the one labeled SPAN is used to adjust the maximum output current (20 ma) to correspond with the maximum input signal [6]. The input signal is the electromotive force (emf) associated with the TC temperature. These values, measured in absolute millivolts, are found in standard TC tables [7]. Each transmitter has a built-in 32°F reference junction [6].

Using the procedure outlined in Figure 3, the transmitters were calibrated for the temperature ranges shown in Table 2. After the calibration procedure was completed, the TC leads were connected to the appropriate transmitter inputs, and the calibrated end points were checked for the temperature range of each TC using a well-mixed oil bath. The calibrated endpoints are designated as T_{min} and T_{max}.

To interface each transmitter to the a/d converter, a precision resistor with a nominal value of 500 ohms was placed across the output terminals of each transmitter. The subsequent voltage drop across each resistor ranges from 2 to 10 volts relative to ground. Equation 4 defines the relationship between the transmitter output voltage, V_{output}, and the TC temperature, T.

$$V_{output} = 8.00 \frac{T - T_{min}}{T_{max} - T_{min}} + 2.00 \tag{4}$$



<u>Calibration Procedure</u>

1. Connect the circuit as shown above.

2. Set the mv source equivalent to the emf associated with the minimum TC temperature, T_{min}.

3. Adjust the ZERO potentiometer to give the minimum output current of 4 ma.

4. Set the mv source equivalent to the emf associated with the maximum TC temperature, T_{max}.

5. Adjust the SPAN potentiometer to give the maximum output current of 20 ma.

6. Repeat these adjustments to obtain the desired accuracy.

Figure 3. Thermocouple Calibration Procedure

Table 2. Thermocouple Calibration Ranges

	Thermocouple Transmitter Location		
	Inlet Dry-Bulb	Outlet Dry-Bulb	Outlet Wet-Bulb
Minimum Temp. (°F)	75	75	50
Emf (mv)	1.22	1.22	0.50
Maximum Temp. (°F)	375	325	110
Emf (mv)	10.25	8.71	2.23

The overall interface between the thermocouples and the a/d converter is portrayed in Figure 4. The positive terminal from each transmitter is input to a specific channel of the a/d converter and each negative terminal is connected to the converter's -5 volt reference. Relative to this reference voltage the analog signals from the transmitters will range from -3 volts to +5 volts. Therefore, eighty percent of the full-scale span of the converter is utilized for the TC transmitter signals. Digital values from the converter will range from 51 to 255 for this span. The channels of the a/d converter that were used for the TC transmitter inputs are shown in Table 3.

Based on the interfacing of each transmitter to the a/d converter channels and the -5 volt reference, equations 5, 6 and 7 define the relationship between the average a/d converter output value [AVE(CH), for channel CH] and the TC temperatures.

$$T_{i,db} = \frac{AVE(01) - 51}{255 - 51} (375 - 75) + 75 \qquad (5)$$

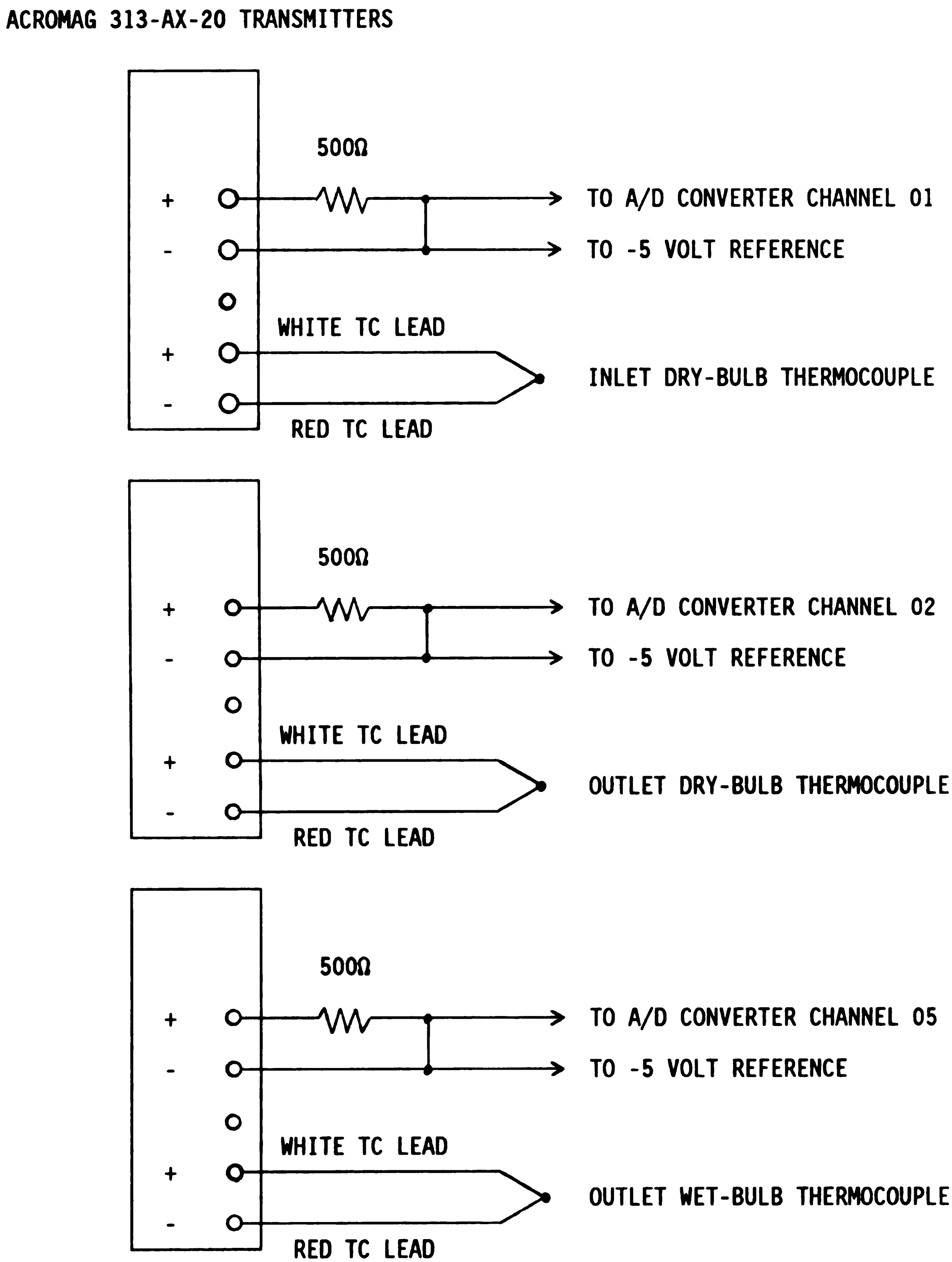


Figure 4. Interface Between Thermocouples and A/D Converter

Table 3. A/D Converter Channels For Thermocouple Transmitter Input Signals

Thermocouple Transmitter	Converter Channel
Inlet Dry-Bulb	01
Outlet Dry-Bulb	02
Outlet Wet-Bulb	05

$$T_{o,db} = \frac{AVE(02) - 51}{255 - 51} (325 - 75) + 75 \tag{6}$$

$$T_{o,wb} = \frac{AVE(05) - 51}{255 - 51} (110 - 50) + 50 \tag{7}$$

A subroutine has been written to calculate the TC temperatures from average values of a/d conversions for channels one, two and five. A flowchart of the subroutine is shown in Figure 5 and the subroutine program steps are listed in Figure A2. The average values from the a/d conversions are obtained through subroutine 7010 as described in section 3.2.1.

The subroutine also performs a check on the wet-bulb temperature. The wet-bulb TC transmitter has been calibrated for a maximum temperature of 110°F, but the maximum attainable operating wet-bulb temperature for the current dryer system is less than 100°F. Therefore, if the calculated wet-bulb temperature corresponds with the maximum possible (110°F) (due to an a/d converter value of 255), then either of two conditions may exist: 1) The water level in the dew cup may be too low resulting in insufficient evaporative cooling, or 2) a grounding loop may be present

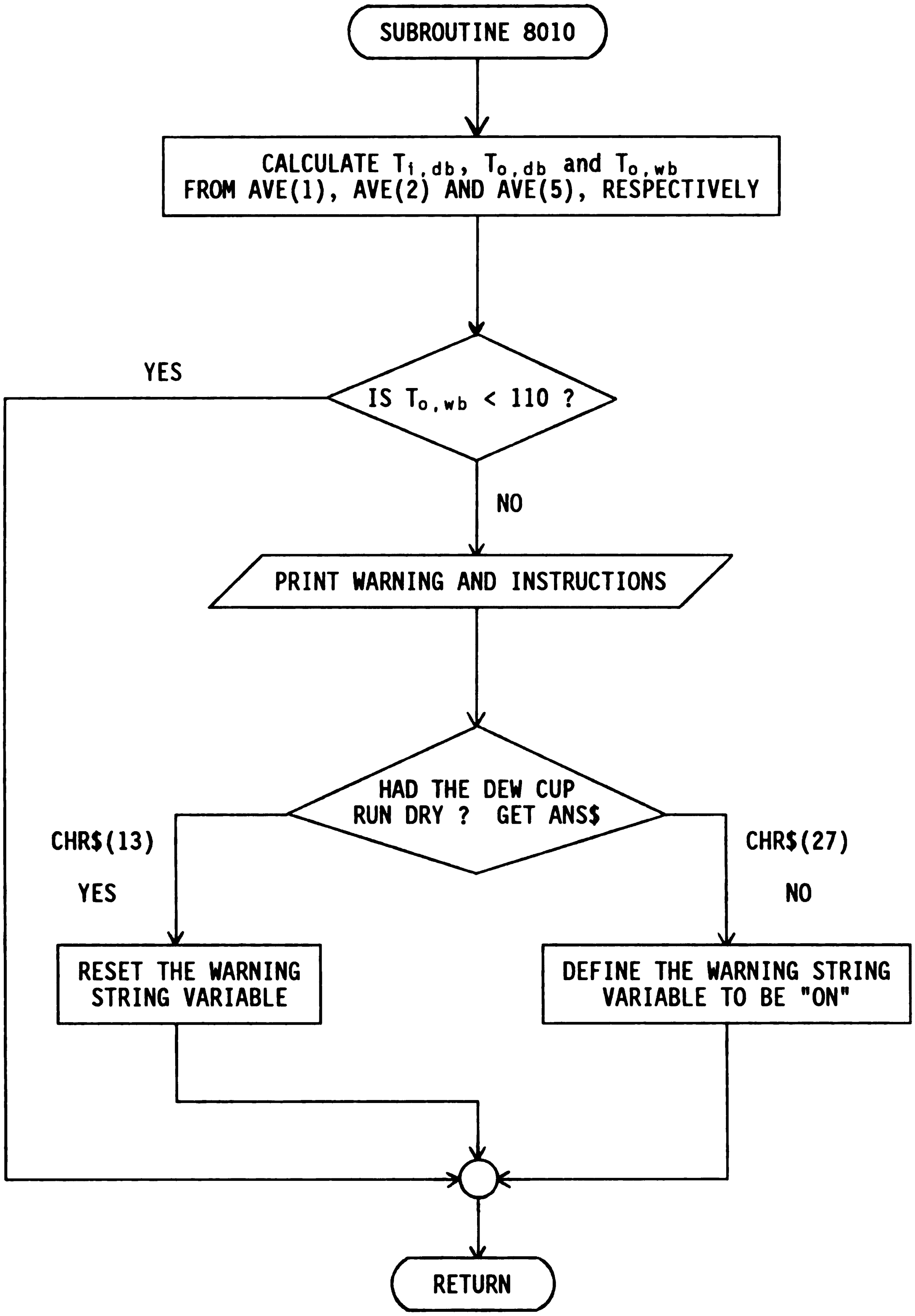


Figure 5. Temperature Calculation Subroutine (8010) Flowchart

in the system that would cause excessive voltage to be delivered from the TC transmitters and would result in digital values of 255 from the a/d converter. If a grounding loop is present then the system power must be turned "off" and the problem rectified.

3.5.2. Natural Gas Flow Rate Measurement

The flow rate of gas being fed to the combustion chamber is measured using a wet-test meter placed in-line as shown in Figure 1. The shaft of the meter turns one complete revolution per 3000 cubic centimeters (cc) of gas flow, and the maximum capacity of the meter is 18,000 cc per minute.

To obtain an electronic signal from the wet-test meter, a Hewlett-Packard incremental optical encoder (Model HEDS-6010) was attached to the shaft. The encoder translates the rotation of the shaft into interruptions of a light beam which are then output as electrical pulses. The encoder is operable to a maximum shaft speed of 12,000 rpm, which greatly exceeds the relative capacity of the flow meter [8].

The electrical pulses output from the encoder are made through three channels (A, B and I), each with a characteristic waveform for each cycle as shown in Figure 6. Channels A and B are the data channels and the output from each has a pulse width of 180 electrical degrees. The output from channel B is in quadrature to the output from channel A (there is a phase difference of 90 electrical degrees between the two). Channel I is the "index" channel. An index pulse of 360 electrical degrees is

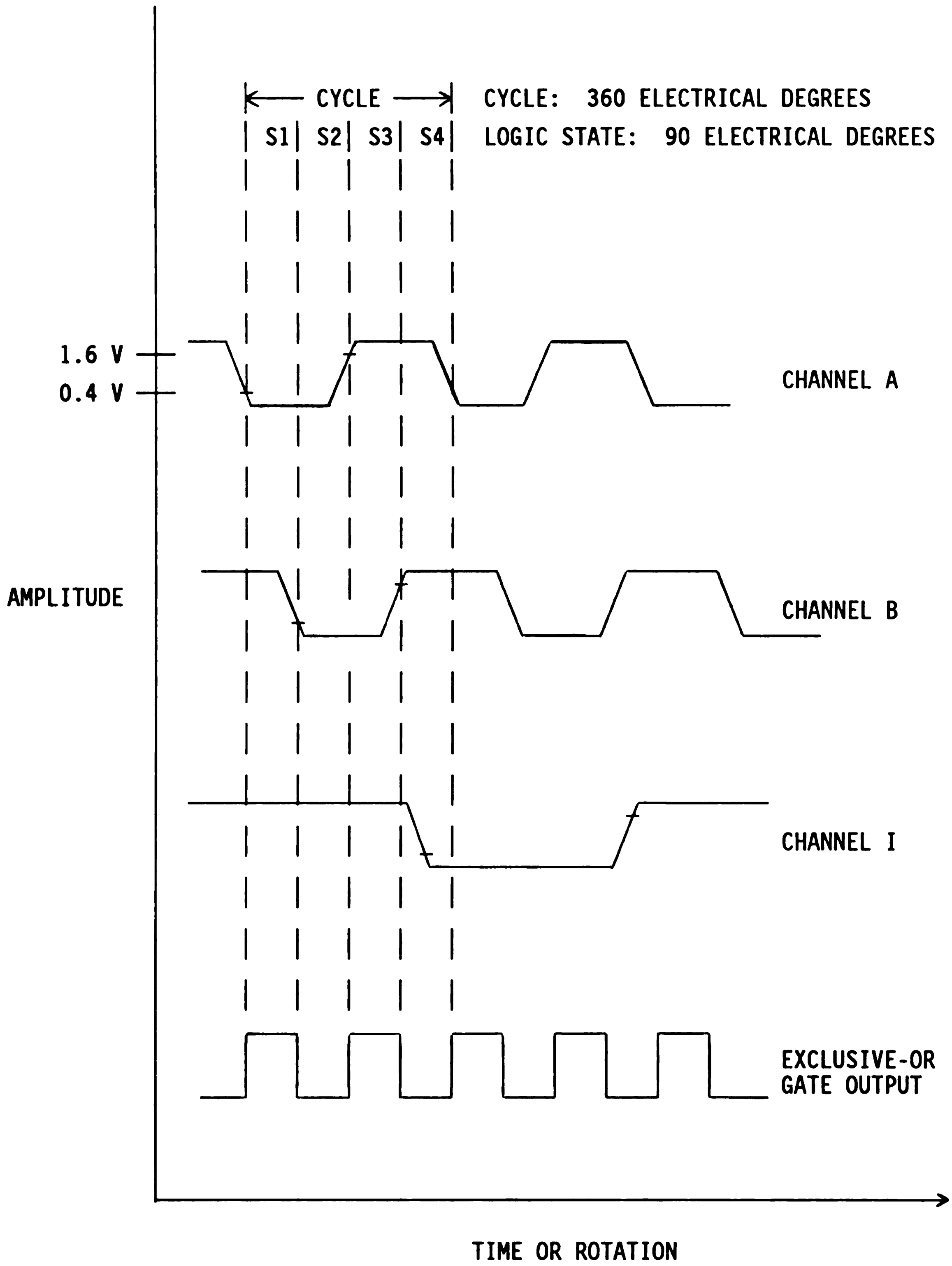


Figure 6. Signal Output Waveforms For Optical Encoder

generated for each complete shaft rotation, but it is not utilized for this application [8].

Due to the relative output waveforms from channels A and B, four distinct logic states occur during each cycle. The output from channels A and B for each logic state is summarized in Table 4. By definition, the duration of each overall logic state is 90 electrical degrees.

Table 4. Optical Encoder Signal Logic States

	Individual Logic State	
Overall Logic State	Channel A	Channel B
S1	High	Low
S2	High	High
S3	Low	High
S4	Low	Low

The encoder outputs and the 5 volt power supply input (V_{cc}) are Transistor-Transistor Logic (TTL) level signals. The output signals, V_{cc}, and electrical ground are accessed through a 10-pin connector mounted on a 60-cm ribbon cable. A pinout diagram for the connector is shown in Figure B8 [8].

The 10-pin connector plugs onto wire-wrap posts that are mounted on a small circuit board that is described below. The 5 volt power supply (V_{cc}) and ground for the encoder and the integrated circuits on the board are obtained indirectly from the Vector Electronics Plugboard, through the appropriate screw terminals of the auxiliary i/o box.

The outputs from channels A and B are input to a circuit with an exclusive-or gate, to translate the output delivered during one cycle into two pulses. A schematic diagram of the circuit is shown in Figure 7. The encoder signals (from A and B) are inverted and then re-inverted (using a Schmitt Inverter integrated circuit, 74LS14) to produce a "clean" signal to the gate. The output from this circuit for each encoder logic state is also shown in Figure 6 and is summarized in Table 5. The output is accessed through two screw terminals that are mounted on the circuit board.

Therefore, the circuit will output 2000 TTL level pulses per shaft revolution. For this application, one pulse will be delivered per 1.5 cc of gas flow. These pulses are input to an Analogic Rate Monitor (Model AN25M03), with a digital display and an analog output option (0 to 5 volts). The monitor can be set to display 0 to 1999 for a full-scale input rate from 50 to 10,000 Hertz (Hz) [9]. For the given conditions, the span and decimal point have been set to display "19.99" for an input rate of 222.1 pulses per second (Hz), since this frequency represents

$$222.1\ \frac{\text{pulses}}{\text{sec}}\ 1.5\ \frac{\text{cc gas}}{\text{pulse}}\ 60\ \frac{\text{sec}}{\text{min}}\ \frac{1\ \text{liter}}{1000\ \text{cc}} = 19.99\ \frac{\text{ltr}}{\text{min}} \qquad (8)$$

Refer to the Analogic instruction manual for specific information regarding the required set-up procedures [9]. In general, the span has been set by switching on the necessary switches (SA-7, SB-2, SB-3 and

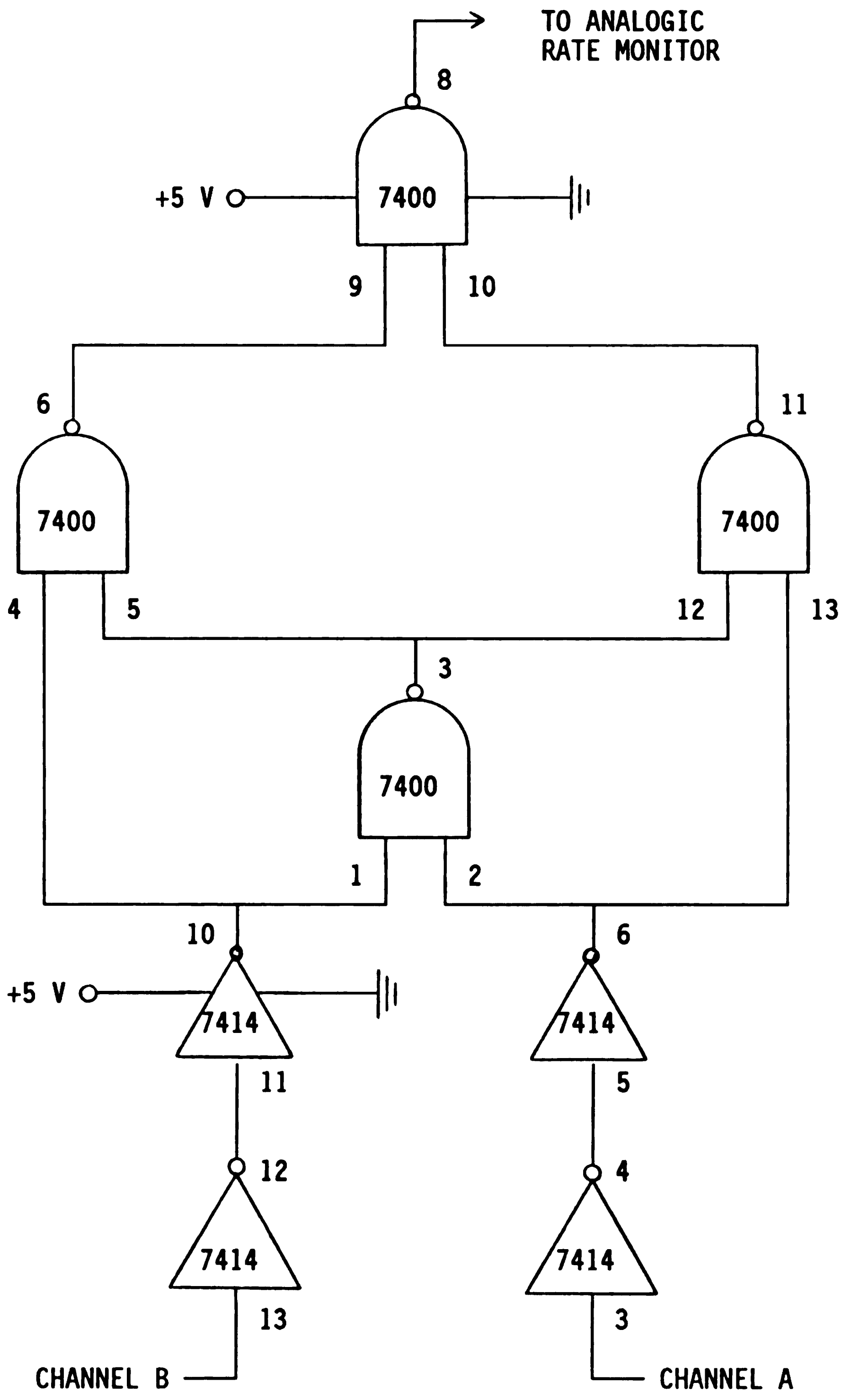


Figure 7. Schematic Diagram of Exclusive-Or Circuit

Table 5. Exclusive-Or Circuit Output Signal Logic States

	Individual Logic State		
Overall Logic State	Channel A	Channel B	Ex-Or Circuit
S1	High	Low	High
S2	High	High	Low
S3	Low	High	High
S4	Low	Low	Low

SB-4) to obtain a value for K of approximately 4502, where

$$K = 500 \frac{1 + \text{Display Value}}{\text{Frequency Input}} = 500 \frac{1 + 1999}{222.1} = 4502 \qquad (9)$$

The analog output from the rate monitor ranges from 0 to 5 volts, representing display values from 0 to 1999 counts. Therefore, equation 10 defines the relationship between the analog output (V_1, volts) and the gas flow rate (Gas) in liters per minute.

$$\text{Gas} = 19.99 \frac{V_1}{5} \qquad (10)$$

To interface the analog output signal from the rate monitor to the a/d converter, an inverting operational-amplifier (op-amp) circuit was designed, and was constructed on the Vector Plugboard described in Section 3.3. A schematic diagram of this circuit is shown in Figure 8. Input and output signals to and from the circuit are accessed through the auxiliary i/o box. The output (V_2) from this circuit is defined by equation 11.

