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GENERAL DESCRIPTION AND EVALUATION OF AN ON-LINE OXYGEN UPTAKE COMPUTER

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Foreword

This study was accomplished by the Biothermal Branch, Environmental Medicine Division, Biomedical Laboratory of the Aerospace Medical Research Laboratories. This report represents one phase of the research and development programs being conducted by the Biothermal Branch under Project 7222, "Biophysics of Flight," Task 722207, "Human Thermal Stress."

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This technical report has been reviewed and is approved.

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Abstract

A series of experiments has been designed to evaluate the performance of an oxygen uptake computer. The Model OCC-2500 oxygen uptake computer is an electronic instrument including a mask-sensor assembly and a special-purpose analog computer. Intended for the analysis of respiratory gases in human subjects, the system produces a real-time analog voltage proportional to the oxygen uptake in one minute or other time periods controlled by the operator. Expired air samples, monitored by the polarographic oxygen sensor and mass gas flowmeter of the computer system were simultaneously collected in a gasometer and analyzed by gas chromatography. Oxygen uptake values (200-3200 cc/min) obtained from 15 subjects (297 observations) during rest and after exercise produced a sample correlation coefficient of 0.998. Subjects enjoy virtually unrestrained mobility using the device, in that attachment to monitoring equipment is limited to electrical leads. Personnel support requirements and errors, associated with conventional procedures, are significantly reduced. The compact nature of the device permits application in almost any experimental design situation including pressurized suits and underwater studies.

SECTION I.
Introduction

Under circumstances which are peculiar to our experimental programs, we often find it impractical, if not impossible, to determine oxygen uptake using conventional procedures. Isolation and restrictive confinement of the subject in environmental simulators as well as programs involving environmental extremes usually preclude the use of Douglas bags, spirometers, and related equipment.

The Model OCC-2500 oxygen uptake computer was developed under United States Air Force contract with Technology Incorporated, Dayton, Ohio. Its construction and functions are based on principles incorporated into a prototype model designed by the Aerospace Medical Research Laboratories (ref 1).

The OCC-2500 is an electronic instrument including a mask-sensor assembly and a special-purpose analog computer. Intended for the analysis of respiratory gases in human subjects, the system produces a real-time analog voltage proportional to the oxygen uptake in one minute or other periods controlled by the operator. In this evaluation study the configuration of the mask-sensor assembly has been modified to synchronize the output of the OCC-2500 with the collection of expired air in a gasometer. Appropriate statistical correlation analysis can then be applied to the OCC-2500 output and data derived from conventional oxygen consumption determination procedures. The purpose of this report is to satisfy two requirements: first, to describe the construction and operation of the OCC-2500 complex, and second, to present data obtained from an extensive evaluation study that establishes the device as a valuable research and operational tool.

SECTION II.

General Description of the OCC-2500 Oxygen Uptake Computer

THEORY OF OPERATION

Oxygen Consumption Equation

The mass of one of the constituents of a gas mixture may be determined from the equation of state of an ideal gas assuming constant volume and temperature as follows:

$$PV = nRT = \frac{m}{M} RT \tag{1}$$

$$pO_2V = \frac{mO_2}{MO_2} RT \tag{2}$$

$$P_AV = \frac{m_A}{M_A} RT \tag{3}$$

divide equation (2) by (3) and solve for m_{O_2}:

$$mO_2 = \frac{pO_2}{P_A} \frac{MO_2}{M_A} m_A \tag{4}$$

where:

P = total pressure

V = volume

n = moles

m = mass

M = Molecular weight (or apparent Molecular weight)

R = universal gas constant

T = absolute temperature

p = partial pressure

O_2 refers to oxygen

Subscript A refers to total gas mixture (air)

Equation (4) may be rewritten in terms of mass rate ($\dot{m}_A$)

$$mO_2 = \int_o^t \frac{MO_2}{M_A} \frac{pO_2}{P_A} \dot{m}_A dt \tag{5}$$

Adding subscripts for inspired (I) and expired (X) the mass of oxygen consumed in time, t, is

$$\Delta mO_2 = mO_2{}^I - mO_2{}^X \tag{6}$$

or

$$\Delta mO_2 = \int_o^t \frac{MO_2}{M_{AI}} \frac{pO_2{}^I}{P_{AI}} \dot{m}_{AI} dt - \int_o^t \frac{MO_2}{M_{AX}} \frac{pO_2{}^X}{P_{AX}} \dot{m}_{AX} dt \tag{7}$$

and simplifying gives,

$$\Delta mO_2 = \int_o^t \left[\frac{MO_2}{M_{AI}} \frac{pO_2{}^I}{P_{AI}} \dot{m}_{AI} - \frac{MO_2}{M_{AX}} \frac{pO_2{}^X}{P_{AX}} \dot{m}_{AX} \right] dt \tag{8}$$

A gross simplification may be made if it is assumed that the total mass of inspired air is related to the total mass of expired air by a parameter σ, i.e.

$$\int_o^t \dot{m}_{AI} dt = \int_o^t \sigma \dot{m}_{AX} dt \tag{9}$$

Since PO_{2I} remains substantially constant through a determination, insertion of equation (9) into equation (8) is permissible, ultimately giving,

$$\Delta mO_2 = \int_o^t \left[\sigma \frac{MO_2}{M_{AI}} \frac{pO_2{}^I}{P_{AI}} - \frac{MO_2}{M_{AX}} \frac{pO_2{}^X}{P_{AX}} \right] \dot{m}_{AX} dt \tag{10}$$

The desired result is obtained by dividing equation (10) by the density of oxygen at standard conditions (ρsc),

$$SCCO_2 = \frac{1}{\rho sc} \int_o^t \left[\sigma \frac{MO_2}{M_{AI}} \frac{pO_2{}^I}{P_{AI}} - \frac{MO_2}{M_{AX}} \frac{pO_2{}^X}{P_{AX}} \right] \dot{m}_{AX} dt \tag{11}$$

Computer Equation

Equation (11) can be put into more usable terms that facilitate computer calibration and set-up. That is,

$$SCCO_2 = \frac{1}{\rho sc} \int_o^t \left[\frac{\sigma MO_2}{\lambda M_{DA}} N_I - B_X N_X \right] \dot{m}_{AX} dt \tag{12}$$

and further,

$$SCCO_2 = \frac{1}{\rho sc} \int_o^t \left[\phi B_I N_I - B_X N_X \right] \dot{m}_{AX} dt \tag{13}$$

where N_X = mole fraction of oxygen in the expired air (pO_2^X/P_{AX})

N_I = mole fraction of oxygen in the inspired air (pO_2^I/P_{AI})

$$B_X = \text{Constant} = 1.1159 = \frac{MO_2}{M_{AX}}$$

$$B_I = \text{Constant} = 1.1047 = \frac{MO_2}{M_{DA}}$$

$\sigma = m_{AI}/m_{AX}$ in time t

$$\lambda = \frac{\text{Apparent Molecular Weight of Humid Air}}{\text{Apparent Molecular Weight of Dry Air}} = \frac{M_{WA}}{M_{DA}}$$

$$\phi = \frac{\sigma}{\lambda}$$

Equation (13) is that which is implemented in the oxygen uptake computer. The mathematical operations of multiplying by a constant, subtraction, multiplication of two time variables, integration, scaling, and mass flow transducer sensitivity are fixed and not under control of the operator. N_X and N_I are calibrated as a function of dew point and barometric pressure. B_X is a constant based upon an average apparent molecular weight of expired air, the average having been determined from an analysis of typical expired gases having a respiratory quotient (RQ) ranging from 0.8 to 1.0. B_I is constant and is merely the ratio of the molecular weight of oxygen to the apparent molecular weight of dry air (M_{DA}). λ is a function of dew point and barometric pressure and is the ratio of apparent molecular weights of moist air to dry air. σ is the average ratio of the inspired air mass to the mass of expired air, calculated as a function of dew point and barometric pressure from an analysis of typical expired gases having an RQ in the range of 0.8 to 1.0, holding the mass of nitrogen constant. That is, when the mass of inspired N_2 was set equal to the mass of expired N_2, the basic mass difference between inspired and expired gases was due solely to the water vapor content of the ambient air.

Since mole fraction is defined by,

$$N = \frac{p}{P}$$

where

p = partial pressure of a constituent

P = total pressure of the gas

both N_I and N_X must, in general, be monitored and this capability is provided, using two oxygen polarographic electrodes that produce an output proportional to the partial pressure of oxygen. The remaining time variable, $\dot{m}_X$, is monitored by a Technology Incorporated LINŪRMASS® flowmeter which provides a linear output voltage proportional to the instantaneous mass flow rate of the expired gases.

After appropriate signal conditioning, standard analog techniques are used to perform the operations required of equation 13. The operations include multiplying by a constant, inserting parameters, and taking a difference. A quarter-square multiplier (QSM) is used to form the product of two variables and then a stable integrator develops a signal proportional to the oxygen uptake.

Miscellaneous Equations

The derivation of miscellaneous equations involving gas mixtures and the relationships existing between humid and dry air are given in the appendix.

THE MASK-SENSOR ASSEMBLY (Fig. 1)

A standard Globe Industries mask was modified by bonding a plexiglass tube (containing two 1-way valves) to the mask at the mouth port. A flexible plastic exhaust tube connects the plexiglass housing with the sensor system.

The heart of the sensor system is a thin-walled version of the MFG-16 flow section. Two thermistors are mounted on a 4-terminal transistor header and then mounted on the flow section such that the thermistors are in the flow stream. Technical data concerned with the flowmeter are given in the appendix.

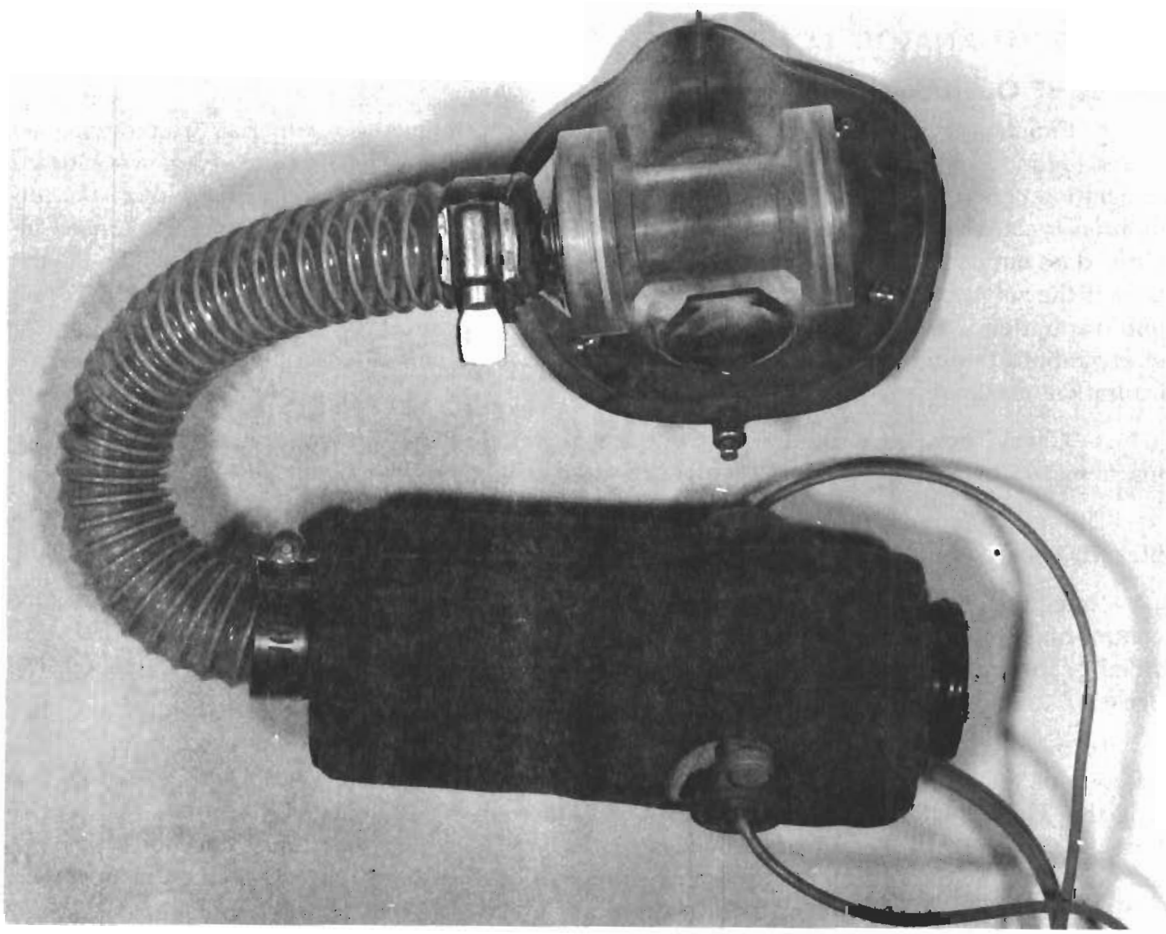


Fig. 1. Mask-sensor assembly

Two aluminum and plastic assemblies are bonded to the flow section: one is designed to accept the pO_2^X transducer, the membrane of which is subjected to the flow stream, while the other accepts the pO_2^I transducer, which samples the ambient air. Technical data concerned with the pO_2 electrodes are given in the appendix.

A thermistor bonded to the flow section is used as a temperature sensor and in conjunction with a heater, which encompasses the pO_2 sensors and main body of the flow section, is used to control the sensor assembly at a temperature of approximately 104F (40C).

Two plastic end fittings are bonded to the flow section to facilitate attachment of the orifice section to the mask at the inlet and either a flapper valve or hose at the exhaust. The entire assembly is then covered with an insulating material to minimize heat loss or gain at temperature extremes. A single cable leads from the assembly and plugs into the rear panel of the electronic package.

The ambient range for the assembly is from 32 to 120F with a normal temperature set point of 104F. Control accuracies are: in ambient from 32 to 105F ± 1F; at constant ambient temperature ± 0.1 F.

THE SPECIAL-ANALOG COMPUTER (Fig. 2)

Modes of Operation

A "Function Switch" permits selection of a manual control mode, or either of two programmed cycles. "Mode I" offers a one-minute timed integration period. "Mode II" is also an automatic timed integration period that does, however, start and stop the integration at the same point in the respiration cycle, viz, during an inspiration (no flow through the flowmeter). That is, the timed interval does not begin until or unless the subject is inspiring. The integration will cease one minute later if the subject is inspiring. If he is in the process of exhaling, the integration will not cease until expiration is complete. Hence, oxygen uptake in this mode is based upon an integral number of expirations through a period of one minute, minimum, to one minute plus the time of a single expiration, maximum.

A "Check" position is used with the "Check" switch and "Consumption Rate" switch offering a means by which the instrument calibration may be automatically tested.

The "Consumption Rate" switch offers three full-scale ranges where an integrator output of plus 10 volts corresponds to 500, 1500, and 2500 standard cubic centimeters.

"Integrate," "Hold," and "Reset" pushbutton switches and indicator lights are provided for control and status indication of the logic relays and cam timer. A fourth light, "Ready" is provided to inform the operator when the cam timer is in position for the start of a new automatic cycle.

In the manual mode, depressing the "Reset" switch discharges the integrating capacitor. Depression of the "Integrate" switch starts the integration cycle, which may be stopped by depressing the "Hold" switch. The appropriate status lights will be illuminated during the respective parts of the cycle. In the automatic modes (including "Check"), the "Reset" switch is the only active control at the operator's disposal. Depression of the "Reset" switch in these modes when the "Ready" light is illuminated will institute an automatic cycle.

Front panel, 10-turn locking potentiometersare provided for pO_2 amplifier calibration, and setting of the constants ϕB_I and B_X. In addition, a potentiometer associated with the "Sensor"

Fig. 2. Front panel of the computer

switch may be used to replace the $pO_2{}^I$ electrode and amplifier and manually set in a signal proportional to N_I, under conditions of constant ambient.

