BuMines OFR 25-85

PB 85-185247

A mining research contract report
JANUARY 1984

DEVELOPMENT OF AN AUTOMATED BREATHING METABOLIC SIMULATOR (ABMS)

Contract No. J0100098
Reimers Consultants

Bureau of Mines Open File Report 25-85

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

REPORT DOCUMENTATION PAGE	1. REPORT NO. BuMines OFR 25-85	2.	3. Recipient's Accession No. PB85 185247/AS
4. Title and Subtitle: Development of an Automated Breathing Metabolic Simulator (ABMS)			5. Report Date: Jan. 1984
7. Author(s): Larry L. Wischhoefer and Stephen D. Reimers			8. Performing Organization Rept. No.
9. Performing Organization Name and Address: Reimers Consultants, 6269 Leesburg Pike, Falls Church, VA 22044			10. Project/Task/Work Unit No.
			11. Contract(C) or Grant(G) No. (C) J0100098 (G)
12. Sponsoring Organization Name and Address: Office of Assistant Director--Mining Research, Bureau of Mines, U.S. Department of the Interior, Washington, DC 20241			13. Type of Report & Period Covered: Contract research, 9/30/80--4/30/84
			14.

15. Supplementary Notes

Supplements BuMines OFR 3-74 (PB 226687).
Approved for release March 4, 1985.

16. Abstract (Limit: 200 words)

The automated breathing metabolic simulator (ABMS) is a versatile machine capable of performing almost any physiologically appropriate respiratory simulation. Since the first ABMS was delivered to the Bureau of Mines in 1973, efforts have been made to refine the systems and components that make up the ABMS, including the breathing simulator module, gas analysis module, and supervisory controller, each of which are capable of stand-alone operation. In order to improve the equipment and to develop simulation criteria and parameters, testing and modifying the ABMS has been continuing since 1980. Changes have been made to the phase I design plan and performance specifications, future improvements based on current experience are recommended, and test results of full-scale testing conducted in November 1983 on several types of breathing apparatus are reported and illustrated.

17. Document Analysis a. Descriptors

Mining research
Automated breathing metabolic simulator
Breathing simulator module
Gas analysis module
Supervisory controller
Stand-alone operation

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group: 08I

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited by NTIS.	Unclassified	51
	20. Security Class (This Page) Unclassified	22. Price

FOREWORD

This report was prepared by Reimers Consultants, 6269 Leesburg Pike, Falls Church, VA 22044, under Contract number J0100098. The contract was initiated under the Minerals Health and Safety Technology Program. It was administered under the technical direction of the Pittsburgh Research Center with Mr. Nicholas Kyriazi acting as Technical Project Officer. Janice Johnson was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period 9/80 to 1/84. This report was submitted by the authors on 1/84.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

I. INTRODUCTION

A. Development History

The first Automated Breathing Metabolic Simulator (ABMS) was delivered to the Bureau of Mines by IBM in 1973 (1). That unit was basically an automated version of a manually controlled Breathing Metabolic Simulator that IBM had developed previously (2). The IBM ABMS continued in service until early 1980 when increasing maintenance difficulties and apprehensions centered around the oxygen uptake process used, the catalytic combustion of methane, prompted its retirement. In mid 1980 Reimers Consultants (RC) won two contracts from the Bureau. The first was a supply contract for a manually controlled Breathing Metabolic Simulator (BMS) based on standard RC designs in use at the time. The second was a development contract for a prototype automated unit which was originally intended to employ process designs as similar to the manual BMS as possible. The basic criteria which guided the ABMS development were:

- o The simulations produced by the ABMS were to be as physiologically appropriate as possible.
- o The construction was to employ low cost methods using standard, commercially available items wherever possible.
- o Operation was to be simple and easily learned. Complex computer programs were to be avoided.
- o The ABMS was to be capable of manual as well as automatic operation. All data inputs into the computer were to be paralleled with analog outputs suitable for general purpose laboratory recorders.

The manual BMS went into service in mid 1981. Experience with it quickly indicated that some adjustments in the oxygen uptake process used, an early version of the volume exchange process described herein, were required. It removed oxygen just fine. However, it also had a tendency to alter the nitrogen constituent in the process gas. This effect, if not properly managed, can lead to abnormally low oxygen concentrations and breathing bags which run either too full or too flat. The discussions herein regarding "nitrogen fidelity" are a direct result of the experience with that manual BMS. The nitrogen fidelity of the oxygen uptake system discussed herein is at least an order of magnitude better, and it is expected to function well.

B. System Description And Performance Capabilities

Figure 1 shows the general arrangement of the ABMS. It has been designed in three modules: a Breathing Simulator Module (BSM), a Gas Analysis Module (GAM) and a Supervisory Controller (SC). Each of the modules is capable of stand-alone operation. The BSM can be run in a completely manual mode without the SC and with gas analysers of convenience. Similarly both the SC and GAM are capable of being put to general purpose use apart from their designated applications as portions of the ABMS.

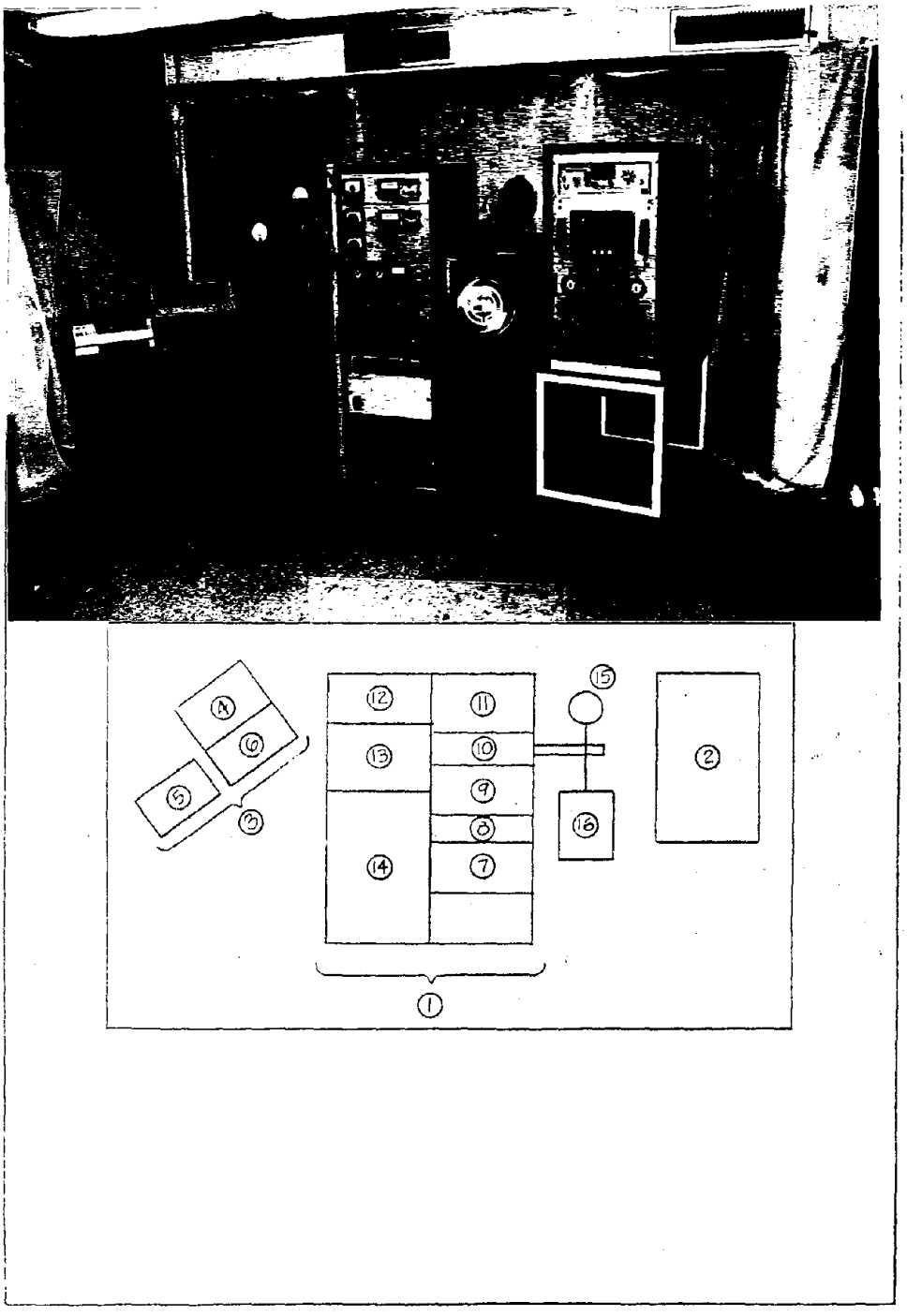

FIGURE 1. ABMS General Arrangement

KEY TO FIGURE 1

1. Breathing Simulator Module

7. HP-2240A Data Acquisition and Control System
8. Pull-Out Shelf
9. Waveform Generator Module
10. CO_2 Add Module
11. Temperature and Humidity Monitoring and Control Module
12. Differential Pressure Measurement Module
13. Oxygen Uptake Module
14. Piston and Cylinder Assembly
15. Manikin Head (with mask)
16. Bio-Pak 60 Closed Circuit Rebreather (for illustration purposes only)

2. Gas Analysis Module

3. Supervisory Controller

4. HP-85 Scientific Calculator
5. HP-9876A Thermal Printer/Plotter
6. HP-82901M Dual Floppy Disk Drive

The principal performance capabilities of the ABMS are given in Table 1. The following paragraphs provide brief explanations of how the various ABMS systems function.

1. Breathing Simulator Module

The BSM is the heart of the ABMS. It is designed to be operated either manually or by means of the SC. The principal elements which make up the BMS are as follows:

Main Cylinder Assembly

The Main Cylinder Assembly consists principally of a rolling seal piston and cylinder assembly, a zero backlash ball screw drive and high response servomotor as shown in Figure 2. The rolling seal piston design provides excellent sealing reliability with very low friction. However, rolling seals behave in a reliable fashion only when in tension.

Consequently, two seals with a vacuum in between are used as shown. Further, since the differential pressures normally existing in the process loop are small relative to the vacuum applied to the rolling seal, they have virtually no effect on system behavior. Measured compliance values for the rolling seal designs employed are on the order of 0.01 cm^3 increase in net cylinder volume per cm H_2O increase in process loop pressure, e.g., the rolling seal is effectively non-stretching and therefore has no detrimental effects on the accuracy of the waveform. A pressure switch on the vacuum circuit is used to prevent operation of the drive if insufficient vacuum exists to ensure satisfactory seal performance.

The servomotor drive is controlled by voltage signals sent to the amplifier by the Waveform Generator (WG). Signals sent back to the WG by the rotary digital shaft encoder keep it informed as to the exact location of the drive. Upper and lower travel limit switches wired to the signal locking circuits on the amplifier are employed to prevent overtravel of the drive in the event of an erroneous control signal. The velocity transducer shown has no specific control function. However, the SC monitors its output to verify that it is getting the velocity-versus position profiles it requests of the Waveform Generator.

2. Waveform Generator

The Waveform Generator is the real-time system which controls the velocity position-time characteristics of the piston drive. It consists of several components which together provide accurate, yet flexible and simple-to-use waveform control. See Figure 3. Each component is described briefly below:

- Microprocessor CPU: Interprets the permanent program and directs the operation of the other subsystems.

TABLE 1. Principal Process Performance Capabilities of the ABMS

FUNCTION	ABMS PROCESS PERFORMANCE CAPABILITIES
Waveform Control:	
Tidal Volume:	0.5 to 3.5 liters
Breathing Rate:	5 to 50 breaths/minute *
Peak Instantaneous Flow Rate:	550 lpm *
Shape Control:	Any mathematically well behaved waveform that meets the above three constraints and which can be represented by a series of 1014 velocity segments per liter tidal volume.
Oxygen Uptake:	0.0 to 0.2 times the product of RMV and inspired oxygen concentration
CO_2 Addition:	0.5 to 4.0 slpm
Expired Temperature:	Room temperature plus 10°F (up to 110°F)
Expired Relative Humidity:	Inspired dewpoints or 90°F dewpoint (whichever is lower) to 100% R.H.
Dead Space:	Simulator dead space is effectively zero. Dead space can be added at any time by inserting a volume (cavity, tube, etc) plumbed for bi-directional flow into the breathing gas loop adjacent to the mouth opening of the test manikin.
Functional Residual Volume:	Approximately 7 liters with all gas processing functions operating. Lower volumes are possible with modifications to the process gas circuit.