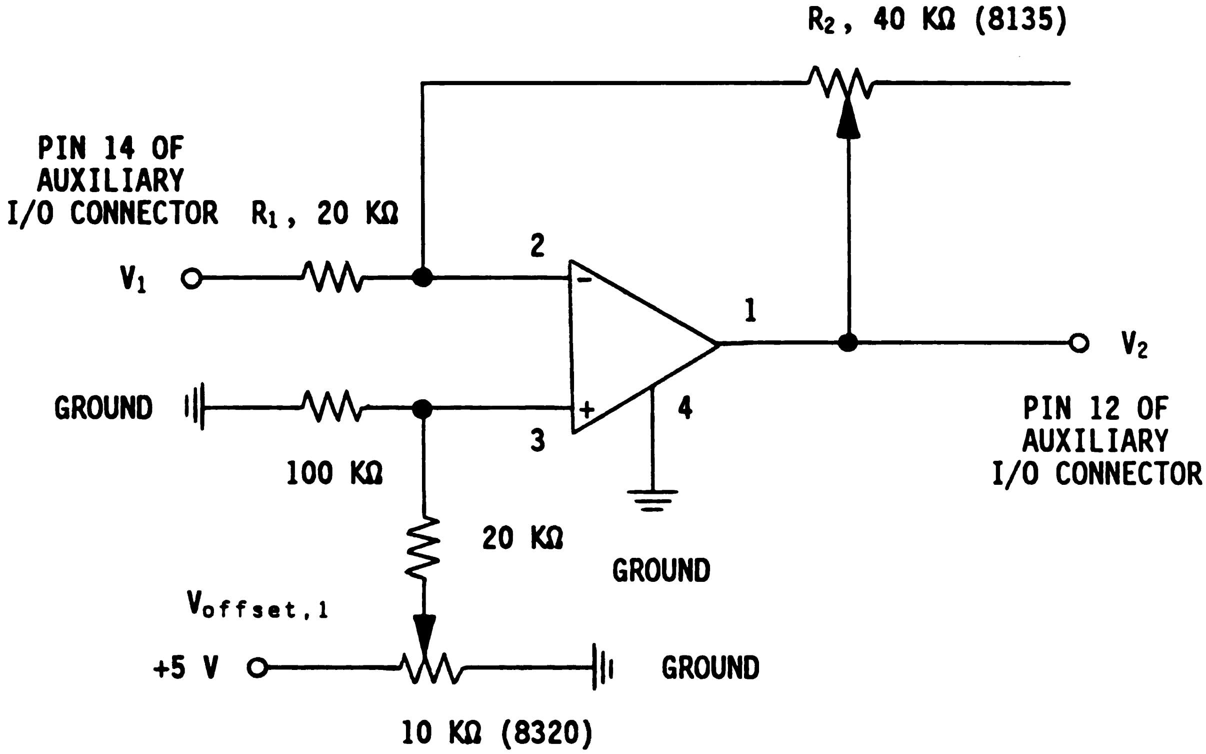


Figure 8. Schematic Diagram of Op-Amp Circuit For Gas Flow Rate Measurement

$$V_2 = V_{offset,1} - \frac{R_2}{R_1} V_1 \tag{11}$$

where

$$V_{offset,1} = +5 \text{ volts}$$

$$0 \leq V_1 \leq 5$$

Therefore, equation 11 can be simplified to

$$V_2 = 5 - 2\ V_1 \tag{12}$$

which results in an output voltage range of -5 volts to +5 volts. The op-amp circuit converts the input voltage to the useful range of the a/d converter, -5 to +5 volts. The positive lead from the op-amp circuit is input to channel 11 of the converter and the negative lead is connected to ground.

The electronic interfacing between the gas flow meter and the a/d converter described above is portrayed in Figure 9. Equation 13 defines the relationship between the average a/d converter output value for channel 11 [AVE(11)] and the gas flow rate.

$$\text{Gas} = 19.99 \, \frac{255 - \text{AVE}(11)}{255} \tag{13}$$

A subroutine has been written to calculate the gas flow rate from an average a/d conversion value for channel 11. A flowchart of the subroutine (10010) is shown in Figure 10 and the program steps are listed in Figure A3.

3.5.3. Natural Gas Flow Rate Control

As shown in Figure 1, the natural gas stream flows through the wet-test meter, enters the Honeywell pilot assembly and branches into two separate streams. The pilot assembly contains an internal valve that opens when the pilot stream is ignited, and closes when the pilot is "out", as sensed by a thermocouple near the burner. The flow rate of the pilot stream is constant, and the flow rate of the main gas stream that leads to the combustion chamber is controlled by a pneumatic, air-to-open control valve. It was necessary to interface the computer to the gas flow control valve. Output leads from channel 11 and ground of the d/a converter are input to an inverting operational amplifier circuit to

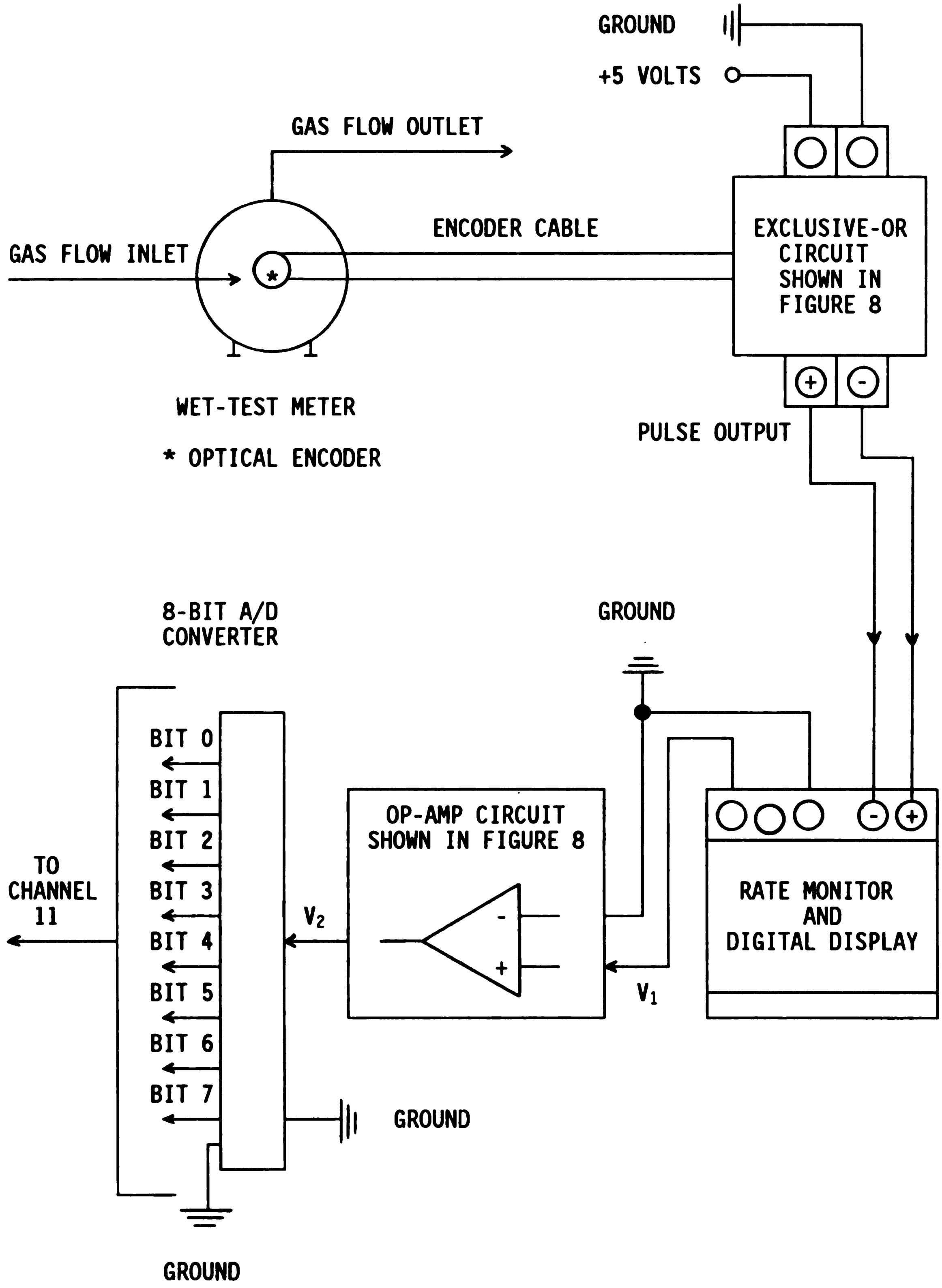


Figure 9. Interface Between Gas Flow Meter and A/D Converter

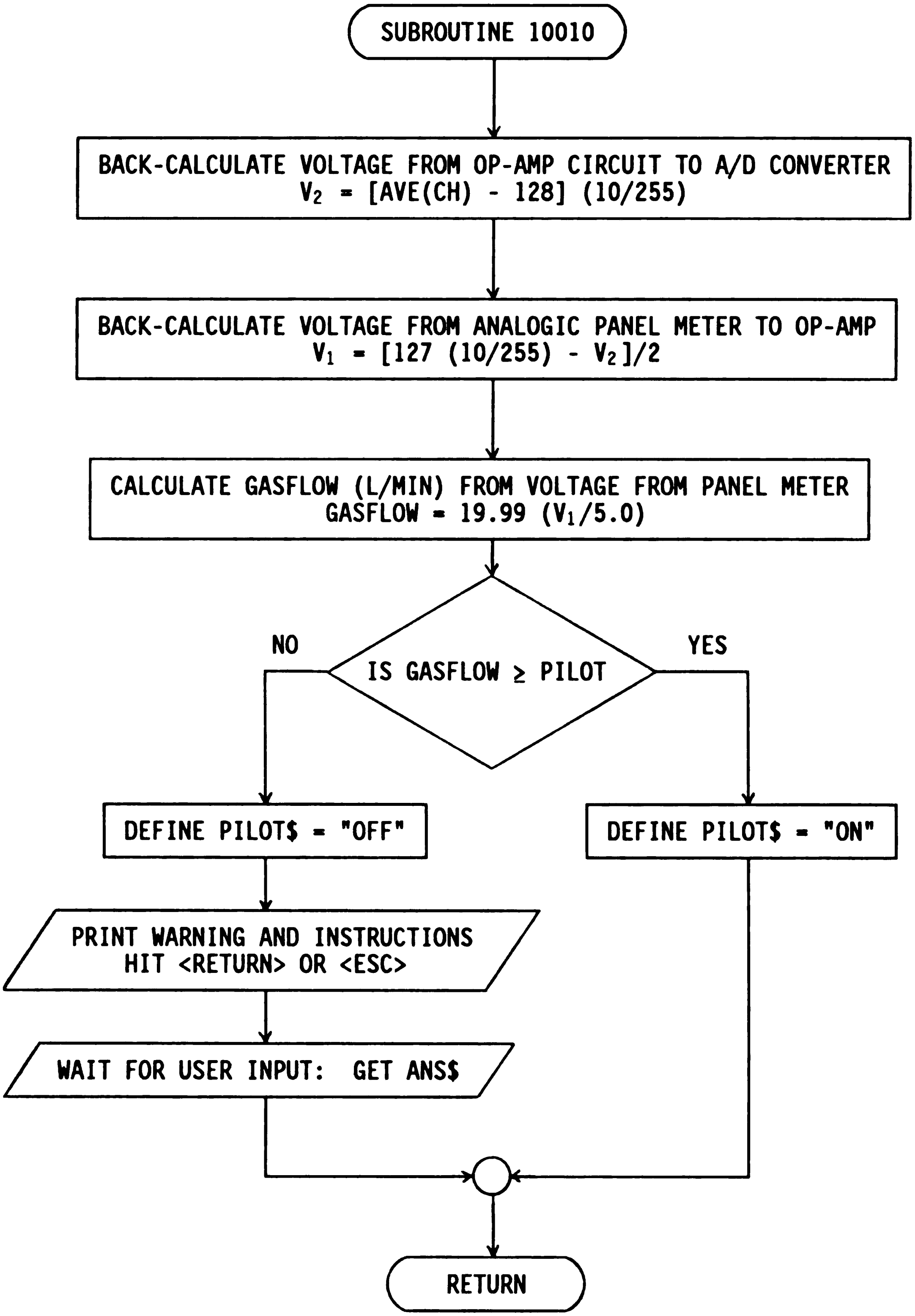


Figure 10. Gas Flow Rate Calculation Subroutine (10010) Flowchart

produce a voltage signal in the necessary range. A schematic diagram of this circuit is shown in Figure 11.

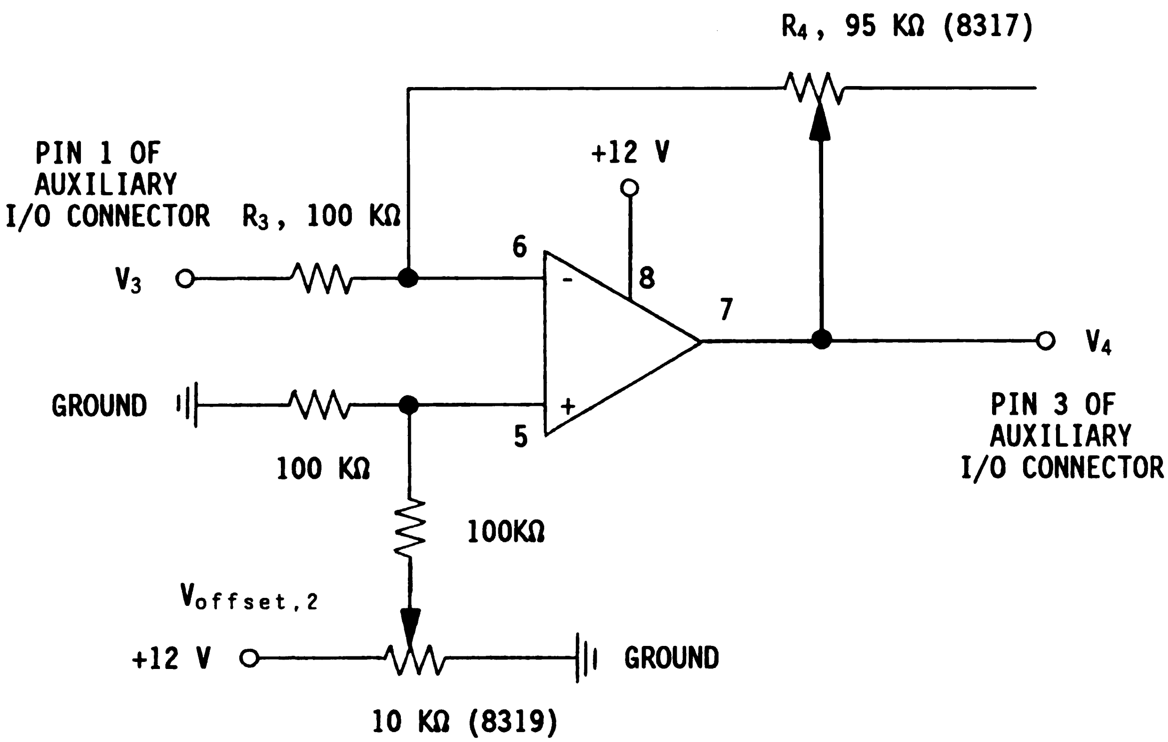


Figure 11. Schematic Diagram of Op-Amp Circuit For Gas Flow Rate Control

This circuit was also constructed on the Vector board and is accessed through the auxiliary i/o box. Output from channel 11 will range from -5 to +5 volts relative to ground for digital inputs from 0 to 255, respectively, and the resulting output from the op-amp circuit is defined by equation 14.

$$V_4 = V_{offset,2} - V_3 \frac{R_4}{R_3} \tag{14}$$

where

$$V_{offset,2} = 6.75 \text{ volts}$$

$$-5 \leq V_3 \leq +5 \text{ volts}$$

Therefore,

$$2.00 \leq V_4 \leq 11.50 \text{ volts}$$

The output voltage from this circuit is applied across the input terminals of a Honeywell current-to-pressure (I/P) electro-pneumatic transducer (Model 685437-002). The transducer operates over the input range of 4 to 20 ma of current, and will output a 3 to 15 psig air signal for this input range (the transducer is furnished with an air supply line pressure of 20 to 25 psig, manually set with a pressure regulator). The transducer has a nominal internal resistance of approximately 525 ohms, and subsequently requires an input voltage range of 2.10 to 10.50 volts as shown below [10]. The op-amp output voltage range, 2.00 to 11.5 volts, slightly exceeds the required range to accommodate relatively small deviations in the internal resistance due to changes in ambient temperature.

According to Ohm's law, the voltage drop (V, volts) between two points in a circuit is equal to the resistance (ohms) multiplied by the current (amperes). Therefore, for a resistance of 525 Ω and a current between 0.004 and 0.020 amps,

$$2.10 \leq V \leq 10.50 \text{ volts}$$

The air signal from the transducer is input to a volume booster, which then provides an air signal equivalent in pressure to the input, with the necessary volume to operate the diaphragm control valve. A diagram of the previously described interfacing between the computer and the control valve is shown in Figure 12.

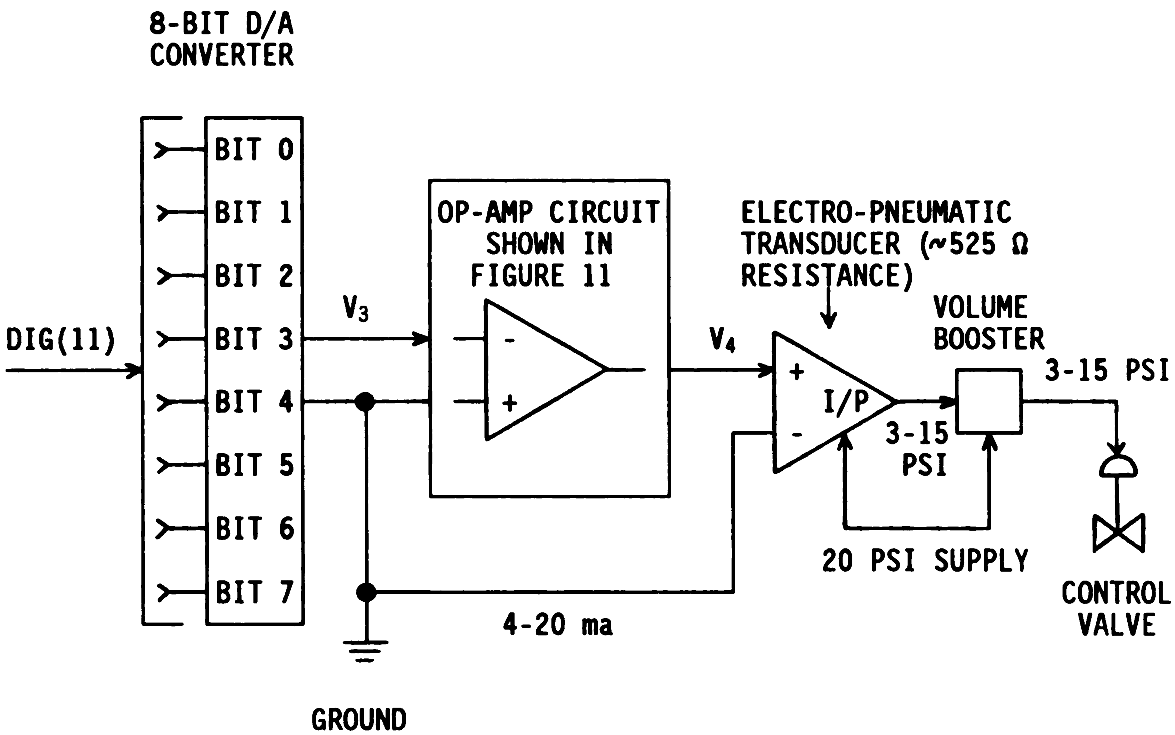


Figure 12. Overall Conversion of Digital Signal to Valve-Top Pressure Signal

Overall, the relationship between the digital signal [DIG(11)] to channel 11 of the d/a converter and the control valve pressure (psig) is defined as

$$\text{Pressure} = \frac{255 - \text{DIG(11)}}{255}(15.0 - 3.0) + 3.0 \qquad (15)$$

3.5.4. Air Flow Rate Control

As shown in Figure 1, a blower is positioned within the combustion chamber to draw feed air into the chamber and to drive the heated air through the dryer. A second blower, located at the opposite end, also draws air through the dryer and exhausts it. The feed air flow rate is controlled by a damper that is driven by a bi-directional Slo-Syn Synchronous stepping motor. The interfacing between the computer and the air damper is described below.

Two annunciator outputs, AN0 and AN1, of the game i/o connector are used to trigger the control of the stepping motor. Each output can source 0.4 ma at 5 volts in its logic 1 ("on") state or sink 8 ma in its logic 0 ("off") state. The logic state of each annunciator is controlled by the BASIC software command

```
POKE address, 0
```

where the address specifies the output location and logic state as shown in Table 6 [11].

Table 6. Addresses For Annunciator Output Signals

Decimal Address	Output Location	Logic State
49240	AN0	0 ("off")
49241	AN0	1 ("on")
49242	AN1	0 ("off")
49243	AN1	1 ("on")

Each annunciator is employed in a circuit that drives a mechanical relay that is, in turn, connected to the Slo-Syn Translator. A schematic diagram of the circuitry is shown in Figure 13. The circuits were constructed on the Vector Plugboard, and the annunciator output signals are accessed via the DIP socket linked with the game i/o connector as described in Section 3.4. The annunciator output is input to a 7406 hex inverter buffer-driver that can source or sink much more current than the annunciator. Sufficient current flow through the relay coils results in magnetic induction that causes the relay switch to close. Therefore, turning the annunciator "on" and "off" will "close" and "open" the switch, respectively. Additionally, the relay provides good isolation between the computer circuit and the controlled circuit, because there is no permanent, direct electrical connection between the two circuits. The Slo-Syn Translator converts electrical pulses from an external source into the correct motor switching sequence, and the motor shaft advances one step per pulse. The stepping increment is 1.8 angular degrees and the direction of rotation is determined by the signal input terminal that is used [12].