The quarter-square multiplier is temperature-controlled by an "on-off" controller. The "QSM Heater" light indicates when power is applied to the heater. The "Sensor Temperature" meter indicates the temperature of the aluminum shell of the flow transducer. Normal operation is in the green zone which represents approximately a 1.0C temperature span.

The Electronic Circuit

We shall not attempt to include here a detailed description of the circuitry. This information is available in the appendix. A simplified block diagram of the electronic circuit is illustrated in figure 3. Immediately before each experiment, both oxygen sensors are exposed to ambient air. The dewpoint and barometric pressure values of the ambient air are determined. Finally, the p_{O_2} amplifiers are calibrated by adjusting appropriate potentiometers, and the coefficient potentiometers concerned with B_I and B_X are set. Once calibrated and in operation, the outputs of the $pO_2{}^X$ and $pO_2{}^I$ channels are electronically compared, and the difference obtained is multiplied by the output of the flow channel. Integration of the product thus obtained, over time, yields the mass of oxygen consumed for that unit of time. If the mass of oxygen consumed is multiplied by the reciprocal of the density of oxygen at standard conditions, the product is standard cubic centimeters of oxygen consumed. This multiplication process is accomplished in the integration portion of the circuit. The final output of the circuit may therefore be expressed as cubic centimeters of oxygen uptake per unit time at standard conditions.

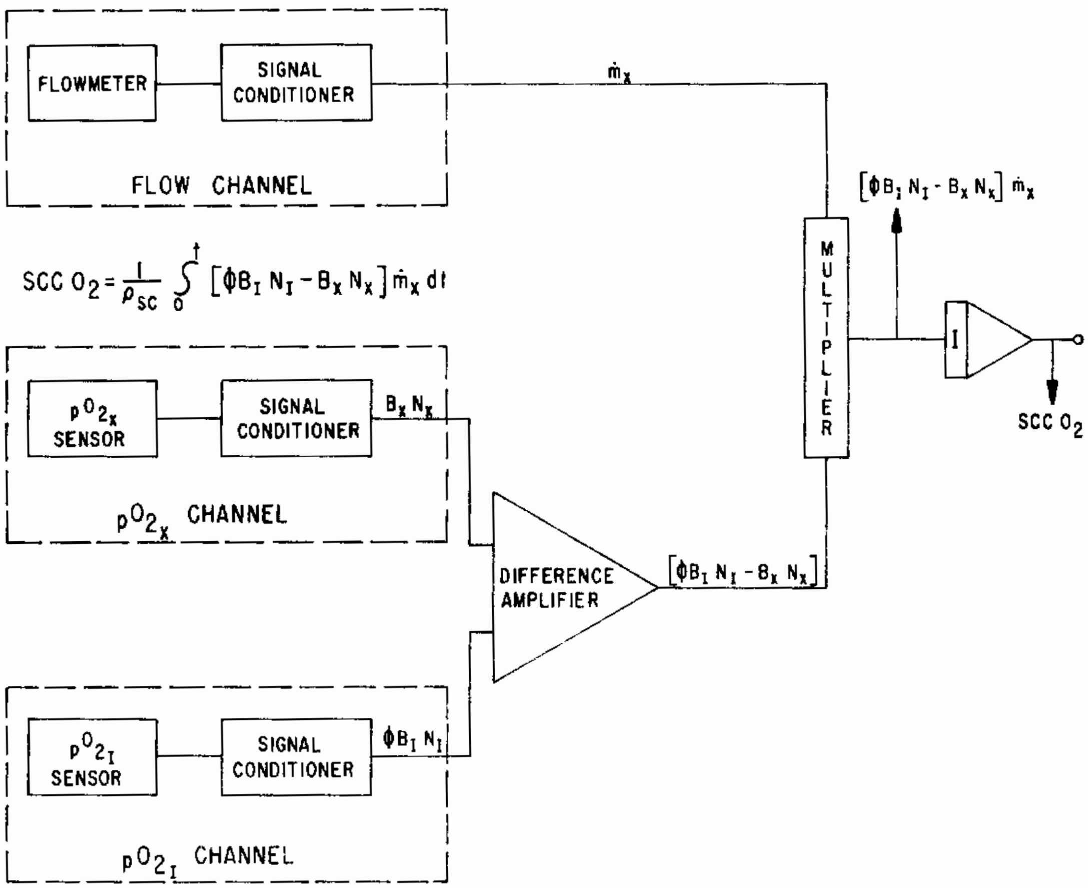


Fig. 3. Simplified block diagram of the electronic circuit. The signal conditioners employed in the pO_2 channels consist of two commercially available operational amplifiers. The signal conditioner associated with the flowmeter is a component which is supplied with the transducer by the manufacturer.

BACKGROUND TO THE DEVELOPMENT OF THE OCC-2500 OXYGEN CONSUMPTION COMPUTER

Evaluation of mass flowmeter and polarographic oxygen sensor

From 1963 to 1964 an evaluation of the mass flowmeter and polarographic sensors was accomplished where the transducers served as components of a purely physical system. A sinusoidal pump delivered specific volumes of ambient air through the flowmeter and into a respirometer for comparison. The output of the flowmeter, correlated significantly with respirometer values. Analysis of various oxygen and nitrogen mixtures by the polarographic and paramagnetic oxygen sensors, yielded an excellent correlation between their respective outputs. Finally, the combined output of the flowmeter and polarographic sensors were simultansously evaluated against the combined output and measure of the paramagnetic sensor and respirometer respectively. The ultimate output of the two systems, expressed as the volume of oxygen in a specific volume of mixed gas, were found to correlate significantly. The results of qualifying tests encouraged us to investigate the performance of these sensors as components of a system designed to monitor oxygen in human subjects.

Design of the oxygen consumption computer prototype

From 1964 to 1965 a prototype of the present OCC-2500 was developed in the Aerospace Medical Research Laboratories. As in the present system, this bench model was provided with a mask-sensor assembly to monitor and deliver exhaled air samples to a gasometer and subsequently a gas chromatograph for standard analysis. Oxygen uptake values (200-2400 cc O_2/min) obtained from 31 subjects (132 observations) during rest and after exercise produced a sample correlation coefficient of 0.993 (95% confidence interval 0.990, 0.995). Results of this study were presented at the Las Vegas meeting of the Aerospace Medical Association, April 1966.

Development of the OCC-2500 oxygen consumption computer

On the basis of the performance of the prototype an Air Force contract AF 33(615)-3230 was negotiated with Technology Incorporated, Dayton, Ohio. The Model OCC-2500 Oxygen Uptake Computer was delivered to the Aerospace Medical Research Laboratories in March 1966 as an end item of this contract. After a series of check out tests for acceptance of the device, a calibration and evaluation procedure was initiated. Description and results of these tests are given in a subsequent section of this report.

SECTION III.

Calibration and Evaluation of the Model OCC-2500 Oxygen Uptake Computer

METHOD

The mask-sensor assembly was modified, in that one end of a length of flexible tubing was joined to the distal end of the flow section, and the other end to a Collins 120-liter gasometer. A three-way, solenoid-operated valve was inserted into the length of flexible tubing. The operator of the OCC-2500 was thus able to depress the "integrate" button on the computer and, simultaneously, activate the solenoid valve thereby delivering identical gas samples to the OCC-2500 and standard systems. Immediately after each sampling period, 100 cc of the volume collected in the gasometer was drawn off by syringe and processed through a gas chromatograph for oxygen, carbon dioxide and nitrogen determination. Before collecting exhaled air samples from each subject, the gas chromatograph was calibrated with gas samples taken from the ambient air and tanks containing known mixtures of oxygen and carbon dioxide. Also, at this time, prevailing barometric pressure and dew point temperature values were determined. As part of the overall calibration of the OCC-2500, the barometric pressure and dew point temperature values are used in calibrating the pO_2 amplifiers and constants This is perhaps the most crucial calibration, as small errors in adjustment of the parameters will cause gross errors in computer readings.

Oxygen uptake determinations, after rest and during graded exercise levels on a Collins bicycle ergometer, were made on 15 healthy, male, college students. Upon arrival at the laboratory, the subjects were given brief instructions regarding the test and mounted the bicycle. No attempt was made to achieve absolute basal metabolic states by regulating the pretest diet or activity levels of the subjects. After donning the mask, the subjects sat quietly for about 2 minutes while the exhaust tubing and gasometer stand-pipe were purged of residual ambient air. On completion of this flushing operation, a 2-minute rest sample was obtained, followed by exercise levels, the magnitude and duration of which are given in table I.

TABLE I

EXERCISE – SAMPLE TIME REGIME

Ergometer setting in watts	*Ft lb/min equivalent*	*Presample cycle time*	*Cycle and sample time*	*Total cycle time*
13	590	↑	↑	↑
40	1770			
60	2656	1 min.	1 min.	2 min.
80	3541			
100	4426			
130	5754	↓	↓	↓
160	7082	↑	↑	↑
190	8409			
210	9294	45 sec.	30 sec.	1.25 min.
230	10178			
250	11065	↓	↓	↓

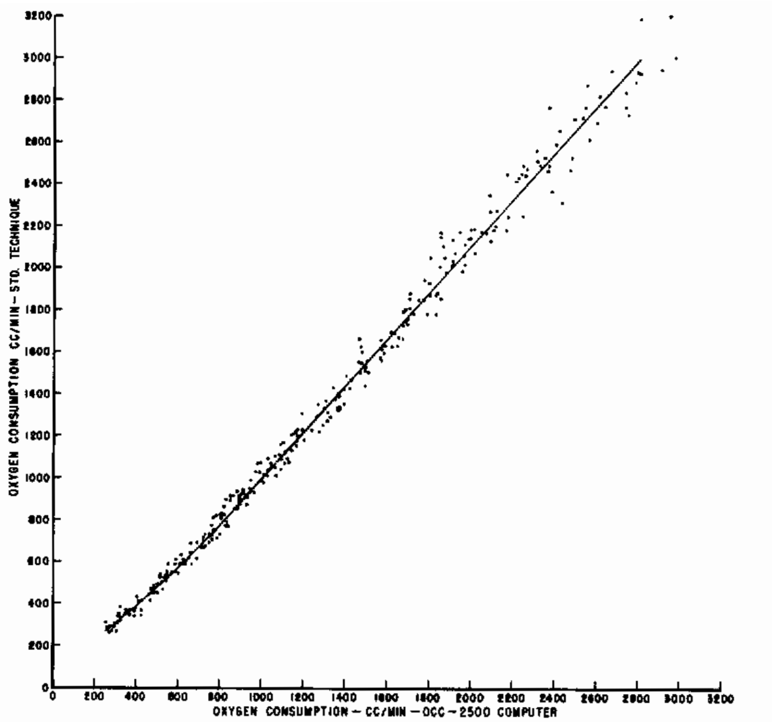


Fig. 4. Initial plot of correlation points resulting from the simultaneous analysis of expired air samples of oxygen consumption values as by the OCC-2500 O_2 uptake computer and the standard technique.

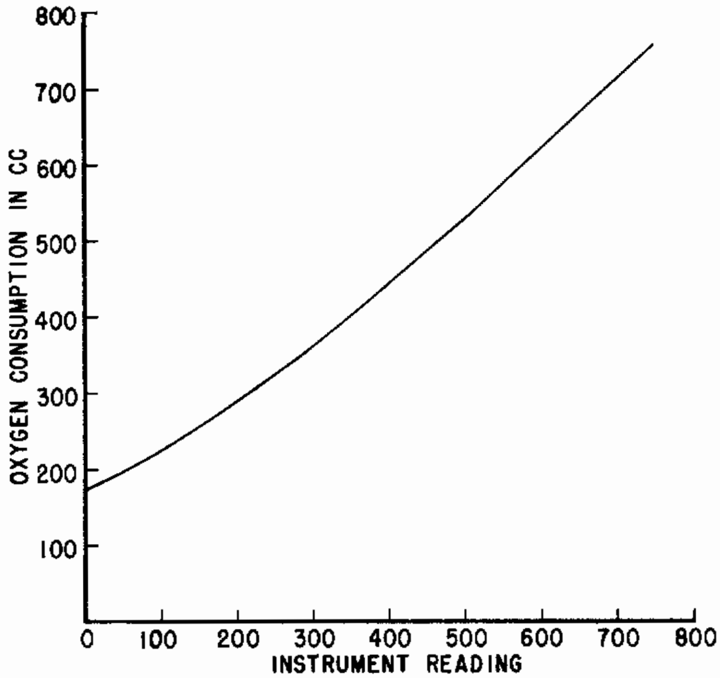


Fig. 5. Calibration curve for O_2 consumption values below 750cc as obtained on the 1500 and 2500cc range after treatment of all data points shown in figure 4 by the equation 1.108 x —108.0=Y.

RESULTS

To obtain a direct readout of oxygen uptake, in cubic centimeters, the voltage output of the OCC-2500 was compared to a fixed voltage thereby providing the required ratio and digitally displayed on a voltmeter. Figure 4 illustrates the initial, graphic relationship between the OCC-2500 and standard technique. Direct observation of the best-fit line indicates a two-segment composition. For oxygen uptake values of approximately 750cc and above (as determined by the standard technique) the relationship is linear, while below 750cc, it is curvilinear and does not pass through zero. It was determined that the linear segment could be expressed by the equation $1.108\ x - 108.0 = y$, where the terms x and y are values obtained by the OCC-2500 and standard techniques, respectively. The terms of the equation were incorporated, electronically, in the OCC-2500 circuit for the 1500 and 2500cc ranges so that readings in this order of magnitude require no correction. This circuit modification altered the slope of the line segment below 750cc on the 1500 and 2500cc scales and resulted in the calibration curve for values below 750cc, as shown in figure 5.

Referring back to figure 4, we decided that a straight line approximation for computer values below 500cc would not introduce serious errors. We determined that this straight line approximation could be mathematically expressed by the equation $0.8333\ x + 58.34 = y$, where the terms x and y are values obtained as in the previous equation. The terms of this equation were similarly

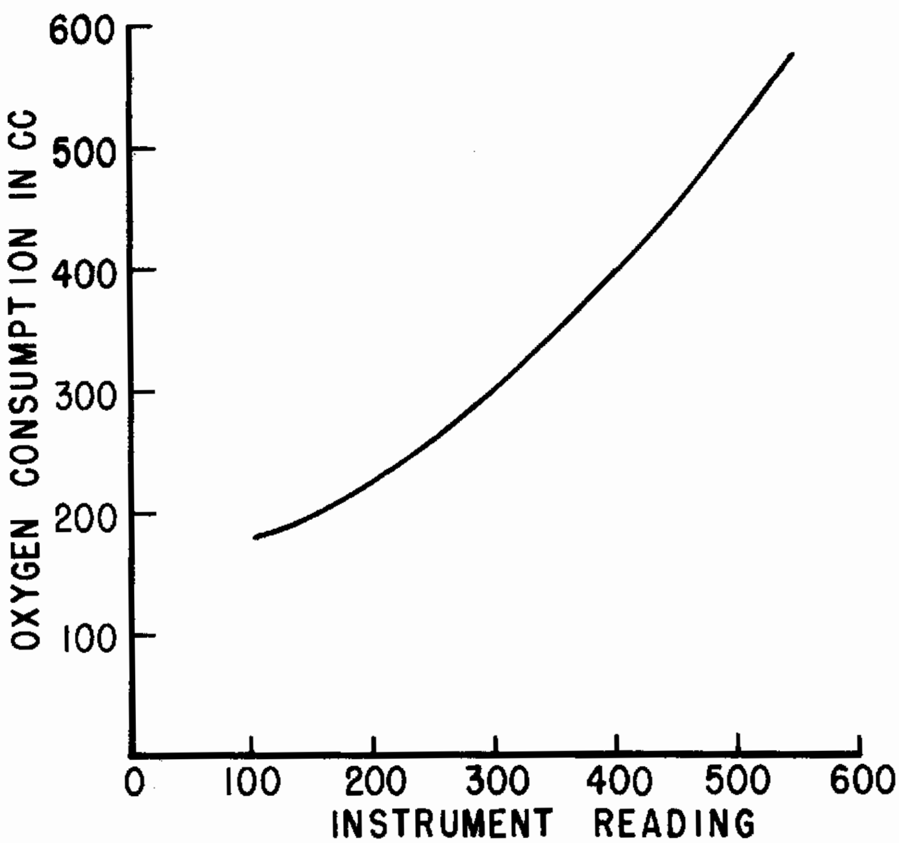


Fig. 6. Calibration curve (for higher order of accuracy) for O_2 consumption values below 500cc (on the 500cc range only) after treatment of data points restricted to this range by the equation $0.8333\ x + 58.34 = Y$.

incorporated, electronically, in the OCC-2500 circuit for the 500cc range. The calibration curve, shown in figure 6, was then obtained for use when an even higher degree of accuracy is required in this range.