* Under control of Supervisory Controller (due to unresolved problem at time of shipment), these specs are: 5-35 BPM/175 lpm

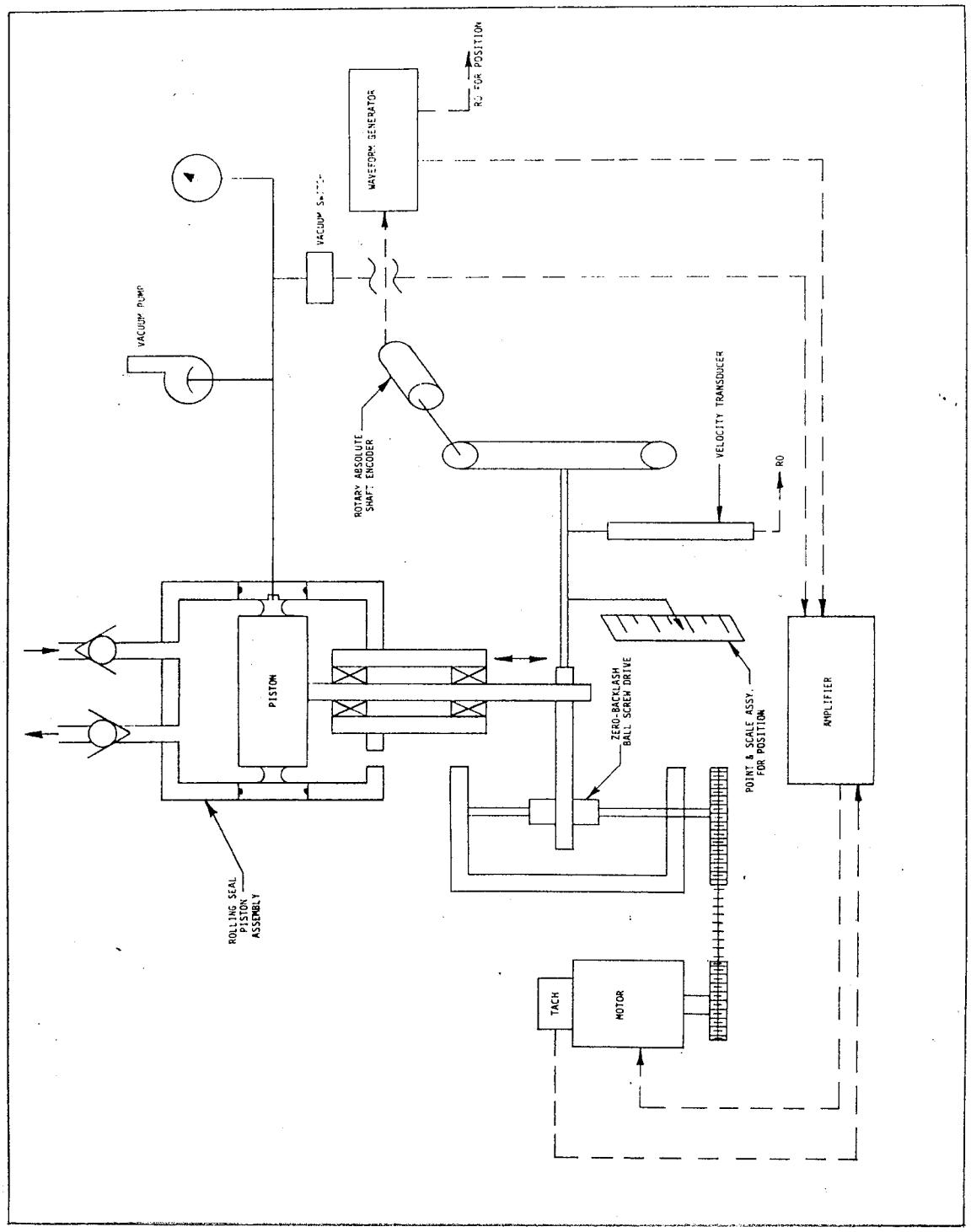

FIGURE 2. Waveform Generator, General Arrangement

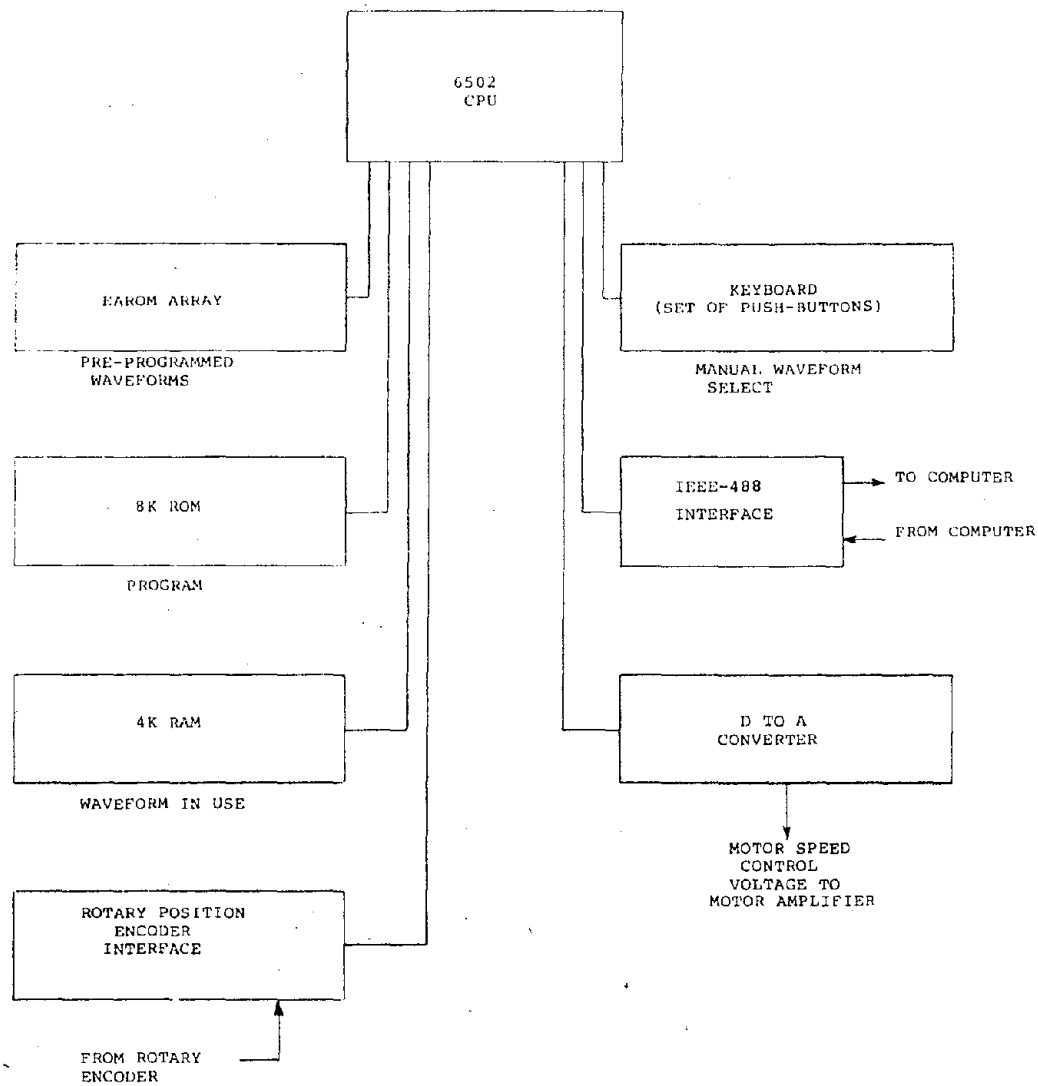

FIGURE 3. Waveform Generator, Principal Components

- o Keyboard/Display: Provides local input-output for manual operation as well as status information (breathing rate and breath number) when the system is running.

- o Non-Volatile Memory: Stores 20 separate waveforms from which several test sequences can be developed.

- o Permanent Memory: Stores the program which defines Waveform Generator operation.

- o Volatile Memory: Stores detailed waveform parameters for the piston profile currently running.

- o Process Interface: Monitors piston position and produces the piston velocity control signal.

- o IEEE-488 Interface: Communicates with the SC.

When a sequence of individual waveforms is defined, each being specified as to duration and storage number, the WG automatically extracts them in the specified sequence from the non-volatile memory. As they are executed, the system controls piston motion to accurately reproduce the waveform profile. If the SC is used, the WG maintains synchronous communication with it to assist in the correct timing of data acquisition. A sequence of up to 20 waveforms can be included in an automatically controlled test. Each waveform can be used for up to 9,999 sequential breath cycles before the test sequence must move to the next waveform.

Waveforms in non-volatile storage can be replaced with new ones as desired, either by the SC or with more effort through the manual keyboard. Similarly, a sequence of waveforms can be defined either by the SC or manually. The WG may be used either in conjunction with the SC or as a stand-alone system without sacrificing performance. This permits manual use of the BMS module in the event that the SC is "down" or being used elsewhere. It also permits simple tests and process system diagnostic work to be performed without the need to activate the SC.

Display prompts are used to guide the operator through routine set-up steps. Consequently, manual operation of the WG has proven to require very minimal operator training.

3. Temperature and Humidity Monitoring and Control Systems

The operation of this system can best be described by dividing it into three elements: the inhalation mixing box and associated instruments, the main piston assembly (discussed previously), and the exhalation temperature and humidity control system. When the simulator inhales, gas is drawn through the test manikin head and into the inhalation mixing box. The inhalation mixing box has an internal volume of approximately 2 liters, and causes the gas to be pneumatically homogenized thus enabling accurate readings of volume-average gas properties to be made with common laboratory

grade instrumentation. The mixing box also provides a convenient location for mounting the necessary sensors. This method is especially useful for obtaining accurate measurements of inspired gas temperature. The pneumatic homogenizing slows down the rates of temperature change so that a good laboratory grade thermistor can follow them accurately and generally eliminates any measurement problems due to condensate formation on the thermistor bead.

The expired temperature and humidity control system is a slightly modified version of a standard design that Reimers Consultants has used with good success for several years (10). As the process leaves the main cylinder assembly, it passes first through the bubble chamber where it passes from a bubble tube through a heated water bath. The water bath temperature is controlled by an indicating temperature controller which is set for the desired exhalation dewpoint and senses the temperature of the gas leaving the bubble chamber. A separate temperature sensor in the water is used in conjunction with a limit switch in the heater line to prevent overheating of the water when the simulator is idle or in the event of a heater controller malfunction. From the bubble chamber, the process gas travels to the exhalation mixing box via the afterheater assembly where dry heat is added. The power to the afterheater assembly is also controlled by an indicating temperature controller which senses the dry bulb temperature in the exhalation mixing box. As is the case with the inhalation mixing box, the exhalation mixing box, also approximately 2 liters internal volume, serves to pneumatically homogenize the gas and to provide a convenient mounting place for the temperature and humidity sensors. The afterheater assembly and exhalation mixing box are mounted inside an insulated box which is heated by the waste heat off the afterheater assembly. A small fan is used to circulate the air inside the box. This arrangement keeps the outside surfaces of the afterheater assembly and exhalation mixing box as warm as the inside surfaces. This has been found to help prevent heat loss from the exhalation gas and also to help prevent condensation due to cold spots in the flow path.

The temperature controllers which control the temperatures of the bubble chamber and afterheater assembly are both capable of either local or remote setpoint control. When in the local control mode, the controllers accept their setpoint commands from a knob on the panel face. In the remote mode, they take their setpoint command from the SC.

The circuit shown in Figure 4 was developed to permit accurate measurement of true volume-average parameters with common laboratory grade instrumentation. However, the penalty is a circuit with about 7 liters internal volume. If studies are to be performed where the variable of interest is sensitive to the circuit volume, such as a study of nitrogen wash-out in an oxygen self-rescuer, then the circuit volume must be reduced to about 1.5 liters or roughly the equivalent of human FRC at moderate work

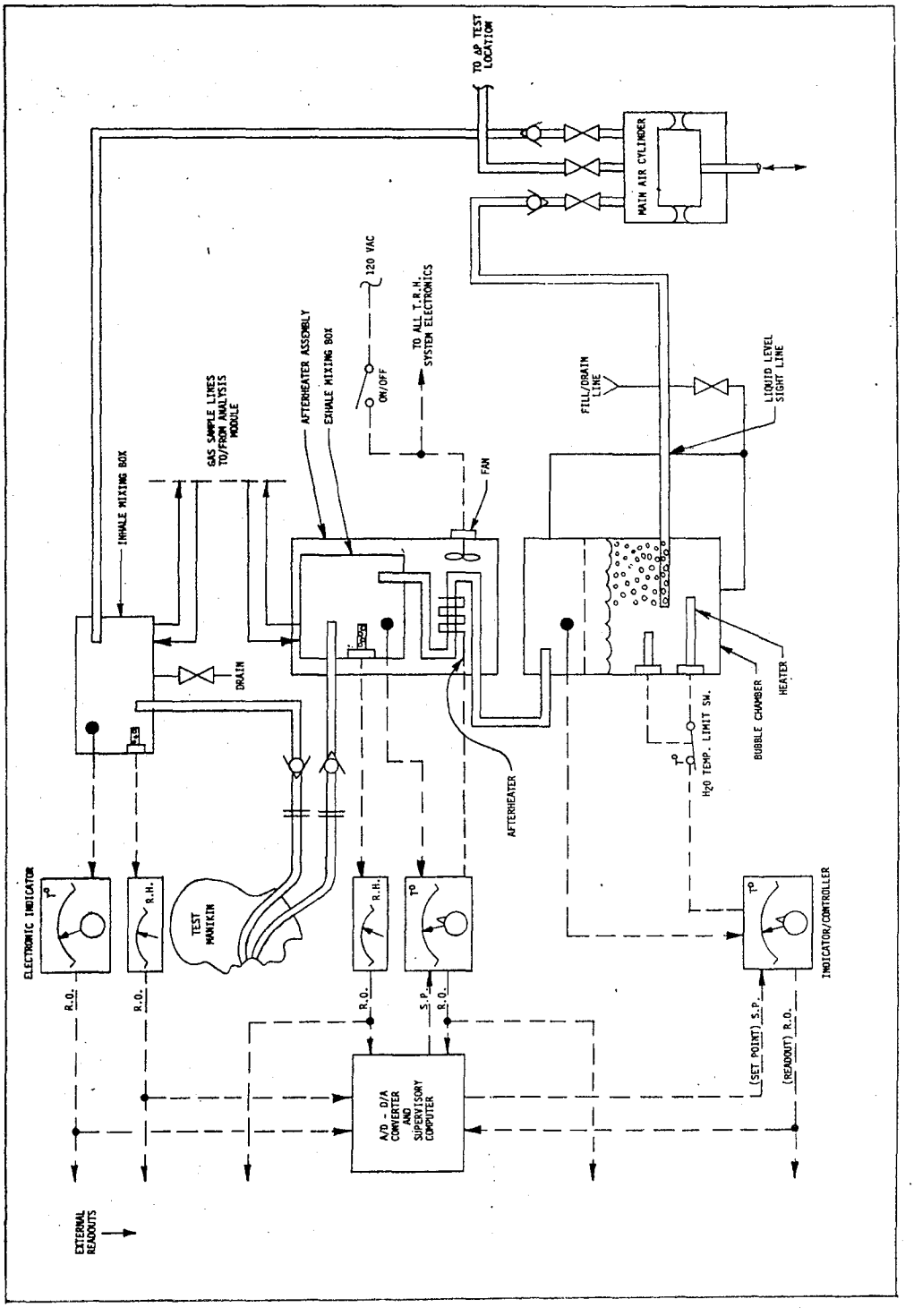

FIGURE 4. Temperature and Humidity Monitoring and Control Schematic

(12). This can be accomplished by eliminating the mixing boxes and reducing system volumes elsewhere. However the instrumentation necessary in that case to achieve the desired accuracies becomes significantly more sophisticated.

4. CO_2 Addition System

Figure 5 shows principal elements in the CO_2 addition system which is basically a constant flow addition process controlled by an indicating mass flow controller. The setpoint signal to the system may be generated from either a manual control on the front of the BMS module or sent in by the SC. The 4-way selector valve allows the CO_2 flow to be blocked, directed to a vent (useful for calibration checks), or directed to the appropriate point in the process loop depending on whether or not the oxygen uptake is in use. The CO_2 add rate process shown is simple and has been found to work very well.