The required triggering pulse is a 10 to 15 negative change of voltage at input terminal A for clockwise (cw) rotation or at input terminal B for counterclockwise (ccw) rotation, relative to neutral terminal C. A 12 volt positive direct-current (dc), 6000 ohm supply is provided at terminal X [12]. The mechanical relays are incorporated with these terminals as shown in Figure 14, to provide external shorting switches and the required triggering pulses. The relay output signals are

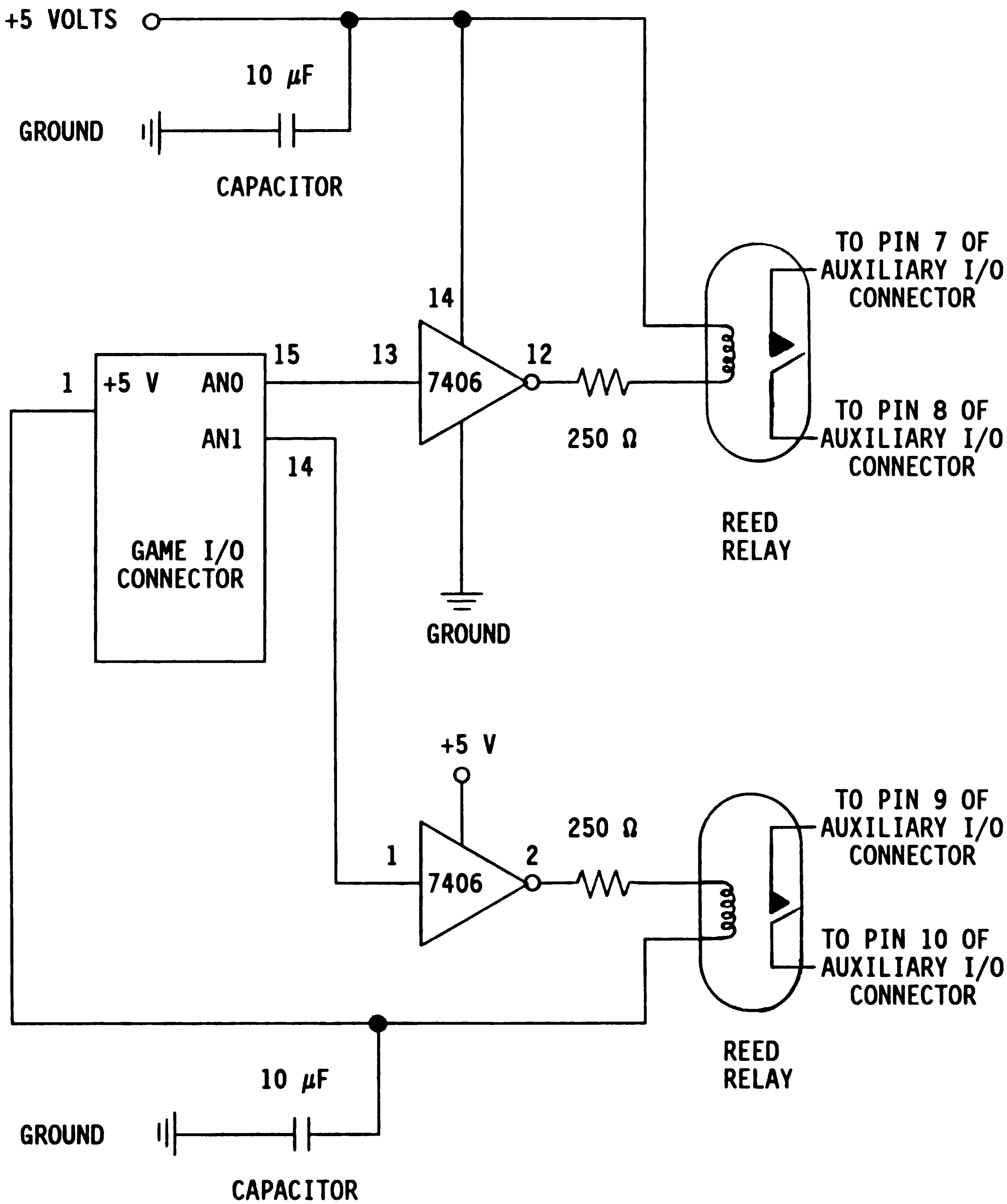


Figure 13. Schematic Diagram of Relay Circuitry

accessed through the screw terminals (pin numbers 7, 8, 9 and 10) of the auxiliary i/o box.

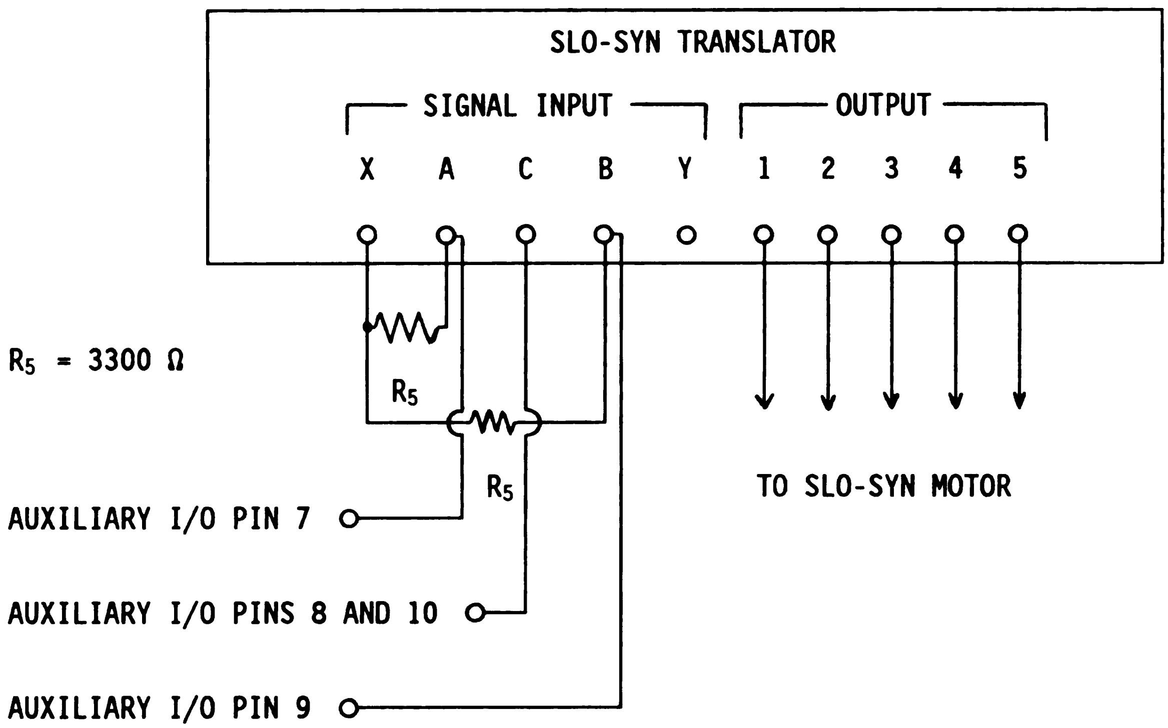


Figure 14. Translator Input Terminals and Relay Interface

The connection of terminal X to terminals A and B maintains a positive voltage at A and B, until the relay switch in either circuit is closed. Closing switch A or B reduces the voltage to zero at terminal A or B, respectively, thereby providing the negative change of voltage needed to trigger the translator. The switch must then be opened to reinstate the positive voltage at the terminal. The sequence of closing and opening the proper switch is repeated to trigger the number of motor steps in the desired direction [12].

A 6-toothed sprocket is mounted on the stepper motor shaft and an 18-toothed sprocket is mounted on the shaft of the air damper, resulting in a three-to-one gear ratio. Since the motor shaft rotates 1.8 degrees per step, the air damper shaft rotates 0.6 degrees per step. As shown in Figure 15, the damper position is changed from completely "open" to completely "closed" (and vice versa) by a 90 degree rotation, or 150 motor steps.

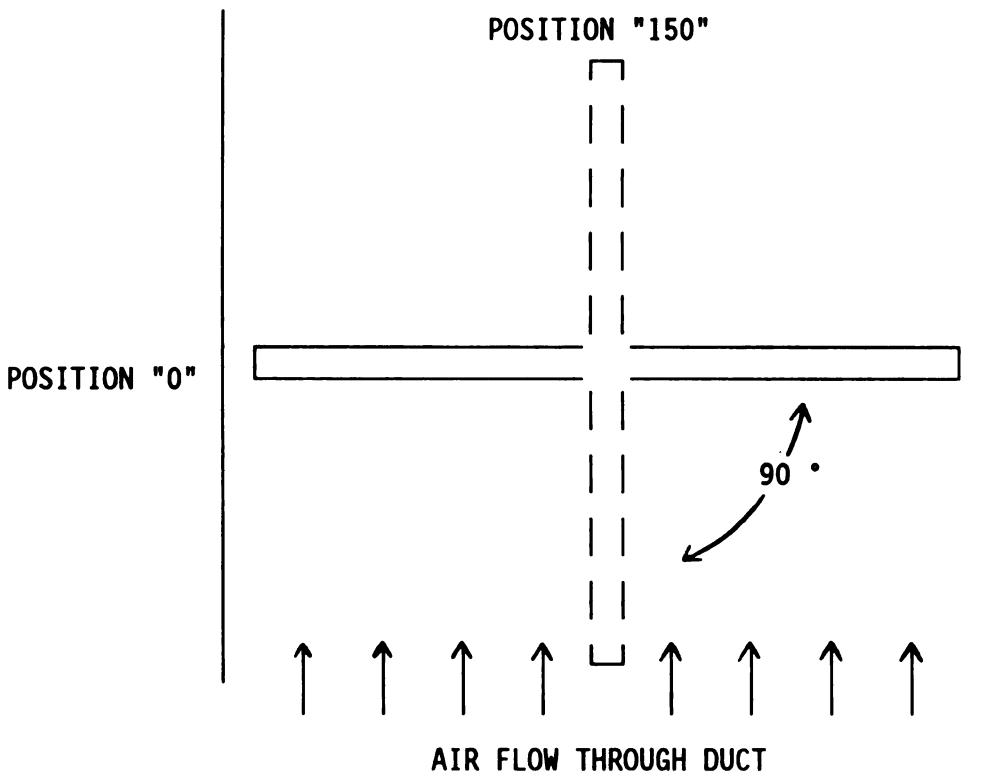


Figure 15. Air Damper Position

A subroutine has been written to control the changes in annunciator logic states to initiate stepper motor movement, and to document changes in the damper position. A flow chart of this subroutine is shown in Figure 16 and its program steps are listed in Figure A4. The specified number of

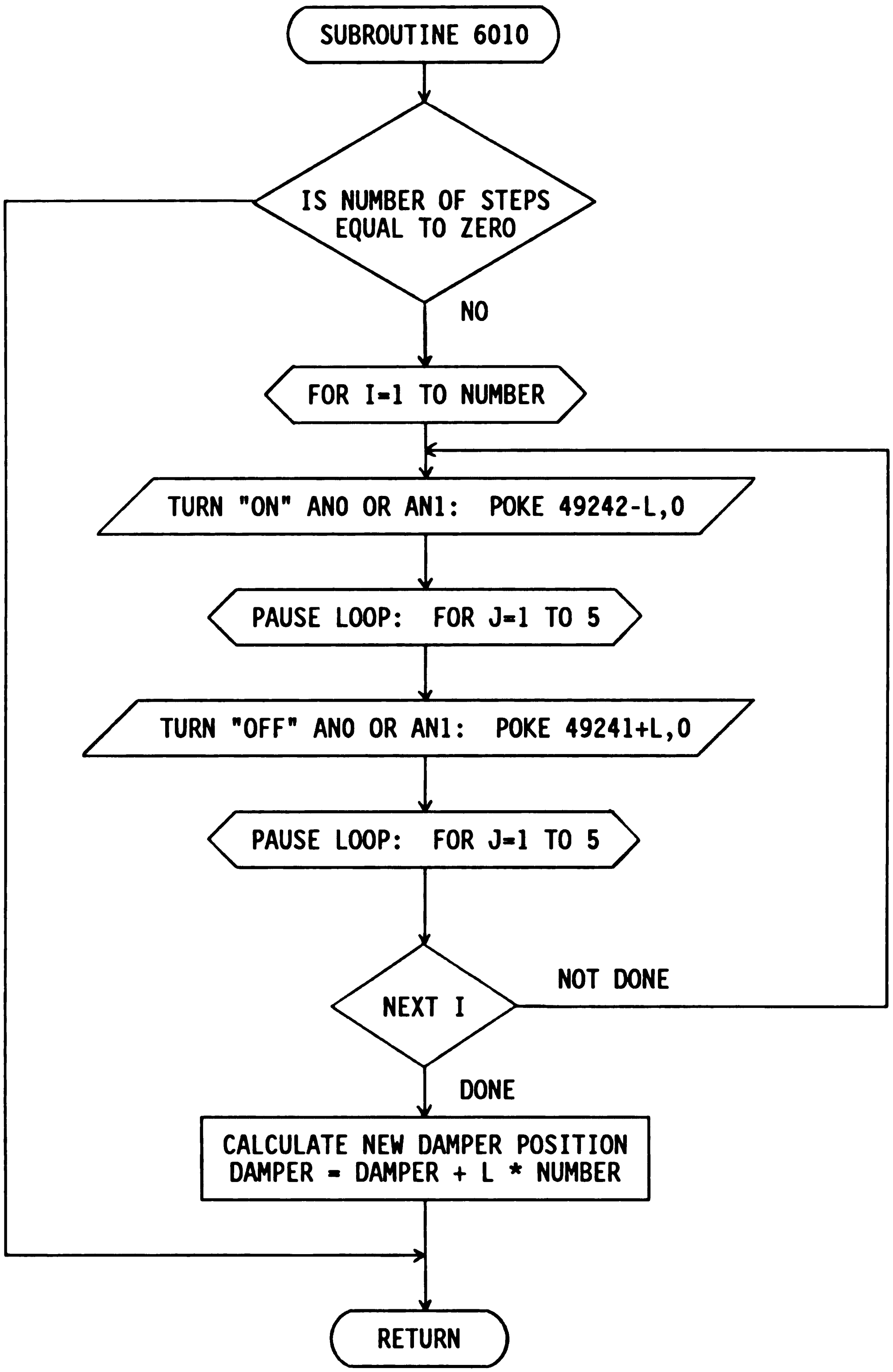


Figure 16. Stepper Motor Control Subroutine (6010) Flowchart

motor steps (Number) and the direction of rotation are input to the subroutine. The variable, L, represents the direction of rotation as follows:

L = +1, for clockwise rotation

L = -1, for counterclockwise rotation

Therefore, the BASIC software commands

```
POKE (49242 - L), 0
POKE (49241 - L), 0
```

will turn the appropriate annunciator output "on" and "off", respectively, to induce one motor step.

After a change in the damper position, the new position, DP_{new}, is calculated from the previous position, DP_{old}, using equation 16.

$$DP_{new} = DP_{old} + L * Number \qquad (16)$$

IV. Water Material Balance

Continuous operation and control of the dryer requires the continuous determination of the product moisture content. Since it can not be automatically and directly measured on an ongoing basis, the product moisture content must be calculated from its relationship with other, measured process variables. With the variables defined in Figure 17, a water material balance is derived and is shown below.

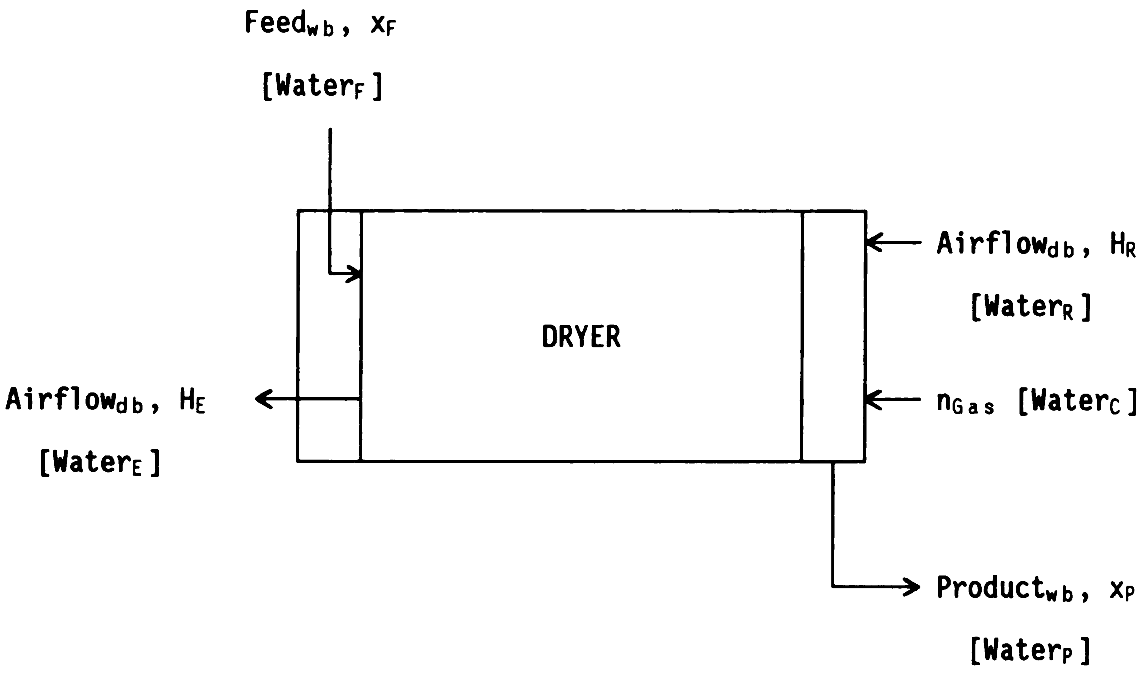


Figure 17. Water Material Balance For Dryer

$$Accumulation = Water_{in} - Water_{out} = 0 \tag{17}$$

$$Water_{in} = Water_F + Water_C + Water_R \tag{18}$$

$$Water_{out} = Water_E + Water_P \tag{19}$$

where

$Water_F$ = rate of water entering dryer in feed

$Water_C$ = rate of water generated by combustion

$Water_R$ = rate of water entering dryer in room air

$Water_E$ = rate of water exiting dryer in exhaust air

$Water_P$ = rate of water exiting dryer in product

4.1. Water in the Feed Material

The wet-basis feed rate ($Feed_{wb}$) and the feed moisture content (x_F) are measured by the operator prior to an experiment and are held constant throughout. Therefore, the rate of water entering the dryer in the feed ($Water_F$) can be directly calculated from equation 20.

$$Water_F = Feed_{wb}\ x_F \tag{20}$$

4.2. Water Generated by Combustion

The rate of water generated by combustion ($Water_C$) is calculated from the volumetric gas flow rate, the gas temperature and pressure (approximately 770 mm Hg), the ideal gas law and the combustion stoichiometry shown below.

$$CH_4 + 2\ O_2 \rightarrow 2\ H_2O + CO_2$$

For an ideal gas at 770 mm Hg (1.013 atm) and 25°C (298 K), the molar volume (V_m) is defined as

$$V_m = \frac{RT}{P_1} = 0.08205 \frac{\text{l-atm}}{\text{mol-K}} \frac{298\ \text{K}}{1.013\ \text{atm}} = 22.44 \frac{1}{\text{mol}} \qquad (21)$$

and the molar flow rate (n_{Gas}) and the mass flow rate (Gas_{mass}) of natural gas can be calculated from equations 22 and 23.

$$n_{Gas} = \frac{Gas}{V_m} = 4.46 \times 10^{-2}\ Gas \qquad (22)$$

$$Gas_{mass} = n_{Gas}\ MW_{Gas} \frac{\text{pound}}{454\ \text{g}} \qquad (23)$$

The molecular weight of natural gas (MW_{Gas}) is equal to 16.04 [13]. Based on the combustion stoichiometry, the flow rate of water due to combustion is equal to 2.25 times the mass flow rate of natural gas [13], and

$$Water_C = 2.25\ (16.04) \frac{1}{454}\ n_{Gas} = 7.95 \times 10^{-2}\ n_{Gas} \qquad (24)$$

4.3. Water in the Room (Supply) and Exhaust Air Streams

The rates of water entering and exiting the dryer in the room air (dryer supply air) and exhaust air streams, $Water_R$ and $Water_E$, respectively, can be determined from the flow rates and moisture contents of the air streams as shown in equations 25 and 26.

$$Water_R = Airflow_{db}\ (H_R) \qquad (25)$$

$$Water_E = Airflow_{db}\ (H_E) \qquad (26)$$

where H_R is the absolute humidity of the room air (lb water/lb dry air) and H_E is the absolute humidity of the exhaust air. The dry-basis supply air flow rate ($Airflow_{db}$) is calculated from an energy balance performed around the combustion chamber that is described in Section 4.3.1. It is assumed that the dry-basis supply air flow rate and exhaust air flow rate are equivalent.

The absolute humidities of the air streams (H_R and H_E) are determined from dry-bulb and wet-bulb temperature measurements as described in section 4.3.2. The humidity of the room air is determined as part of the dryer experiment start-up procedure and is assumed to be constant throughout an experiment. The humidity of the exhaust air is continually determined during an experiment from ongoing temperature measurements.

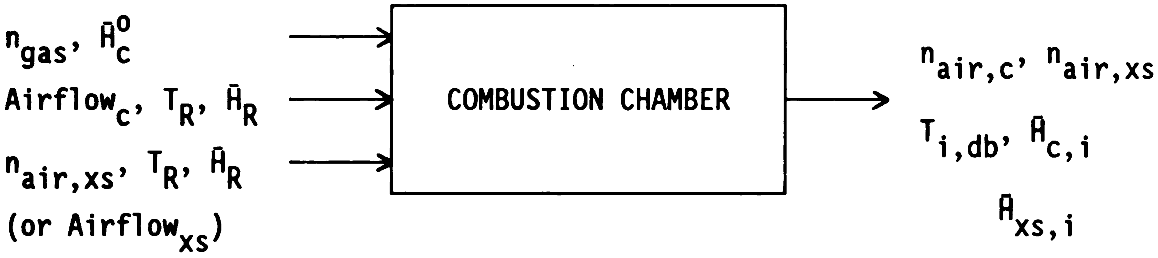
4.3.1. Air Flow Rate Determination

Based on the assumptions listed below and the variables defined in Figure 18, the air flow rate through the dryer is calculated from an energy balance performed around the combustion chamber as shown in equation 27.

<u>Assumptions</u>

- Complete combustion of methane occurs
- No heat is lost from the combustion chamber
- The steady-state air flow rate is attained instantly after start-up

$$\text{Accumulation} = \Delta H_c + \Delta H_p + \Delta H_{xs} = 0 \qquad (27)$$



$Airflow_c$ = air flow rate required for complete combustion, lb/min

$Airflow_{xs}$ = air flow rate in excess of amount required for combustion, lb/min

$\bar{H}_c^o$ = molar heat of combustion of natural gas

$\bar{H}_{c,i}$ = molar enthalpy of combustion products at T_i

$\bar{H}_R$ = molar enthalpy of room air at T_R

$\bar{H}_{xs,i}$ = molar enthalpy of excess air at T_i

$n_{air,c}$ = molar flow rate of air for combustion

$n_{air,xs}$ = molar flow rate of excess air

n_i = molar flow rate of the i^{th} component

T_i = air temperature downstream of the combustion chamber

T_R = room air dry-bulb temperature

Figure 18. Energy Balance For The Dryer

where

ΔH_c = rate of total heat of combustion

ΔH_p = enthalpy change of reaction products

ΔH_{xs} = enthalpy change of excess air

The total heat of combustion is calculated from the molar natural gas flow rate (n_{Gas}) and the molar heat of combustion ($\bar{H}_c^o$) as shown in equation 28. The molar heat of combustion with gaseous water as a product is equal to -191,760 cal/gmol [12].

$$\Delta H_c = n_{Gas}\, \bar{H}_c^o \tag{28}$$

The enthalpy change due to the temperature rise of the combustion products and the nitrogen that enters the combustion chamber with the combustion air is written as

$$\Delta H_p = \sum_{\text{products}} n_i \int_{T_R}^{T_i} C_{p_i}\, dT \tag{29}$$

where

C_{p_i} = molar heat capacity of the i^{th} component

The molar flow rates of the gaseous products and the unreacted nitrogen can be determined from the combustion stoichiometry and the composition of the combustion air. It is assumed that the air is 79% nitrogen and 21% oxygen, since the water content of the room air is less than one percent and the heat capacity of water vapor is close in value to those of the primary components.

$$n_{H_2O} = 2\ n_{CO_2} = 2\ n_{Gas}$$

$$n_{N_2} = \frac{0.79}{0.21}\ n_{O_2} = 2\ \frac{0.79}{0.21}\ n_{Gas}$$

The heat capacities of the gases can be expressed as a function of temperature as

$$C_{p_i} = A_i + B_i\ T + C_i\ T^2 \tag{30}$$

The values of the heat capacity constants (A_i, B_i and C_i) for various gases are shown in Table 7 [15].