Correction values derived were applied to the original set of data points and the resulting correlation plot is shown in figure 7. The correlation coefficient, as determined for these points, is 0.998, (297 observations) and the calculated accuracy of the OCC-2500 is ±5% of reading ±20cc.

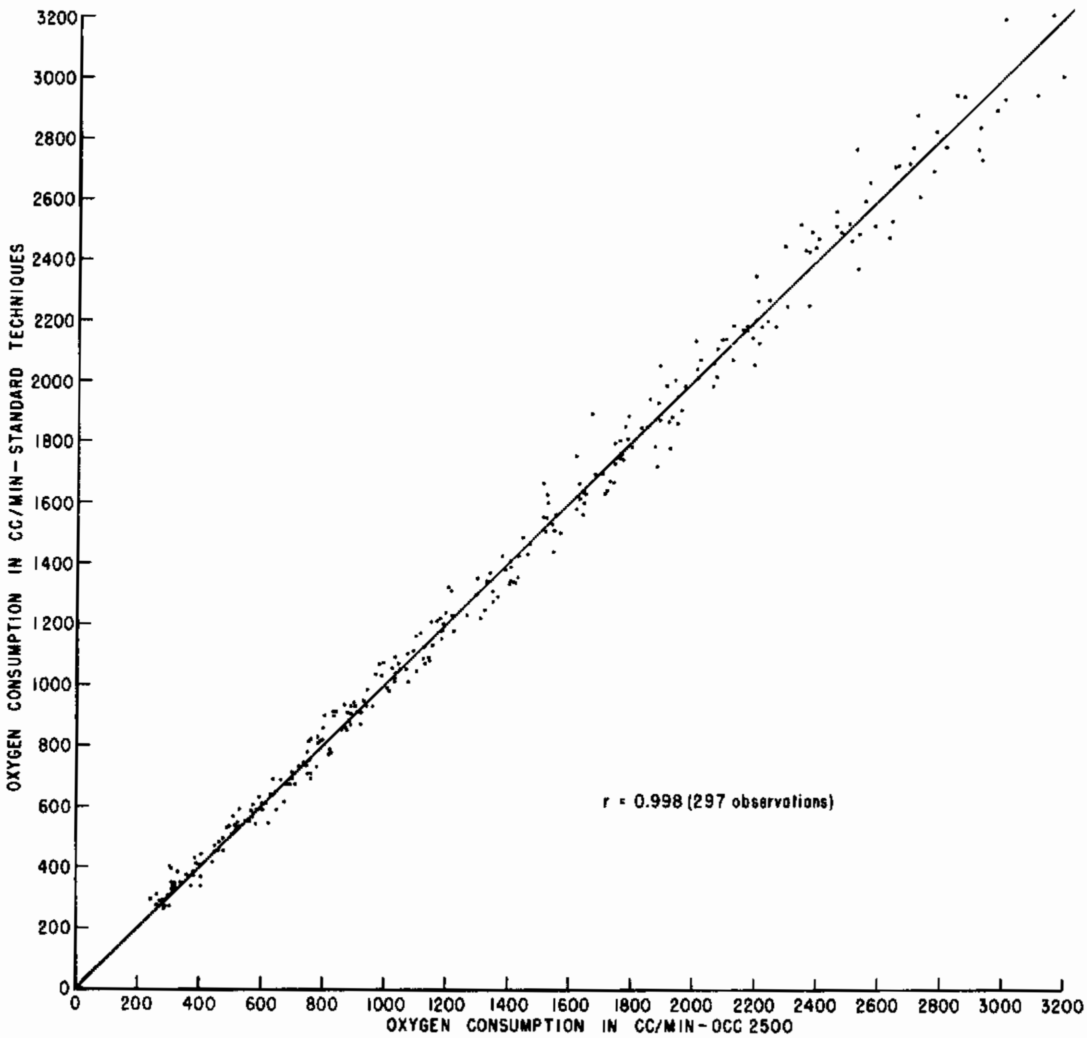


Fig. 7. Final plot of correlation points resulting from the simultaneous analysis of expired air samples by the OCC-2500 oxygen consumption computer and the conventional system.

SECTION IV.
Discussion

All possible precautions were taken to achieve the highest order of accuracy in the standard procedure. As previously indicated, expired air volumes were collected in a Collins 120 liter, chain-compensated gasometer. We sought to preclude parallax and other simple reading errors of the meter stick by attaching a precision potentiometer to the pulley of the gasometer. The potentiometer voltage was fed to a digital voltmeter whose error in agreement with meter stick readings was determined as less than ±0.5%. Silicon-treated 100 cc syringes were used to draw samples of gas from the gasometer and deliver them to a Fischer Hamilton (Model 29) gas partitioner for analysis. By establishing two or three calibration points in both the morning and afternoon, just before testing, the accuracy of the chromatograph could be maintained at better than ±5.0% of reading and the accuracy of the entire standard system at approximately ±5.0% of reading. Gases used for oxygen calibration were obtained from the ambient air (20.93%) and from a tank containing a prepared mixture of oxygen (16.90%) and other gases. Two calibration points for carbon dioxide (4.75% and 4.00%) were also obtained from tanks containing mixed gases of known concentrations. In any case, the calibration point represented a mean value derived from three analyses of a given gas sample. Oxygen and carbon dioxide values obtained from the test samples were used to determine the respiratory quotient. A correction factor, based upon the RQ was applied to relevant oxygen uptake values obtained by standard techniques. The output of the OCC-2500 is substantially independent of RQ. The mathematic basis of this independence is actually beyond the scope of the present report, however, at the risk of over-simplification, it can be said to be related to the measurement of gas mass by the OCC-2500, rather than gas volume.

An accurate calibration of the OCC-2500 requires a rather extensive test procedure, involving a number of subjects monitored at various levels of oxygen utilization. Data output by the OCC-2500 must be compared to values simultaneously obtained by the standard technique. The choice of this laborious procedure, rather than the relatively simple method of calibration with samples of known gas mixtures, is dictated by the response time characteristic of the polaragraphic oxygen sensor. With respect to the double oxygen sensor configuration of the OCC-2500, we refer, in this discussion, specifically to that member of the pair of sensors which is located in the exhalation line. This sensor is exposed to (1), oxygen partial pressures of gas mixtures which vary from ambient air (dead air space) to end-tidal air, and (2), to breathing frequencies which may extend from 5 to 65 breaths per minute. Although the oxygen sensor is exposed to end-tidal air during inhalation, no product is generated by the multiplier during this phase of the respiratory cycle. The reason for this lies in the fact that the function of the flowmeter is restricted to monitoring exhaled air and its output during inspiration is zero. If the oxygen sensor were capable of virtually instantaneous response its output, averaged over time, would represent a true average value of expired oxygen and could be calibrated with known gas mixtures containing appropriately varied concentrations of oxygen. However, with its relatively slow response time of approximately 5 seconds, the sensor output is not representative of a true average, but rather some mean value, of the indicated exhaled oxygen. The significance of this mean value is contingent upon an evaluation of all the various physical and physiological characteristics of all types of subjects. The nonlinearity of the calibration curves is directly attributable to the response time characteristics of the oxygen sensor. It would be impractical, if not impossible, to obtain these curves using a purely physical system and known gas mixtures. The requirement, therefore, of an involved calibration procedure is obviously the greatest disadvantage of the OCC-2500 system. The response time characteristic of the oxygen sensor is also the source of other system limitations. These relate to the unreliability of the system in monitoring transient episodes of metabolic activity and conditions involving excessive or forced hyperventilation.

Appendix

TECHNICAL DATA, OPERATING INSTRUCTIONS, CIRCUITRY, CALIBRATION, MAINTENANCE, AND SCHEMATICS OF THE OCC-2500 OXYGEN UPTAKE COMPUTER

1. OPERATING INSTRUCTIONS

1.1 *General*

Before attempting to use the oxygen uptake computer, the operator should become thoroughly familiar with the instrument, the General Description (section II in the body of the report), and the Calibration and Maintenance sections of this appendix.

Note especially that an adequate warm-up time of from one-half hour to one hour is desirable in that both the sensor assembly and the quarter-square multiplier are relatively massive and temperature controlled. Further, there exists a pO_2 electrode polarization time constant of up to 10 minutes which is dependent upon temperature, condition of electrode, and *past history*. Since a 1% error between pO_2^I and pO_2^X can typically cause up to a 5% error of O_2 consumption, one must be assured that the N_I and N_X readings are stable, or be prepared to recalibrate the pO_2^I and pO_2^X amplifiers periodically.

1.2 *Check Calibration*

Determine that the instrument and pO_2 calibration are correct (see section 3).

1.3 *Position Mask-Sensor Assembly*

Place the mask-sensor assembly on the subject taking special care that a tight but comfortable fit is obtained. Care should also be exercised to avoid potential damaging flexures of the transducer cable.

1.4 *Select Consumption Rate*

Knowing the body weight and the approximate level of work of the subject, an estimation may be made of the rate of oxygen consumption. (See for example, *Bioastronautics Data Book*, P. W. Webb, M.D., editor, NASA SP-3006, 1964, pp 173-177.) Hence, the appropriate range, 500, 1500, or 2500 SCCM may be selected. Operation on a range such that full-scale readings are approached, provides optimum resolution and to some extent, better accuracy, due to the constant percent of full-scale instrument accuracy. It is stressed that the basic accuracy of the transducers is independent of the "Instrument Consumption Rate" range.

1.5 *Select Mode of Operation*

1.5.1 *Manual Mode*

This mode will generally be used when encountering either very low or very high oxygen consumption rates wherein the period of integration must either be extended or shortened. Note that a manual timing of the integration period must simultaneously be effected if results in terms of standard cubic centimeters per minute are required.

1.5.2 *Mode I*

This mode should find the broadest area of application in that it is completely programmed for a fixed one-minute determination.

1.5.3 *Mode II*

This mode should be of greatest value in correlating oxygen uptake computer data with that of other researchers. That is, this mode determines the oxygen consumption by the analysis of an integral number of expirations, as has been accomplished by the classical techniques. Note, however, that the operator must simultaneously time the integration period.

1.6 *Making the Determination*

It is recommended that the output of J-5 (a voltage proportional to pO_2^I-pO_2^X) be monitored on a recorder so it may be assured that all transient conditions have ceased as in the case of the subject establishing a new level of work or simply eliminating ambient oxygen from contact with the pO_2^X transducer. The voltage proportional to oxygen consumption should be monitored at J-9 by a four-digit digital voltmeter to take advantage of the system accuracy.

1.6.1 *Manual Control*

i) Depress "Reset" button momentarily ("Reset" light is on).

ii) *Simultaneously* depress "Integrate" button and start timer ("Integrate" light is on).

iii) Simultaneously depress "Hold" button and stop timer. ("Hold" light is on).

iv) Measure and record output from J-9 and time in minutes.

v) Determine $SCCO_2$ by the following formula:

$$SCCO_2 = \frac{\text{Range (SCC) x } V_J\text{-9 (volts)}}{\text{Time (min.) x 10.000 (volts)}}$$

1.6.2 *Mode I Control*

i) Make sure that "Ready" and "Hold" lights are both illuminated.

ii) If not go to "Manual" mode and cycle to "Hold." Return to Mode I.

iii) Depress "Reset" button momentarily ("Reset" light is on, "Hold" and "Ready" lights extinguished).

iv) Observe automatic cycling to "Integrate" and one minute later to "Hold." When "Hold" light turns on, record output from J-9.

v) Determine $SCCO_2$ by the following formula:

$$SCCO_2 = \frac{\text{Range (SCC) x } V_J\text{-9 (volts)}}{\text{10.000 (volts)}}$$

1.6.3 *Mode II Control*

i) Make sure that "Ready" light and "Hold" light are both illuminated.

ii) If not go to "Manual" mode and cycle to "Hold." Return to Mode II.

iii) Depress "Reset" button momentarily. ("Reset" light is on, "Hold" and "Ready" lights extinguished).

iv) When "Integrate" light turns on, simultaneously start timer.

v) When "Hold" light turns on, simultaneously stop timer.

vi) Record time and output of J-9.

vii) Determine $SCCO_2$ by the following formula:

$$SCCO_2 = \frac{\text{Range (SCC) x } V_J\text{-9 (volts)}}{\text{Time (min.) x 10.000 (volts)}}$$

1.7 *Examples*

1.7.1 *Manual Mode*

Range = 2500 SCC

V_J-9 = 8.324 volts

Time = 0.810 minutes

$$SCCO_2 = \frac{2500 \times 8.324}{0.810 \times 10.000} = 2569 \ SCCO_2$$

1.7.2 *Mode I*

Range = 1500 SCC

V_J-9 = 6.873 volts

$$SCCO_2 = \frac{1500 \times 6.873}{10.000} = 1031 \ SCCO_2$$

1.7.3 *Mode II*

Range = 500 SCC

V_J-9 = 5.216 volts

Time = 1.150 minutes

$$SCCO_2 = \frac{500 \times 5.216}{1.150 \times 10.000} = 227 \ SCCO_2$$

1.8 *Technical Data*

1.8.1 *Power Requirements*

110 volt a.c. ±10% at 60 cps, 1.5 amp.

Two fuses located on rear panel: F-1: 1.0 amp.
F-2: 0.5 amp. (slo-blo)

1.8.2 *Transducers*

Mass Flowmeter

Model: Modified Technology Incorporated MFG-16

Calibration: 240 standard liters (Standard liter at T = 70F, P = 1 atmosphere) dry air/minute (calibration performed with 6.6K-ohm load resistance)

Temperature range: 90 to 120F

Absolute accuracy: ±2.0% of full scale

Linearity through temperature range: ±0.6% of full scale

Linearity at 105F: ±0.2% of full scale

pO_2 Electrodes

Yellow Springs Instrument Company assembly per YSI drawing 05906

Temperature compensated range: 90 to 120F

Accuracy through temperature range: ±1% of reading

Accuracy of compensation through limited temperature range: 100 to 110F ±0.2% of reading

Response time: Estimated 5 seconds

Sensor Assembly Temperature Control

Ambient range: 32 to 120F

Normal temperature set point: 104F

Control accuracy: In ambient from 32 to 105F ±1F; at constant ambient temperature ±0.1F

1.8.3 *Instrument*

General

Temperature range: 60 to 90F

Accuracy on any range: Better than ±0.5% of full scale (this does not include accuracy of transducers)

Outputs

Type	*Jack*	*Normal Range (volts)*
pO_2^I	J-1	+5.25
pO_2^X	J-2	+2.0 to +5.25
$\phi B_I pO_2^I$	J-3	–5.50
$B_X pO_2^X$	J-4	–2.0 to –6.0
$\phi B_I pO_2^I - B_X pO_2^X$	J-5	0 to –10
$\dot{m}_x$	J-6	0 to +5
$\dot{m}_x$	J-7	0 to –10
$SCCO_2$	J-8	0 to –10
$SCCO_2$	J-9	0 to +10

Note: All jacks are two-terminal standard phone jacks with the common terminal fixed directly to chassis common. Loading should be limited to one milliampere maximum.