5. Oxygen Uptake System

The oxygen uptake process employed involves removing gas from the process gas at a rate calculated to give the desired removal rate of oxygen and the simultaneous replacement with an equivalent volume of oxygen-free gas. See Figure 6. In the circuit shown this is accomplished by a set of three pistons which are driven from the main piston drive via a movable fulcrum lever. The removal cylinder pumps gas out of the circuit at a rate calculated to give the desired oxygens removal rate; see Equation 1. The supply cylinder pumps an equivalent volume of CO_2 and diluent (normally nitrogen) back in. The balance chamber mirrors the flow effect that the supply and removal cylinders have on the process gas flow so that the oxygen uptake rate can be adjusted without disturbing the flow rate of the process gas.

The rate at which oxygen is removed is:

$$V_{O2} = [O_2] \times RMV \times ER \qquad (1)$$

where V_{O2} = oxygen removal rate at ambient conditions

O_2 = oxygen concentration in the process loop

RMV = ABMS respiratory minute volume

ER = exchange ratio, the ratio of removal flow to RMV

In most test situations, V_{O2} is linearly related with RMV. In the design shown, V_{O2} is nearly linear with RMV. Thus, the appropriate ER setting is determined principally by the oxygen concentration in the process loop, with a slight secondary effect due to ABMS tidal volume. This basically single variable relationship between process variables and the appropriate ER setting plus the automatic nature of the diluent gas replacement process makes it possible for

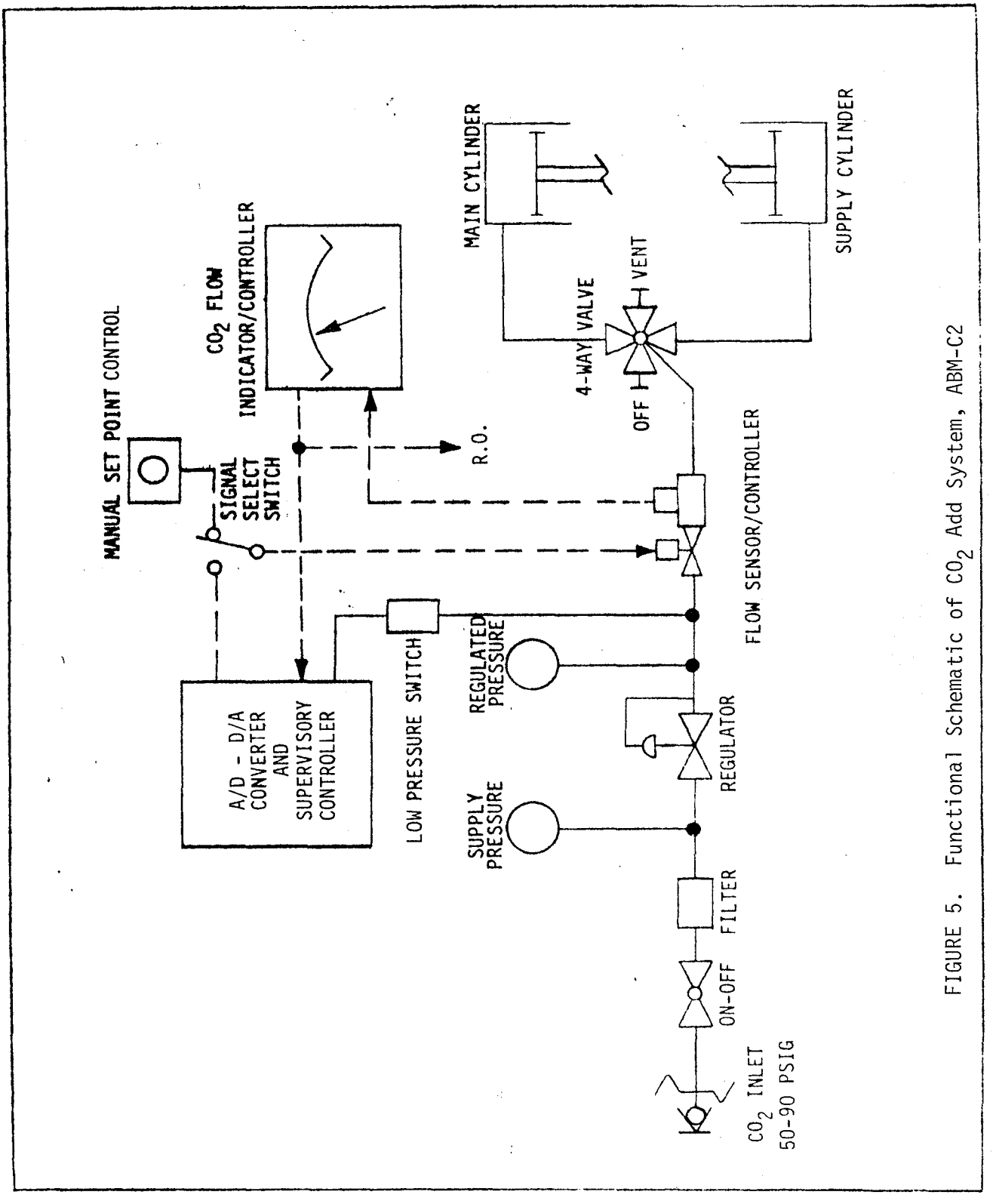

FIGURE 5. Functional Schematic of CO_2 Add System, ABM-C2

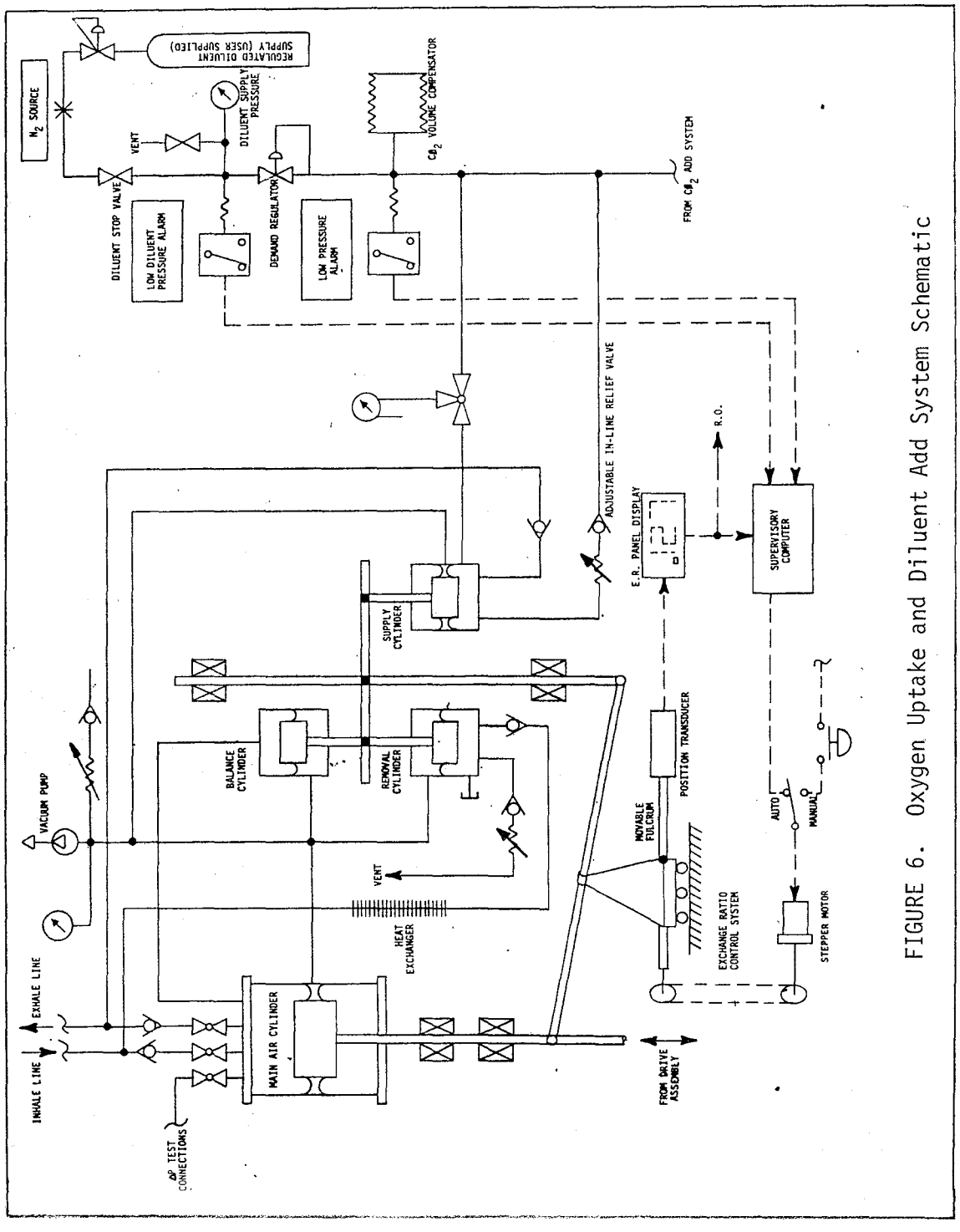

FIGURE 6. Oxygen Uptake and Diluent Add System Schematic

a good operator to achieve adequate oxygen uptake control manually. Oxygen uptake control can also be effected by the SC via the SC input to the ER controls.

The volume exchange process described above appears simple at first glance. Indeed, it is a very straightforward process if the types of breathing apparatus to be tested all have some type of volume generation/regulation system, as for instance do all types of underwater breathing apparatus. However, if apparatus are to be tested which possess no significant volume generation capacity, such as potassium superoxide oxygen self-rescue apparatus, then the fidelity requirements on the nitrogen constituent in the process gas become quite stringent if normal counterlung (breathing bag) behavior is to be achieved. For these apparatus the difference between the amount of nitrogen removed and the amount of nitrogen returned to the circuit must be less than about 0.1% of tidal volume (2cc in a 2-liter tidal volume). Assuming an average RMV over a one hour test of 30 liters per minutes (lpm), that accuracy gives a potential net gain or loss of the nitrogen constituent in the circuit of 1.8 liters. That is quite enough to create some confusion on the part of the test director, especially if he is unaware of what is going on.

The circuit shown is capable of a "nitrogen fidelity" within the 0.1% of tidal volume target given as long as the simulation respiratory quotient, R, (ratio of CO_2 added to oxygen removed) remains at one pre-selected value. Experimental data available to date at R=1.00 indicates that the nitrogen fidelity of the ABMS varies no more than 0.11% of tidal volume over a wide range of RMV and ER with variations much less than that over the most frequently used values of RMV and ER. However, for the circuit shown, a 10% variation in R, for example from 1.0 to 0.9, will cause the nitrogen fidelity to change by 1% of tidal volume. Fixing R at a specific value for test situations where very accurate nitrogen fidelity is required is a testing limitation that can be readily tolerated. Indeed test protocols for underwater breathing apparatus have fixed R at 1.00 for years, (5, 8, 9) without any hardware necessary for doing so. However as simulation procedures and the expectations of those procedures advance it may become desirable to achieve both very accurate nitrogen fidelity and wide variability in R. In that case the circuit shown would require some modification to accommodate the variability in R or a different uptake process would have to be used. One presently available such process is to use sample pumps and mass flow meters for the removal and supply functions instead of the cylinders shown. However, such an approach is not manageable except under computer control, and it requires the flowmeters to operate at the very best possible accuracies. The optimum method in terms of nitrogen fidelity involves chemically scrubbing the oxygen in a manner that does not upset the nitrogen content of the circuit. The old Bureau ABMS employed such a method. However, it involved the catalytic combustion of methane with all of the hazards attendant thereto (1). What is needed is a chemical scrubbing process that operates without requiring high temperatures,

combustible gas or expensive non-reusable chemicals. Such an optimum scrubbing system is not yet, to the author's knowledge, available.

6. Differential Pressure Measurement System

A Differential Pressure Measurement System complete with a primary calibration source (water manometer) is self-contained within the ABMS. See Figure 7.

7. Test Manikin

The ABMS is provided with 5, 50 and 95th percentile anthropormorphic male heads plumbed as shown in Figure 4. As a matter of design philosophy, all RC breathing simulators are configured so that the conditions existing at the plane of the mouth opening of the test manikin can be controlled (exhalation half cycle) and monitored (inhalation half cycle) as accurately as possible. That is the reason for the dual uni-directional tracheas shown in Figure 4. Dead space can easily be added to the manikin head by teeing the tracheas together at some point appropriately distant from the mouth opening. However, it has been the author's experience that in a testing situation, dead space serves little purpose and complicates the establishment of well defined and easily reproducible test criteria.

8. Gas Analysis Module

The Gas Analysis Module (GAM) is designed to continuously draw gas samples from the inhale and exhale mixing boxes; analyze the samples' carbon dioxide and oxygen concentrations; and then return the gas samples to their respective locations. See Figure 8. Both sample streams have individual sample pumps and flow controls. Both analyzers employ 100 ms response time medical cells. In the present system, the analyser readouts lag real time by about 8 seconds. However, faster response capabilities can readily be achieved with different plumbing arrangements. The GAM contains a calibration gas panel that allows up to four externally located calibration gases to be supplied to the analysers. Since the analysers measure partial pressures rather than concentrations, per se, a pressure gauge is provided for each sample cell so that sample cell pressures during calibration evaluations can be controlled at the same pressure as they are during normal operation.

9. Supervisory Controller

Figure 9 shows the general arrangement of the Supervisory Controller (SC). The SC programs are organized into several major and minor functional areas as described below and presented in the block diagrams contained in Figures 10, 11 and 12. All the SC programs are menu driven with liberal prompts. Consequently user training is expected to be easily accomplished.