Table 7. Molar Heat Capacities for Gases in the Ideal-Gas State [where T is in (K) and C_{p_i} is in cal/gmol/°C]

Component, i	A_i	$B_i \times 10^3$	$C_i \times 10^5$
CO_2	10.57	2.10	-2.06
H_2O	7.30	2.46	0.00
N_2	6.83	0.90	-0.12
O_2	7.16	1.00	-0.40

Equations 29 and 30 can be combined to get

$$\Delta H_p = n_{Gas} \int_{T_R}^{T_i} (\Delta A_c + \Delta B_c\ T + \Delta C_c\ T^2)\ dT \tag{31}$$

$$\Delta H_p = n_{Gas}\ [\Delta A_c\ (T_i - T_R) + \frac{\Delta B_c}{2}\ (T_i^2 - T_R^2) + \frac{\Delta C_c}{3}\ (T_i^3 - T_R^3)] \tag{32}$$

where

$$\Delta A_c = A_{CO_2} + 2A_{H_2O} + 2\,\frac{0.79}{0.21}\,A_{N_2} = 76.6$$

$$\Delta B_c = B_{CO_2} + 2B_{H_2O} + 2\,\frac{0.79}{0.21}\,B_{N_2} = 1.38x10^{-2}$$

$$\Delta C_c = C_{CO_2} + 2C_{H_2O} + 2\,\frac{0.79}{0.21}\,C_{N_2} = -2.96x10^{-5}$$

The enthalpy change of the excess air, ΔH_{xs}, can be calculated by rearranging equation 27 to get

$$\Delta H_{xs} = -\ (\Delta H_c + \Delta H_p) \qquad (33)$$

which can also be written as

$$\Delta H_{xs} = n_{air,xs} \int_{T_R}^{T_i} C_{p_{air}}\, dT \qquad (34)$$

The molar heat capacity of air can be determined from equation 30. The heat capacity constants (A_{air}, B_{air} and C_{air}) can be determined from the composition of the air and the appropriate constants in Table 7 as shown below. As before, it is assumed that the effect of the water vapor content on the heat capacity of the air is negligible.

$$A_{air} = 0.79\ (6.83) + 0.21\ (7.16) = 6.90$$

$$B_{air} = [0.79\ (0.90) + 0.21\ (1.00)]\ 10^{-3} = 0.92 \times 10^{-3}$$

$$C_{air} = [0.79\ (-0.12) + 0.21\ (-0.40)]\ 10^{-5} = -0.18 \times 10^{-5}$$

Equation 34 can be simplified to

$$\Delta H_{xs} = n_{air,xs} \left[A_{air} (T_i - T_R) + \frac{B_{air}}{2} (T_i^2 - T_R^2) + \frac{C_{air}}{3} (T_i^3 - T_R^3)\right] \quad (35)$$

which can be rearranged to solve for $n_{air,xs}$

$$n_{air,xs} = \frac{\Delta H_{xs}}{A_{air} (T_i - T_R) + \frac{B_{air}}{2} (T_i^2 - T_R^2) + \frac{C_{air}}{3} (T_i^3 - T_R^3)} \quad (36)$$

The wet-basis mass flow rate of room air entering the dryer, $Airflow_{wb}$, is equal to the sum of the mass flow rate of air required for complete combustion ($Airflow_c$) and the mass flow rate of excess air ($Airflow_{xs}$).

$$Airflow_{wb} = Airflow_c + Airflow_{xs} \quad (37)$$

where $Airflow_c$ is equal to 17.27 times the mass flow rate of natural gas (Gas_{mass}) [13] and

$$Airflow_{xs} = n_{air,xs} \, MW_{air} \frac{\text{pound}}{454 \text{ g}} \quad (38)$$

The molecular weight of air (MW_{air}) is equal to 28.92 [13]. Therefore,

$$Airflow_{wb} = 17.27 \, Gas_{mass} + 28.92 \, n_{air,xs} \frac{\text{pound}}{454 \text{ g}} \quad (39)$$

The dry-basis mass flow rate of air, $Airflow_{db}$, can be calculated from equation 25 and the relationships shown below. The flow rate of water in the air, $Water_R$, can be calculated from the combustion stoichiometry and the total air flow rate and absolute humidity of the room air (H_R).

$$Airflow_{db} = Airflow_{wb} - Water_R \quad (40)$$

$$Airflow_{db} = Airflow_{wb}/(1 - H_R) \quad (41)$$

A subroutine has been written to calculate the steady-state dry-basis air flow rate as described in this section. A flowchart of the subroutine is shown in Figure 19 and the program steps are listed in Figure A5.

4.3.2. Humidity Determination

The moisture content of air can be determined from its dry-bulb temperature (T_{db}) and wet-bulb temperature (T_{wb}). The wet-bulb temperature is measured by passing a stream of air by the wet surface of a thermometer (or thermocouple) as shown in Figure 20. Due to evaporative cooling, the wet-bulb temperature is lower than the dry-bulb temperature for an unsaturated air stream. The following assumptions are made that allow the definition of the appropriate mass and energy balances for the system.

<u>Assumptions</u>

1. The air at the surface of the wick is saturated.
2. There is an infinite supply of water to the wick.
3. Steady state has been attained.

The mass balance for evaporating water is defined as the mass flux of water (N_{water}) and is defined as

$$N_{water} = MW_{water}\ k_x\ (x_{water,s} - x_{water}) \quad (42)$$

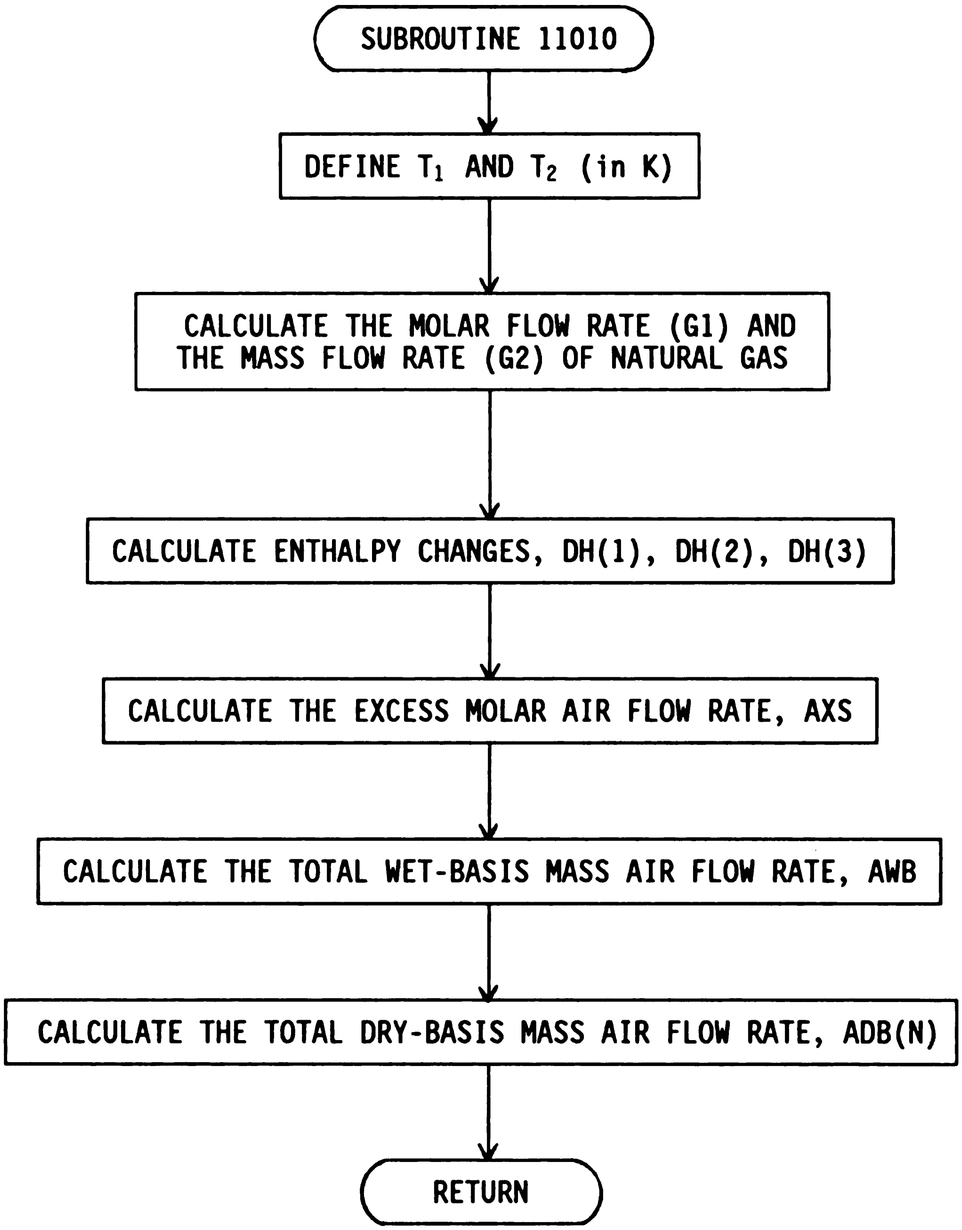


Figure 19. Air Flow Rate Calculation Subroutine (11010) Flowchart

where

k_x = mass transfer coefficient

$x_{water,s}$ = mole fraction of water in air at saturation temperature, T_{db}

x_{water} = mole fraction of water in air

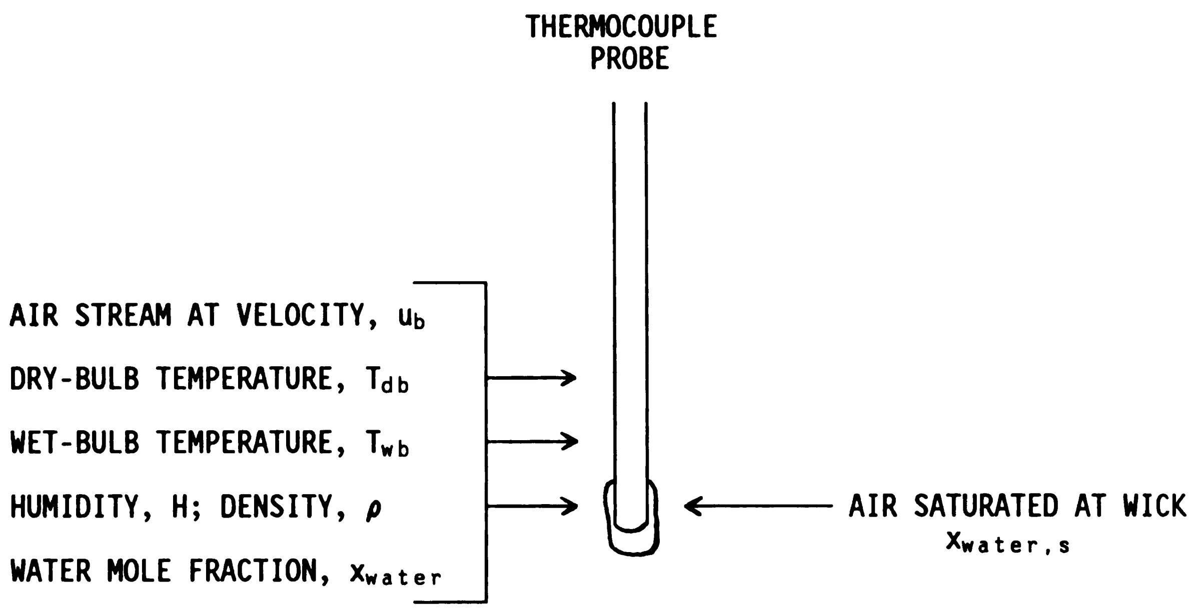


Figure 20. Wet-Bulb Temperature Measurement

The energy balance for convective heat transfer is defined as

$$h\ (T_{db} - T_{wb}) = \lambda\ N_{water} \tag{43}$$

where

h = heat transfer coefficient

λ = latent heat of vaporization of water

Substituting equation 42 into 43 to eliminate N_{water} yields

$$h\ (T_{db} - T_{wb}) = \lambda\ MW_{water}\ k_x\ (x_{water,s} - x_{water}) \tag{44}$$

Rearrangement of equation 44 to solve for x_{water} gives

$$x_{water} = x_{water,s} - \frac{h}{k_x\ \lambda\ MW_{water}} (T_{db} - T_{wb}) \tag{45}$$

From the Colburn analogy [16], at turbulent flow

$$j_H = \frac{h}{C_p\ u_b\ \rho} Pr^{2/3} = j_M = \frac{k_x\ MW_{mix} Sc^{2/3}}{u_b\ \rho} \tag{46}$$

where

j_H = heat transfer factor

Pr = Prandtl number

ρ = density of fluid

C_p = specific heat or humid heat

u_b = velocity of fluid

j_M = mass transfer factor

MW_{mix} = molecular weight of humid air

Sc = Schmidt number

Therefore,

$$\frac{h}{k_x} = C_p\ MW_{mix} \left(\frac{Sc}{Pr} \right)^{2/3} = C_p\ MW_{mix}\ Le^{2/3} \tag{47}$$

where Le is the Lewis number which is the ratio of the Schmidt number to the Prandtl number.

Substitution of equation 47 into equation 45 yields

$$x_{water} = x_{water,s} - \frac{T_{db} - T_{wb}}{\lambda\ MW_{water}} C_p\ MW_{mix}\ Le^{2/3} \tag{48}$$

The mole fraction of water, x_{water}, can be calculated from the absolute humidity (H) as shown below.

$$x_{water} = \frac{n_{water}}{n_{water} + n_{dry\ air}} \tag{49}$$

For derivation purposes, x_{water} can be expressed as

$$x_{water} = \frac{n_{water}/n_{dry\ air}}{n_{water}/n_{dry\ air} + 1}\ \frac{MW_{water}/MW_{dry\ air}}{MW_{water}/MW_{dry\ air}} \tag{50}$$

Based on the definition of the absolute humidity equation 50 can be simplified to

$$x_{water} = \frac{H}{H + \dfrac{MW_{water}}{MW_{dry\ air}}} \tag{51}$$

Therefore, at saturated conditions,

$$x_{water,s} = \frac{H_s}{H_s + \dfrac{MW_{water}}{MW_{dry\ air}}} \tag{52}$$

where H_s is equal to the humidity at the wet-bulb temperature.

Saturation humidity data is contained in the computer program for temperatures ranging from 50° to 200°F in 2°F increments. For the measured wet-bulb temperature, the saturation humidity is estimated by linear interpolation between input data (H_1 and H_2) for a lower and higher temperature. In Applesoft Basic this interpolation is programmed as

$$H_1 = H_s \text{ at } 2\,[\text{INT}\,(T_{wb}/2)]$$

$$H_2 = H_s \text{ at } [2\,[\text{INT}\,(T_{wb}/2)] + 2]$$

$$H_s \text{ at } T_{wb} = H_1 + [T_{wb} - 2\,[\text{INT}\,(T_{wb}/2)]]\,(H_2 - H_1)/2 \qquad (53)$$

where INT ($T_{wb}/2$) is the integer value of $T_{wb}/2$.

The heat of vaporization (λ) and the Prandtl number are calculated from the wet-bulb temperature through linear interpolation as shown below. The Schmidt number (Sc) is fairly constant over the temperature range of operation, and has an approximate value of 0.60 [17].

For the wet-bulb temperature range, $50°F \le T_{wb} \le 200°F$,

$$\lambda(T_{wb}) = \lambda(50°F) + [\lambda(200°F) - \lambda(50°F)]\,\frac{T_{wb} - 50}{200 - 50} \qquad (54)$$

where

$$\lambda(50°F) = 1065.3 \text{ BTU/lb } [18]$$

$$\lambda(200°F) = 977.9 \text{ BTU/lb } [18]$$

and

$$Pr(T_{wb}) = Pr(50°F) + [Pr(200°F) - Pr(50°F)] \frac{T_{wb} - 50}{200 - 50} \qquad (55)$$

where

$$Pr(50°F) = 0.709 \; [19]$$

$$Pr(200°F) = 0.697 \; [19]$$

For simplification purposes equation 48 will be expressed as

$$x_{water} = x_{water,s} - F \, C_p \, MW_{mix} \qquad (56)$$

where the quantity, F, is defined as

$$F = \frac{T_{db} - T_{wb}}{\lambda \, MW_{water}} Le^{2/3} \qquad (57)$$

The two remaining variables in equation 56, the molecular weight (MW_{mix}) and specific heat (C_p) of the humid air, are defined as functions of the mole fraction of water in the air (x_{water}) and the absolute humidity (H) as shown below.

$$MW_{mix} = x_{water} \, MW_{water} + (1 - x_{water}) \, MW_{dry\ air} \qquad (58)$$

$$C_p = 0.24 + 0.45 \, H, \text{ BTU/lb dry air/°F} \qquad (59)$$

where 0.24 and 0.45 are the heat capacities of dry air and water vapor, respectively, and both are assumed constant.

The relationship shown in equation 51 can be rearranged to

$$H = \frac{MW_{water}}{MW_{dry\ air}} \frac{x_{water}}{1 - x_{water}} \tag{60}$$

Combining equations 59 and 60 yields

$$C_p = 0.24 + 0.45 \frac{MW_{water}}{MW_{dry\ air}} \frac{x_{water}}{1 - x_{water}} \tag{61}$$

Equations 56, 58 and 61 must be solved simultaneously for x_{water}. An iterative procedure is used for this purpose and is described below.

The iterative procedure begins with the calculation of an initial guess for x_{water} that underestimates the actual value. This is accomplished by overstating the values of C_p and MW_{mix}. The maximum value of C_p occurs at saturation, so for the initial guess calculation C_p is overstated as

$$C_{p,sat} = 0.24 + 0.45 \frac{MW_{water}}{MW_{dry\ air}} \frac{x_{water,s}}{1 - x_{water,s}} \tag{62}$$

The maximum value of MW_{mix} occurs when x_{water} is equal to zero. This results in MW_{mix} equal to $MW_{dry\ air}$ which equals 28.97 lb/lbmol. Therefore, the initial guess (x_g) is calculated from

$$x_g = INT[(x_{water,s} - F\ MW_{air}\ C_{p,sat})\ 10000]/10000 \tag{63}$$

The integer function is utilized to truncate the initial guess. The value for x_g is then substituted into equations 58 and 61 to determine MW_{mix} and C_p, then x_{water} is calculated from equation 56. The difference between x_{water} and the guess (Error) is calculated as

$$\text{Error} = x_{water} - x_g \tag{64}$$

The guess is increased in 0.0001 increments until the error is less than zero. The calculated value of x_{water} from the last iteration is the solution, and the humidity of the air is calculated from equation 60.

A subroutine has been written to perform the calculations described in this section. A flowchart of the subroutine is shown in Figure 21 and the subroutine program steps are listed in Figure A6.

4.4. Product Moisture Content Determination

As indicated in Section IV the steady-state product moisture content (x_P) defined by equation 65 must be calculated through the water material balance for the dryer.

$$x_P = \frac{\text{Water}_P}{\text{Product}_{wb}} \tag{65}$$

The amount of water leaving the dryer in the product (Water_P) can be calculated from the water material balance.

$$\text{Water}_P = \text{Water}_{in} - \text{Water}_E \tag{66}$$

The wet-basis product flow rate (Product_{wb}) can be defined as

$$\text{Product}_{wb} = \text{Product}_{db} + \text{Water}_P \tag{67}$$

where Product_{db} is the dry-basis product flow rate.

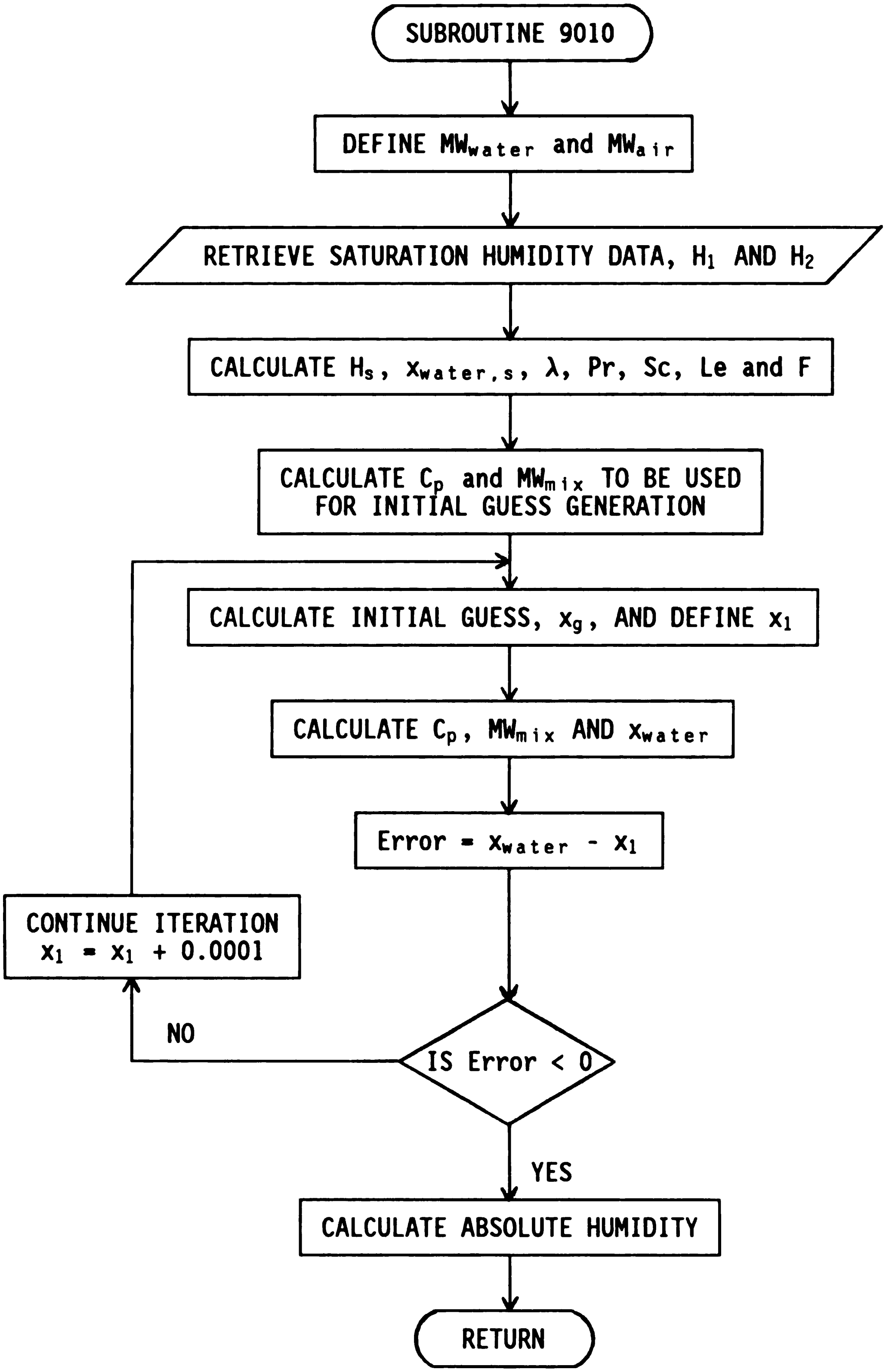


Figure 21. Humidity Determination Subroutine (9010) Flowchart

For a constant material feed rate ($Feed_{wb}$) and moisture content (x_F) the dry-basis feed rate ($Feed_{db}$) is constant and can be calculated from

$$Feed_{db} = Feed_{wb} \, (1 - x_F) \tag{68}$$

Therefore,

$$x_p = \frac{Water_p}{Water_p + Product_{db}} \tag{69}$$

Under these steady-state feed conditions the dry-basis product flow rate is equal to the dry-basis feed flow rate. Therefore, it is possible to quantify all of the defined variables utilized in the water material balance. A subroutine has been written to perform the material balance calculations described above. A flowchart for the program is shown in Figure 22, and the program steps are listed in Figure A7.