2. CIRCUIT DESCRIPTION

2.1 *Analog Section*

The simplified circuit, figure 8, will be used to describe the functional operation of the analog section of the detailed schematic, figure 9.

The YSI pO_2 sensors are excited by a polarizing potential of –0.800 volts, adjusted by potentiometers R-69 and R-65. Operational amplifiers A and C are connected with a standard feedback arrangement, however, the feedback resistors are temperature compensating thermistors. The gain of the pO_2 amplifiers is adjusted by front panel ten turn locking potentiometers labeled pO_2^I and pO_2^X. The output of both amplifiers is positive, of the order of 5 volts, in a normal atmosphere. The pO_2^I signal is fed to an inverting amplifier (B), the gain of which is adjustable from minus one to minus three by a front panel ten turn locking potentiometer labeled ϕB_I. The output of B is (normally) of the order of minus 5 volts. Amplifier D and the front panel gain adjustment, B_X, operates in the same manner. When oxygen is consumed, the magnitude of the output of amplifier D is less than that of B. Both signals are fed to a differential amplifier having a

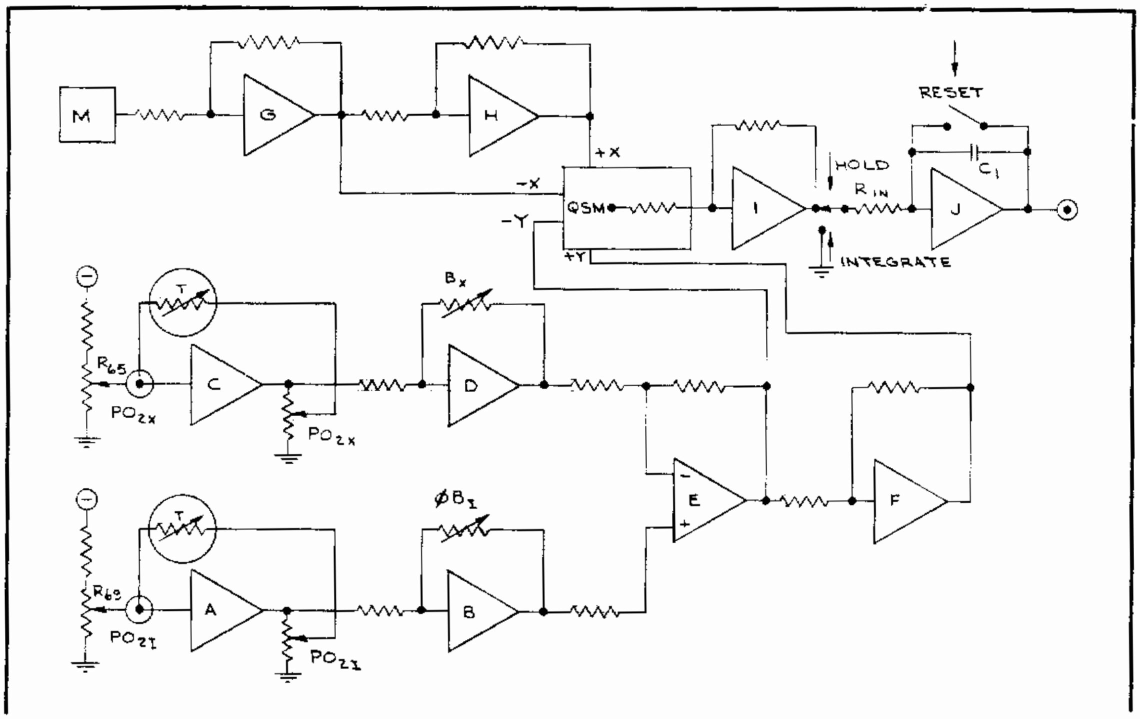


Fig. 8. Simplified analog circuit for oxygen uptake computer

fixed gain of five times the difference between the inputs. Amplifier B feeds a noninverting input labeled "+" and amplifier D feeds an inverting input labeled "–". Since the magnitude of the noninverting input is always greater than that of the inverting input, the output of amplifier E will be negative. This output goes to the negative "Y" input of the quarter-square multiplier (QSM) and to amplifier F which is a unity gain inverting amplifier. The output of F goes to the QSM plus "Y" input. In this chain of amplifiers, we have developed a signal proportional to $\phi B_I \frac{pO_2^I}{P} - \frac{B_X \, pO_2^X}{P}$ and its nverted value as required by the QSM.

The Technology, Incorporated mass flow transducer produces a signal of 0 to +5 volts. To make optimum usage of the QSM, amplifier G amplifies the mass flow signal by a constant, negative 2. The output of G is fed to the minus "X" input of the QSM and to amplifier H, which is a unity gain inverting amplifier. The output of H goes to the QSM plus "X" input.

The QSM in conjunction with amplifier I produces a signal that is equal to the product $-(XY)/10$. Hence, under all conditions of oxygen consumption the output of amplifier I is either zero or negative (0 to 10 volts). This signal is fed through the holding relay contacts to one of three ranging resistors at the input to the integrator, amplifier J. The output of the integrator (E_o) is given by:

$$E_o = -\frac{1}{R_i C_1} \int_o^t e_i(t)dt + \Big[e_o \Big]_{t=o}$$

and since the input (e_i) is negative and proportional to the instantaneous consumption rate, the output is positive and proportional to the total oxygen consumed during the period of integration.

2.2 *Logic and Control Circuitry*

2.2.1 *Manual Mode*

With reference to the detailed schematic, figure 9, with switch S-1, the function switch, in position 2, operation is as follows. Assume that the hold relay, K_1, is energized and the Reset relay K_2 is deenergized. All other relays are passive in this mode. The "Hold" light is on through contacts $K_1(5, 6)$ and $K_2(6, 13)$: all other lights are off. Depression of the "Hold" button (S-5) has no further affect, nor does depression of the "Integrate" button (S-4).

Depression of the "Reset" button (S-6) will energize K_2 and this relay will hold through its own contacts $K_2(2, 1)$, $S_{1C}(2)$ and through the "Integrate" switch S-4. As the "Reset" relay is energized, the reset light turns on through contacts $K_2(5, 6)$, the "Hold" relay deenergizes by opening of the holding contacts $K_2(4\text{-}12)$, and the "Hold" light is turned off by losing power through contacts $K_2(13, 6)$. In this state, Reset relay contacts $K_2(11, 9)$ shunt the integrating capacitor of amplifier J. Also, the QSM output (amplifier I) is fed through the "Hold" relay contacts $K_1(10, 1)$ to the integrator through a resistor selected by the range switch S-2.

Now, depression of the "Integrate" button (S-4) releases the reset circuit through $S_{1C}(2)$, and $K_2(1, 2)$ allowing the "Reset" relay to deenergize, permitting integration to commence. As this occurs, the "Reset" light turns off and the "Integrate" light turns on.

Depression of the "Hold" button energizes the "Hold" relay through S-4, $S_{1C}(2)$, $K_2(1, 10)$, S-5 and $S_{1A}(2)$ contacts. Integration ceases as the QSM output to the integrator is removed by opening of contacts K_1 (10, 1). Also the "Integrate" light turns off and the "Hold" light turns on, which completes the cycle.

2.2.2 *Mode I*

In this mode of operation (S_1 in position 3) relays K_1, K_2 and K_3 and the clutch operated cam timer are used. Operation of relays K_1 and K_2 is the same as in the manual mode, however, the "Integrate" and "Hold" switching functions are accomplished automatically by the cam timer switches. Operation proceeds as follows: assume again that the "Hold" relay (K_1) is energized. Assume also that the cams are in the reference zero time position, hence the "Ready" light is on and the motor is running (although the motor clutch is *not* actuated). The motor receives power through switch $S_{1B}(3)$, while the "Ready" light obtains power through the clutch cam switch, position a. Depression of the "Reset" switch energizes the "Reset" relay and the Mode I relay, both having holding circuits through their own contacts. As previously, the holding relay deenergizes and the "Reset" light goes on. Power is applied to the clutch through the Mode I relay contacts $K_3(3, 12)$, and switch, $S_{1B}(3)$, hence, the cams start rotating and the "Ready" light extinguishes. After approximately one second, the clutch cam switches from a to b (figure 10), which offers another path of current flow to the clutch: viz., through the clutch cam switch position b and through switch $S_{1D}(3)$.

At time equals approximately 2 seconds, the integrate cam switch moves from position e to f thereby deenergizing the "Reset" relay and the Mode I relay, performing the same function

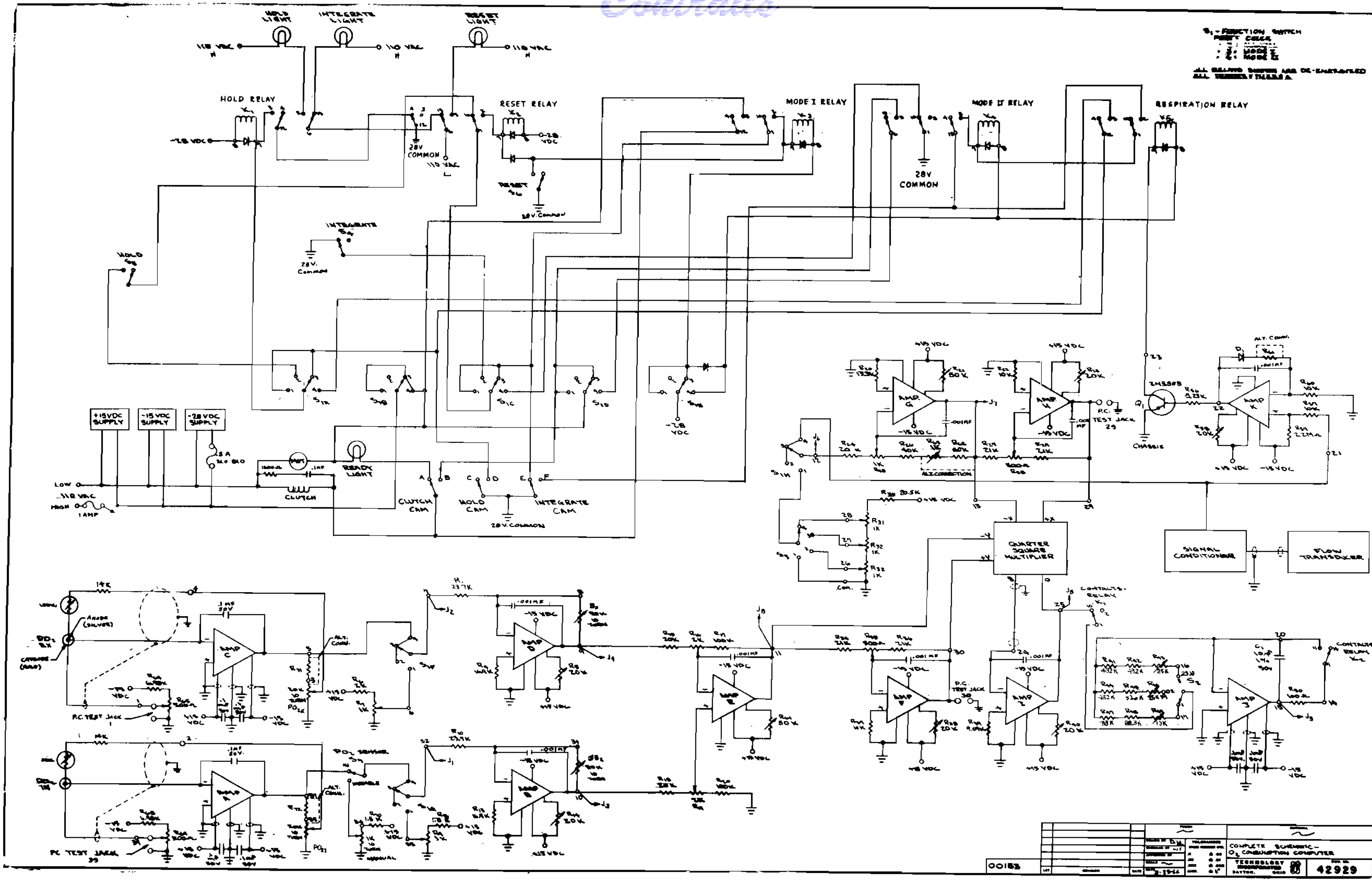


Fig. 9. Complete schematic of the oxygen uptake camputer

as the "Integrate" switch in the manual mode. Hence, integration commences. Sixty seconds later at time equals 62 seconds, the "Hold" cam switch moves from position c to d, performing the same function as the "Hold" switch in the manual mode. Hence, integration ceases. However,

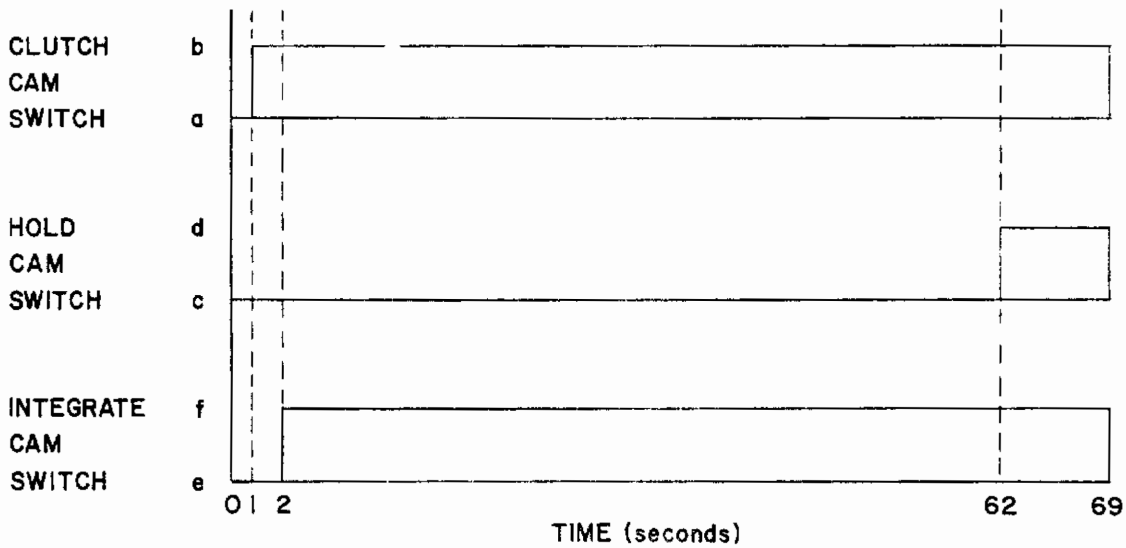


Fig. 10. Mode I and II cam operation for oxygen uptake computer

the clutch is still activated and the cams continue to rotate until time equals approximately 69 seconds, at which time all cam switch contacts return to their original positions and power is removed from the clutch by the clutch cam switch. This ends the cycle.

2.2.3 *Check Mode*

Logically, this mode is precisely the same as that of Mode I. The only difference in the two modes is that in the check mode, constant signals are switched into the circuit by switches S_{1F}, S_{1G}, and S_{1H}, replacing the transducer outputs for a system calibration check.