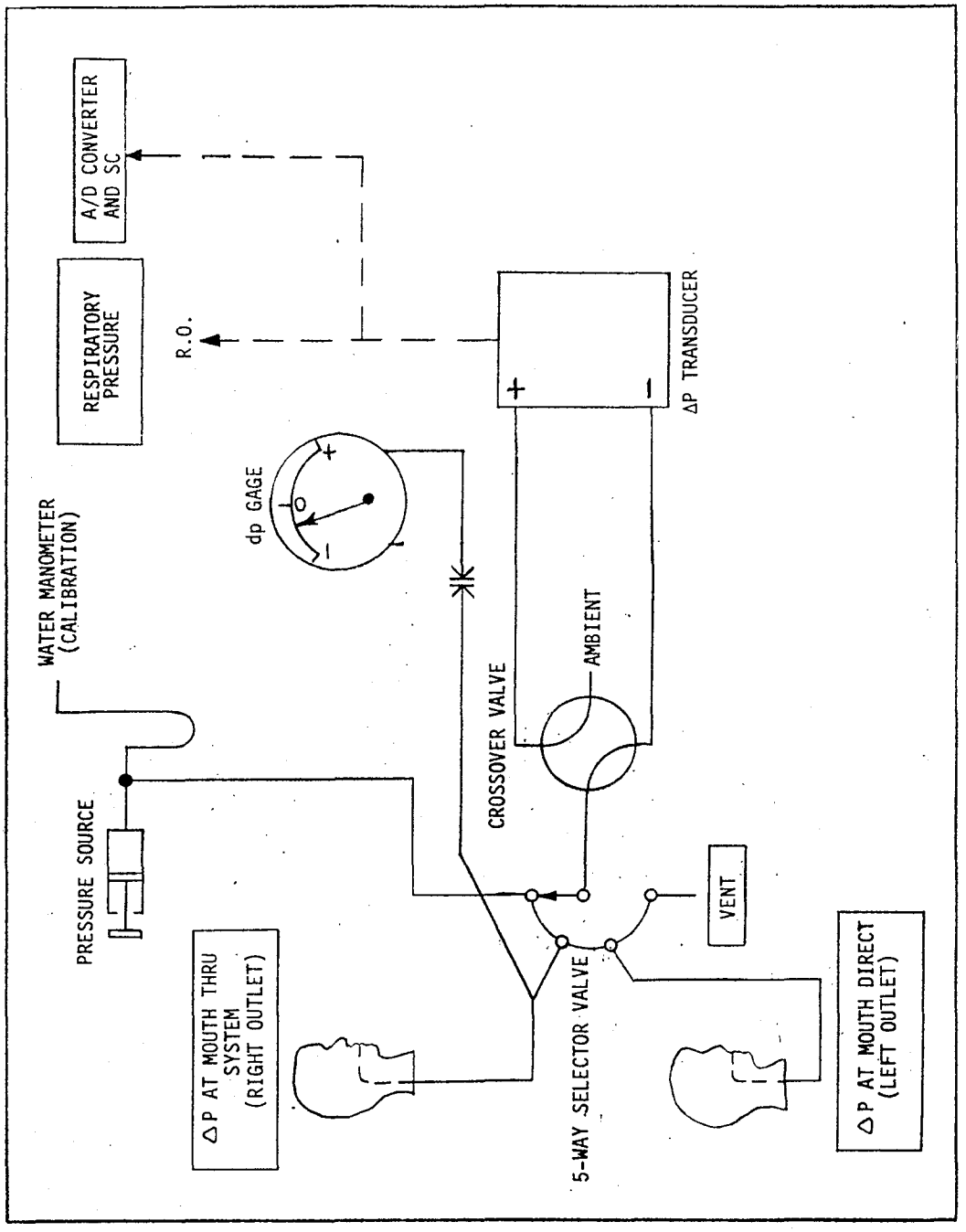

FIGURE 7. ABMS Differential Pressure Measurement System

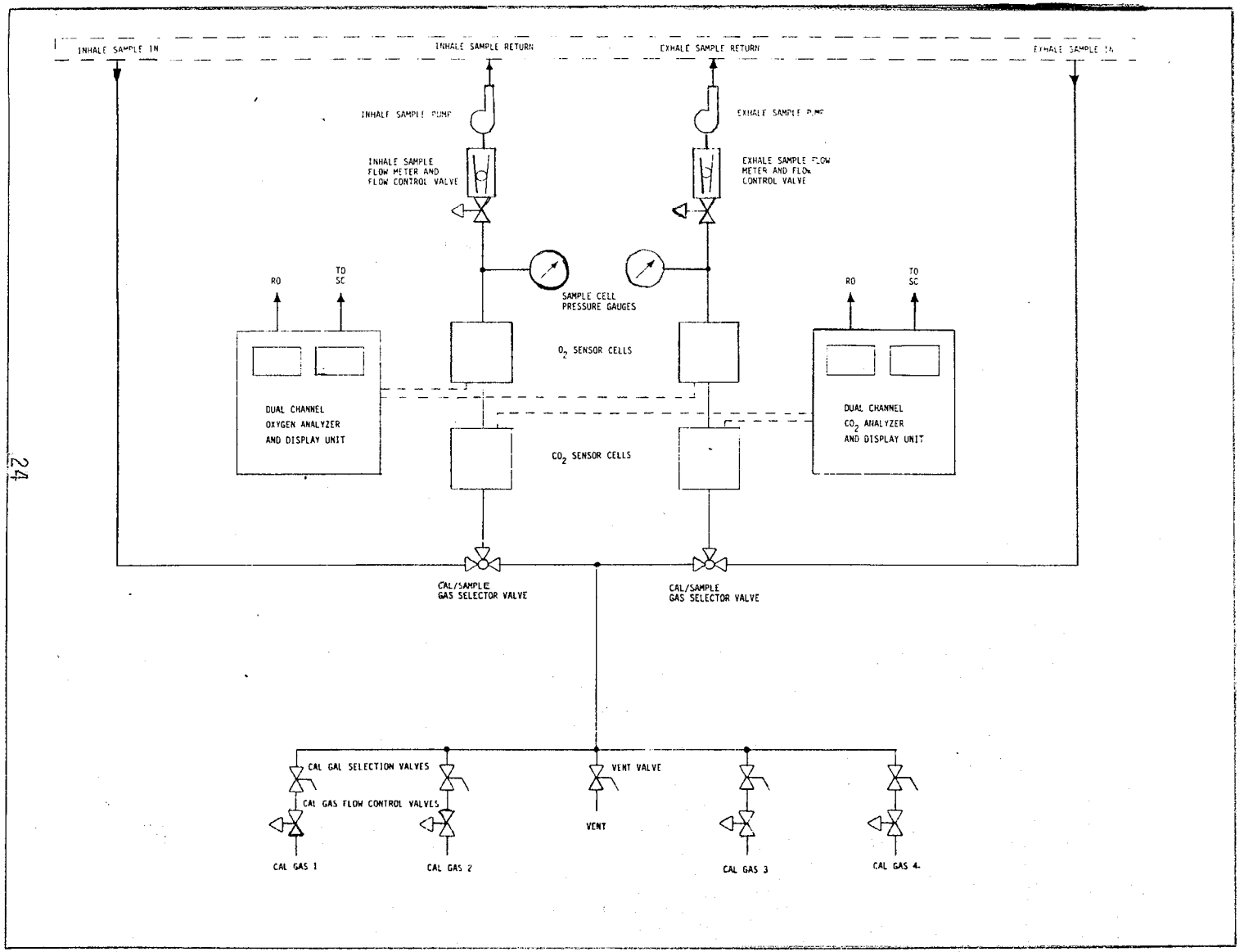

FIGURE 8. Gas Analysis Module Schematic

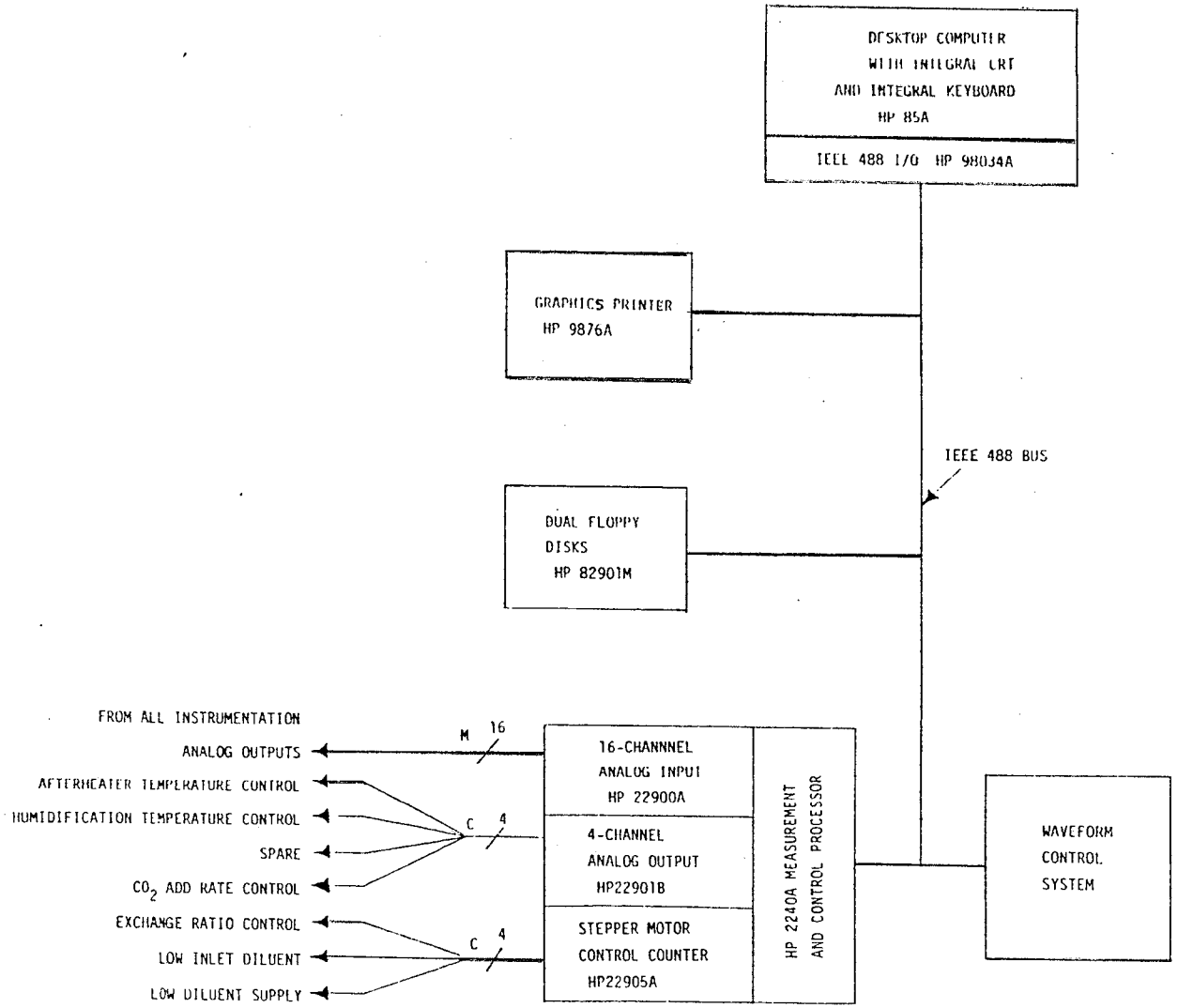

FIGURE 9. Supervisory Controller General Arrangement

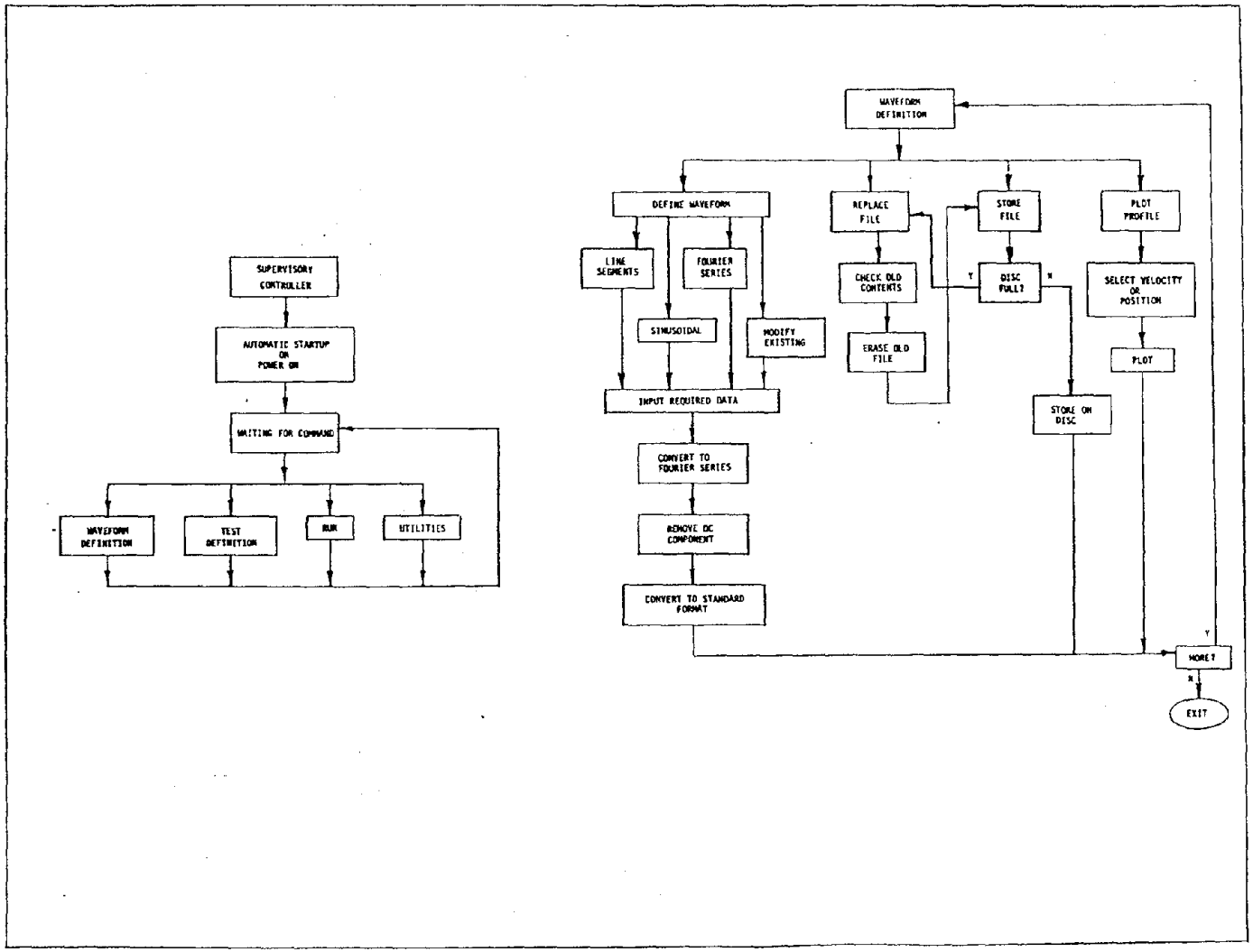

FIGURE 10. SC Startup and Waveform Definition Block Diagram

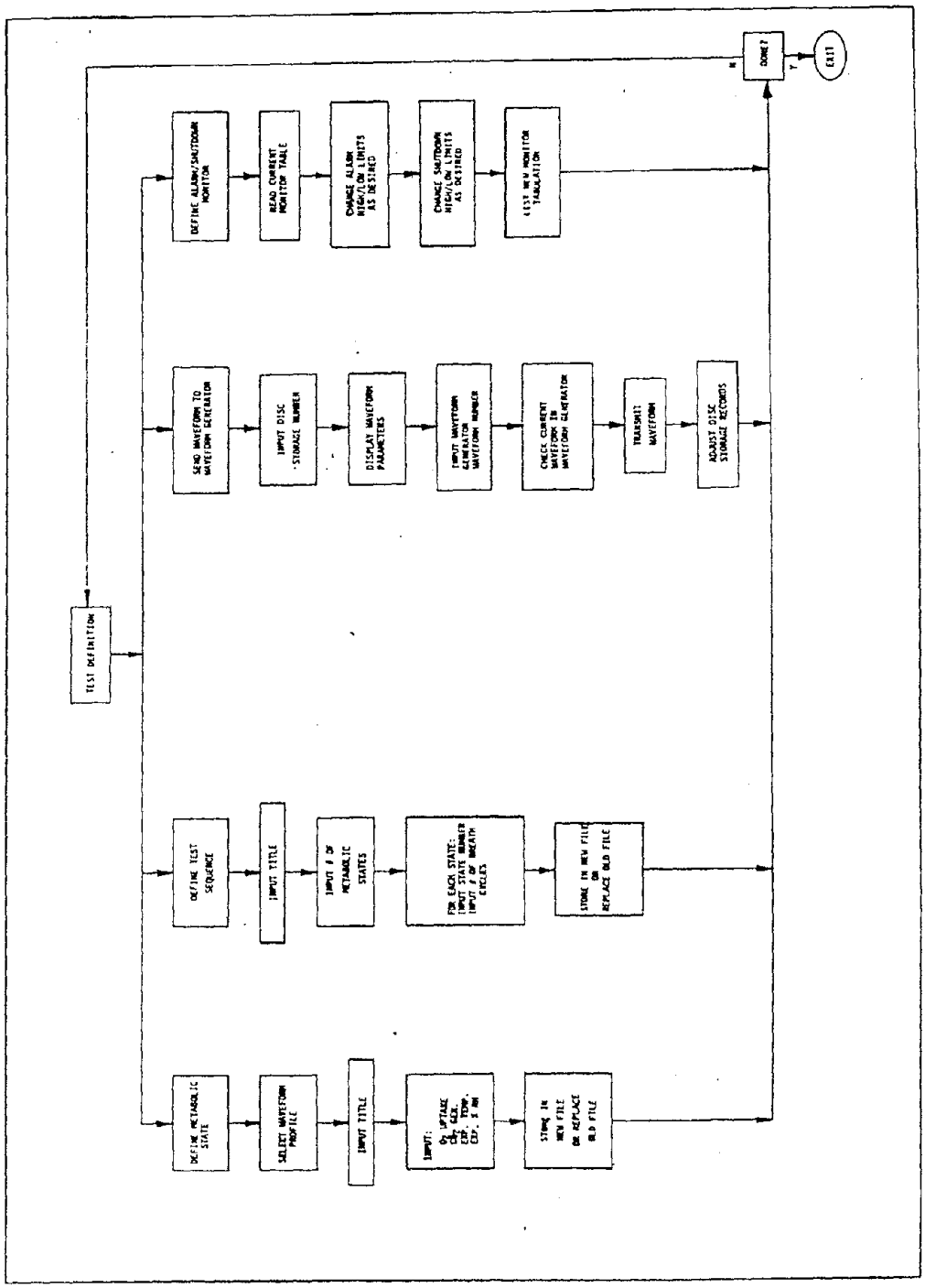

FIGURE 11. Test Definition Block Diagram

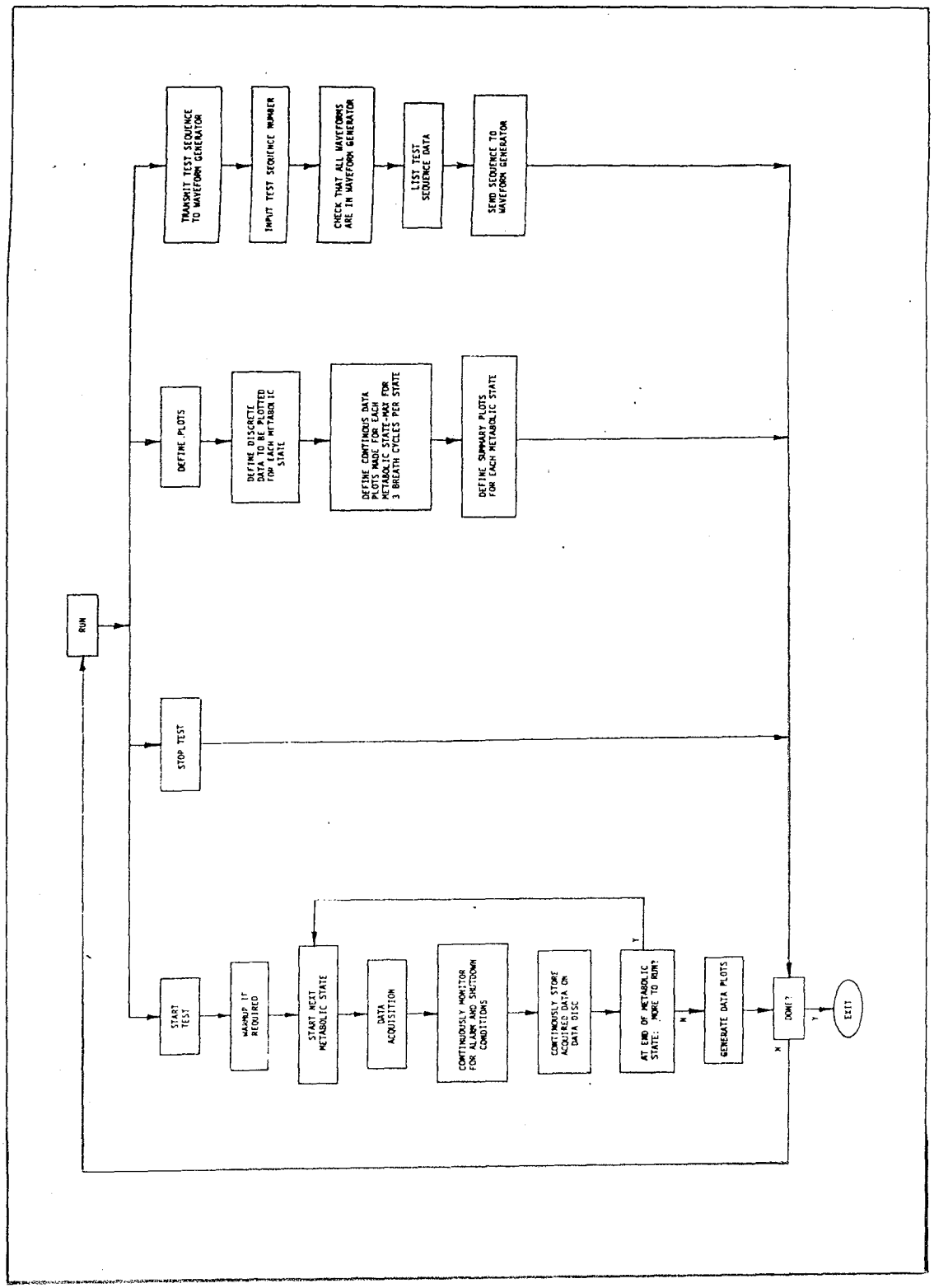

FIGURE 12. Run Program Block Diagram

a. Waveform Definition: Assists in developing waveforms, e.g., the parameters which describe the time-position-velocity profile of piston motion.

   - o Define Waveform - Build a profile from sinusoidal waveshapes, waveshapes made up of linear segments, or those described by a Fourier series.

   - o Store or Replace Waveforms - Provide permanent storage of the profile information on the magnetic disc.

   - o Plot Profile - Generate a plot of a profile for permanent record or for purposes of checking.

b. Test Definition: Generates a series of metabolic states, e.g., the parameters which describe all of the ABMS functions. Once generated, the test series can be automatically run on the ABMS in sequence with all control and data acquisition operations completed with minimal operator intervention.

   - o Define Metabolic State - Build a set of parameters including waveform profile, O_2 uptake, CO_2 generation, temperatures and humidities which specify all ABMS functions for a single test condition; for example, running at 3 mph. Table 2 is a sample list of metabolic states.

   - o Define Test Sequence - Set up a series of metabolic states, each to be run for a defined number of breath cycles. This sequence is then stored on magnetic disc for later transmission to the ABMS where it is used to control a full test series. A tabulation of test sequences is shown in Table 3.

   - o Define System Monitor - Generate a table of alarm and shutdown limits which is used by the SC to alert the operator to abnormal conditions and to shut down the system in the event of conditions hazardous to the ABMS.

   - o Transmit Waveform - Send data to the Waveform Generator through the IEEE-488 bus for storage in non-volatile memory. The Supervisory Controller maintains a record of which waveforms are currently in the Waveform Generator.

c. Run Test: Initiates and controls the operation of the ABMS, as well as the acquisition of data during the running of each test.

   - o Transmit Test Sequence - Sends the test sequence (waveforms and number of breath cycles for each) to the Waveform Generator via the IEEE-488 bus.

   - o Start Test - Parallels the START function on the Wavefrom Generator to initiate ABMS operation.

TABLE 2. Sample Listing of Metabolic States

METABOLIC STATE LISTING

STATE #	TITLE	BPM	TIDAL VOL	RES. VOL	I/X RATIO	O2 UPTK	CO2 GEN	EXP. TEMP	DEWP TEMP	WFORM G#	WFORM D#
1	STAND & SAMPLE	12.0	1.00	0.000	0.70	0.440	0.350	36.8	34.7	1	1
2	WALK-3 MPH	18.0	2.01	0.000	0.80	1.520	1.290	37.8	36.4	2	2
3	CLIMB	31.0	3.88	0.000	1.00	3.600	3.600	37.8	36.7	3	3
4	PULL-45 LBS	26.0	2.04	0.000	0.90	1.810	1.720	37.8	36.4	4	4
5	OVERCAST-50 LBSx4	14.5	2.00	0.000	0.70	1.190	1.010	37.8	36.4	5	5
6	RUN-6 MPH	32.0	3.01	0.000	1.00	3.060	2.910	37.8	36.5	6	6
7	OVERCAST-50 LBSx6	18.0	2.01	0.000	0.80	1.620	1.460	37.8	36.4	2	2
8	CARRY-44 LBS @ 3 MPH	28.0	1.98	0.000	0.90	1.920	1.820	37.8	36.4	7	7

TABLE 3. Sample Tabulation of Test Sequences

TEST SEQUENCE LISTING