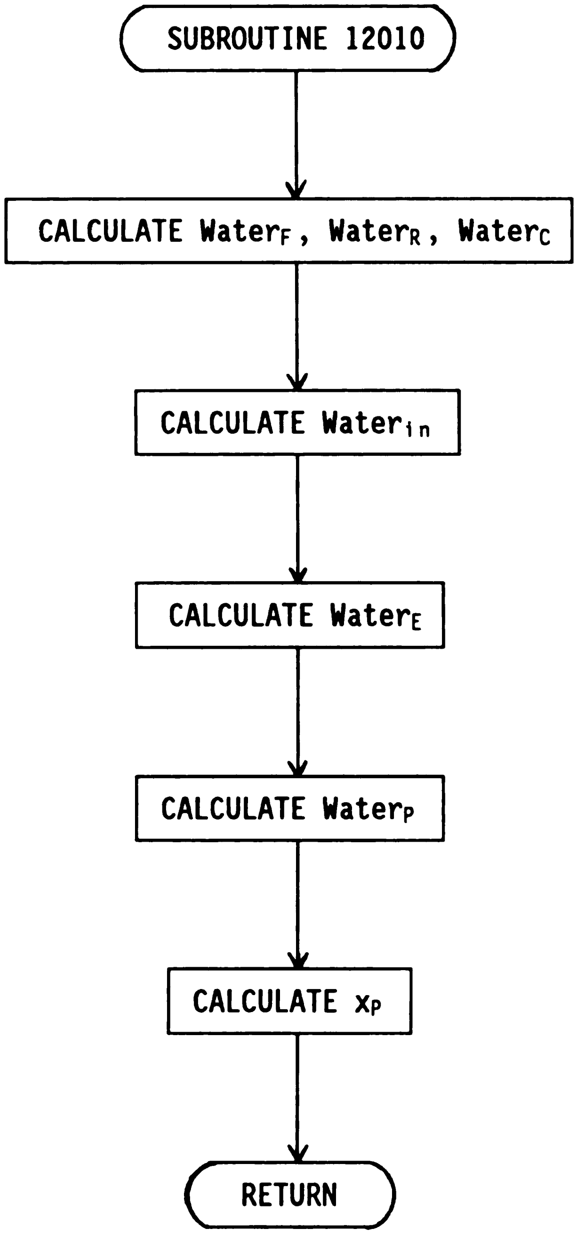


Figure 22. Product Moisture Content Calculation Subroutine (12010) Flowchart

V. Process Control System

A process control system has been developed for the rotary dryer to achieve and maintain the desired product moisture content. The general control system is portrayed in Figure 23 and a block diagram that outlines the relationships between the various process signals is shown in Figure 24. The system may be divided into components that are thoroughly discussed in sections 5.1. to 5.4.

The system involves a closed-loop or feedback system in which the measured value of the controlled variable (product moisture content) is returned to the comparator. In the comparator, the measured variable is compared with the set-point (x_{sp}), and if any difference exists between the two values an error is generated. The error enters the controller, which in turn, adjusts the final control elements to return the controlled variable to the set-point.

5.1. Process (Gas-Fired Dryer)

The control system for the dryer must be able to handle two types of process changes: servomechanism and regulator. The servomechanism type involves a change in the set-point without a change in load, where the set-point changes may be implemented as a step function or as a function of time. Load refers to a change in a process variable that results in

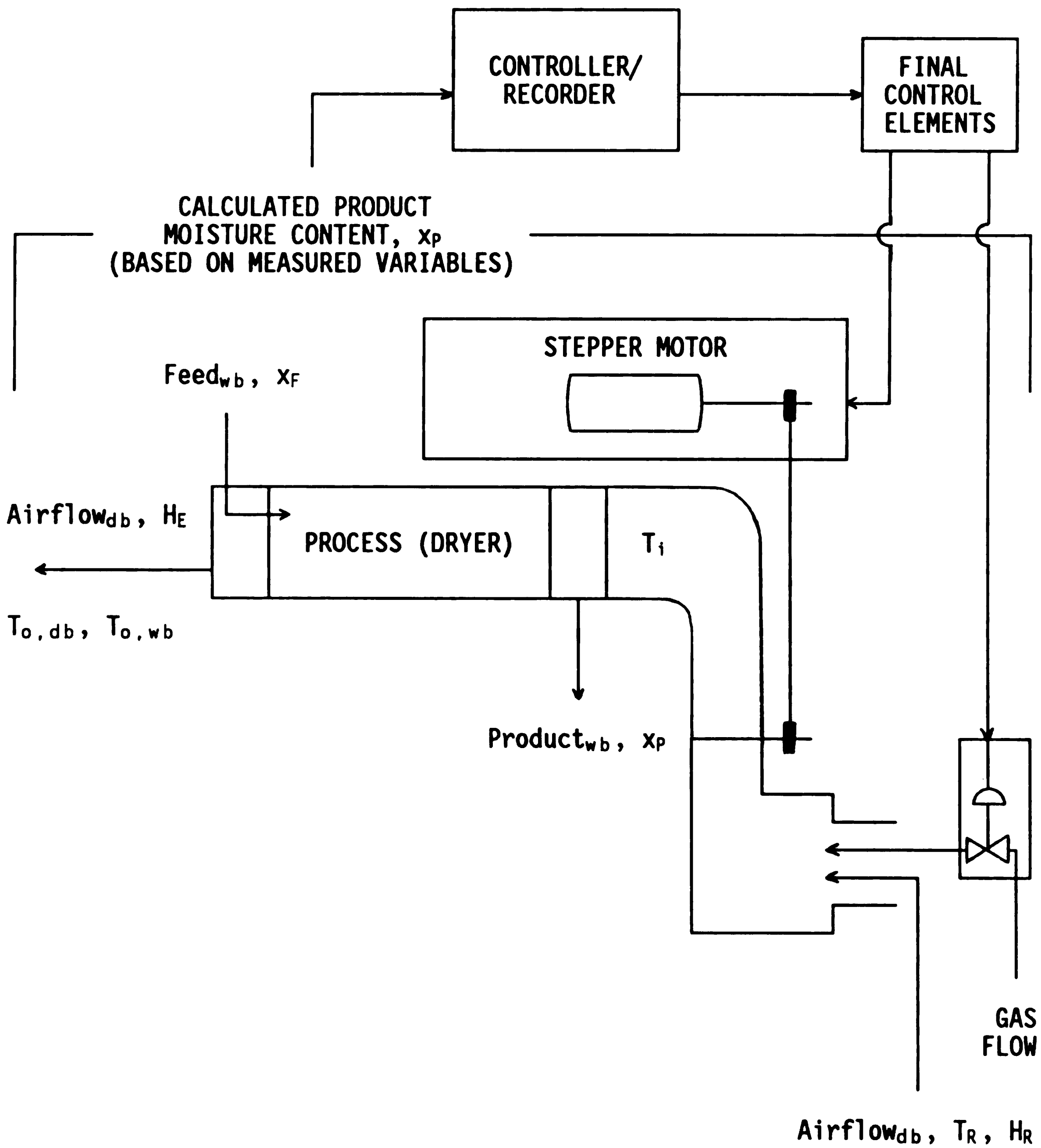


Figure 23. Process Control System

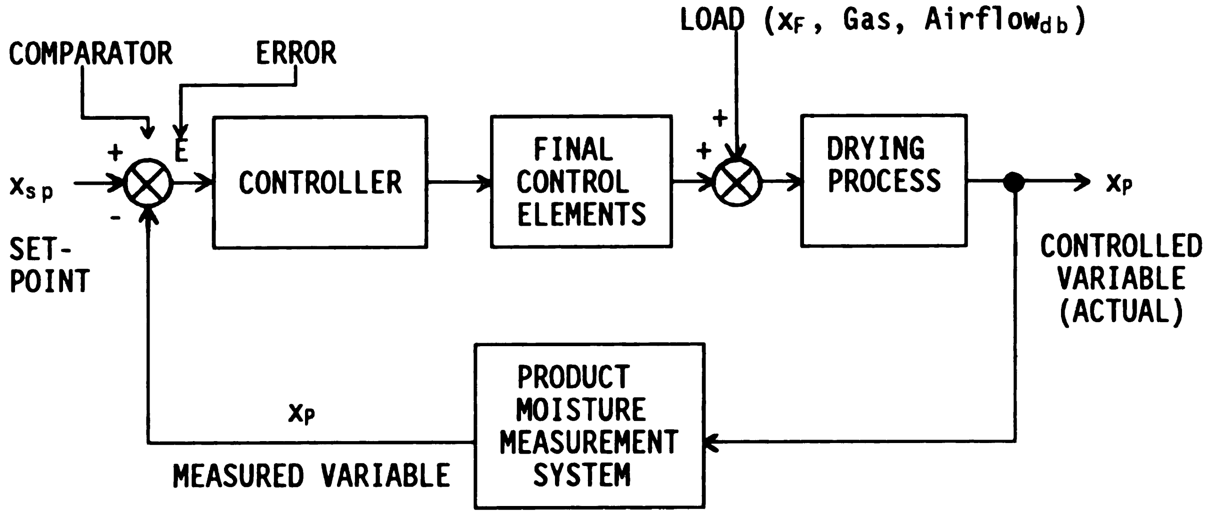


Figure 24. Block Diagram For Process Control System

a change in the value of the controlled variable. For this system the load variables may include the feed flow rate, feed moisture content, gas flow rate and air flow rate. Alternatively, the regulator type of process change involves a change in a load variable without a change in the set-point.

5.2. Measuring Elements and Transmitters

As described in section IV the product moisture content (x_P) is determined from its relationship with several other, measured process variables. These process variables are measured by appropriate sensors including three thermocouples and a gas flow meter, their associated transmitters and the a/d converter. It is assumed that the measurement, transmission, a/d conversion and subsequent calculation processes exhibit negligible dynamic lag. The relationships between the measured variables and the process signals were described in section III and the corresponding transfer functions are described below.

5.2.1. Temperature Measurement

Thermocouples are used to measure three process temperatures and are interfaced with the computer for data acquisition as described in section 3.5.1. The TC (emf) signals are linear with respect to the measured temperature and it is assumed that they exhibit negligible lag. These TC signals are then converted to the appropriate voltage range for the a/d converter. These conversions are also linear and assumed to have negligible lag.

The sensitivities ($K_{i,db}$, $K_{o,db}$ and $K_{o,wb}$) of the temperature measurement systems can be determined from the calibration and interfacing information described in section 3.5.1. The following equations define the sensitivities of the inlet dry-bulb, outlet dry-bulb and outlet wet-bulb temperature measurement systems, respectively.

$$K_{i,db} = \frac{255 - 51}{375 - 75} = 0.680 \ \frac{\text{digits}}{°F} \tag{70}$$

$$K_{o,db} = \frac{255 - 51}{325 - 75} = 0.816 \ \frac{\text{digits}}{°F} \tag{71}$$

$$K_{o,wb} = \frac{255 - 51}{110 - 50} = 3.400 \ \frac{\text{digits}}{°F} \tag{72}$$

At steady-state the a/d converter output can be defined by rearranging equations 5, 6 and 7 and substituting the steady-state values, denoted by superscript s, to get

$$AVE(01)^S = 51 + (T^S_{i,db} - 75)\ K_{i,db} \tag{73}$$

$$AVE(02)^S = 51 + (T^S_{o,db} - 75)\ K_{o,db} \tag{74}$$

$$AVE(05)^S = 51 + (T^S_{o,wb} - 50)\ K_{o,wb} \tag{75}$$

In terms of deviation variables,

$$AVE'(01,t) = K_{i,db}\ T'_{i,db}(t) \tag{76}$$

$$AVE'(02,t) = K_{o,db}\ T'_{o,db}(t) \tag{77}$$

$$AVE'(05,t) = K_{o,wb}\ T'_{o,wb}(t) \tag{78}$$

where the deviation variables are defined as

$$AVE'(CH,t) = AVE(CH,t) - AVE(CH)^S \tag{79}$$

$$T'(t) = T(t) - T^S \tag{80}$$

Therefore, the overall transfer functions for the thermocouples and their associated transmitters and signal converters are

$$K_{i,db} = \frac{AVE(01,s)}{T_{i,db}(s)} \tag{81}$$

$$K_{o,db} = \frac{AVE(02,s)}{T_{o,db}(s)} \tag{82}$$

$$K_{o,wb} = \frac{AVE(05,s)}{T_{o,wb}(s)} \tag{83}$$

where AVE(CH,s) is the transform of the response variable and T(s) is the transform of the forcing or input function.

5.2.2. Natural Gas Flow Rate Measurement

A similar approach can be applied to the gas flow rate measurement to derive its overall transfer function. The flow meter and its interface to the a/d converter are portrayed in Figure 9. The output signals from the wet-test meter and the subsequent converters are linear with respect to the flow rate and it is assumed that they exhibit negligible dynamic lag. The sensitivity (K_{Gas}) of this linear measurement system is defined as

$$K_{Gas} = \frac{0 - 255}{19.99 - 0} = -12.76 \frac{\text{digits}}{\text{l/min}} \tag{84}$$

At steady-state the a/d converter output can be defined by rearranging equation 13 and substituting the steady-state values to get

$$AVE(11)^S = 255 + K_{Gas}\ Gas^S \tag{85}$$

In terms of deviation variables

$$AVE'(11,t) = K_{Gas}\ Gas'(t) \tag{86}$$

where the deviation variables are defined as

$$AVE'(11,t) = AVE(11,t) - AVE(11)^S \tag{87}$$

$$Gas'(t) = Gas(t) - Gas^S \tag{88}$$

Therefore, the transfer function for the linear gas flow measurement system is

$$K_{Gas} = \frac{AVE(11,s)}{Gas(s)} \tag{89}$$

where AVE(11,s) is the transform of the response variable and Gas(s) is the transform of the forcing or input function.

5.3. Controller Mechanism

Proportional-integral (PI) control has been implemented to control the product moisture content. This mode of control is defined by the relationship

$$O(t) = K_c\ E(t) + (K_c/\tau_I)\int_0^t E(t)\ dt + O^s \tag{90}$$

where

$O(t)$ = controller output signal at time t

t = elapsed time

K_c = controller gain

$E(t)$ = error at time t = $x_{sp} - x_P(t)$

τ_I = integral time

O^s = steady-state controller output

The controller output signal is a digital value (sent to d/a converter channel 11) ranging from 0 to 255, that is proportional to the sum of the error and the integral of the error. Since the product moisture content is determined at equal intervals (0.25 minutes) throughout an experiment, the integral term can be simplified to

$$\int_0^t E(t)\,dt = [E(1) + E(2) + \ldots + E(t/0.25)]\,\Delta t \qquad (91)$$

where Δt is the interval between measurements and is equal to 0.25 minutes.

The values of the controller gain (K_c), integral time (τ_I) and set-point (x_{sp}) are specified upon initialization of the CONTROL program that is described in section 6.2. The gain and integral time are held constant, but the set-point is continually changed during the dryer start-up. In the first 5 minutes (equivalent to the dryer residence time), the dryer cylinder is only partially filled. Therefore, the set-point is ramped downward (over a 5 minute period) to its prescribed value (x^*_{sp}) to accommodate the dynamic start-up. The set-point is changed during the first twenty measurement intervals and is calculated from

$$x_{sp} = x_F - N\,\frac{x_F - x^*_{sp}}{20} \qquad (92)$$

where N is the measurement interval and is equal to four times the elapsed time (t). For values of N greater than or equal to twenty, x_{sp} is equal to x^*_{sp}.

A subroutine has been written to perform the control algorithm calculations. A flowchart of the subroutine is shown in Figure 25 and the program steps are listed in Figure A8. The controller output is bounded by the acceptable input range of the a/d converter, 0 to 255.

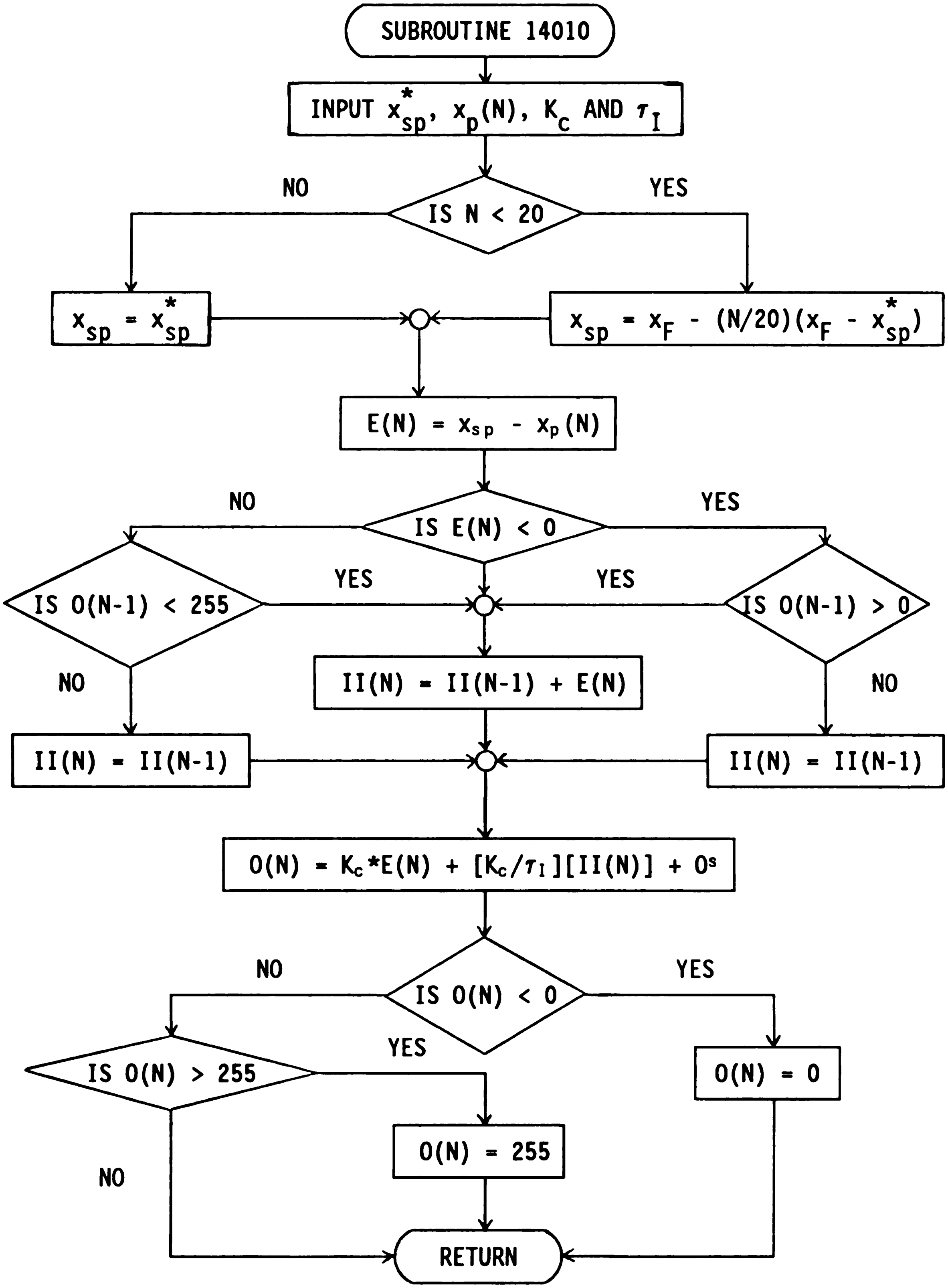


Figure 25. Control Algorithm Subroutine (14010) Flowchart

5.4. Final Control Elements

A final control element converts the controller output signal into a change in a manipulated variable. In the dryer system there are two final control elements: the gas control valve and the inlet air damper positioner (stepper motor). These elements are described in sections 5.4.1 and 5.4.2.

5.4.1. Natural Gas Flow Control Valve

As described in section 3.5.3 a pneumatic control valve is used to manipulate the flow rate of methane to the combustion chamber of the dryer. The valve is designed for fail-safe, air-to-open action and the valve stem position is proportional to the valve-top pressure. The controller output signal is transduced to a corresponding pneumatic signal by the interface that is shown in Figure 12. The conversions are linear and are assumed to exhibit negligible lag relative to the process. Therefore, the relationship between the controller output signal and the resulting pneumatic signal is defined as the overall transfer function (K_p) of the transducers, such that

$$K_p = K_{d/a}\, K_{amp}\, K_{V/I}\, K_{I/P} \tag{93}$$

where

$$K_{d/a} = \frac{5 - (-5)}{255 - 0}\,\frac{\text{volts}}{\text{digit}} \tag{94}$$

$$K_{amp} = \frac{2.1 - 10.5}{5 - (-5)}\,\frac{\text{volts}}{\text{volts}} \tag{95}$$

$$K_{V/I} = \frac{20.0 - 4.0}{10.5 - 2.1} \frac{\text{ma}}{\text{volts}} \tag{96}$$

$$K_{I/P} = \frac{15.0 - 3.0}{20.0 - 4.0} \frac{\text{psi}}{\text{ma}} \tag{97}$$

Therefore,

$$K_p = - \frac{(15.0 - 3.0)}{255 - 0} = - 0.0471 \frac{\text{psi}}{\text{digit}} \tag{98}$$

The relationship between the gas flow rate and the valve-top pressure has been difficult to determine due to the hysteresis effect of the valve. During experimentation, the gas flow rate ranged from 2.39 to 5.38 liters per minute for valve-top pressures of 3.0 to 15.0 psi, respectively. It should be noted that the minimum controlled gas flow rate corresponds to the pilot stream methane flow rate. The rangeability of the valve (R_v) is defined as

$$R_v = \frac{\text{maximum controllable flow}}{\text{minimum controllable flow}} = \frac{5.38}{2.39} = 2.55 \tag{99}$$

5.4.2. Air Flow Control Damper and Positioner

As described in section 3.5.4 a single-speed blower is used to draw air into the combustion chamber, and the flow rate of the air is controlled by a damper in the air duct. The damper position is manipulated by a stepper motor that rotates the damper through ninety radial degrees in 150 steps (of 0.6 degrees each). The interface between the controller and the damper position was previously described in section 3.5.4.