2.2.4 *Mode II*

Although Mode II uses the same basic cam timing period as that of Mode I, the respiration cycle controls the starting of the 60-second timed interval (hence integration) and the instituting of the "Hold" command at the end of the timed interval. Operation is as follows: assuming that the function switch is in position 4 and that the "Hold" and "Ready" lights are on. The Mode II and "Respiration" relays are used in this mode. The "Respiration" relay (K_a) is activated during inspiration. That is, when the subject is exhaling, the flowmeter output is positive, which, as an input to amplifier K at the noninverting input produces a positive voltage out of this amplifier. The voltage is limited by the diode in the feedback circuit to approximately +0.6 volts. The "Respiration" relay driving transistor (Q1) is then biased to cut-off. When expiration has reached the point where the flowmeter signal is less than plus 25 millivolts, the negative bias through R-59 overrides the positive input and the amplifier "switches" to negative saturation at the output. This signal turns Q-1 on and energizes the "Respiration" relay. When expiration starts again, the output switches to +0.6 volts and deenergizes the relay.

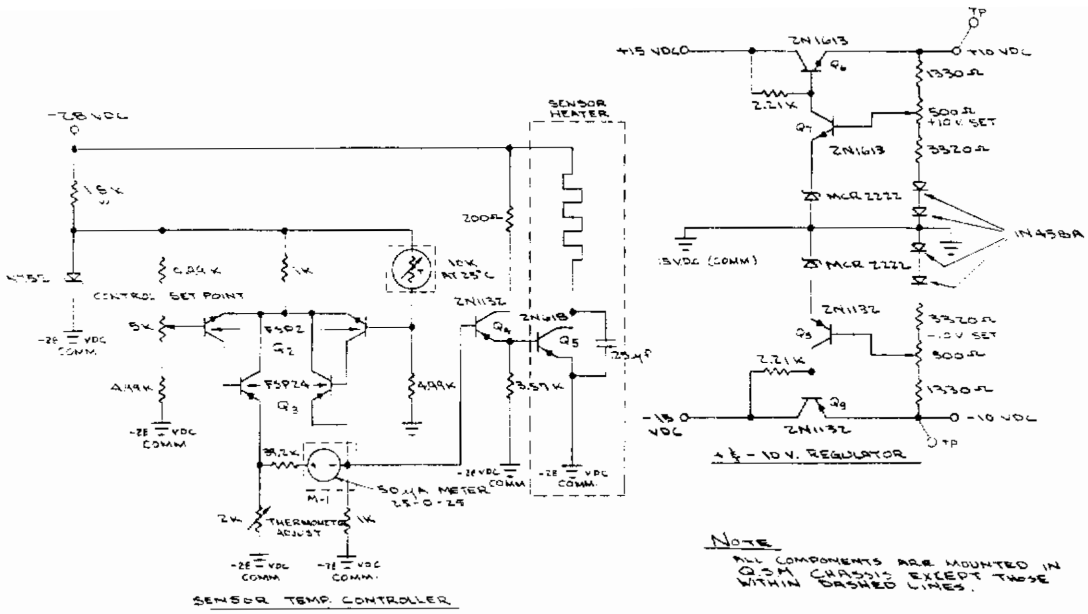


Fig. 11. Reference supply and temperature controller

As before, depressing the "Reset" button energizes the Reset and Mode I relays, and deenergizes the "Hold" relay. Power is applied to the clutch through contacts $K_3(3, 12)$ and the cams rotate. One second later the clutch cam switch moves to position b, but as yet no power is available through this switch since the Mode II relay has not yet been energized. At time equals 2 seconds, the integrate cam switch moves to position f thereby breaking the holding circuit for the Mode I relay, which in turn removes power to the clutch. Rotation of the cams ceases unless the Mode II relay becomes energized. This may occur only after the "Integrate" cam switch has moved to position f. That is, in order that the Mode II relay be energized, the ground path through integrate cam switch (f), and respiration relay contacts $K_5(1, 2)$ must be present. Hence, clutch power and starting of the sixty-second timed interval depends upon the subject being in the inspiration phase of the cycle. When this occurs, the Mode II relay is activated, applying clutch power from $S_{1D}(4)$ through $K_4(6, 5)$, thence through clutch cam switch b. Simultaneously the "Reset" relay is deenergized by losing the ground at $K_4(1, 10)$. Hence integration and the timed interval commences.

Sixty seconds later the "Hold" cam switch goes to position d and will supply the necessary ground return through contacts $K_5(3, 12)$ (when the subject is inspiring) and then through $S_{1A}(4)$ which will end the integration cycle.

The cam timer continues as in Mode I, deenergizing the clutch at the end of the rotational cycle.

2.3 *Temperature Control and ±10 Volt Regulators*

The circuit board incorporating the circuits shown in figure 11 is physically mounted within the QSM, hence, they are temperature controlled at about 90F.

2.3.1 *Temperature Controller*

A 1N752 Zener diode regulates the thermistor bridge voltage to about 5 volts. Q_2 and Q_3 operate as a high input impedance, low output impedance differential amplifier to minimize bridge loading and to permit driving of the panel mounted temperature indicator, M-1. The output from the differential amplifier is fed to an emitter follower, Q_4, which drives a power transistor Q_5 mounted on the chassis. Q_5 provides current to the sensor heater that is proportional to the temperature error as determined by the 10K ohm thermistor temperature and the set point control. The control band is approximately ±½F from the set point: i.e., full power is applied when the actual temperature is ½F below the set point and zero power is applied when the actual temperature is ½F above the set point. The indicator adjusting potentiometer is adjusted to produce zero current in the meter when the sensor temperature is at the nominal 104F. Both adjustments are accessible from the end of the QSM.

2.3.2 *±10 Volt Regulator*

These voltage regulators supply the QSM and are in fact the reference voltages referred to in the QSM manual. Both circuits are essentially identical except that the +10 volt dc circuit uses NPN transistors while the −10 volt dc circuit uses PNP transistors.

Q_6 and Q_9 function as series regulators while Q_7 and Q_8 amplify an error signal that is present between the 500 ohm potentiometer tap and the zener diode MCR-2222. As the +10 volt output tends to increase, for example, the voltage at the base of Q_7 increases, increasing the input current to Q_7, increasing the drop across the 2.21K ohm collector resistor. Hence, the output of Q_6 (+10 volts) tends to decrease. The four IN458A diodes are used for temperature compensation of the emitter base voltage drops in both Q_7 and Q_8. Test points and the 500 ohm adjustments are accessible at the end of the QSM.

2.4 *Power Supplies*

2.4.1 *±15 Volts*

Two Technipower, adjustable and regulated supplies are used for the computer section.

2.4.2 *28 Volts*

One Technipower, nonadjustable, nonregulated, supply is used for relay circuits and as a source of energy for the sensor heaters (20 watts).

2.4.3 *Flowmeter*

The flowmeter uses a chassis mounted transformer in conjunction with a power supply and regulating circuit to provide ±20 volt dc at 40 ma.

3. CALIBRATION

3.1 *Instrument*

Proper operation of the instrument is determined in the Check mode. The system check is based upon insertion of known signals, substituted for transducer outputs, hence, when gains are correct, predictable results are obtained. If any significant errors are noted, adjustments must be made as outlined in section 4, Maintenance. The check mode procedure is as folows:

	Nominal (volts)	Actual
i) Check voltage at J-1	+5.2375	________
ii) Check voltage at J-2	+4.1005	________
iii) Check voltage at J-3 and adjust with ϕB_I	–5.4910	________
iv) Check voltage at J-4 and adjust with B_X	–4.5757	________
v) Check voltage at J-5	–4.5757	________

vi) Check voltage at J-6 with check switch as follows:

Check	Nominal	Actual
0	.000	________
500	.320	________
1500	.960	________
2500	1.600	________

vii) Check voltages at J-7 with check switch as follows:

Check	Nominal	Actual
0	.000	________
500	–0.640	________
1500	–1.920	________
2500	–3.200	________

viii) Check voltages at J-8 with check switch as follows:

Check	Nominal	Actual
0	.000	________
500	–0.293	________
1500	–0.879	________
2500	–1.464	________

ix) Check voltages at J-9 with the check and consumption rate switches as follows after a one minute integration:

Rate	Check	Nominal	Actual
2500	0	0.000	________
	500	2.000	________
	1500	6.000	________
	2500	10.000	________
1500	0	0.000	________
	500	3.333	________
	1500	10.000	________
500	0	0.000	________
	500	10.000	________

3.2 pO_2 *Amplifiers and Constants*

This is perhaps the most crucial calibration, as small errors in adjustment of these parameters will cause gross errors in oxygen consumption. To facilitate calibration, several charts are included. Figure 12, Chart A, relates relative humidity to dew point, and obviously, if a direct determination of dew point is available, will not be required.

Figure 13, Chart B, relates the mole fraction ($N = \frac{pO_2}{P}$) to dew point and barometric pressure for normal atmospheric air.

Figure 14, Chart C, presents the parameter ϕB_1 as a function of dew point and barometric pressure.

Calibration proceeds as follows: After determining barometric pressure, relative humidity, and ambient temperature.

i) determine dew point from Chart A
  a) enter chart at ambient temperature
  b) read vapor pressure, vp = ______________
  c) multiply RH/100X vp = ______________
  d) enter chart at result of (c) and read dp ______________

ii) Calibrate pO_2 electrodes from Chart B. *CAUTION:* both electrodes must be at controlled temperature, allowed adequate warm up time (30 minutes to one hour), and if respiration gases have been in contact with the $pO_2{}^X$ electrode ESPECIALLY, the sensor must be flushed with ambient air to avoid catastrophic errors.
  a) enter chart at dew point and read B FACTOR on appropriate pressure line and record B FACTOR ______________ (mole fraction)
  b) multiply above factor by 0.225 volts. 0.225 x B FACTOR = ______________.
  This is the voltage to which both J-1 and J-2 are set with $pO_2{}^i$ and $pO_2{}^X$ potentiometers respectively, in the MANUAL mode.

iii) Determine ϕB_1 from Chart C.
  a) enter chart at dew point and read factor on appropriate pressure line and record C FACTOR ______________.
  b) set function switch to check mode.
  c) read voltage at J-1 and record ______________.
  d) multiply (c) by the C FACTOR ______________.
  e) adjust the ϕB_1 potentiometer until the voltage in (d) is obtained at J-3.

iv) Check that B_X is adjusted to provide a gain in amplifier D of -1.1159.
  a) in the check mode measure voltage at J-2 ______________.
  b) adjust B_X until voltage at J-3 is -1.1159 times the voltage in (a) $-1.1159 \times V_{J-2}$ = ______________

3.2.1 *Single Electrode* ($pO_2{}^X$) *Operation*

i) Place the sensor switch in the manual position

ii) Adjust the Sensor Manual Potentiometer until the voltage at J-1 is set to the value as determined in 5.2 ii, b in the manual mode.