SEQUENCE# 1 MAN TEST IV-50%ILE TOTAL OF 18 METABOLIC STATES & 1447 BREATHS

METABOLIC STATE #'s:
1 2 3 2 4 2 5 1 2 6 7 4 1 2 4 8 1 2
OF BREATHS:
36 36 31 36 130 54 116 24 72 32 162 78 24 108 130 84 24 270

SEQUENCE# 2 ABMS TEST 1 TOTAL OF 5 METABOLIC STATES & 145 BREATHS

METABOLIC STATE #'s:
1 2 3 4 6
OF BREATHS:
20 20 30 25 50

SEQUENCE# 3 TEST OF SYSTEM TOTAL OF 3 METABOLIC STATES & 36 BREATHS

METABOLIC STATE #'s:
1 3 5
OF BREATHS:
12 12 12

- o Stop Test - Similarly parallels the STOP function.

- o Define Plots - For each segment of the test sequence, defines which test parameters are to be plotted to provide a permanent record of test results.

d. Utility Programs: Provides various housekeeping functions for the ABMS system.

- o Disc Utilities - Enables simple disc initialization for data storage and duplication of program discs for safe program storage.

- o Lists - Provides hard-copy lists of the stored system information, including waveforms stored on disc and in the Waveform Generator, metabolic states and test sequences available, and an alarm/shutdown condition tabulation.

- o Calibration - Provides for calibration of the data acquisition system and outputs an archival record of the calibration data.

C. Simulation Parameters

As of the writing of this paper, work in the area of establishing optimum simulation parameters is continuing. However, the following comments can be made.

1. The metabolic states shown in Table 3 are based on the work of Kamon, et al (4). RC's experience with them (pre-NIOSH approval tests on two one-hour oxygen self-rescuers and one one-hour entry and escape device) has been that they produce apparatus performance on a simulator (RC's house simulator) which closely resembles the apparatus performance in actual man-tests.

2. Bernard et al (3) have published the equations for use with simulation tests of breathing apparatus for use by coal miners.

$$V_E = 8.35 + 15.7\ V_{O2}^{1.35}$$

$$V_{CO2} = 0.094 + 0.846\ V_{O2}^{1.18}$$

where:

V_E = minute ventilation, lpm, STPD

V_{O2} = oxygen uptake, lpm, STPD

V_{CO2} = carbon dioxide production, lpm, STPD

3. In the area of underwater breathing apparatus, well defined sets of simulation criteria have been published by Reimers (11), Morrison and Reimers (6) and Middleton and Thalman (5).

4. Myhre (7) has published results of the ventilation responses of Air Force firefighters to exercise that are useful when performing tests on breathing apparatus for firefighting use.

D. Summary

The ABMS described herein is a versatile machine capable of performing almost any physiologically appropriate respiratory simulation. Several sets of useful simulation criteria are also available for use. However, the establishment of widely accepted simulation criteria has not yet occurred and each investigator must satisfy himself that the simulations he is using are appropriate.

E. References

1. Automated Breathing Metabolic Simulator, Final Report, IBM Corp. to Bureau of Mines (Contract H0112269), January 1973.

2. Bartlett, R. G., C. M. Hendricks, and W. B. Morison. "Breathing Metabolic Simulator", Second Conference on Portable Life Support Systems, NASA SP-302, NASA, Washington, D.C., 1972.

3. Bernard, J. E., E. Kamon, and R. L. Stein. "Respiratory Responses of Coal Miners for Use with Mechanical Respirators", U.S. Dept. of the Interior, February 9, 1977.

4. Kamon, E., and T. Bernard. "Steady State Respiratory Responses to Tasks Used in Federal Testing of Self-Contained Breathing Apparatus", American Industrial Hygiene Association Journal, December 1975.