The controller output determines the required damper position (0 to 150) and a subroutine initiates the stepper motor control. The transfer function (K_{air}) that characterizes the relationship between the air flow rate and the damper position is defined as

$$K_{air} = \frac{\text{Air Flow Rate}}{\text{Damper Position}} \tag{100}$$

It is assumed that there is negligible dynamic lag in the response of the air flow rate to damper position changes.

VI. Operation of the Dryer

Two computer programs (CONTROL and DATA RETRIEVE) have been written in Applesoft Basic to facilitate the dryer operation, and have been stored on separate working diskettes for which the Apple Disk Operating System (DOS) is self-relocating. When DOS is booted from either disk, the corresponding program is subsequently loaded and executed.

The CONTROL program contains the necessary software to operate the dryer with computerized control and has been specifically written to be used in the teaching laboratory. In particular, the operator must develop the material and energy balances that were described in section IV, utilizing the appropriate program variables and line numbers. The operator is requested to input the corresponding subroutine steps upon start-up. This requirement is further discussed in section 6.2.1.

Process data is collected during an experiment and may be stored by the CONTROL program (at the end of a run) in a file that is named by the operator. The DATA RETRIEVE program can be subsequently executed to read and print the data from this file. This program is described in section 6.2.

6.1. Equipment and Material Preparation

In preparation for an experiment the operator must saturate the feed material with water and determine its moisture content, fill the feed hopper, establish and measure the feed flow rate and empty the dryer cylinder of any contents from a previous experiment. The operator should also select the desired product moisture content and calculate the rate of drying (pounds of water per minute) required to achieve it under the given conditions. Naturally, the required evaporation rate cannot exceed the pre-determined drying capacity.

Once these tasks have been completed and the material and energy balances have been developed by the operator, DOS may be booted from the aforementioned CONTROL working disk to initiate the computer start-up. Either of two methods may be used to boot DOS: 1) Insert the disk in the drive and turn the computer power "on", or 2) Insert the disk with the power "on" (the disk drive must not be running) and type: PR#6 <RETURN>. The program title will appear on the screen and the CONTROL program is loaded and executed.

6.2. CONTROL Program

The CONTROL program consists of a main program and fifteen subroutines. The main program directs the start-up, continuous operation and shutdown of the dryer, and utilizes the subroutines for data acquisition and manipulation and to print process data displays on the screen.

During the dryer start-up and shut-down, instructions are frequently displayed on the screen and the operator is prompted to press <RETURN> to acknowledge that the activities have been completed and to continue. At any time during an experiment the operator may press <ESC> to end the session, or the operator may press a specific key (1 or 2) to change the data display on the monitor as described in section 6.2.7.

6.2.1. User Input of the Material and Energy Balances

When the CONTROL program is executed, the program title is displayed and the operator must press <RETURN> to continue. The program continues and the operator is asked if the subroutine program steps have been entered (for a previous run). If they have, the operator may continue. Otherwise, he must hit <ESC> to edit the program. A separate subroutine has been written to display additional instructions for the editing of the material and energy balance subroutines, and its program steps are listed in Figure A9. After the subroutines have been entered the operator must type "RUN" <RETURN> to continue.

6.2.2. Initialization of Variables and Functions

When the CONTROL program resumes, the screen is cleared, the arrays are dimensioned and the output signals from the d/a converter channels and two of the game i/o connector annunciators (AN0 and AN1) are initialized as described below. The arrays that are used for continuous data storage are allocated 140 elements to accommodate approximately thirty-five minutes of data acquisition. A one hundred thirty element array is established for storage of the saturation humidity data that is input as part of the program start-up. The d/a outputs from the un-used fifteen channels are initialized at zero volts and the output from channel eleven is initialized at +5 volts (to maintain the gas control valve in the closed position as described in section 3.5.3). The annunciator outputs, AN0 and AN1, are set at zero volts.

Next in this section of the program, a function [RR(A)] is defined by the statement

$$\text{DEF FN RR(A)} = \frac{\text{INT }(A * 10^{P} + 0.5)}{\text{INT }(10^{P})} \tag{101}$$

The function is subsequently used to "round off" any calculated variable (A is a dummy variable) to the specified number of decimal places (P). This "rounding" function is especially useful in controlling the number of digits that are displayed in a table, and is extensively used in the subroutines described in section 6.2.7.

Overall, the computer steps described above are executed in less than one second. During this time the screen remains blank, providing a brief, desired pause after which the following instructions appear on the screen.

6.2.3. Equipment Set-Up Instructions

A series of eight instructions are listed on the monitor to direct the operator through a specific equipment set-up procedure. Through the established for storage of the saturation humidity data that is input as part of the program start-up. The d/a outputs from the un-used fifteen channels are initialized at zero volts and the output from channel eleven is initialized at +5 volts (to maintain the gas control valve in the closed position as described in section 3.5.3). The annunciator outputs, AN0 and AN1, are set at zero volts.

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Overall, the computer steps described above are executed in less than one second. During this time the screen remains blank, providing a brief, desired pause after which the following instructions appear on the screen.

6.2.3. Equipment Set-Up Instructions

A series of eight instructions are listed on the monitor to direct the operator through a specific equipment set-up procedure. Through the first six steps (shown by two consecutive displays) the operator is instructed to check the cable connections, turn "on" the power to the stepping motor translator and the air blowers, and to check the water levels in the dew cup and the wet-test meter.

Next the operator is prompted to check the inlet air duct damper position (DP). At the beginning of an experiment the damper position must be initialized to the "wide-open" position (DP equal to 150) and operator input may be needed at the outset to adjust the position. A trial-and-error procedure (contained in program lines 910 through 1470) is implemented until the "wide-open" position is attained. A flowchart of this section of the program is shown in Figure 26.

This procedure requires the operator to input the direction of rotation (clockwise or counter-clockwise) and the estimated number of steps needed to achieve the proper position. The subroutine described in section 3.5.4 is utilized to trigger the stepper motor movement. When the operator responds that the damper is in the "wide-open" position and verifies the second check, step eight of the instructions is displayed and the operator is directed to turn "on" the power supply to the TC transmitters. When this action is completed and verified, the program continues.

6.2.4. Room Air Temperature and Humidity Determination

As discussed in section IV, the room air temperature and moisture content are utilized in the system material and energy balances. Therefore, the

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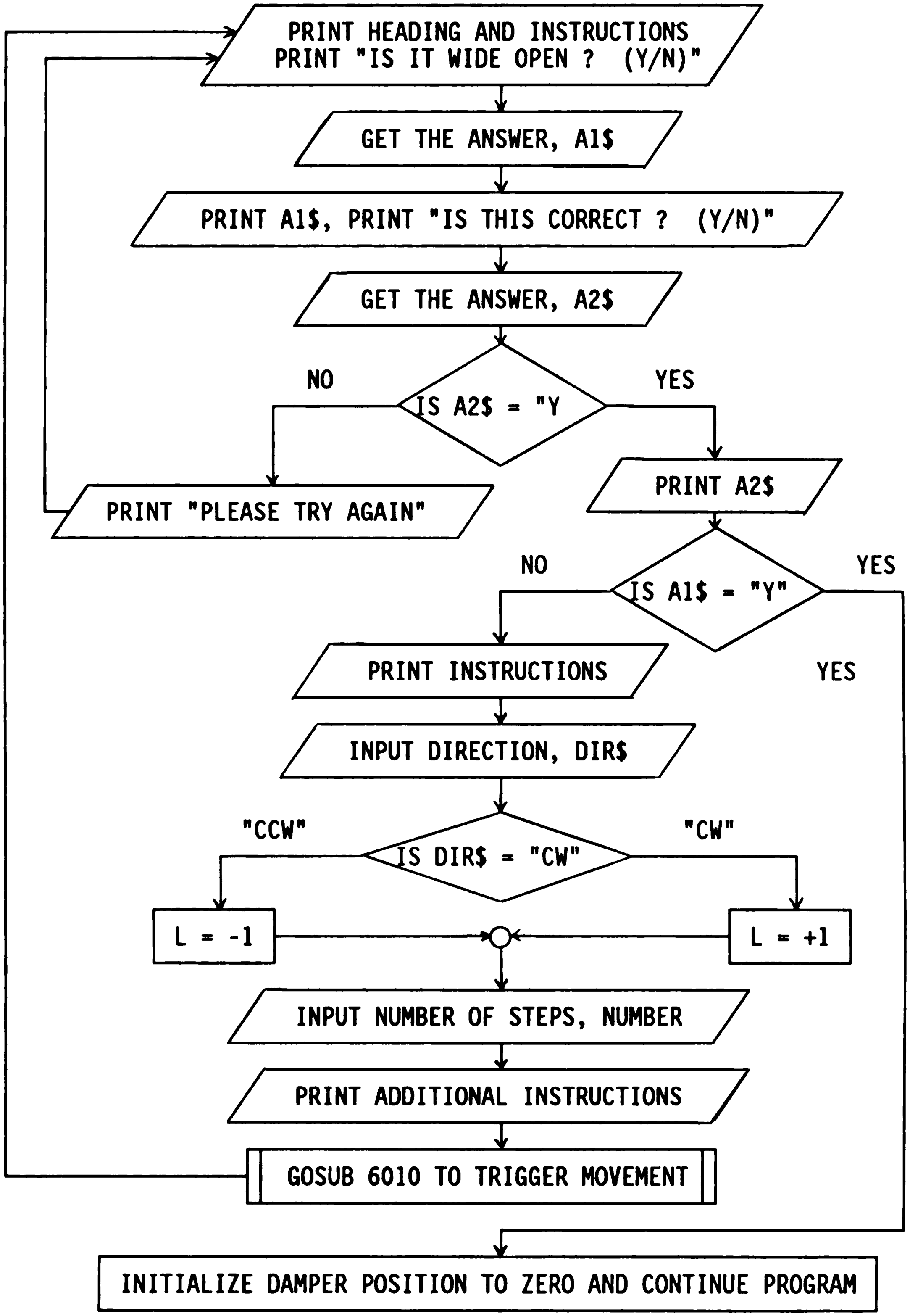

Figure 26. Air Damper Position Initialization Flowchart

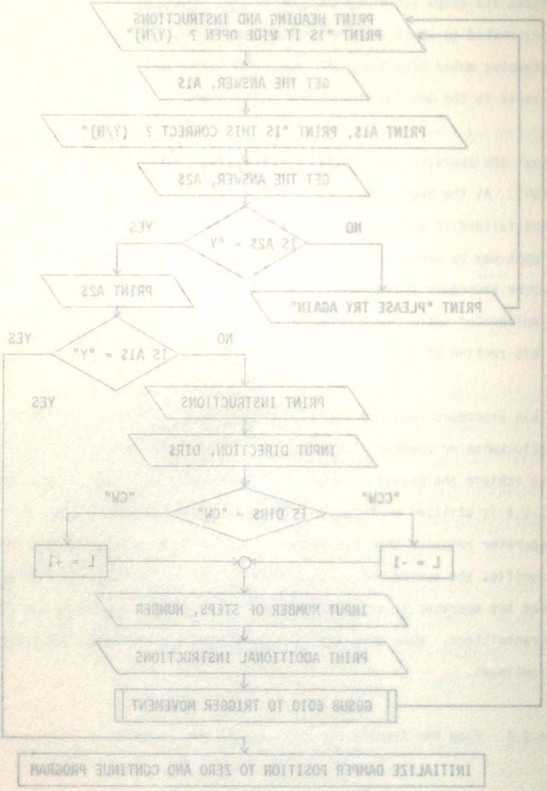

Figure 26. Air Damper Position Initialization Flowchart

room air dry-bulb and wet-bulb temperatures must be measured at the beginning of the first experiment, before the dryer is heated, so that the measurements are not biased upward. The operator is prompted to respond whether or not the current run is the first of the day. If it is, the operator's response initiates the determination of the dry-bulb and wet-bulb temperatures of the air stream passing through the dryer, through the execution of main program lines 1740 through 2040 and the data acquisition and temperature calculation subroutines.

Initially, the wet-bulb temperature will decrease due to evaporative cooling until steady-state is attained. Therefore, the temperatures are repeatedly measured at approximate fifteen-second intervals until two consecutive wet-bulb measurements differ by less that 0.2°F. When steady-state is reached, the program continues and the temperature measurements from the last interval are used for additional calculations as described below.

If the operator responds that the current run is not the first of the day, the operator is prompted to manually input the dry-bulb and wet-bulb temperatures. It is assumed that these data are known from the previous run.

Once the temperature data is measured or manually input, the subroutine described in section 4.3.2 is utilized to determine the room air moisture content (mass fraction), absolute humidity and molecular weight. When the iteration is completed the measured and calculated data are stored in the appropriate elements of the array, ROOM(N), and the data is displayed room air dry-bulb and wet-bulb temperatures must be measured at the beginning of the first experiment, before the dryer is heated, so that the measurements are not biased upward. The operator is prompted to respond whether or not the current run is the first of the day. If it is, the operator's response initiates the determination of the dry-bulb and wet-bulb temperatures of the air stream passing through the dryer, through the execution of main program lines 1740 through 2040 and the data acquisition and temperature calculation subroutines.

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6.2.5. Feed and Product Specifications

The next stage of the main CONTROL program pertains to the feed material and product specifications. The operator is prompted to enter the numerical values of three variables (using the specified units): 1) the wet-basis feed flow rate (pounds per minute), 2) the feed moisture content (mass fraction) and 3) the desired product moisture content (mass fraction). As the computer awaits the input value of each respective variable, the variable text is highlighted and the cursor is located in the proper space.

After the three values have been input, the operator may press <ESC> to correct any data-entry errors, or press <RETURN> to continue the program. The mass fraction input values are then checked to verify that they are less than or equal to one, and the drying rate [Evap(1)] needed to achieve the desired product moisture content is calculated from equation 102 and is compared to the maximum drying rate [Evap(2)].

$$\mathrm{Evap}(1) = \mathrm{Feed}_{wb}\ (x_F - x^*_{sp}) \tag{102}$$

The values are further compared to verify that the set-point is less that or equal to the moisture content of the feed (x_F), and to determine if the value of Evap(1) is less than or equal to the dryer capacity. If an error is detected an appropriate error message is displayed and the operator is given the opportunity to make the necessary corrections.

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When the respective relationships are satisfied the dry-basis feed flow rate ($Feed_{db}$) is calculated from equation 68 and stored in the corresponding array element, FEED(0,1). The program continues as described in section 6.2.6.

6.2.6. Gas Pilot Lighting and Start-Up

The damper is automatically closed, the computer monitor is momentarily cleared and the pilot lighting instructions are then displayed. The operator is instructed to turn "off" the main blower fan (near the combustion chamber) and to proceed with the ignition of the gas pilot. When the pilot remains lighted, the blower should be turned "on" and the air supply line pressure to the electro-pneumatic transducer must be increased to approximately 20 psig. The operator must hit <RETURN> to acknowledge completion of these instructions and to continue the program. The gas control valve is then completely opened and the air damper is placed in the appropriate position.

6.2.7. Data Displays

Two displays are used to continuously present the data for the process variables listed in Figure 27. Subroutines 16010 and 18010 are used to print the display headings and subroutines 17010 and 19010 are used to print the data for displays one and two, respectively. The program steps for subroutines 16010 through 19010 are listed in Figures A11 through A14, respectively. Throughout an experiment the operator may alternate

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Display One	Display Two
Gas Flow Rate	Feed Flow Rate
Air Flow Rate	Feed Moisture Content
Inlet Dry-Bulb Temp.	Set-Point
Outlet Dry-Bulb Temp.	Outlet Dry-Bulb Temp.
Outlet Wet-Bulb Temp.	Outlet Wet-Bulb Temp.
Product Moisture Content	Outlet Humidity

Figure 27. Process Variables Shown in Computer Displays

Initially, Display One appears on the screen and the operator is instructed to monitor the inlet air temperature (T_i) and to press the space bar when it becomes stable.

When a key on the Apple keyboard is pressed, it can be identified by checking the numeric value at a specific memory location (-16384), which becomes greater than or equal to 128. The BASIC command

```
XX = PEEK (-16384)
```

assigns the value at this location, which is specific to the last key that was pressed, to the variable, XX. The CONTROL program periodically checks and interprets the value at this address. The values of XX that correspond with certain keys are shown in Table 8. When it is determined between displays by pressing the appropriate key (1 or 2), or he may end the experiment by pressing <ESC>.

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Table 8. Values at Location -16284 and Corresponding Keys

Depressed Key	Value at Location -16284
<ESC>	155
Space Bar	160
1	177
2	178

6.2.8. Initiation of Data Acquisition and Computer Control

When the space bar is pressed the operator is instructed to turn "on" the dryer cylinder drive motor and set the rotational speed, align the feeder with the chute, place receptacles under the feed and discharge breechings and turn "on" the vibratory feeder and acknowledge its start-up. The program resumes with the initiation of the data acquisition and computer control.

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VII. Dryer Experiments

Several experiments were conducted to evaluate the performance of the dryer and its control system. The experiments were especially designed to study the controller response to changes in the set-point using various values for the controller gain (K_c) and integral time (τ_I).

7.1. Feed Material Preparation

Linde molecular sieves were selected as the feed material. Approximately one kilogram of this material was poured into a stainless steel tray and dried to a constant weight in an oven at 70°C. Five 125 ml flasks were tared, filled with the dried sieves, weighed, and then filled with water and allowed to stand overnight. The excess water (that was not absorbed) was poured off and the flasks and their contents were weighed. The net weights of the dry and water saturated materials were calculated. The flasks were then emptied, cleaned, tared, filled with water and weighed, and the net weight of the water was determined. Since the density of water at room temperature is approximately 1 g/ml the bulk densities of the dried and wet materials ($\rho_{F,db}$ and $\rho_{F,wb}$, respectively) were determined. The results from this work are shown in Table 9.

The moisture content (weight percent) of the saturated feed material (x_F) is calculated from

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Table 9. Feed Material Bulk Density Determination

Measured Weights (g)	Flask 1	Flask 2	Flask 3	Flask 4	Flask 5
Filled with dry sieves	210.1	215.5	213.4	214.4	213.2
Tare weight	78.8	87.3	80.0	83.4	87.2
Net weight of dry sieves	131.3	128.2	133.4	131.0	126.0
Filled with water	226.5	229.5	229.8	227.5	230.4
Tare weight	78.8	87.3	80.0	83.4	87.2
Net weight of water	147.7	142.2	149.8	144.1	143.2
Bulk density of dry sieves (g/ml)	0.8890	0.9016	0.8905	0.9091	0.8799
Filled with wet sieves	243.0	245.0	244.9	242.9	246.7
Tare weight	78.8	87.3	80.0	83.4	87.2
Net weight of wet sieves	164.3	157.8	165.0	159.5	159.5
Filled with water	226.5	229.4	229.9	227.7	230.5
Tare weight	78.8	87.3	80.0	83.4	87.2
Net weight of water	147.8	142.2	150.0	144.3	143.3
Bulk density of wet sieves (g/ml)	1.111	1.110	1.100	1.105	1.113

$$x_F = \frac{\rho_{F,wb} - \rho_{F,db}}{\rho_{F,wb}} \tag{103}$$

Based on the results from the five measurements the average feed moisture content is 19.3%. Prior to each experiment, approximately thirty-five pounds of saturated feed material were prepared and loaded into the feed hopper above the dryer.

7.2. Servomechanism Problems (Set-Point Changes)

Two servomechanism problems were studied using a constant wet-basis feed flow rate of 0.65 pounds per minute and a drum speed controller setting of six. In each case the set-point was initially set at 16.3% and a step change of -1.0% was induced after steady-state was achieved.

In the first experiment the controller settings were set at K_c equal to 4.0 and τ_I equal to 2.5 minutes. In the second experiment values of K_c equal to 3.0 and τ_I equal to 2.3 minutes were used. The responses of the product moisture content are discussed in Section VIII.

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VIII. Experimental Results

The following results were obtained from the servo-mechanism problems that were described in section VII. During the first experiment the dryer had reached steady-state and then the set-point was lowered to 15.0% by a step change of -1.0% (with controller settings of $K_c = 4.0$ and $\tau_I = 2.5$). The response of the product moisture content to the step change is shown in Figure 28, and the responses of the natural gas flow rate and the air flow rate are shown in Figure 29. A new steady-state was achieved after approximately 6 minutes. The steady-state process conditions before and after the set-point change are shown in Table 10.

For the second experiment, the dryer was started under the same conditions as the first experiment, but the controller settings were changed to $K_c = 3.0$ and $\tau_I = 2.3$. When steady-state conditions were achieved, the set-point was lowered again to 15.0% by a step change of -1.0%. The response of the product moisture content is shown in Figure 30. After the step change, it is evident that the dryer system became unstable with these controller settings.