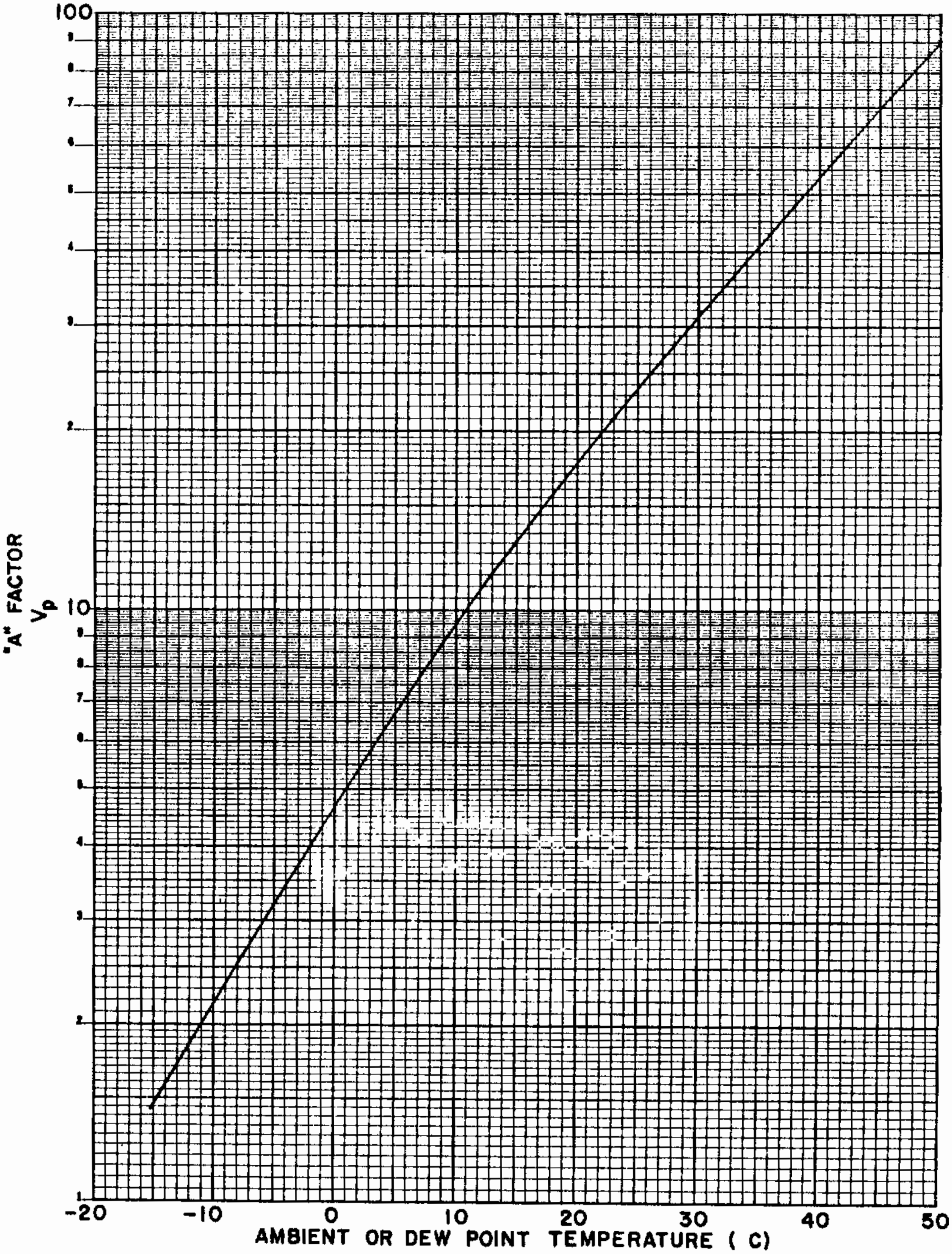


Fig. 12. Chart A

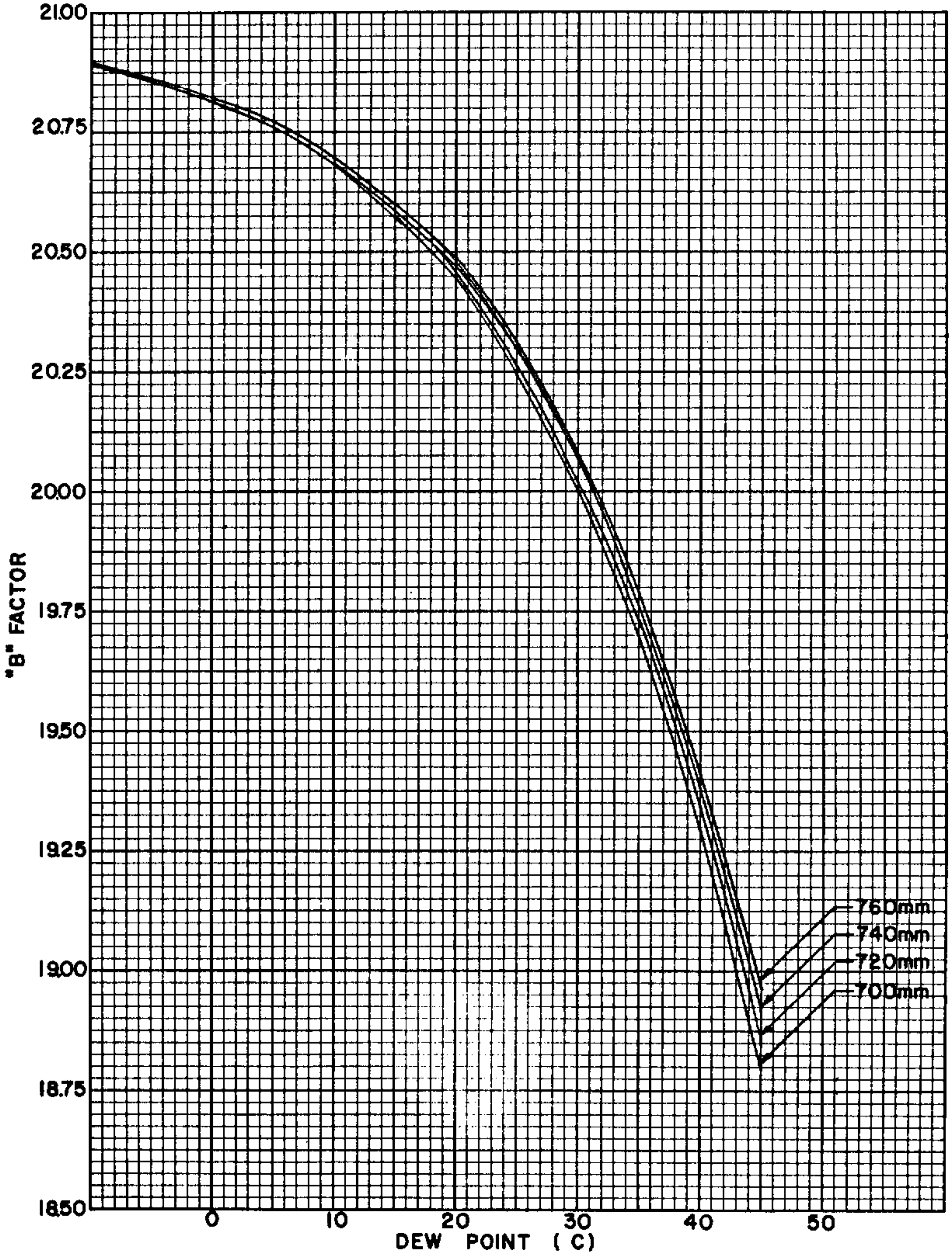


Fig. 13. Chart B

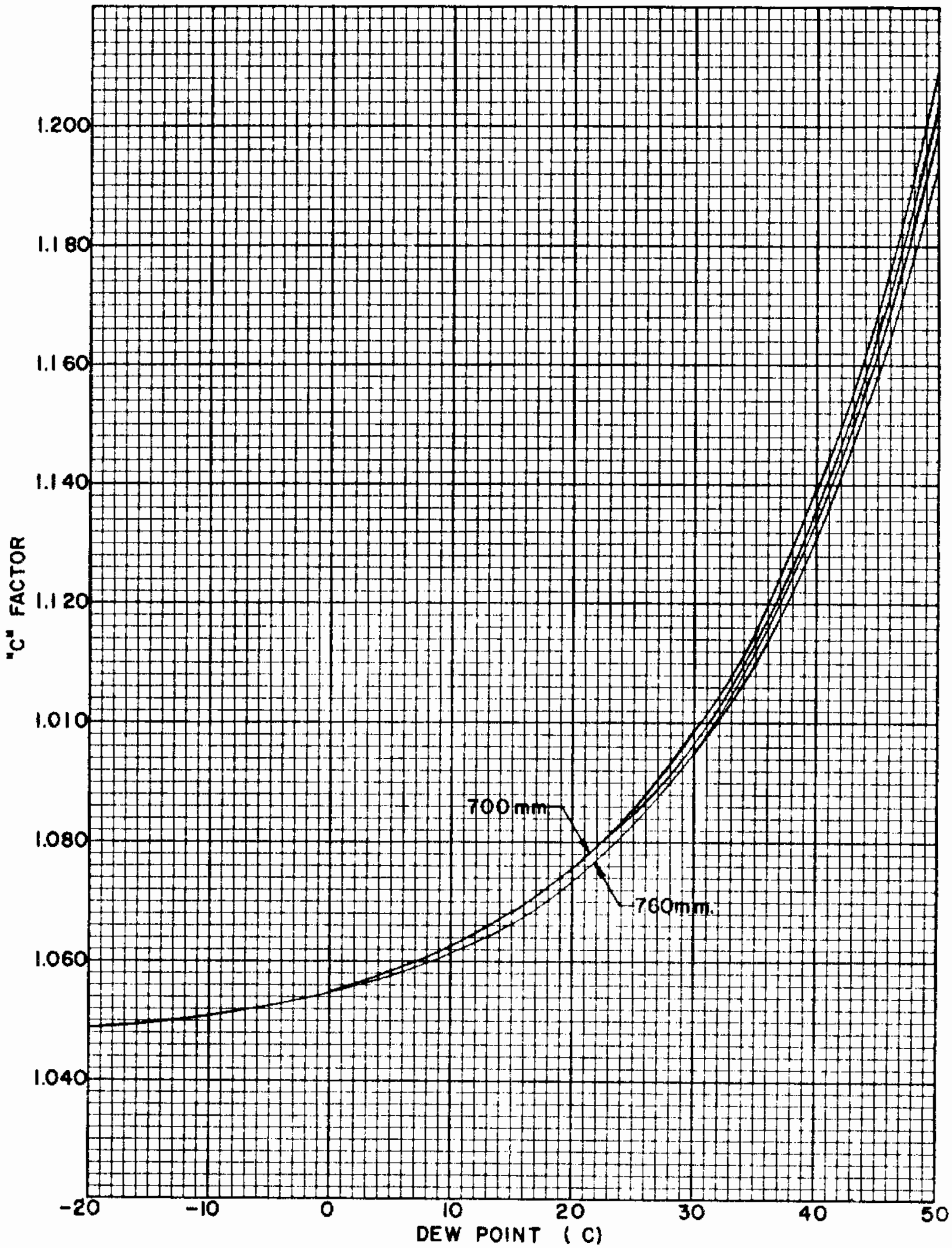


Fig. 14. Chart C

4. MAINTENANCE

4.1 *Routine*

4.1.1 *Voltages*

The ±15 volts should be checked periodically and adjusted to within ±10 mv of 15 volts. This is accomplished from the underside of the chassis measuring at the power supply terminals and adjusting with their respective screwdriver adjustments.

The ±10 volt QSM regulators should be checked periodically and adjusted within ±5 millivolts of nominal. For optimum results, the regulators should be adjusted to within 1 millivolt of each other; i.e., $|+10| - |-10| \leq 1mv$. This is accomplished by measuring the voltages at the test points provided at the end of the QSM and adjusting with the special tool provided as shown in figure 15.

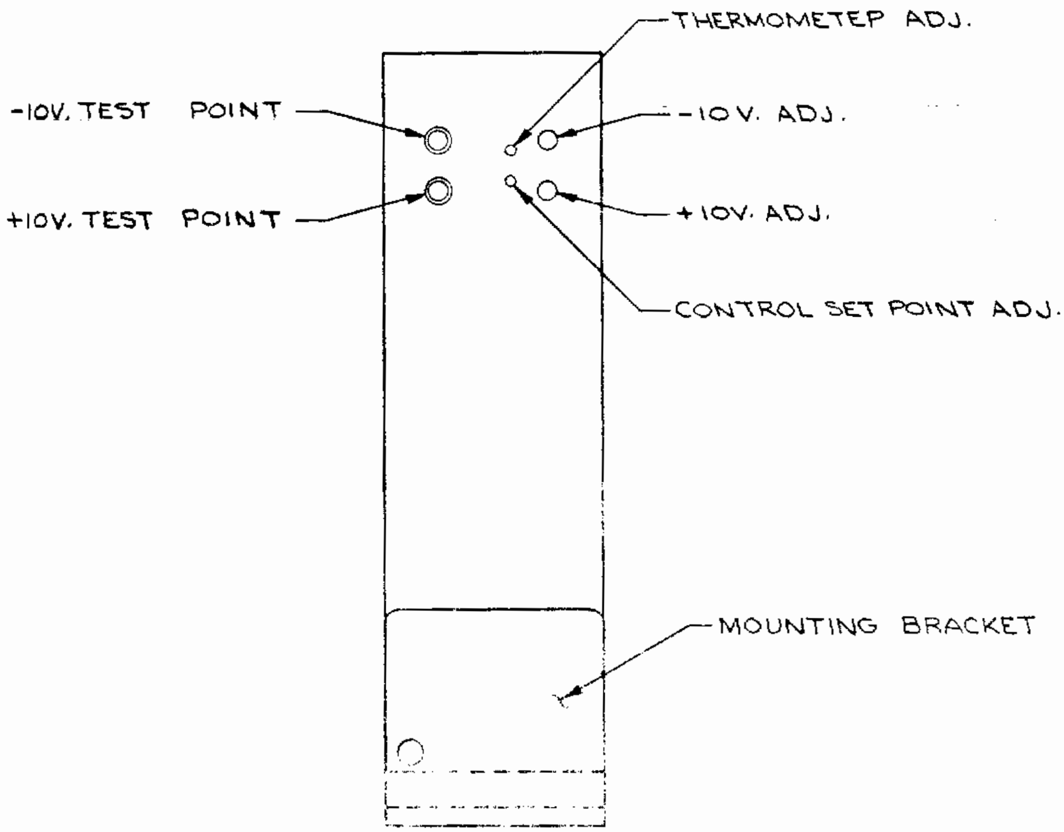


Fig. 15. Rear view of multiplier (QSM) oxygen uptake computer

4.1.2 *pO_2 Electrodes*

Loss of electrolyte or a damaged film may be expected after operating for periods of from weeks to months. In the event that either of the above has occurred, as would be evidenced by noisy operation, slow response, sensitivity to position, or a drastic change in the pO_2^I or pO_2^X potentiometer settings, refer to the manufacturers instructions for "Preparation for Operation" included in section 6 of the appendix.

Note especially that the electrolyte must wet the entire membrane surface and that the film must be strenuously stretched.

4.1.3 *Flowmeter*

The only maintenance that should be required is that of cleaning the flow orifice. The only reason for this need is that smoke, oils, etc., may accumulate on the sensor head, hence modifying the output as would be evidenced by a shift in the zero flow output. This may be checked in the manual mode from J-6. With no flow, the output should remain within 10 millivolts of zero. Refer to the LINŪRMASS® Operating Instruction Booklet, section 6 of the appendix.

4.2 *Instrument*

When difficulties are encountered during the check mode calibration procedure, section 3.1, it may be necessary to check the gain and offset voltages of all stages in the Analog Section.

4.2.1 *Zero Offsets*

Every amplifier has a potentiometer to adjust the zero offset. On the P-2A amplifier, it is built in: on the pp65AU amplifier, a 20K ohm potentiometer is associated with each amplifier; the SQ-6 amplifier requires 50K ohms and is also on the circuit board. Adjustments are made as follows:

i) Amplifier A – manual mode, sensor plug disconnected and a resistor network connected to the female plug as shown in figure 16, monitor the output at J-1 and adjust the CORRECT potentiometer until output is 0.000 ±0.001 volt. *CAUTION:* there are two pots available from the underside of the chassis for each P-2A amplifier. One, closest to the end, is a factory adjustment and must not be disturbed. The other, closest to the amplifier terminals, is the zero offset pot.

ii) Amplifier C – same as above except monitor output at J-2.

The following amplifiers will be adjusted in the Check mode, Check switch to "O" and two shorting plugs in Jacks J-1 and J-2.

iii) Amplifier B – check output at J-3 and adjust R-14 until voltage is 0.000 ±0.001 volt.

iv) Amplifier D – check output at J-4 and adjust R-5 until output is 0.000 ±0.001 volt.

v) Amplifier E – check output at J-5 and adjust R-61 until output is 0.000 ±0.001 volt.

vi) Amplifier F – check output at test point 30 and adjust R-38 until output is 0.000 ±0.001 volt.

vii) Amplifier G – check output at J-7 and adjust R-21 until output is 0.000 ±0.001 volt.

viii) Amplifier H – check output at test point 29 and adjust R-23 until output is 0.000 ±0.001 volt.

ix) Amplifier I – check output at J-8 and adjust R-40 until output is 0.000 ±0.001 volt. Remove shorting plugs, set function switch to MANUAL mode 2500 SCC range, and cycle to the "Hold" position, going *quickly* from "Integrate" to "Hold" after resetting.

x) Amplifier J – follow instructions and caution as in amplifiers A and C with the following exception: this amplifier is connected as an integrator, hence, adjust the potentiometer

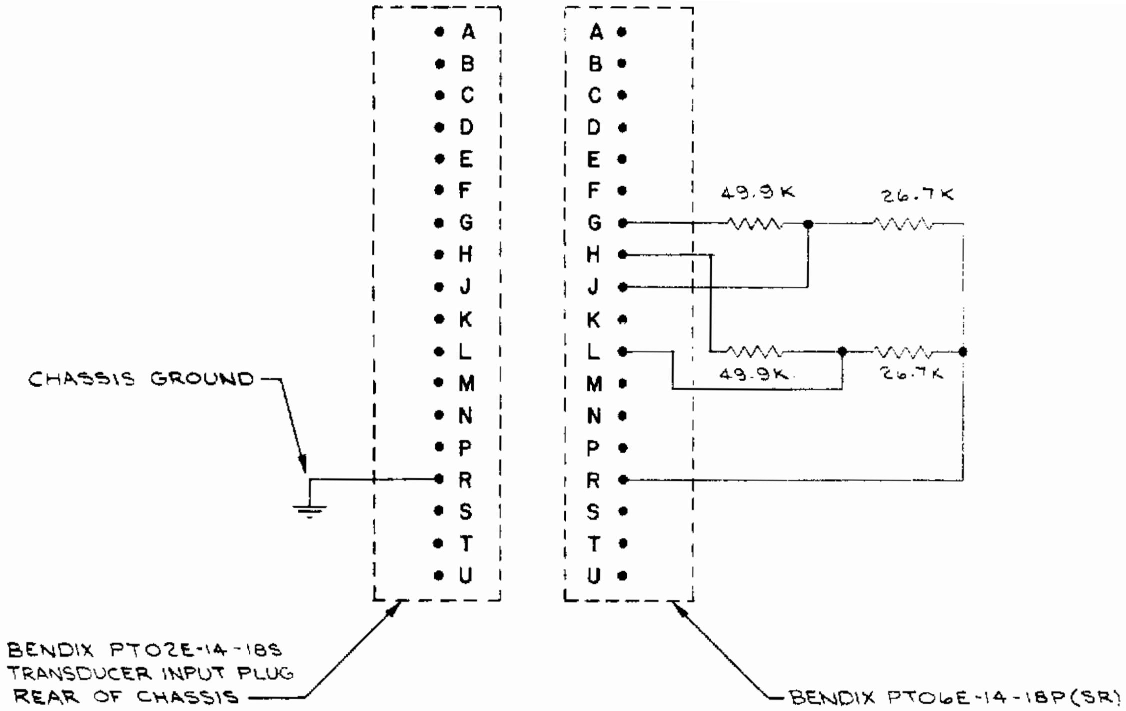


Fig. 16. Schematic of resistor network to replace pO_2^I and pO_2^X sensors for amplifier A and C zero offset adjustment

until rate of change of output voltage approaches zero. This is a trial and error process wherein adequate adjustment is assumed when the output changes less than ±10 millivolts per minute.

xi) Amplifier K – should require no adjustment.