5. Middleton, J. R., and E. D. Thalman. "Standardized NEDU Unmanned UBA Test Procedures and Performance Goals", U.S. Navy Experimental Diving Unit Report 3-81, July 1981.

6. Morrison, J. B., and S. D. Reimers. "Design Principles of Underwater Breathing Apparatus", Chapter 3, Physiology and Medicine of Diving, Brailliere-Tindall, London, 1983.

7. Myhre, L. G., R. D. Holden, F. W. Baumgardner, and D. Tucker. "Physiological Limits of Firefighters", U.S. Air Force Engineering and Services Laboratory Report ESL-TR-70-06, NTIS No. ADA 079413, June 1979.

8. Reimers Consultants data unpublished as of the date of writing of this paper.

9. Reimers, S. D. "Testing Procedures for Closed Circuit and Semi-Closed Circuit Underwater Breathing Apparatus", U.S. Navy Experimental Diving Unit Report 19-74, January 1974.

10. Reimers, S. D. "Breathing Simulators for Use in the Evaluation of Underwater and Hyperbaric Breathing Apparatus". ASME Paper 77-WA/OCE-6 Winter Annual Conference, December 1977, Atlanta, Georgia.

11. Reimers, S. D. "Proposed Standards For The Evaluation of the Breathing Resistance of Underwater Breathing Apparatus", U.S. Navy Experimental Diving Unit Report 19-73, January 1974.

12. Sparks, A. W., R. L. Stein, and J. W. Stengel. "A Breathing Metabolic Simulator for Testing Respiratory Protective Equipment", RI 8496, Bureau of Mines Report of Investigations/1980.

13. Webb, M. D. Bioastronautics Data Bank, NASA SP-3006, NASA Scientific and Technical Information Division, Washington, D.C., 1964.

II. SYSTEM DEVELOPMENT

This section covers the construction of the ABMS and associated software. Emphasis is placed on any changes made to the Phase I Design Plan and performance specifications to achieve the present configuration. Recommendations are presented on any areas where current experience indicates that improvements might be made.

A. Hardware Subsystems

1. Waveform Generator/Drive System

The present drive system is basically the one conceived in the original design. The rack and pinion drive was changed to a ball screw drive in order to reduce mechanical backlash and to obtain smoother operating performance. The ball screw drive performance has been found to be eminently satisfactory. An optical rotary position encoder was chosen to provide waveform position information to the Waveform Generator. Because of the layout of the various oxygen uptake and main piston components, it was necessary to limit the tidal volume stroke to 3.5 liters and the actual exchange ratio to approximately 0.21. It is felt that this should pose little, if any, limitation on testing capabilities. Some slight modifications in the layout geometry in future design will allow larger tidal volumes and exchange ratios to be obtained, if necessary. The original bellows design of the main air cylinder was changed to a rolling seal piston design. The reasons for this are discussed in Section II.A.2.

Overtravel limit switches have been installed on both the main drive and the exchange ratio drive to protect the mechanics of those systems.

2. Oxygen Uptake (Figure 6)

The basic design of this system has not been changed from the original design. However, a few changes have been made in certain components. First and foremost, the bellows pumping mechanisms were changed to rolling seal pistons in order to improve the performance of the system under the various operating conditions specified (see Section III.A.2.b. for a full discussion of volume fidelity requirements). The rolling seal pistons have been found to perform very predictably and reliably to date. A vacuum system was added in conjunction with the rolling seal pistons for the reasons given in Section I.B.1. The vacuum system, consisting of a few valves and a simple constant displacement diaphragm pump, is very reliable and should require very little maintenance or attention.

A heat exchanger was added to the line between the process breathing loop and the removal cylinder. The purpose of this is to reduce the removal gas temperature to a known, predictable value for better control of the gas exchange in the uptake process.

Next, several check relief valves were tried in the supply and removal cylinder lines before the present valves were settled upon. The performance of these valves was found to be crucial to the proper functioning of the uptake system under various operating conditions. The valves need to work smoothly and at repeatable cracking pressures and must permit no backflow on closing (a specification which most check valves do not meet in practice). The Circle Seal valves used are felt to be the best obtainable for this stringent application, and they have the added advantage that their cracking pressures can be adjusted to a limited extent without completely removing them from the line and disassembling them.

3. Temperature and Relative Humidity (Figure 4)

This system has been built according to the preliminary design with the addition of humidity monitoring instrumentation for the inhale circuit. Efforts were made in certain areas to upgrade the reliability of the plumbing and to add protective features for system components.

The plumbing used in this system consists of clear, rigid PVC tubing and flexible PVC fittings to allow visual monitoring of system conditions (moisture accumulation, etc.). Plumbing is joined to flow components with hose clamps to permit easy disassembly. All other joints are permanently made using solvent cement. The manufacturer of this plumbing system states that it is very reliable, and so it has appeared to be up to this writing. We recommend that, if a glued plumbing joint should fail in the future, the joint simply be hose clamped.

The bubble chamber box design was improved to incorporate a seamless lexan box. All plumbing connections to the box are made with o-ring seal joints to provide positive leak protection. In addition, a water temperature limit switch has been added to the bubble chamber heater circuit in order to protect the bubble chamber from a situation in which the heater circuit is energized when the simulator is off and thus not pumping air through the bubble chamber. One other condition that needs to be protected against is low water level in the bubble chamber. If the water level falls below the heater rod, heat is not conducted away from the rod fast enough and the box's plastic around the heater's threaded fitting can melt, ruining the box. Water level may presently be monitored by an operator via a water level tube on the front of the simulator. We recommend that the operator be relieved of full responsibility for protecting the bubble chamber by the installation of a small liquid level switch in the water level monitoring circuit which would turn off the bubble chamber heater circuit at low water level (much like the temperature limit switch does now). Time did not permit the installation of this

switch arrangement. Finally, it was determined during operation of the system that the rheostats in both heater circuits were necessary. In order to simplify system operation and reduce maintenance, these rheostats were eliminated.

4. Carbon Dioxide Add (Figure 5)

A few minor changes were made in the initial design to improve system performance. A pressure switch, operating from CO_2 supply line pressure, was fed to the Supervisory Controller to provide a low supply pressure warning that would allow time to switch to a new CO_2 supply during testing. A flow select valve was added to the circuit so that CO_2 may be added to the main cylinder, to the supply cylinder, stopped, or vented as required. Finally, a CO_2 volume accumulator bellows was added to the diluent supply plumbing (Figure 6). During the half breathing cycle when the supply cylinder is pumping gas to the exhale line, the supply cylinder inlet check valve is closed. The CO_2 volume accumulator prevents the buildup of pressure in the diluent supply line due to the entering CO_2 which would otherwise tend to distort the supply cylinder pumping volume (because of the effect of cylinder clearance volume) and decrease the volume fidelity of the uptake system. One condition was noted during operation of the system which necessitates operator attention during running of the simulator. That is, when a zero CO_2 flow setpoint is given to the flow controller, there may be leakage of between 0 and 10 cc/min. CO_2 through the control valve. Thus, the operator should turn the flow selector valve to "OFF" or "VENT" whenever CO_2 flow to the breathing system is to be off in order to prevent buildup of unwanted CO_2 in the breathing loop. A way around this, if it is found to be a problem, would be to install a normally closed solenoid valve in the plumbing between the selector valve and the flow controller. The solenoid could be activated, via appropriate circuitry, by the control signal to the flow controller of above 50 or 100 mV (a flow command of 40 or 80 cc/min.), for example.

5. Gas Analysis Module (Figure 8)

A few minor modifications were made in the original design to improve performance and to satisfy Bureau of Mines requirements. It was originally planned to mount calibration gas cylinders in the Gas Analysis Module cabinet. This was changed to mounting four calibration gas connectors on the cabinet to which externally supplied calibration gases could be routed. In conjunction with this, each of the four calibration gas channels was supplied with a needle valve which is to be used to control calibration gas pressure to the analysers' sample cells; it is necessary that the analysers be calibrated with sample cell pressures equal to the pressures of the measured unknown gases.

One feature was added to the CO_2 analyser inhale channel which may be found useful in practice - the option to select either of two recorder voltage output scales, HI or LO, for given CO_2 indications. The HI setting has been calibrated to provide a 0-5

VDC output for a 0-5% CO_2 reading, while the LO setting will provide the 0-5 VDC output over a 0-2% CO_2 indication range. The LO range selection may provide better data for many test situations in which inhale CO_2 concentrations can be expected to be well under 2%.

Experience to date has shown the Gas Analysis Module and its components to be extremely reliable. If, in future day to day continuous use of the apparatus, water vapor is found to accumulate in the analyser plumbing, it is suggested that water traps or even desiccant filters (if the problem should be severe enough) be installed in the sample inlet lines.

6. Differential Pressure Measurement (Figure 7)

One change made from the original design was to add a crossover valve in the transducer circuit which allows the (differential) transducer to be calibrated for both positive and negative pressures from a single (positive pressure) calibration source.

During calibration testing of the system (III.A.6.), it was found that the panel differential gauge, because of its relatively large volume capacity and its position in the system (originally connected in parallel with the transducer), acted to significantly dampen pressure signals received from the test ports during dynamic operating conditions. For this reason, the gauge was plumbed into its present position (Figure 7) directly to the right test port line downstream of the five-way selector valve. In this position, the damping effect of the gauge is almost negligible since the damping is not combined with the resistive effects of the selector valve and crossover valve flow restrictions. Only the high frequency (above 10 Hz) components of the pressure signal are damped in this configuration, an effect which is not important for most work. The gauge may be removed from the line altogether by uncoupling the quick connect fitting. Comparison of dynamic pressure signals received by the transducer with and without the gauge in the line are presented as Appendix C to the ABMS Operating Manual.

B. Software/Programming

1. Waveform Generator (WG)

The building and programming of the Waveform Generator microprocessor unit was carried out as in the original design plan. The Waveform Generator, when run by itself (i.e., not under control of the Supervisory Controller) has been found to perform reliably and according to the specified objectives. However, when the Waveform Generator is functioning under the control of the Supervisory Controller (SC), there occurs, in apparently random fashion, a loss of communication between the two which causes a system shutdown. The source of this problem has not yet been located. The following analysis of this loss of motor control is based on knowledge existing at the time the simulator was shipped.

It has been observed that the ABMS piston, under certain conditions, is driven to the limit switch position. The following points have been noted regarding this loss of normal waveform control:

1) It only occurs when the Waveform Generator (WG) is operating under supervisory control from the HP-85.
2) The frequency of occurrence increases with RMV, seldom occurring below an RMV of 50 to 60 liters per minute.
3) The actual occurrence is quite random within the above constraints.
4) The probability of hitting the upper or lower limit switch is about equal.
5) The velocity during loss of control is constant, and is equal to the desired velocity immediately prior to loss of control.
6) Loss of control occurs during or immediately after the period when the "Computer Communication" (CC) light is illuminated.

The following is postulated as the cause of this problem. It has not been proven as the cause, since no success in solving the problem based on this analysis has been had.

During the portion of the data acquisition cycle when data is being written to the data disc, the CC light remains "ON" longer than at other times. The extent of time it is "ON" varies randomly. This may be explained due to the expected variation in disc access time with disc position at the start of disc write.

The WG system is interrupt driven; that is, all of its functions are controlled by a hardware-vectored priority interrupt system. This includes both the motor control system (responding to an interrupt generated by the position encoder) and the computer communication (responding to an interrupt generated by the IEEE-488 interface circuit). It is postulated that the delay in responding to the CC interrupt caused by slow disc write interferes with the motor control interrupt. The exact form and sequence of interference has not been determined, although many attempts have been made to diagnose and correct the interference.

Two approaches to solving the problem are possible:

1 - Diagnose and correct the interrupt interference. So far, this approach has not been successful.
2 - Eliminate the interference by reducing disc access time. This approach will also solve a second problem briefly noted below. Access time could be reduced by using a disc with fast access (such as a Winchester hard disc), or by utilizing random access memory for data storage during execution of each metabolic state followed by transfer to disc storage between metabolic states.

A second ABMS problem occurs at high BPM's, especially when per-breath data is stored on the data disc. Delays in disc access cause loss of synchronization between the WG and the HP-85, resulting in the HP-85 not responding to the end of a metabolic state, and on occasion resulting in a halt in 2240A data acquisition. Since this problem was overshadowed by the problem of loss of motor control, little effort was expended in solving it. A reduction in disc access time will eliminate this problem also.

2. Supervisory Controller (SC)

All of the programs for the SC have been completed in basically the form envisioned in the Design Plan. Due to the limits on the storage capacity of the data (floppy) discs, provision has been made in the "Run" program to change data discs during a long test when the disc is filled up and to print out the data at a later time. A subroutine has also been added in the "Disc Utility" to enable the user to clean the heads of the Disc Drive unit. It has been found extremely important to clean the heads regularly in order to avoid numerous problems which can arise when erroneous data transmission occurs as a result of dirty heads. It has also been found important to use the mass storage mediums (floppy discs) no longer than is recommended by the disc manufacturers. For this reason, a disc copying subroutine is also included in the software.

III. TEST REPORT

A. Subsystems/Hardware

1. Waveform Generator/Main Drive

a. Main Cylinder Tidal Volume. The tidal volume (TV), or main cylinder pumping volume was determined by coupling the output of the main cylinder to a medical gas spirometer and turning the drive mechanism by hand. The data was corrected to STP conditions, and this information was used to construct a Tidal Volume Scale from which further determinations of system performance could be determined. Spirometer data was also obtained with the simulator running at several moderate BPM rates to determine that the actual pumping volume was independent of BPM.

b. Waveform Control. Waveform parameters BPM, TV, and Inhale/Exhale Time Ratio were checked to compare actual performance against those values programmed into the Waveform Generator (for simple sinusoidal waveforms). Actual tidal volume during simulator operation, as determined by observation of the TV pointer/scale assembly and by the results of the data printout for "Piston Position", conformed very precisely to the programmed values. The measured BPM were generally on the order of 4% to 6% higher (see Table 4) than the values programmed into the Waveform Generator. The reason for this has not been determined; however, the BPM indicated on the WG panel display is an accurate representation of the actual value. Table 4 also illustrates that the I/X (Inhale/Exhale Time Ratio) values, as determined from strip chart recordings of piston velocity transducer output, are reasonably close to the programmed values.