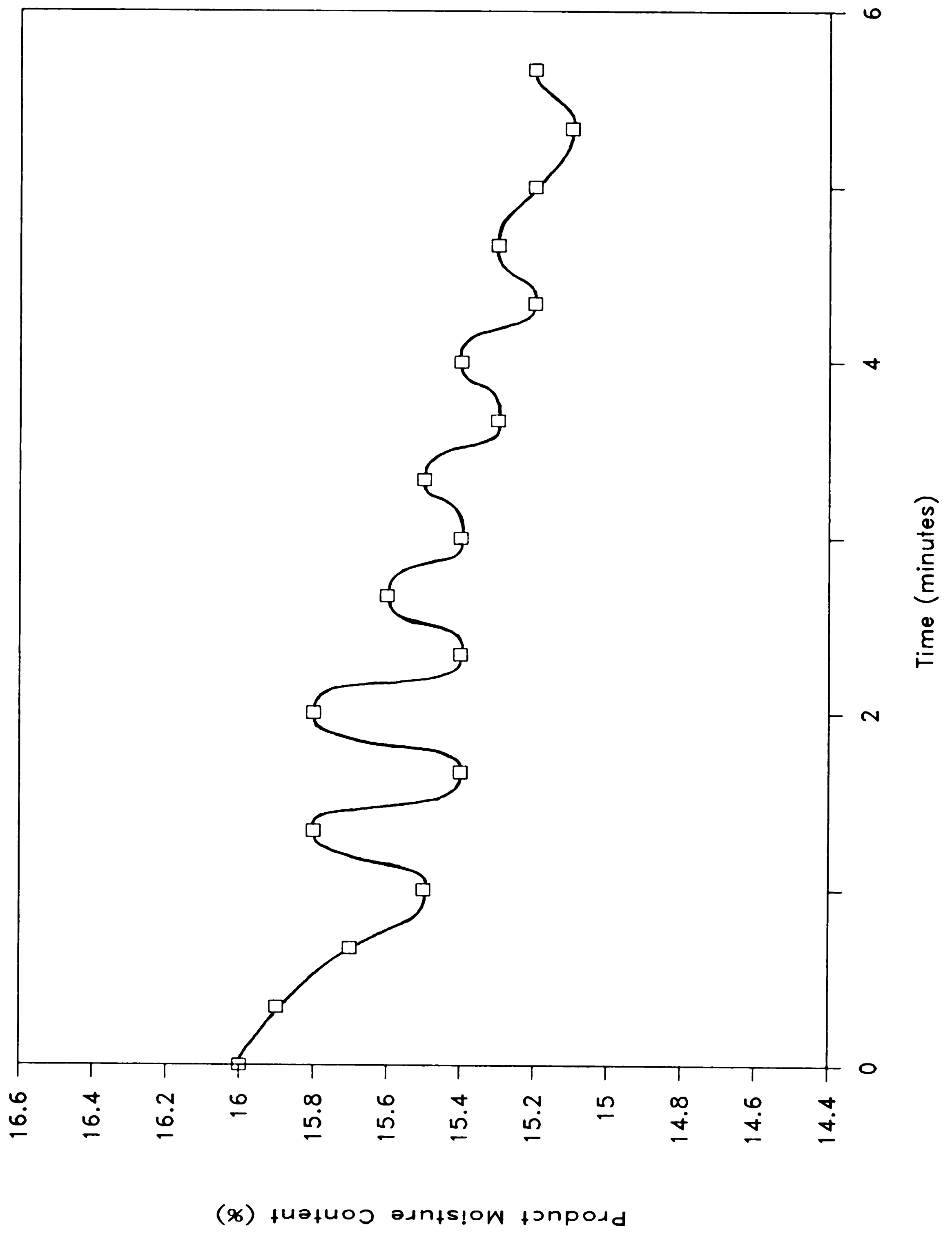
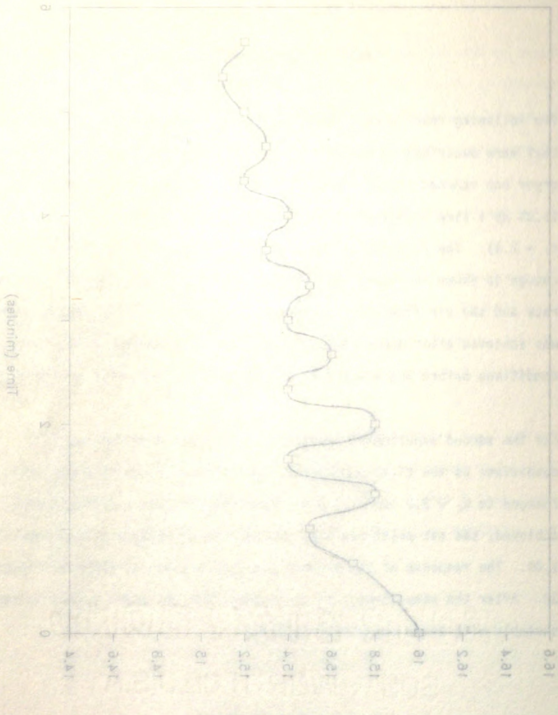


Figure 28. Response of Product Moisture Content After Set-Point Change (K_c = 4.0, and τ_I = 2.5)



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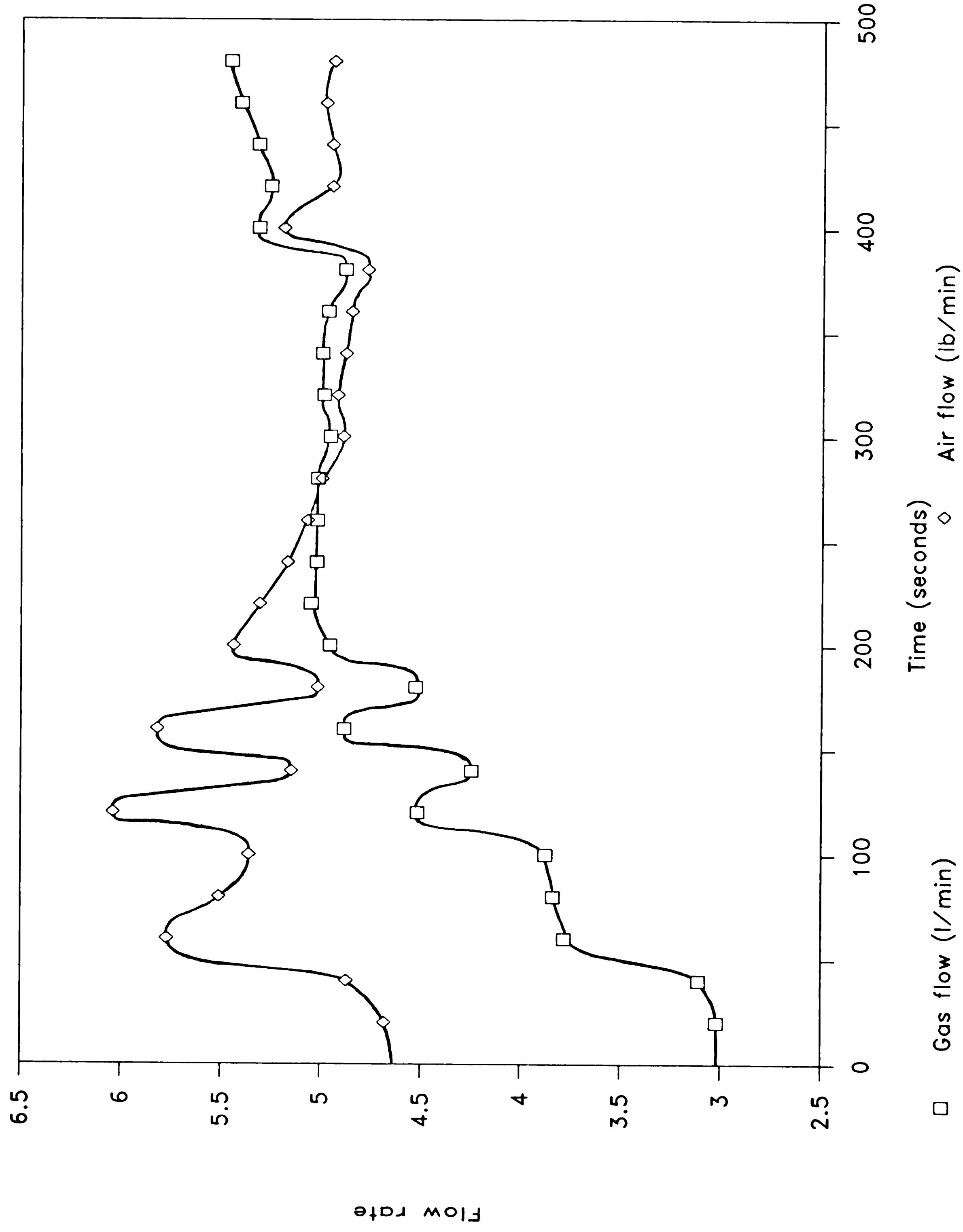

Figure 29. Responses of Gas Flow Rate and Air Flow Rate After Set-Point Change (K_c = 4.0 and τ_I = 2.5)

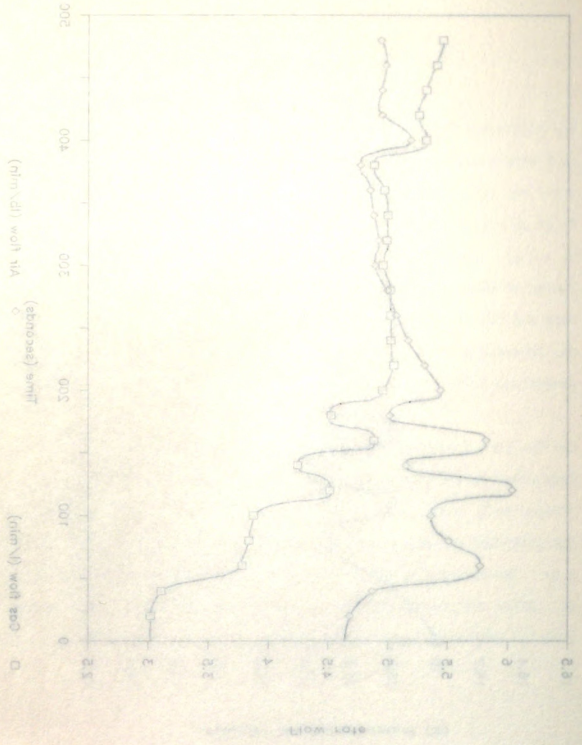

Figure 29. Responses of Gas Flow Rate and Air Flow Rate After Set-Point Change (K_c = 4.0 and τ_i = 2.5)

Table 10. Dryer Operating Conditions Before and After Set-Point Change

Parameter	Before	After
Gas (l/min)	3.02	5.46
$T_{in,db}$ (°F)	174	238
$T_{o,db}$ (°F)	136	173
$T_{o,wb}$ (°F)	80	91
x_p (%)	16.0	15.2

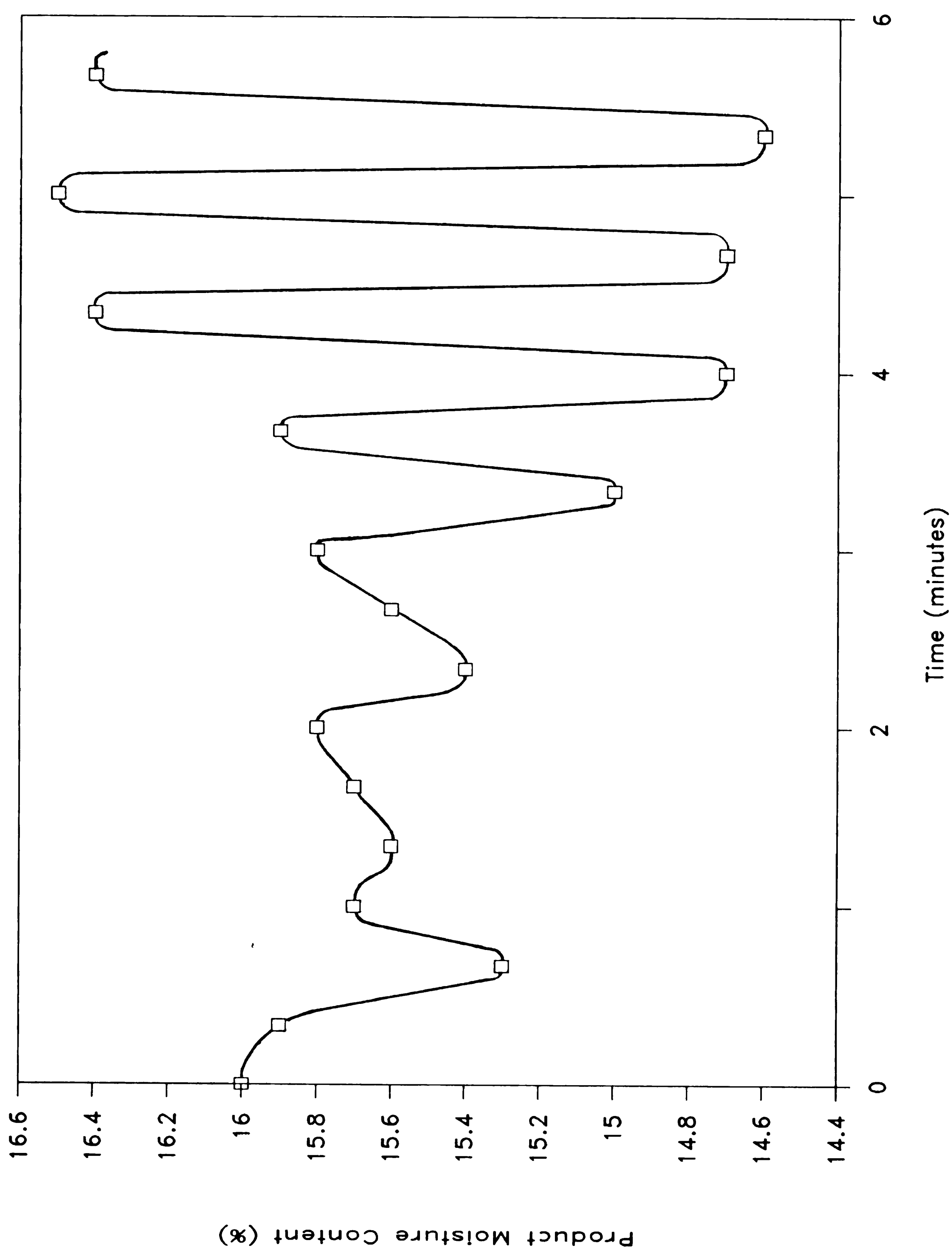

Figure 30. Response of Product Moisture Content After Set-Point Change (K_c = 3.0, and τ_I = 2.3)

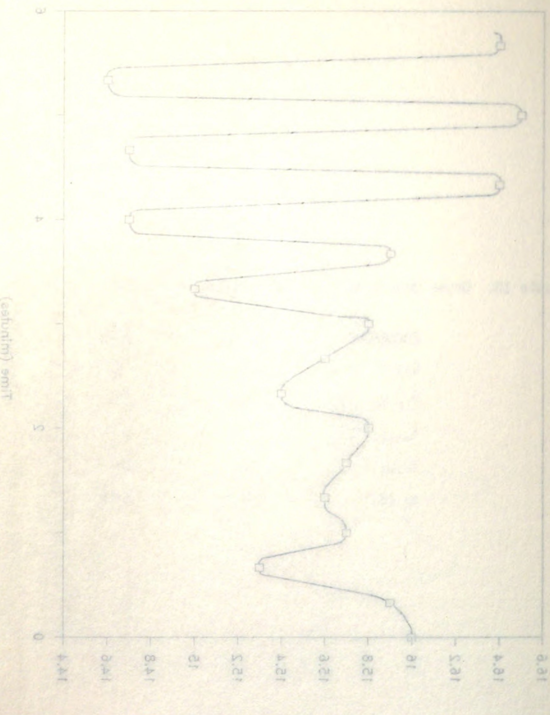

Figure 30. Response of Product Moisture Content After Set-Point Change (K_c = 3.0, and τ_I = 2.3)

IX. Summary and Conclusions

The dryer system has been equipped with the instrumentation necessary to measure and control several process variables, and a suitable computer interface has been constructed for data acquisition and control. In general, the components of the dryer system are adequate, but a few specific aspects must be changed or improved to prepare the dryer for the teaching laboratory. The following conclusions and recommendations are based on observations that have been made throughout this project.

9.1. Dryer Equipment

It has been demonstrated that the pilot-scale rotary dryer is suitable for running various drying experiments. The equipment is appropriately-sized and easy to operate. For counter-current operation acceptable material flow has been attained with a dryer slope of one-eighth inch per foot and a revolutionary speed between 3 and 10 rpm. Additionally, it is concluded that the vibratory feed system provides a stable and controllable feed flow rate.

9.2. Natural Gas Supply Pressure

As stated in section II, the recommended gas supply pressure for the dryer is 5 to 30 psig and the maximum operating temperature is 1000°F

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It has been demonstrated that the pilot-scale rotary dryer is suitable for running various drying experiments. The equipment is appropriately-sized and easy to operate. For counter-current operation acceptable material flow has been attained with a dryer slope of one-eighth inch per foot and a revolutionary speed between 3 and 10 rpm. Additionally, it is concluded that the vibratory feed system provides a stable and controllable feed flow rate.

9.2. Natural Gas Supply Pressure

As stated in section II, the recommended gas supply pressure for the dryer is 5 to 30 psig and the maximum operating temperature is 1000°F

[1]. However, the existing supply pressure is approximately seven inches water gauge and the maximum attainable inlet air temperature is approximately 240°F (with a gas flow rate of 5 l/min and a moderate air flow rate of 1.8 lb/min). Therefore, the maximum drying rate that can be achieved is relatively low, and has been measured at less that 0.05 pounds of water per minute. It is necessary to increase the gas supply pressure to realize the design capacity of the dryer.

9.3. Process Instrumentation and Interfacing

The electronic interface that has been developed provides adequate communication between the Apple computer and the process instrumentation. Conclusions and recommendations that can be made regarding the instrumentation are discussed in the following sections.

9.3.1. Temperature Measurement

The thermocouples and transmitters have typically provided accurate temperature measurements over the calibrated ranges. However, intermittent problems were encountered with the wet-bulb thermocouple (TC), which was occasionally found in error of approximately 5°F. From a psychrometric chart it is apparent that a 1% error in the wet-bulb temperature measurement results in an approximate error of 5% to 10% in the humidity determination. This problem was attributed to the close proximity of the TC probe to the dryer feed chute and was corrected. It is recommended that the three transmitters be calibrated at six-month intervals using the procedure outlined in section 3.5.1. Additionally,

[1]. However, the existing supply pressure is approximately seven inches water gauge and the maximum attainable inlet air temperature is approximately 240°F (with a gas flow rate of 5 l/min and a moderate air flow rate of 1.8 lb/min). Therefore, the maximum drying rate that can be achieved is relatively low, and has been measured at less that 0.05 pounds of water per minute. It is necessary to increase the gas supply pressure to realize the design capacity of the dryer.

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9.3.2. Natural Gas Flow Rate Measurement

As described in section 3.5.2 a wet-test meter is utilized to measure the gas flow rate. However, the range of this meter is 0 to 18 liters per minute, which could be exceeded if the gas flow rate was significantly increased (by an increase in the supply pressure).

A Cox turbine flowmeter that has been calibrated for the range of 0.75 to 3.00 cubic feet per minute of methane and has an accuracy of 0.5% is available for use. This flowmeter has a magnetic frequency pickup that can be interfaced with the Analogic panel meter that is presently used. If this meter is installed, the panel meter and the op-amp circuit to which it is interfaced must be adjusted accordingly.

9.3.3. Natural Gas Flow Control Valve

The existing diaphragm valve is not suitable for controlling gas flow rates in the current operating range, as evident by the hysteresis effect that was discussed in section 3.5.3. If the gas supply pressure is increased, the performance of this valve must be re-evaluated. If it is inadequate, a new control valve must be obtained and installed.

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9.3.4. Stepper Motor Control

The stepper motor and air damper arrangement provides excellent control of the air flow rate. The "switching" interface to the stepper motor is responsive and reliable, executing approximately fifteen motor steps per second.

9.4. Data Acquisition System

The data acquisition system that has been developed provides continuous acquisition, manipulation, storage and display of process data for the significant process variables. Two separate displays are utilized to portray the data and are updated at approximate fifteen second intervals throughout an experiment. It should be noted that the entire system has been structured to easily accommodate any necessary or desired changes. Therefore, if any changes are needed (i.e. new data displays), it is recommended that the existing program be used as the framework, and that the changes be implemented through the use of appropriately written subroutines.

9.5. Process Control System

With the present process control system, the dryer experiments may be conducted with fixed controller settings, or the program may be modified to accommodate desired changes. Specifically, it is recommended that the controller settings be tuned once the appropriate changes are made to increase the gas flow rate and dryer capacity.

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APPENDICES

APPENDIX A

SUBROUTINE PROGRAM LISTINGS

```
7010  SUM(CH) = 0
7020  DIG(CH) = PEEK (49296 + CH)
7030  FOR I = 1 TO NN
7040  DIG(CH) = PEEK (49296 + CH)
7050  SUM(CH) = SUM(CH) + DIG(CH)
7060  FOR J = 1 TO JJ: NEXT J
7070  NEXT I
7080  AVE(CH) = SUM(CH) / NN
7090  RETURN
```

Figure A1. Subroutine 7010 (Data Acquisition)

```
8010 TIN = (AVE(1) - 51) / 204 * (375 - 75) + 75
8020 TDB = (AVE(5) - 51) / 204 * (325 - 75) + 75
8030 TWB = (AVE(2) - 51) / 204 * (110 - 50) + 50
8040 IF TWB < 110 GOTO 8220
8050 HOME : VTAB 4: HTAB 15: FLASH
8060 PRINT " WARNING "
8070 VTAB 7: NORMAL
8080 PRINT "THE WET-BULB TEMPERATURE EXCEEDS LIMIT !"
8090 VTAB 10
8100 PRINT "CHECK THE WATER LEVEL IN THE 'DEW CUP'."
8110 VTAB 13
8120 PRINT "IF THIS IS THE SOURCE OF THE PROBLEM, CORRECT IT THEN
     CONTINUE THE PROGRAM."
8130 VTAB 16
8140 PRINT "IF THIS IS NOT THE SOURCE OF THE PROBLEM, PLEASE END THIS
     SESSION AND REPORT THIS PROBLEM IMMEDIATELY."
8150 VTAB 21
8160 PRINT "HIT <RETURN> TO CONTINUE THIS PROGRAM OR HIT <ESC> TO END
     THIS SESSION"
8170 VTAB 22: HTAB 34: GET ANS$
8180 PRINT
8190 IF ANS$ = CHR$ (27) THEN WARNING$ = "ON": GOTO 8220
8200 IF ANS$ <  > CHR$ (13) GOTO 8170
8210 WARNING$ = "RESET"
8220 RETURN
```

Figure A2. Subroutine 8010 (Temperature Calculation)

```
10010  V2 = (AVE(CH) - 128) * 10 / 255
10020  V1 = ((127 * 10 / 255) - V2) / 2
10030  GASFLOW = V1 * 4.00
10040  IF GASFLOW > PILOT THEN PILOT$ = "ON": GOTO 10170
10050  PILOT$ = "OFF"
10060  HOME : VTAB 4: HTAB 16: FLASH
10070  PRINT " WARNING "
10080  NORMAL : VTAB 9: HTAB 10
10090  PRINT "THE PILOT HAS GONE OUT"
10100  PRINT : HTAB 5
10110  PRINT "CLOSE THE GAS VALVE IMMEDIATELY"
10120  VTAB 16: HTAB 5
10130  PRINT "HIT <RETURN> TO RESTART THIS RUN"
10140  PRINT : HTAB 5
10150  PRINT "OR HIT <ESC> TO SAVE YOUR DATA"
10160  VTAB 18: HTAB 36: GET ANS$
10170  RETURN
```

Figure A3. Subroutine 10010 (Gas Flow Rate Calculation)

```
6010  IF NUMBER = 0 GOTO 6090
6020  FOR I = 1 TO NUMBER
6030  POKE (49242 - L),0
6040  FOR J = 1 TO 5: NEXT J
6050  POKE (49241 - L),0
6060  FOR J = 1 TO 5: NEXT J
6070  NEXT I
6080  DAMPER = DAMPER + (L * NUMBER)
6090  RETURN
```

Figure A4. Subroutine 6010 (Stepper Motor Control)

```
11010  T1 = (ROOM(1) + 460) / 1.8
11020  T2 = (TIN + 460) / 1.8
11030  G1 = 0.0446 * GASFLOW
11040  G2 = 0.0353 * G1
11050  DH(1) = HC * G1
11060  DH(2) = G1 * (AC*(T2 - T1) + BC/2 * (T2^2 - T1^2) + CC/3 * (T2^3 -
       T1^3))
11070  DH(3) = -DH(1) - DH(2)
11080  AXS = DH(3) / (AAIR * (T2 - T1) + BAIR/2 * (T2^2 - T1^2) + CAIR/3
       * (T2^3 - T1^3)
11090  AWB = 17.27 * G2 + 28.92 * AXS / 454
11100  ADB(N) = AWB / (1 - ROOM(4))
11110  RETURN
```

Figure A5. Subroutine 11010 (Air Flow Rate Calculation)

```
9010  MH2O = 18.0152 : MAIR = 28.97
9020  H1 = SH( INT (TWB / 2) * 2)
9030  H2 = SH( INT (TWB / 2) * 2 + 2)
9040  HS = H1 + (TWB - INT (TWB / 2) * 2) * (H2 - H1) / 2
9050  XS = HS / (HS + MH2O / MAIR)
9060  LAMBDA = 1065.3 - (TWB - 50) * 87.4 / 150
9070  SCHMIDT = 0.60
9080  NPR = .709 - (TWB - 50) * .012 / 150
9090  LEWIS = SCHMIDT / NPR
9100  F = (LEWIS ^ (2 / 3)) * (TDB - TWB) / (MH2O * LAMBDA)
9110  CP = .24 + .45 * (MH2O * XS) / (MAIR * (1 - XS))
9120  MMIX = MAIR
9130  XG = XS - CP * MMIX * F
9140  XG = INT (10000 * XG) / 10000
9150  X1 = XG
9160  FOR I = 1 TO 1000
9170  CP = .24 + .45 * (MH2O * X1) / (MAIR * (1 - X1))
9180  MMIX = (X1 * MH2O) + (1 - X1) * MAIR
9190  X = XS - CP * MMIX * F
9200  E1 = X - X1
9210  IF E1 < 0 GOTO 9240
9220  X1 = X1 + .0001
9230  NEXT I
9240  H = (X * MH2O / MAIR) / (1 - X)
9250  RETURN
```