4.2.2 *Amplifier Closed Loop Gain Adjustments*

Amplifiers A, B, C, and D have gains that are adjustable from the front panel with potentiometers pO_2^I, pO_2^X, ϕB_I, and B_X. See section 3 for the appropriate procedures for checking these amplifiers. The following amplifiers have fixed gains and must be adjusted with care, after zero-offsets have been eliminated (see section 4.2.1).

i) Amplifier E – check the gain with the function switch in the check mode. The output voltage V_{J5} should be equal to $5X(V_{J3} - V_{J4})$. For example:

$$V_{J5} = 5[-5.491 - (-4.576)] = -4.575 \text{ volts}$$

If a discrepancy exists R-16 and R-19 must be adjusted as follows. In the check mode, insert a shorting plug in J-1. Insert a plug connected to a 10K ohm decade resistor into J-2. Adjust the decade resistance until the voltage at J-4 reads –2.000 volts. Now adjust R-16 until the output at J-5 reads +10.000 ±0.001 volts. Reverse the position of the two plugs: shorting plug to J-2, decade resistor plug to J-1. Adjust the decade resistance until the voltage at J-3 reads −2.000 volts. Adjust R-19 until the output at J-5 reads −10.000 ±0.001 volts. Thus, amplifier E has been adjusted to provide a fixed gain of five times the difference in input voltages. The adjustment should be checked by the method outlined previously.

ii) Amplifier F – is an inverting amplifier having a gain of unity. In the check mode, measure the voltage at J-5. The voltage at Test Point 30 should be the negative of that appearing at J-5. If not, adjust R-35 until the gain is set to −1.

iii) Amplifier G – is an inverting amplifier having a gain of negative two. In the check mode, check switch to 2500 SCCM, measure the voltage at J-6. This should be +1.600 volts. Measure the voltage at J-7 and adjust R-25 if necessary until the voltage is −3.200 volts.

iv) Amplifier H – is an inverting amplifier having a gain of unity. Proceed as in (ii) above using J-7, test point 29, and R-28.

v) Amplifier I – has no adjustments, the input and feedback resistors being an integral part of the QSM.

vi) Amplifier J – operates as an analog integrator. Utilizing the Check mode, Consumption Rate, and Check switches, proper operation may be determined as follows:

Check the 2500 SCCM Range

a_1) Check switch and Consumption Rate switch in the 2500 SCCM posit ion.

b_1) Measure voltage at J-8 and record.

c_1) Depress reset switch and after the one minute integration, measure and record integrator output at J-9.

d_1) This voltage should be $V_{J-9} = \frac{10.000}{1.464} V_{J-8}$

e_1) If the actual voltage is higher than the calculated increase (turn clockwise) R-43; if smaller, decrease R-43. Adjust until agreement within ±10 millivolts is obtained.

Check the 1500 SCCM Range

a_2) Check switch and consumption rate switch in the 1500 SCCM position.

b_2) Measure voltage at J-8 and record.

c_2) Depress reset switch and after the one minute integration, measure and record ingrator output at J-9.

d_2) This voltage should be $V_{J-9} = \frac{-10.000}{0.879} V_{J-8}$

e_2) If the actual voltage is higher than the calculated increase (turn clockwise) R-46; if smaller, decrease R-46. Adjust until agreement within ±10 millivolts is obtained.

Check the 500 SCCM Range

a_3) Check switch and consumption rate switch in the 500 SCCM position.

b_3) Measure voltage at J-8 and record.

c_3) Depress reset switch and after the one minute integration measure and record integrator output at J-9.

d_3) This voltage should be $V_{J\text{-}9} = -\frac{10.000}{0.293} V_{J\text{-}8}$

e_3) If the actual voltage is higher than the calculated, increase (turn clockwise) R-49; if smaller, decrease R-49. Adjust until agreement within ±10 millivolts is obtained.

viii) Amplifier K has no gain adjustment.

4.2.3 *Polarizing Voltages*

The –0.800 volt pO_2 electrods polarizing voltages may be checked at test points provided on the circuit board. The pO_2^I voltage is checked at Test Point 39, while the pO_2^X voltage is checked at Test Point 1. R-69 and R-65 are used to establish the –0.800 ±0.005 volts.

4.2.4 *Calibration Voltages*

In the check mode, the following voltages should be measured and if necessary adjusted with the appropriate potentiometer.

Phone Jack	*Voltage*	*Potentiometer*	*Check Switch*
J-1	+5.2375	R-9	N.A.
J-2	+4.1005	R-7	N.A.
J-6	0.000	None	0
J-6	+0.320	R-33	500
J-6	+0.960	R-32	1500
J-6	+1.600	R-31	2500

4.2.5 *Check and Calibration Voltage Value Changes*

The function of this report is dual in nature. One aspect is to provide general operating instructions which could be applied to any OCC-2500. On the other hand, we are reporting evaluation data generated by a specific instrument in our possession. In this context we invite the reader to refer again to the voltage values and formulae given in sections 3.1, 4.2.2, and 4.2.4 of this appendix. These are idealized values as developed by the contractor on the basis of the instrument's design and anticipated performance. It is freely acknowledged that variations of these values will be coincident with variations in an individual instrument's calibration which, in turn, is dependent upon the physical characteristics of the mask sensor assembly, the electrical characteristics of the transducers and the analysis technique chosen as the standard. In evaluating the instrument at our disposal and as a consequence of any one or possibly all of the conditions given above, we found it necessary to modify some of the voltage values listed in the general description. It is emphasized that these corrections, applying, specifically, to our instrument may be of only academic interest to the reader but are nevertheless presented in the interests of completeness.

Listed below are the altered voltage values and formulae derived from those found in sub-sections 3.1, 4.2.2, and 4.2.4 of this appendix.

The Check Mode Procedure: (Refer to section 3.1)

i) through v) The same

vi) Check voltage at J-6 with check switch as follows:

Check	*Nominal*	*Actual*
0	.000	________
500	0.340	________
1500	0.929	________
2500	1.506	________

vii) Check voltage at J-7 with check switch as follows:

Check	*Nominal*	*Actual*
0	.000	________
500	–0.680	________
1500	–1.858	________
2500	–3.012	________

viii) Check voltage at J-8 with check switch as follows:

0	.000	________
500	–0.311	________
1500	–0.850	________
2500	–1.378	________

ix) Check voltages at J-9 with the check and consumption rate switches as follows after a one minute integration:

Rate	*Check*	*Nominal*	*Actual*
2500	0	0.000	________
	500	1.922	________
	1500	6.000	________
	2500	10.000	________
1500	0	0.000	________
	500	3.200	________
	1500	10.000	________
500	0	0.000	________
	500	10.000	________

Amplifier Closed Loop Gain Adjustments (refer to section 4.2.2)

i) through ii) The same

iii) Amplifier G – is an inverting amplifier having a gain of negative two. In the check mode, check switch to 2500 SCCM, measure the voltage at J-6. This should be +1.506 volts. Measure the voltage at J-7 and adjust R-25 if necessary until the voltage is –3.012 volts.

vi) through c_1) The same

d_1) This voltage should be $V_{J\text{-}9} = -\frac{10.432}{1.378} V_{J\text{-}8} - 0.432$

e_1) Through c_2) The same

d_2) This voltage should be $V_{J\text{-}9} = -\frac{10.720}{0.850} V_{J\text{-}8} - 0.720$

e_2) Through c_3) The same

d_3) This voltage should be $V_{J\text{-}9} = -\frac{8.833}{0.311} V_{J\text{-}8} + 1.167$

e_3) Through viii) The same

Calibration Voltages

Phone Jack	*Voltage*	*Potentiometer*	*Check Switch*
J-1	+5.2375	R-9	N.A.
J-2	+4.1005	R-7	N.A.
J-6	0.000	None	0
J-6	+0.340	R-33	500
J-6	+0.929	R-32	1500
J-6	+1.506	R-31	2500

4.2.6 *Timing Motor*

The basic timing period of one minute may be checked in the Mode I position or the Check mode by manually timing, with a stop watch, the period in which the "Integrate" light is on. A factory adjustment using relay contacts and a precision timer was effected and unless there is a positive indication that the period has changed significantly it is recommended that no adjustments be made.

4.2.7 *Additional Drawings*

Figures 17, 18, 19, and 20 are included in the Maintenance Section to assist the potential user of this report in trouble shooting and location of parts.

5. DERIVATIONS

5.1 *Oxygen Uptake and Computer Equations*

Both the derivation of the oxygen uptake equation and the computer equation are given in section II of the report under the heading "Theory of Operation."

5.2 *Miscellaneous Equations*

5.2.1 *Flowmeter Equation for a mixture of gases*

$$e_o = K \left[\dot{m}_1 c_{p1}^{1.1} \mu_1^{.36} + \dot{m}_2 c_{p2}^{1.1} \mu_2^{.36} + \ldots\ldots + \dot{m}_n c_{pn}^{1.1} \mu_n^{.36} \right] \qquad (1)$$

5.2.2 *Apparent Molecular Weight of a mixture of gases*

$$M = \frac{p_1}{P} M_1 + \frac{p_2}{P} M_2 + \ldots\ldots\ldots + \frac{p_n}{P} M_n \qquad (2)$$

5.2.3 *Apparent Molecular Weight ratio of humid air to dry air*

$$\frac{M_{WA}}{M_{DA}} = 1 - \frac{pH_2O}{P}\left[\frac{M_{DA} - MH_2O}{M_{DA}}\right] \tag{3}$$

$$= 1 - \frac{pH_2O}{P}(0.37859) \tag{4}$$

5.2.4 *Ratio of Mass of Water Vapor to Mass of Dry Air*

$$\frac{mH_2O}{m_{DA}} = \frac{MH_2O}{M_{DA}} \times \frac{pH_2O}{P - pH_2O} \tag{5}$$

5.2.5 *Mass of Humid Air as a function of Mass of Dry Air*

$$m_{WA} = m_{DA}\left(1 + \frac{mH_2O}{m_{DA}}\right) \tag{6}$$

5.3 *Terminology*

e_o = output voltage
K = calibration constant
$\dot{m}_n$ = mass flow rate of the n^{th} constituent (liters/minute)
$cp_n^{1.1}$ = specific heat at constant pressure of n^{th} constituent (cal/g°K)
$\mu^{.36}$ = absolute viscosity (μ poises)
M = apparent molecular weight of a gas mixture
p_n = partial pressure of the n^{th} constituent (mm)
P. = total pressure of the mixture (mm)
M_n = molecular weight of the n^{th} constituent (g)
M_{WA} = apparent molecular weight of moist air (g)
M_{DA} = apparent molecular weight of dry air (g)
pH_2O = partial pressure of water vapor (mm)
MH_2O = molecular weight of water vapor
mH_2O = mass of water vapor (g)
m_{DA} = mass of dry air (g)
m_{WA} = mass of humid air (g)

6. OPERATING INSTRUCTIONS FOR LINŪRMASS® AND pO_2 ELECTRODES

6.1 *Precautionary Procedures in Handling the LINŪRMASS Flowmeter*

Care should be exercised to protect the sensing elements from contact with anything except a gaseous fluid; the sensors are suspended on fine wire capable of withstanding shock and vibration but not direct contact with foreign objects.

DO NOT PROBE SENSING ELEMENTS

Avoid using test procedures where inadvertant flow of cryogenics or other liquids can occur. The instrument is designed for gaseous flow.

Inlet lines should be thoroughly cleaned prior to supplying gas to the instrument. Questionable sources should be filtered.

Do not exceed a flow velocity in excess of five times the normal full scale flow rate.

When using Model "A" (28 volt dc) signal conditioners:

Damage will result to the instrument if improperly wired. Refer to wiring diagram included with instrument before applying power. Before connecting transducer to power supply, turn power supply on and check output for proper voltage level. *Excessive switching transients may cause permanent damage.*

Do not short the output leads together or connect the positive output lead to power ground. This unit is protected against momentary shorting; however, a prolonged short may degrade performance.

6.2 *Maintenance and Cleaning*

The instrument as supplied has been thoroughly cleaned. Should the unit require internal re-cleaning, gently flush trochloroethylene through the flow section followed by flushing with dry nitrogen. Insure that the dry nitrogen flushing does not exceed the flow velocity limits specified. When possible bake at 150F for a few minutes to hasten evaporation of solvent.

6.3 *Instructions for YSI Oxygen Probes*

Oxygen diffuses through a Teflon membrane to the gold cathode surface where electroreduction to water occurs. The cathode, which is maintained at 0.80 volts, is depolarized by this oxygen allowing a current to flow which is proportional to the oxygen contacting the cathode surface. The reference anode, together with the electrolyte is also behind the membrane, thus no current flows through the solution being measured. For this reason, the electrode may be used to measure oxygen in nonconducting liquids or gases. Further, the electrodes are bathed in a known medium and protected from contamination by the plastic membrane.

6.3.1 *Description:*

Cathode – Gold imbedded in lucite
Anode – Silver pre-coated with AgCl
Polarizing Voltage – 0.8 volt

Membrane – 0.001" Teflon
Electrolyte – half saturated KCl

6.3.2 *Preparation for Operation:*

1. Remove the membrane and inspect the probe tip for cleanliness – rinse with DISTILLED water to remove dirt, salt crystals or other foreign materials.

2. Prepare KCl solution by diluting a saturated KCl solution with an equal part of DISTILLED water. Note: Use of DISTILLED water is required or performance will be affected by contaminate reactants.

3. Fill the central well with KCl solution using an eyedropper. Avoid trapped air. Add more KCl solution until a large drop accumulates above the probe surface.

4. Select a membrane strip (1½ x 3 inches). Grasp the probe in one hand and secure one end of the strip against the side of the probe with the thumb. Grasp the free end of the membrane strip and stretch over the end of the probe in an up, over and down motion. Stretch an "O" ring over the end of the probe by rolling with thumb and forefinger – seat the "O" ring in the groove provided. The membrane must be wrinkle free and tight like a drum head. Inspect the membrane for wrinkles or tears. With a pair of small scissors trim away the excess membrane so that it will not interfere with the threads on the body,

5. Protect membrane from damage – use probe guard if provided on this model.

6.3.3 *Performance Characteristics:*

Room Temp. (68F) – Air Electrode Current	15 microamps
Temp. Coeff. (membrane characteristic)	about 4%/°C
Response Time – Affected by membrane material and thickness – also by "tightness" of membrane	90% in 10 sec
Zero current (taken in pure nitrogen gas)	0.03 microamps

6.3.4 *Notes:*

1. Sluggish response is probably due to a slack membrane.

2. A slack membrane also results in sensitivity to shock or rapid movement in liquid media. A unit with a properly tensioned membrane is insensitive to moderate shocks and recovers rapidly from severe jolts.

3. When detecting dissolved oxygen – agitate the medium to avoid local oxygen depletion in the vicinity of the cathode, which results in low O_2 readings.

4. Avoid fingerprints on the membrane.

5. A small brush may be used when filling with KCl solution to eliminate trapped air bubbles and insure complete wetting of the cathode area.

6. Occasionally, defects in the membrane material or stretching produces very thin spots which result in high currents or erratic behavior.

7. Halogens and H_2S are interfering gases. Extended use of H_2S contaminates the cell. Polish gold by rubbing lightly with soft wet cloth – use no abrasives.