2. Oxygen Uptake System

a. Leak Tests

Leak testing of breathing loop plumbing. After the hardware was installed and all mechanical adjustments of the previous section were made, the entire breathing loop system was tested for leak tightness. This test was performed by connecting a medical gas spirometer to the test port and running the simulator at moderate breathing rates with the Exchange Ratio (i.e., Oxygen Uptake Ratio) set to zero. With the ER equal to zero, the breathing loop functions as a closed loop system (no gas is being pumped into or out of the loop) and any leakage out of the breathing loop envelope would show up on the spirometer as a steady loss of volume. In this way leaks in the entire breathing loop plumbing were detected and corrected and the system was made leak free.

TABLE 4. Comparison of Measured I/X and BPM Values With Programmed Values

WAVEFORM STORAGE LISTING

DISC #	TITLE	MEASURED BPM	BPM	TIDAL VOLUME	RESIDUAL VOLUME	I/X RATIO	W/G #	I/X RATIO (MEASURED)
1	12 BPM*TV=1*I/X=.7*SINE	12.4	12.0	1.000	0.000	0.70	1	0.748
2	18BPM*TV=2.01*I/X=.8*SINE	18.7	18.0	2.010	0.000	0.80	2	0.809
3	34.5BPM*TV=3.5*I/X=1*SINE	36.3	34.5	3.500	0.000	1.00	3	1.025
4	26BPM*TV=2.04*I/X=.9*SINE	27.4	26.0	2.040	0.000	0.90	4	0.912
5	14.5BPM*TV=2*I/X=.7*SINE	15.0	14.5	2.000	0.000	0.70	5	0.718
6	32BPM*TV=3.01*I/X=1*SINE	33.9	32.0	3.010	0.000	1.00	6	1.000
7	28BPM*TV=1.98*I/X=.9*SINE	29.7	28.0	1.980	0.000	0.90	7	0.895
8	WARMUP WAVEFORM-20BPM*2L SINE	20.7	20.0	2.000	0.000	1.00	20	0.973
9	BPM TEST	31.6	30.0	3.000	0.000	1.00	15	
10	SINUSOIDAL TEST 2		25.0	2.500	0.500	1.15		
11	KKKKK		22.0	2.000	0.500	1.00		

b. Volume Fidelity

The next step in calibrating the uptake system was to test the effectiveness of the heat exchanger in the removal lines. This was accomplished by inserting a thermistor in the removal cylinder through the removal cylinder exhaust line in order to measure the temperature of the gas in the removal gas at various pumping rates. It was found that the removal gas was brought to within 4°F of room temperature even at the highest pumping rates (i.e., high BPM, TV, and ER settings and high inhale temperatures). At more moderate pumping rates, the removal gas was brought to within 1°F to 2°F of room temperature. These figures were within the design targets which were felt necessary in order to achieve volume fidelity on the order of 0.1%.

c. Exchange Ratio Control

Adjustment of the volume fidelity of the uptake system was carried out next. In simple terms, volume fidelity is related to the balance between the volumes of gas removed from the breathing loop and the gas added to the loop in the gas exchange method used in the present simulator. Ideally, the two volumes should be equal, but because of component tolerances and a wide range of dynamic operating conditions, there will be a small range of differences between these volumes which we relate to the tidal volume and call "volume fidelity." The design goal was to achieve volume fidelities within the range of 0.1% of tidal volume over the operating range of the machine, a fairly stringent goal. The results of our tests and adjustments indicate that we have achieved this goal. Again, a medical gas spirometer was connected to the breathing loop test port and the simulator was run at various breathing rates, tidal volumes, and exchange ratio settings. For each condition (run over a 5 to 10 minute period) the net change in system volume per breath was determined from the spirometer. Adjustments were made in the cracking pressures of the in-line adjustable check valves in the uptake system (for a detailed discussion of this adjustment procedure, see the ABMS Operating Manual) based on this data array. The test procedure was then repeated, as necessary, until the data array was judged to fall within an optimal value, i.e., until the changes in volume were within about $\pm$ 0.1% of tidal volume. Table 5 is a presentation of the data obtained from the final test. It is expected that such factors as changes in check valve spring constants over time may shift these values slightly, but we believe the data to indicate the basic soundness of the design.

Based on the test results, it is believed that the system volume fidelity is most sensitive to the properties of the in-line check valves used. The system can tolerate no check valve back flow, and the valves must operate smoothly

TABLE 5. Volume Fidelity Test Data - 8/1/83

Waveform		ER Lever Position	d (System Vol.)/dt		Vol. Fidelity
TV (l)	BPM	(inches)*	(cc/min)	(cc/breath)	(cc/breath/TV)X100%
1.0	12.5	1.00	+4	+0.32	.03
1.0	12.5	3.50	+3	+0.24	.02
1.0	12.5	5.00	+14	+1.12	.11
2.0	20.7	1.00	+18	+0.87	.09
2.0	20.7	3.50	+8	+0.39	.02
2.0	20.7	5.00	+42	+2.03	.10
3.0	33.9	1.00	+18	+0.53	.02
3.0	33.9	3.50	+40	+1.18	.04
3.0	33.9	5.00	+4	+0.12	.004

* Zero defined as position at which no uptake cylinder motion occurs (approximately 0.275 inches from end block).

reproducibly under all flow conditions. Several check valve brands were tested with the system before the final valve was selected. The valve selected is felt to be very reliable for this stringent task and to far surpass the other valves in performance and utility.

d. Actual Exchange Ratio Measurement

The final calibration procedure performed on the uptake system was to determine the Actual Exchange Ratio, i.e., the actual pumping volumes as a fraction of tidal volume for various exchange ratio lever arm settings. The medical gas spirometer was connected to the outlet of the removal cylinder exhaust line and the simulator was run at various tidal volumes and exchange ratios. It was found that the Actual Exchange Ratio was dependent on tidal volume as well as on the setting of the Exchange Ratio lever arm. From these datum a graph of actual exchange ratio versus exchange ratio lever arm position for several tidal volumes was constructed and presented in the ABMS Operating Manual. The datum were also incorporated into a look up table in the Supervisory Controller for use in control of the uptake system.

e. Diluent Add System

This relatively simple component has been found to function reliably and to require little attention. The alarm and shutdown pressure switches were adjusted to their proper values and then tested in conjunction with the automated control system - the Supervisory Controller (SC). The switches, when tripped, caused the proper alarm flags and shutdown routines to be executed by the SC. It should be mentioned at this point that all of the other safety switches in the ABMS system (CO_2 supply switch, main drive limit switches, Exchange Ratio control limit switches, humidification chamber temperature switch, and the vacuum system pressure switch) have been similarly adjusted and tested for proper function.

3. Temperature and Relative Humidity (TRH)

The system plumbing was installed and leak tested in conjunction with and in the same manner as the plumbing in the oxygen uptake system. The temperature controller/indicating devices are standard, reliable instrumentation which has functioned properly and without incident. The H_2O temperature limit switch for the bubble chamber was adjusted to 125°F using the temperature readout of the bubble chamber temperature controller as a control. The relative humidity indicators were found to function reliably as long as their probes did not become over saturated or too dry.

4. CO_2 Add System

All system plumbing, especially that downstream of the flow controller, was pressure tested for, and brought to, leak tightness. Actual CO_2 flow was determined using a medical gas spirometer and compared to the CO_2 Flow Control Indicator on the panel. The indicator was thereby calibrated according to the manufacturer's instructions (Operating and Maintenance Manual). The mass flow controller has proven to be an extremely reliable unit which exhibits very quick (less than 1 second) response to changes in setpoint commands. It is well suited to use with computer control and is also very easy to control manually.

5. Gas Analysis Module (GAM)

All plumbing of this system was pressure tested for leak tightness and brought up to a completely leak free condition. The oxygen and carbon dioxide analyser readouts were compared against several calibration gases and found to be within the manufacturer's specifications. Extensive experience to date with these analysers has proven them to be very reliable and relatively easy to operate for this type of equipment. Their stability over time has also proven to be quite good.

6. Differential Pressure Measurement (DPMS)

All plumbing in this system was pressure tested for leak tightness and all joints tightened, as necessary, until a leak-tight system was obtained. Then the data output of the DPMS pressure transducer was tested under simulator dynamic operating conditions to verify the truth of the data. This was done by teeing a separate transducer into the pressure measurement line directly at the test location. The calibrated outputs of this transducer and the ABMS transducer were displayed on adjacent channels of a strip chart recorder for direct comparison. Initial tests indicated significant damping of the pressure signal by the DPMS plumbing by the time it reached the transducer. Quick connect bulkhead fittings with small orifice diameters were replaced with full diameter bulkhead fittings and the position of the DPMS panel gauge was changed in the plumbing layout (see Section II.A.6.). These measures proved sufficient to bring the performance of the DPMS to an acceptable level.

B. ABMS System

In November 1983, full scale tests were conducted on several types of breathing apparatus in the presence of Bureau of Mines personnel. Except for the communication loss problem (see Section II.B.) with the Supervisory Controller, which made it impossible to run a 60-minute test without interruption, the simulator was judged to function satisfactorily. Figure 13 is a computer-generated printout of all test data for minutes 35 through 60 for one of these tests. The plotting format has been changed slightly since these tests to include a time axis on the printout to aid in data interpretation. As can be