Figure A6. Subroutine 9010 (Humidity Determination)

```
12010  H2O(1) = FEED(1,1) * XFEED
12020  H2O(2) = ADB(N) * ROOM(3)
12030  H2O(3) = (GASFLOW / 22.4) * 2 * MH2O / 454
12040  H2O(4) = H2O(1) + H2O(2) + H2O(3)
12050  H2O(5) = ADB(N) * H
12060  H2O(6) = H2O(4) - H2O(5)
12070  XPRODUCT = H2O(6) / (H2O(6) + FEED(0,1))
12080  RETURN
```

Figure A7. Subroutine 12010 (Product Moisture Content)

```
14010  IF N >= 20  GOTO 14040
14020  XDESIRED = XFEED - (N/20)(XFEED - XDESIRED(1))
14030  GOTO 14050
14040  XDESIRED = XDESIRED (1)
14050  E(N) = XDESIRED - XPRODUCT(N)
14060  IF E(N) < 0   GOTO 14090
14070  IF O(N - 1) < 255  GOTO 14100
14080  II(N) = II(N - 1) : GO TO 14110
14090  IF O(N - 1) < 0 THEN II(N) = II(N - 1) : GOTO 14110
14100  II(N) = II(N - 1) + E(N)
14110  O(N) = GAIN(1) * E(N) + (GAIN(1)/GAIN(2))(II(N)) + O(0)
14120  IF O(N) < 0 THEN O(N) = 0 : GOTO 14140
14130  IF O(N) > 255 THEN O(N) = 255
14140  GG = INT(O(N))
14150  POKE 49307,GG
14160  DP = INT(85 + 15 * GG/255)
14170  DD = DP - DAMPER
14180  IF DD > 0 THEN L = 1
14190  IF DD < 0 THEN L = -1
14200  NUMBER = ABS(DD)
14210  GOSUB 6010
14220  RETURN
```

Figure A8. Subroutine 14010 (Control Algorithm)

```
21010  HOME : FOR J = 1 TO 1000: NEXT J
21020  INVERSE
21030  HTAB 14: PRINT " SUBROUTINE 1 "
21040  NORMAL
21050  PRINT : PRINT
21060  PRINT "PURPOSE: TO CALCULATE THE HOT AIR FLOW RATE THROUGH THE
       DRYER"
21070  PRINT : PRINT
21080  PRINT "METHOD: PERFORM AN ENERGY BALANCE AROUND THE COMBUSTION
       CHAMBER"
21090  PRINT : PRINT
21100  PRINT "VARIABLES: SEE OPERATING MANUAL FOR THE SPECIFIED VARIABLES
       AND UNITS"
21110  PRINT
21120  PRINT "MINIMUM LINE NUMBER : 11010"
21130  PRINT : PRINT
21140  PRINT "MAXIMUM LINE NUMBER : 11990"
21150  VTAB 22
21160  PRINT " HIT <RETURN> FOR INFORMATION ON SUB2 OR"
21170  VTAB 22
21180  PRINT " HIT <ESC> TO CREATE/EDIT A SUBROUTINE "
21190  VTAB 23: HTAB 40: GET ANS$
21200  IF ANS$ = CHR$ (27) GOTO 21410
21210  IF ANS$ = CHR$ (13) GOTO 21190
21220  HOME : FOR J = 1 TO 1000: NEXT J
21230  INVERSE
21240  HTAB 14: PRINT " SUBROUTINE 2 "
21250  NORMAL
21260  PRINT : PRINT
21270  PRINT "PURPOSE: TO CALCULATE THE MASS FRACTION OF WATER IN THE
       PRODUCT"
21280  PRINT : PRINT
21290  PRINT "METHOD: PERFORM AN OVERALL MATERIAL BALANCE FOR WATER FOR
       THE SYSTEM"
21300  PRINT : PRINT
21310  PRINT "VARIABLES: SEE OPERATING MANUAL FOR THE SPECIFIED VARIABLES
       AND UNITS"
21320  PRINT
21330  PRINT "MINIMUM LINE NUMBER : 12010"
21340  PRINT : PRINT
21350  PRINT "MAXIMUM LINE NUMBER : 12990"
21360  VTAB 22
21370  PRINT " HIT <ESC> TO CREATE/EDIT A SUBROUTINE "
21380  VTAB 22: HTAB 40: GET ANS$
21390  IF ANS$ = CHR$ (27) GOTO 21410
21400  GOTO 21380
21410  HOME : FOR J = 1 TO 1000: NEXT J
21420  INVERSE
21430  HTAB 6: PRINT " TO CREATE/EDIT A SUBROUTINE "
```

Figure A9. Subroutine 21010 (Subroutine 11010 and 12010 Set-up Instructions)

```
21440  NORMAL : VTAB 4
21450  PRINT "1. SEE THE OPERATING MANUAL FOR A LIST OF USEFUL APPLESOFT
       BASIC COMMANDS."
21460  PRINT : PRINT "2. ENTER EACH SUBROUTINE USING THE SPECIFIED
       VARIABLES AND LINE NUMBERS."
21470  PRINT "3. BE SURE TO INCLUDE A <RETURN> STATEMENT AT THE END OF
       EACH SUBROUTINE."
21480  PRINT : PRINT "4. AFTER EACH SUBROUTINE IS COMPLETED CORRECTLY,
       TYPE <RUN> TO CONTINUE."
21490  PRINT : PRINT
21500  INVERSE : PRINT " BEGIN "
21510  NORMAL : PRINT
```

Figure A9 (cont'd)

```
15010  HOME
15020  FOR J = 1 TO 1000: NEXT J
15030  VTAB 3: HTAB 7
15040  INVERSE
15050  PRINT " TEMPERATURE (DEGREE F) "
15060  NORMAL
15070  VTAB 6: HTAB 9
15080  PRINT "DRY-BULB      WET-BULB"
15090  HTAB 9
15100  PRINT "========      ========"
15110  VTAB 9: HTAB 11
15120  P = 1: PRINT FN RR(ROOM(1))
15130  VTAB 9: HTAB 24
15140  P = 1: PRINT FN RR(ROOM(2))
15150  VTAB 13: INVERSE
15160  HTAB 7
15170  PRINT "     ABSOLUTE HUMIDITY     "
15180  NORMAL
15190  VTAB 15: HTAB 7
15200  PRINT "   (LBS H20 / LB DRY AIR)   "
15210  VTAB 18: HTAB 17
15220  P = 5: PRINT FN RR(ROOM(3))
15230  RETURN
```

Figure A10. Subroutine 15010 (Room Air Conditions Data Display)

```
16010 HOME
16020 PRINT "DISPLAY 1"
16030 INVERSE
16040 VTAB 1: HTAB 13
16050 PRINT " DRYER TEMPERATURES (DEG F) "
16060 NORMAL
16070 VTAB 3: HTAB 15
16080 PRINT "INLET     OUTLET     OUTLET"
16090 HTAB 13
16100 PRINT "DRY-BULB  DRY-BULB  WET-BULB"
16110 VTAB 5: HTAB 13
16120 PRINT "========  ========  ========"
16130 VTAB 7
16140 PRINT "CURRENT"
16150 PRINT "PREVIOUS"
16160 PRINT "2ND PREV."
16170 PRINT "3RD PREV."
16180 VTAB 12: HTAB 13
16190 INVERSE
16200 PRINT "   FLOW RATES    "
16210 NORMAL
16220 VTAB 12: HTAB 32: INVERSE
16230 PRINT " PRODUCT "
16240 NORMAL
16250 VTAB 14: HTAB 13
16260 PRINT "METHANE  DRY AIR   MOISTURE"
16270 HTAB 13
16280 PRINT "(L/MIN)  (#/MIN)   PERCENT"
16290 HTAB 13
16300 PRINT "=======  =======   ========"
16310 VTAB 18
16320 PRINT "CURRENT"
16330 PRINT "PREVIOUS"
16340 PRINT "2ND PREV."
16350 PRINT "3RD PREV."
16360 PRINT
16370 PRINT "SET-POINT"
16380 RETURN
```

Figure A11. Subroutine 16010 (Display One Headings)

```
17010  P = 1
17020  FOR I = 1 TO 3
17030  VTAB 7
17040  FOR J = 0 TO 3
17050  HTAB 15: IF I = 1 GOTO 17080
17060  HTAB 25: IF I = 2 GOTO 17080
17070  HTAB 35
17080  PRINT  FN RR(T(I,N - J))
17090  NEXT J
17100  NEXT I
17110  P = 2: VTAB 18
17120  FOR J = 0 TO 3
17130  HTAB 15: PRINT  FN RR(GAS(N - J))
17140  NEXT J
17150  VTAB 18
17160  FOR J = 0 TO 3
17170  HTAB 24: PRINT  FN RR(ADB(N - J))
17180  NEXT J
17190  VTAB 18
17200  FOR J = 0 TO 3
17210  HTAB 34: PRINT  FN RR(100 * XPRODUCT(N - J))
17220  NEXT J
17230  VTAB 23: HTAB 34
17240  PRINT  FN RR(100 * XDESIRED(1))
17250  RETURN
```

Figure A12. Subroutine 17010 (Display One Data Entry)

```
18010  HOME
18020  PRINT "DISPLAY 2"
18030  VTAB 1: HTAB 11
18040  INVERSE
18050  PRINT "      OUTLET CONDITIONS      "
18060  NORMAL
18070  VTAB 3: HTAB 11
18080  PRINT "DRY-B  WET-B  ABSOL.   PRODUCT"
18090  VTAB 4: HTAB 11
18100  PRINT "TEMP.  TEMP.  HUMID'Y  MOIST'R"
18110  VTAB 5: HTAB 11
18120  PRINT " (F)    (F)   (LB/LB)  PERCENT"
18130  VTAB 6: HTAB 11
18140  PRINT "=====  =====  =======  ======="
18150  VTAB 8
18160  PRINT "CURRENT"
18170  PRINT "PREVIOUS"
18180  PRINT "2ND PREV."
18190  PRINT "3RD PREV."
18200  VTAB 14: INVERSE
18210  PRINT "      FEED AND PRODUCT SPECIFICATIONS      "
18220  NORMAL
18230  VTAB 17: HTAB 6
18240  PRINT "WET-BASIS    MOISTURE PERCENT IN:"
18250  VTAB 19: HTAB 6
18260  PRINT "FLOW RATE       FEED PRODUCT"
18270  VTAB 20: HTAB 6
18280  PRINT "(LBS/MIN)    (ACTUAL)   (DESIRED)"
18290  VTAB 21: HTAB 6
18300  PRINT "=========    ========   ========="
18310  RETURN
```

Figure A13. Subroutine 18010 (Display Two Headings)

```
19010  P = 1
19020  FOR I = 2 TO 3
19030  VTAB 8
19040  FOR J = 0 TO 3
19050  HTAB 11: IF I = 2 GOTO 19070
19060  HTAB 18
19070  PRINT  FN RR(T(I,N - J))
19080  NEXT J
19090  NEXT I
19110  P = 4: VTAB 8
19120  HTAB 25: PRINT  FN RR(H(N - J))
19130  NEXT J
19140  P = 2: VTAB 8
19150  FOR J = 0 TO 3
19160  HTAB 35: PRINT  FN RR(100 * XPRODUCT(N - J))
19170  NEXT J
19180  P = 4: VTAB 23: HTAB 8: PRINT  FN RR(FEED(1,1))
19190  P = 2: VTAB 23: HTAB 20: PRINT  FN RR(100 * XFEED)
19200  P = 2: VTAB 23: HTAB 30: PRINT  FN RR(100 * XDESIRED(1))
19210  RETURN
```

Figure A14. Subroutine 19010 (Display Two Data Entry)

APPENDIX B

CONNECTOR PINOUT DIAGRAMS

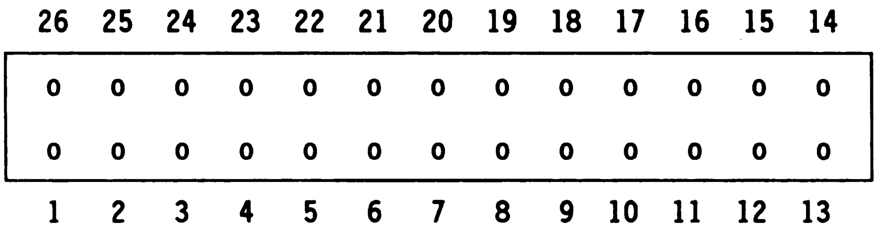
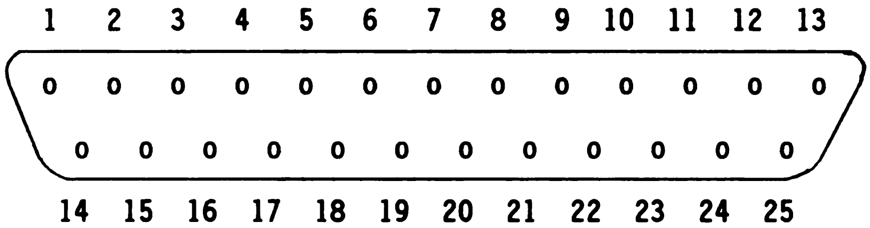


Figure B1. Pinout Diagrams of D/A (J1) + A/D (J2) Connectors (Refer to Table C1 for Signal Descriptions)

DB-25 Male Connector: Access to A/D Converter



DB-25 Female Connector: Access to D/A Converter

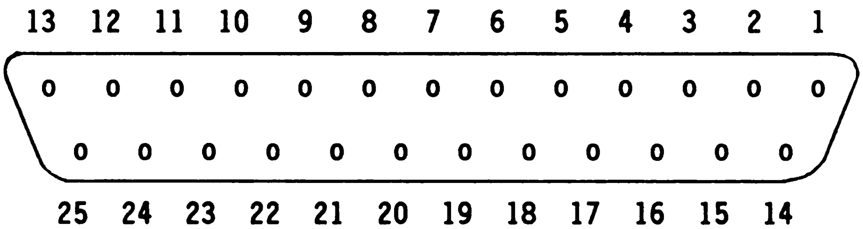


Figure B2. Pinout Diagrams for Cable DB-25 Connectors (Refer to Table C1 for Signal Descriptions)

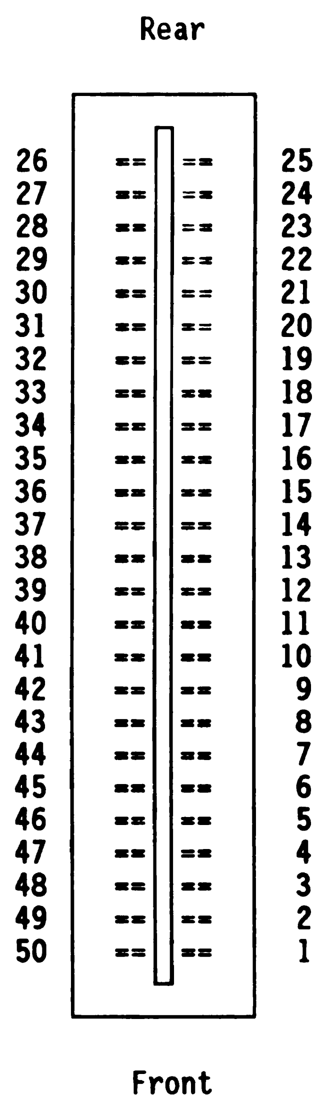


Figure B3. Apple II Peripheral Card Connector Pinout Diagram (Refer to Table C2 for Signal Descriptions)

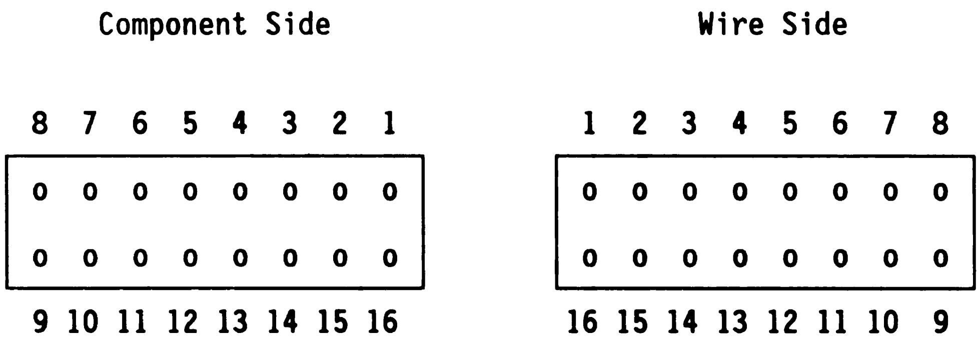


Figure B4. Pinout Diagrams of Vector Board Auxiliary I/O DIP Socket Connector (Refer to Table C3 for Signal Descriptions)

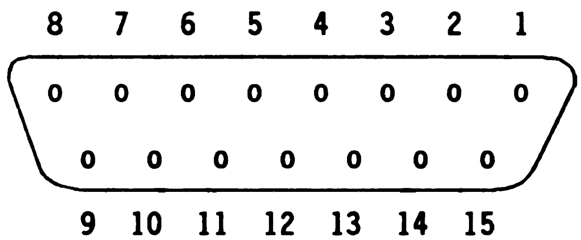


Figure B5. Pinout Diagram of Auxiliary Cable DB-15 Male Connector (Refer to Table C3 for Signal Descriptions)

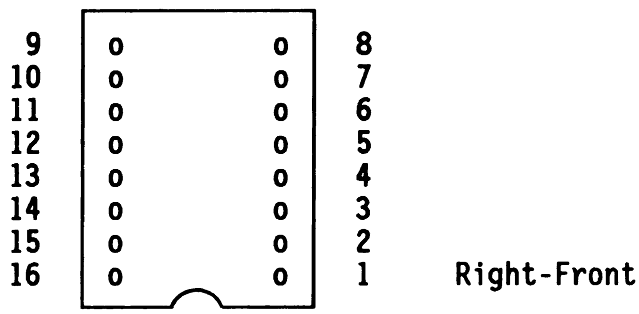


Figure B6. Pinout Diagram of Game I/O Connector (Refer to Table C4 for Signal Descriptions)

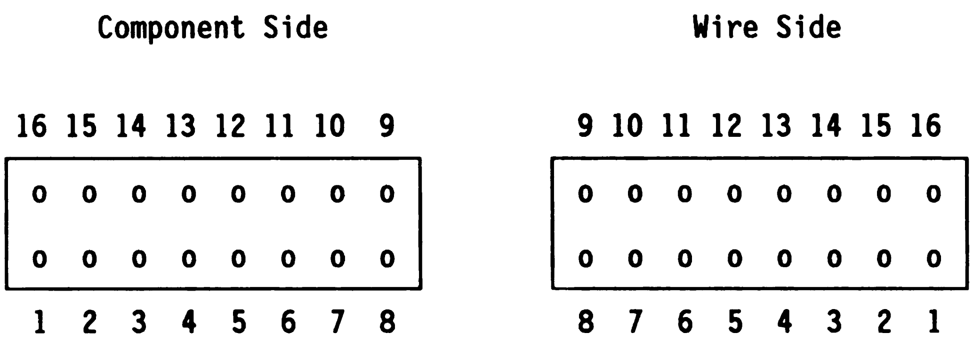
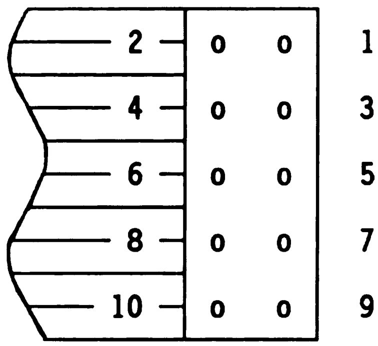


Figure B7. Pinout Diagrams of Vector Board DIP Socket Corresponding With Game I/O Connector (Refer to Table C4 for Signal Descriptions)



Bottom View

Pin #	Function
1	Channel A
2	Vcc (+5V)
3	Ground
4	NC or Ground
5	NC or Ground
6	Ground
7	Vcc (+5V)
8	Channel B
9	Vcc (+5V)
10	Channel I

Figure B8. Pinout Diagram For Optical Encoder Plug

APPENDIX C

SIGNAL DESCRIPTIONS FOR CONNECTORS

Table C1. Signal Descriptions of A/D + D/A Connector Pins

J1 or J2 Connector Pin No.	DB-25 Connector Pin No.	Signal Description
01	01	Channel 15
02	02	Channel 14
03	03	Channel 13
04	04	Channel 12
05	05	Channel 11
06	06	Channel 10
07	07	Channel 09
08	08	Channel 08
09	09	Channel 07
10	10	Channel 06
11	11	Channel 05
12	12	Channel 04
13	13	Channel 03
14	No Connection	No Connection
15	25	Channel 02
16	24	Channel 01
17	23	Channel 00
18	22	**
19 through 26	21 through 14	Ground

** For J1 pin number 18, the signal is no connection; For J2 pin number 18, the signal is a -5 volt reference.

Table C1. Signal Descriptions of A/D + D/A Connector Pins

J1 or J2 Connector Pin No.	DB-25 Connector Pin No.	Signal Description
01	01	Channel 15
02	02	Channel 14
03	03	Channel 13
04	04	Channel 12
05	05	Channel 11
06	06	Channel 10
07	07	Channel 09
08	08	Channel 08
09	09	Channel 07
10	10	Channel 06
11	11	Channel 05
12	12	Channel 04
13	13	Channel 03
14	No Connection	No Connection
15	25	Channel 02
16	24	Channel 01
17	23	Channel 00
18	22	**
19 through 26	21 through 14	Ground

** For J1 pin number 18, the signal is no connection; for J2 pin number 18, the signal is a -5 volt reference.

Table C2. Signal Descriptions For Peripheral Connector Pins

Pin #	Function	Comments
25	+5 volt supply	500 ma maximum current
26	ground	System electrical ground
33	-12 volt supply	200 ma maximum current
34	-5 volt supply	200 ma maximum current
50	+12 volt supply	250 ma maximum current

Table C3. Signal Descriptions For Vector Board Socket

Pin #	Signal Description
01	Input voltage (V_3) to gas flow rate control op-amp circuit
02	System ground
03	Output voltage (V_4) from gas flow rate control op-amp circuit
04	System ground
05	System ground
06	+5 volt supply
07	Positive switching terminal of AN0-controlled Reed relay
08	Negative switching terminal of AN0-controlled Reed relay
09	Negative switching terminal of AN1-controlled Reed relay
10	Positive switching terminal of AN1-controlled Reed relay
11	No connection
12	Output voltage (V_2) from gas flow rate measurement op-amp circuit
13	System ground
14	Input voltage (V_1) to gas flow rate measurement op-amp circuit
15	System ground
16	No connection

Table C4. Signal Descriptions for Game I/O Connector Pins

Pin #	Function	Comments
01	+5 Volt Supply	100 ma maximum current
08	Ground	System Electrical Ground
09	NC	No Internal Connection
14	Annunciator 1	Standard 74LS Series Outputs
15	Annunciator 0	Standard 74LS Series Outputs
16	NC	No Internal Connection