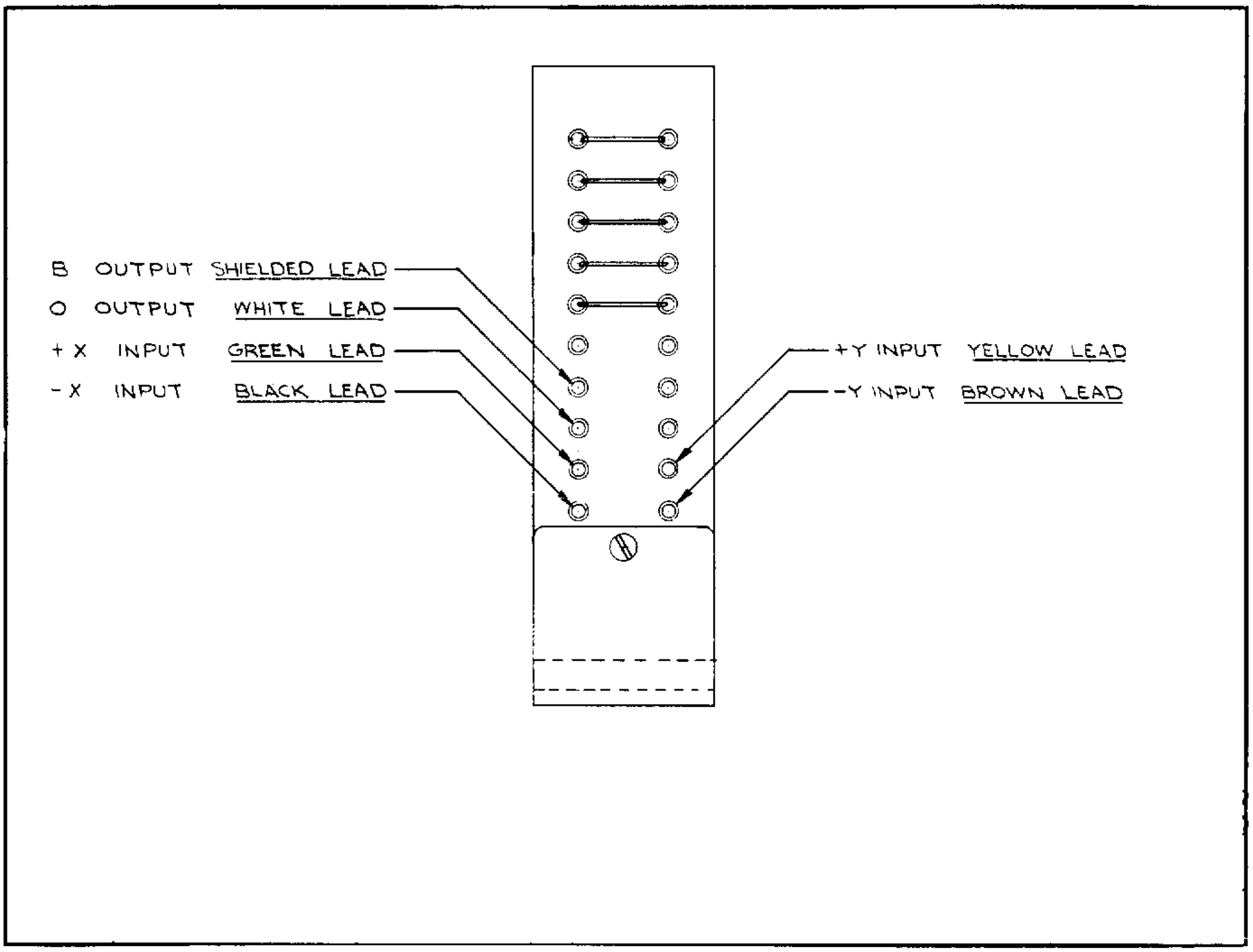


Fig. 17. Front view of multipliex (QSM) oxygen consumption computer

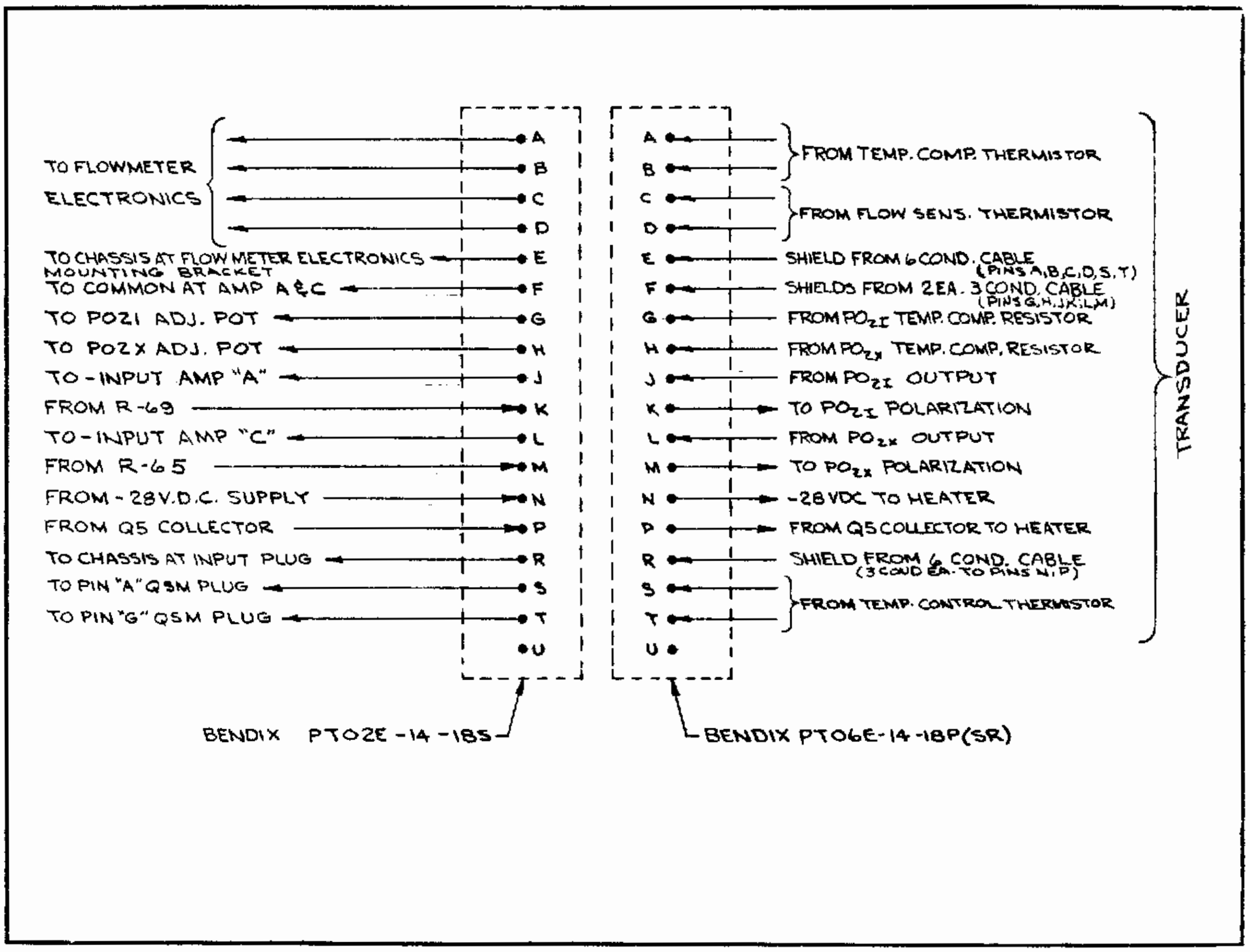


Fig. 18. Transducer input plug connections

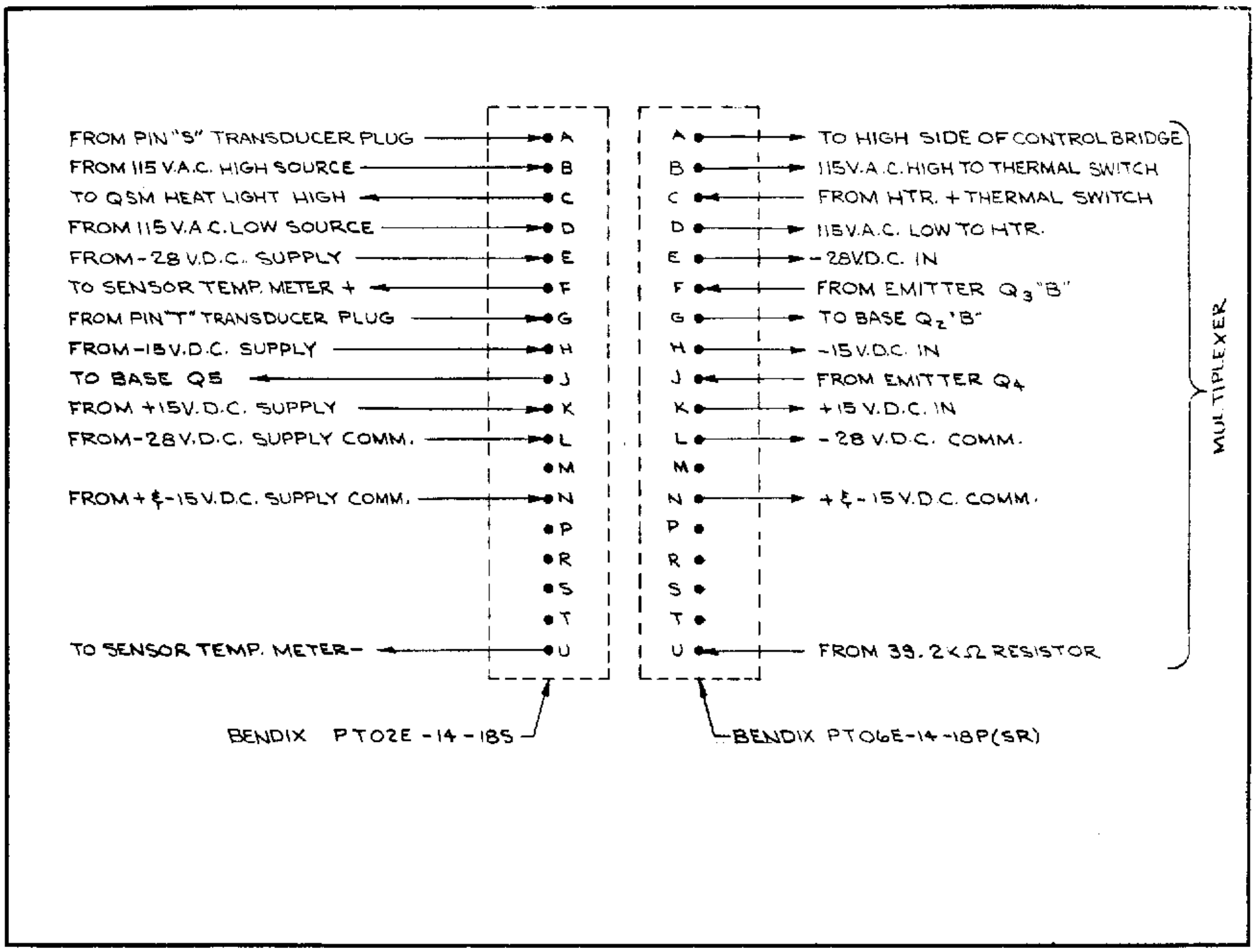
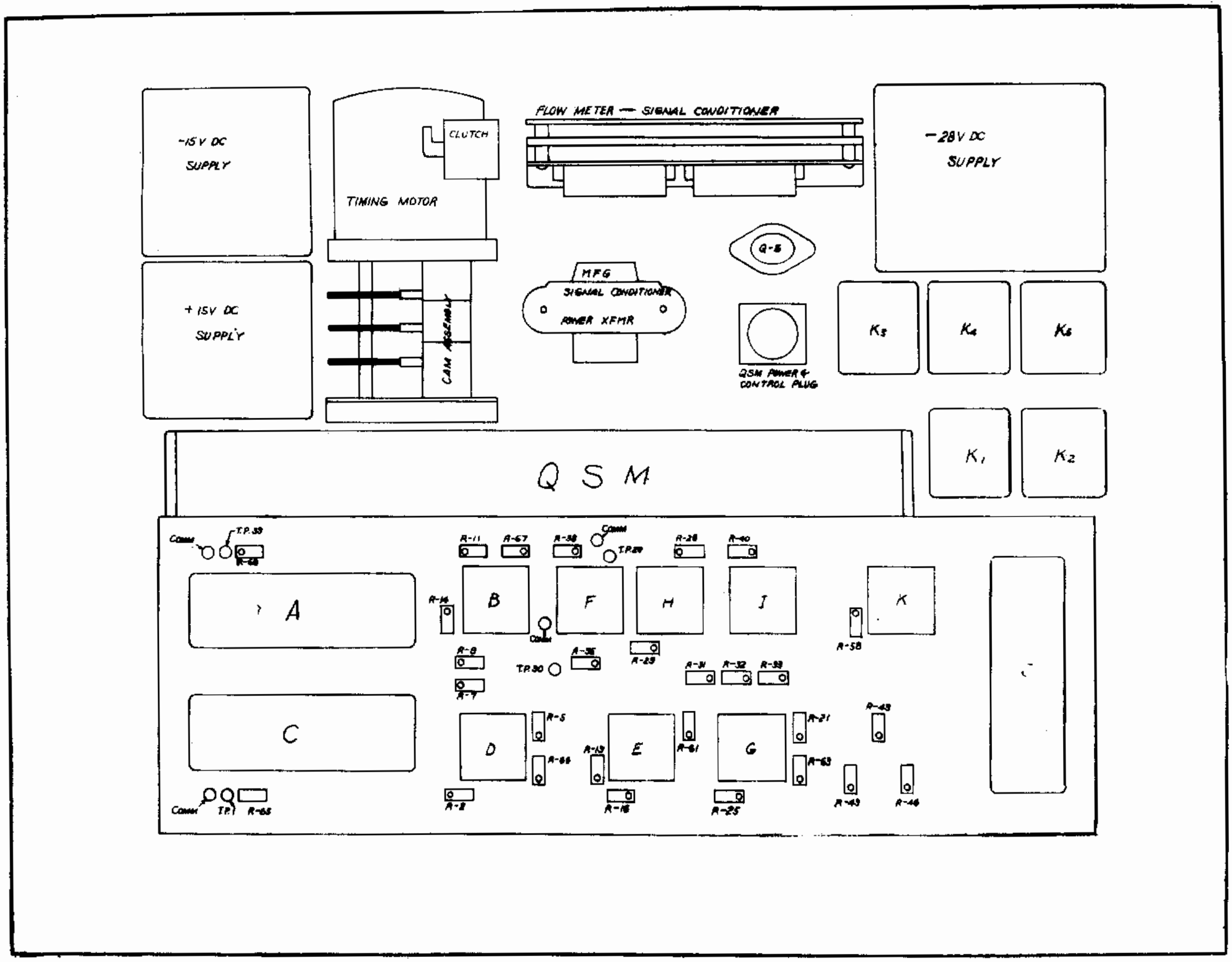


Fig. 19. Multiplier power and control plug connections



-15V DC SUPPLY
+15V DC SUPPLY
CLUTCH
TIMING MOTOR
CAM ASSEMBLY
FLOW METER — SIGNAL CONDITIONER
MFG SIGNAL CONDITIONER POWER XFMR
Q-5
QSM POWER & CONTROL PLUG
-28V DC SUPPLY
K3
K4
K5
K1
K2
Q S M
A
B
C
D
E
F
G
H
I
K

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13. ABSTRACT

A series of experiments has been designed to evaluate the performance of an oxygen uptake computer. The Model OCC-2500 oxygen uptake computer is an electronic instrument including a mask-sensor assembly and a special-purpose analog computer. Intended for the analysis of respiratory gases in human subjects, the system produces a real-time analog voltage proportional to the oxygen uptake in one minute or other time periods controlled by the operator. Expired air samples, monitored by the polarographic oxygen sensor and mass gas flowmeter of the computer system were simultaneously collected in a gasometer and analyzed by gas chromatography. Oxygen uptake values (200-3200 cc/min) obtained from 15 subjects (297 observations) during rest and after exercise produced a sample correlation coefficient of 0.998. Subjects enjoy virtually unrestrained mobility using the device, in that attachment to monitoring equipment is limited to electrical leads. Personnel support requirements and errors, associated with conventional procedures, are significantly reduced. The compact nature of the device permits application in almost any experimental design situation including pressurized suits and underwater studies.

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Bioinstrumentation						
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Mass gas flowmeter						