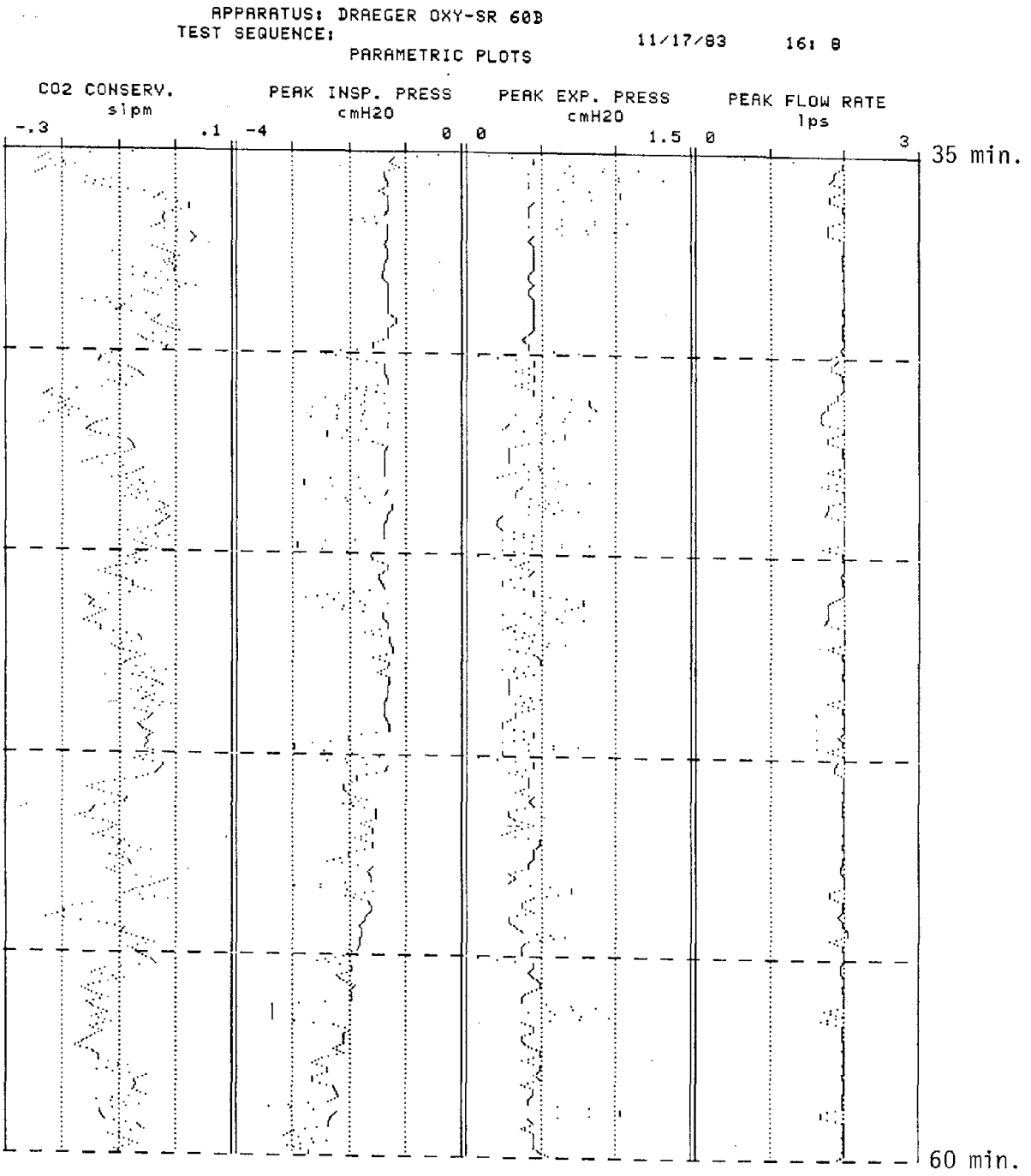

FIGURE 13. Results of Breathing Apparatus Test

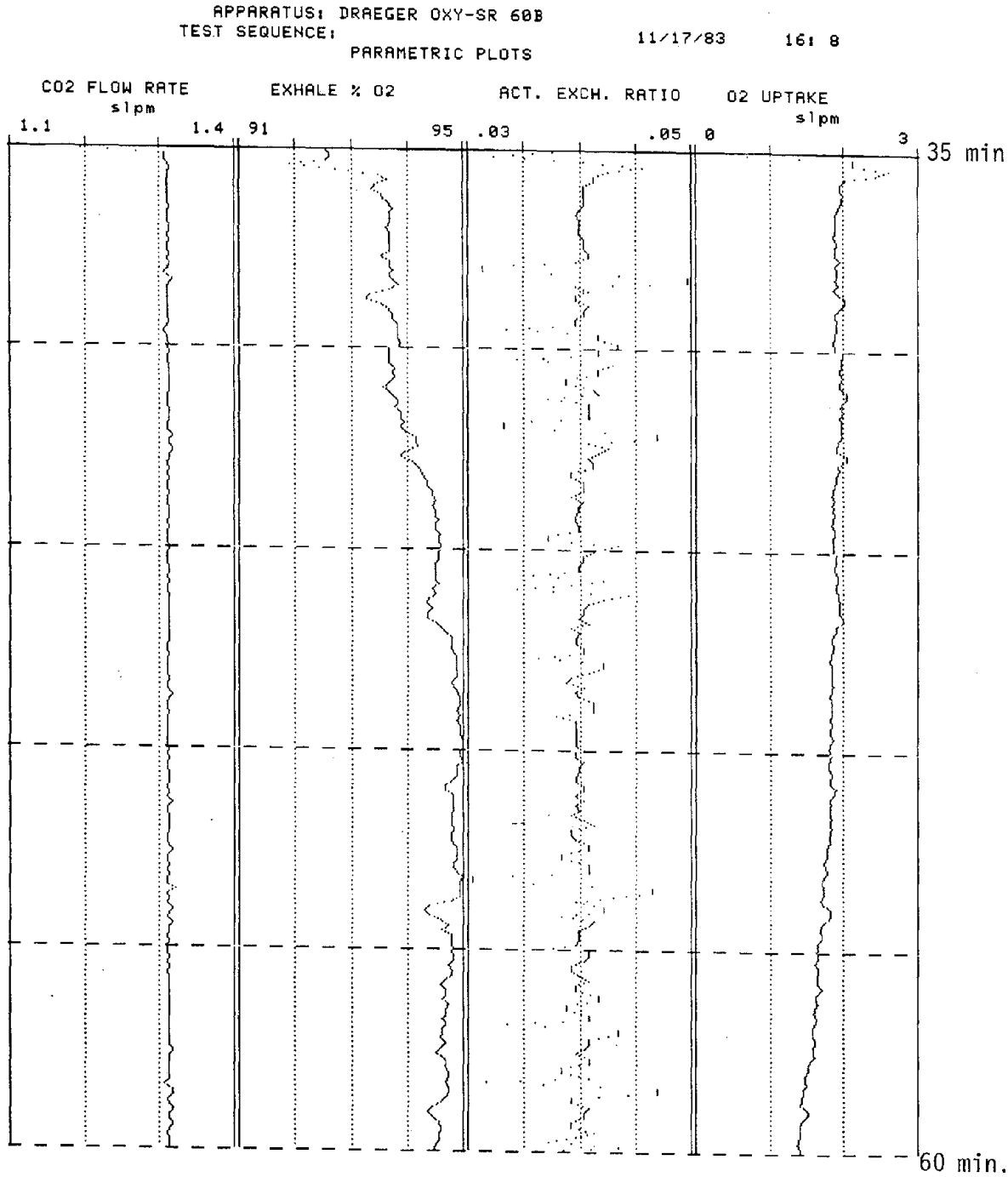

FIGURE 13. Results of Breathing Apparatus Test (Continued)

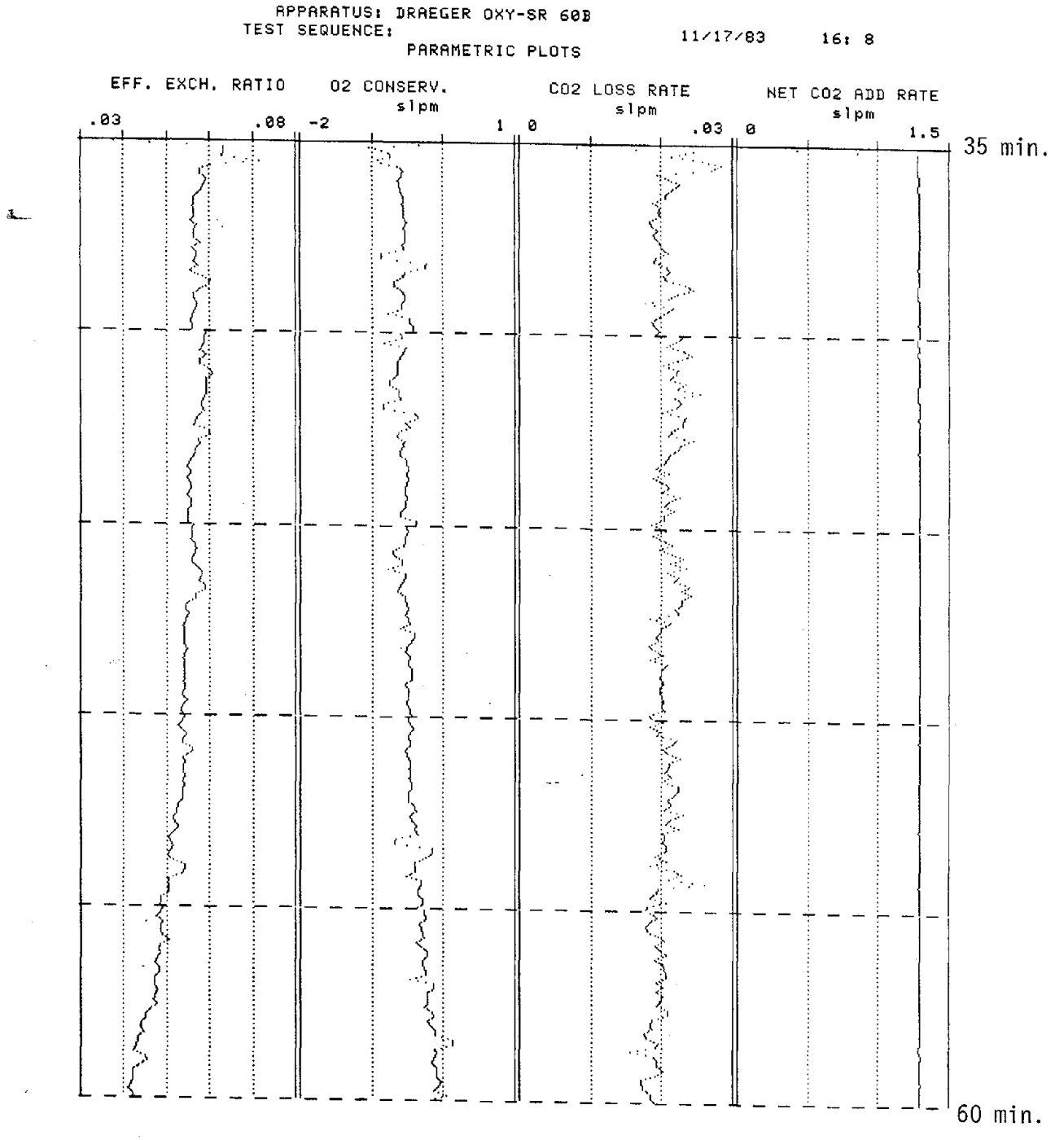

FIGURE 13. Results of Breathing Apparatus Test (Continued)

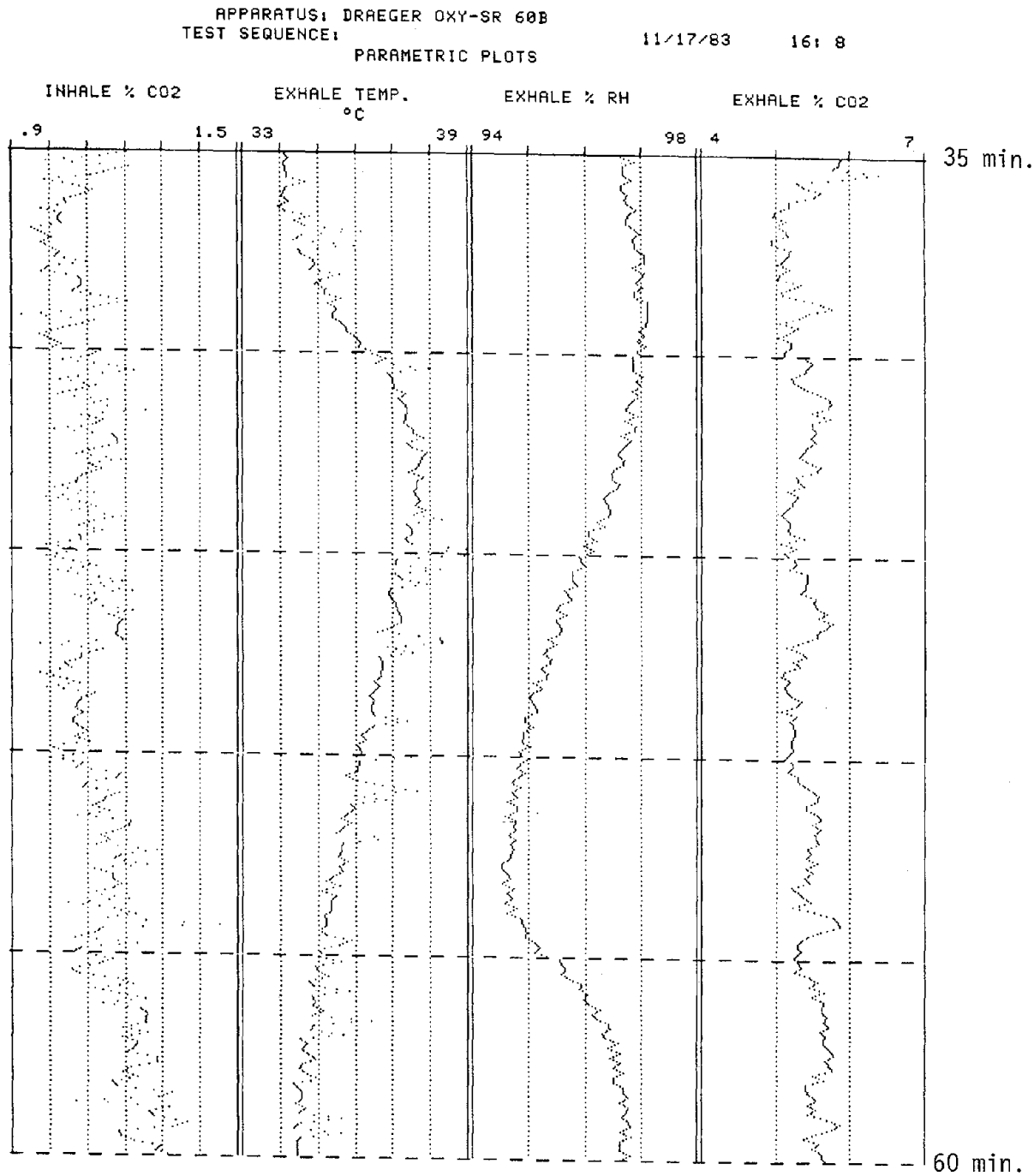

FIGURE 13. Results of Breathing Apparatus Test (Continued)

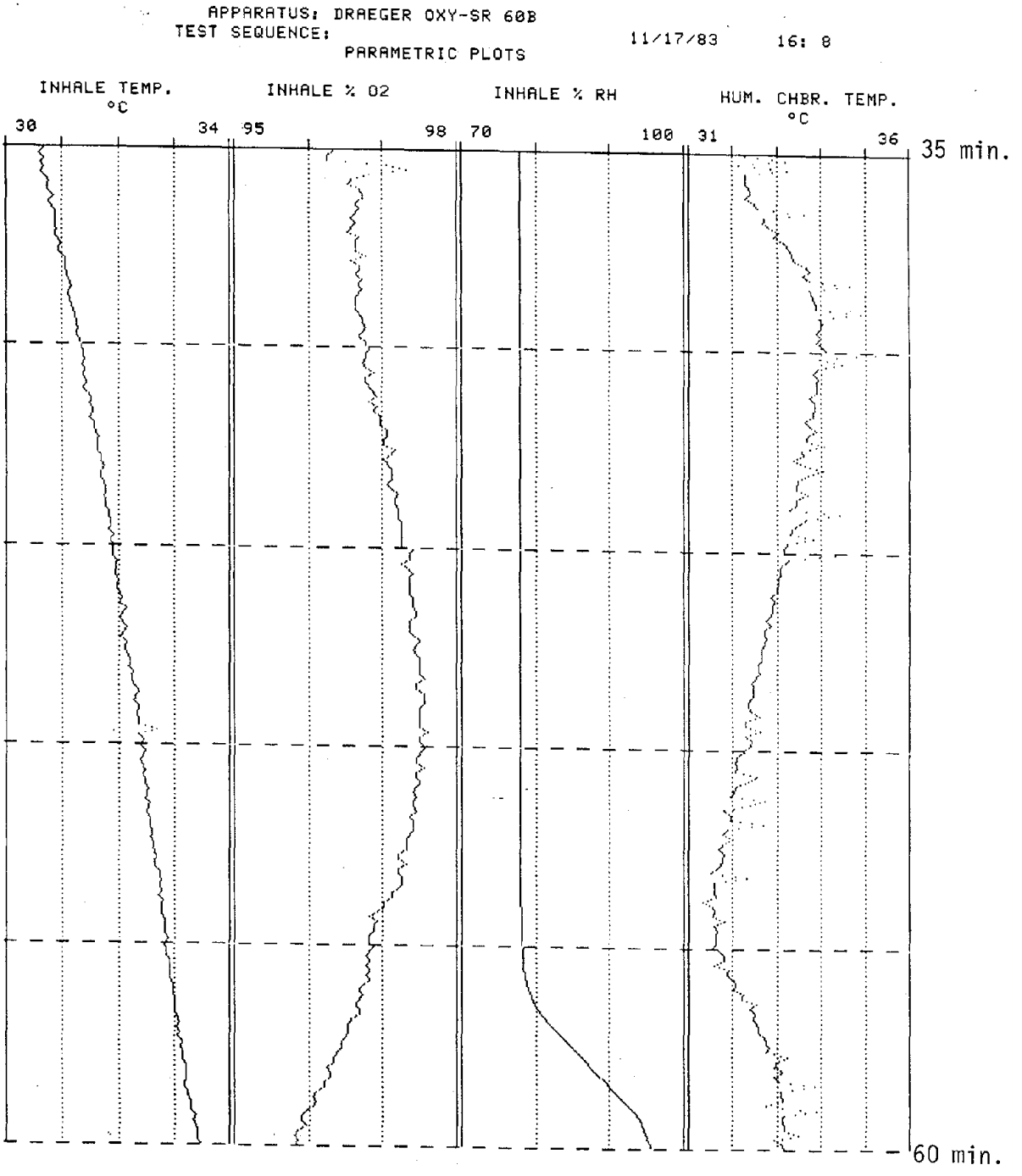

FIGURE 13. Results of Breathing Apparatus Test (Continued)

seen in the figures, many of the plots (peak inspired and expired pressures, inhale O_2%, inhale CO_2%, inhale temperature and R.H., etc.) pertain to the performance of the apparatus being tested while the other parametric plots are checks on the physiological parameters being simulated (exhale parameters, CO_2 add rate, O_2 uptake, etc.) and checks on simulator performance (O_2 and CO_2 conservation, actual exchange ratio, etc.) during the test.

Since these performance tests were conducted, the simulator hardware has been further fine tuned to provide accurate data and better stability in the performance of the oxygen uptake system as part of the final shakedown of the system.