NA-65-22

# DEVELOPMENT AND TESTING OF A PROTOTYPE RESPIRATION ANALYZER

## FINAL REPORT

## PHASE II

NASA CONTRACT NAS 4-367

NORTH AMERICAN AVIATION, INC. / LOS ANGELES DIVISION

SERIAL NO. 11
NA-65-22

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## PHASE II

NASA CONTRACT NAS 4-367

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# INTRODUCTION

The NASA Contract NAS 4-367 Program was initiated for the purpose of developing to prototype status certain respiratory sensors and to test these sensors under various environmental conditions with human subjects. Under the Phase I efforts a prototype analyzer was assembled which utilized a Beckman Instruments, Inc. $P_{O2}$, $P_{CO_2}$, $P_T$ and temperature sensor and NASA supplied mass flow meters. The prototype analyzer was tested at sea level and at 25,000 feet in an altitude chamber with human subjects under three conditions of physical work output for the purpose of evaluating response characteristics and accuracy of the prototype analyzer, and to determine feasibility of the prototype device for eventual airborne utilization.

The Phase II efforts were initiated primarily as a result of several problems encountered during the Phase I efforts. It was also desired that a thermodynamic analysis be performed to verify certain assumptions found necessary in order to use the equipment as it was being used, and to process the data in order to obtain mass flowrate and if possible, to determine oxygen consumption by the human subjects.

The principal work tasks were to make a theoretical comparison of two competitive flowmeters, establish the number of flowmeters required, verify the use of the perfect-gas law, specify requirements for an isothermal system, and specify requirements to achieve the desired degree of measurement accuracy. These work tasks were modified in an effort to determine oxygen consumption from the data taken during Phase I tests. This effort resulted in an error analysis which indicated the futility of trying to determine oxygen consumption by the difference in mass flow of inspired and expired gases.

Recommendations are made as to the use of indirect methods of computing oxygen consumption and as to the direction that should be taken in the follow-on research studies.

## DISCUSSION

### PHASE I WORK EFFORTS

The purpose of the initial phase of work in NASA Contract NAS 4-367 was (as described in detail in Reference 1) to provide data on new instrumentation for monitoring the composition, mass flow rate, and temperature of expired air. These measurements were made with the idea that ultimately the oxygen consumption by human subjects could be determined using these measured data, thus establishing the feasibility of this type of instrumentation for obtaining this important physiological information

Of four parameters that were measured, three of them were sensed in a single compact Beckman Analyzer ($P_{CO_2}$, $PO_2$ and Temperature). The fourth measurement (mass flow rate) was measured b a Technology, Inc. Mass Flow Meter (Pneumotachometer). Although only three parameters were sensed on the Beckman Unit, it was capable of sensing four, the fourth being total pressure. The total pressure sensitivity of the unit, or rather insensitivity, precluded the sensing of breath-to-breath variations in total pressure.

The prototype analyzer was tested at sea level and at 25,000 feet simulated altitude in an altitude chamber with human subjects at rest, and during moderate and heavy exercise on a powered treadmill. The purpose of this testing was to evaluate the response characteristics and accuracy of the prototype analyzer and take initial steps in the determination of the feasibility of the prototype device for eventual in-flight utilization. The altitude of 25,000 feet was chosen to simulate the cockpit pressurization level of a fighter aircraft and the work levels were chosen to produce respiratory activity exhibited by test pilots flying experimental aircraft.

## GENERAL SYSTEM DESCRIPTION

The general layout of test apparatus is shown in schematic form in figure 1. Breathing oxygen was supplied from the chamber oxygen storage manifold by a standard MD-1 crew regulator for both sea level and altitude runs. Demand oxygen passed through a dry gas meter (American Standard, calibrated in liters), thence through the No. 1 or inspiration mass flowmeter and on to the subject via a 3/4-inch flexible tube. The temperature of the inhaled oxygen showed minor variation as measured by a Yellow Springs Teletheromometer and generally remained between 72° and 77°F. The subject breathed through a rubber spirometer mouthpiece and a nose clamp was utilized to prevent any leakage of respiratory gas from the nose. Initially, a modified Sierra oxygen mask as supplied by Beckman with the analyzer was used, but excessive leakage occurred around the mask periphery during respiratory activity associated with heavy exercise. The mouthpiece minimizes leakage, although examination of test results indicates that in a few instances, leakage may have occurred around the mouthpiece. The mouthpiece was attached to a plastic manifold block which contained one inhalation valve and two exhalation valves. Mouthpice dead space was thereby minimized and represented approximately 100 cc. The optical requirements of the analyzer $CO_2$ sensor required a small bore passage through the analyzer (7/16 inch inside diameter). To prevent prohibitively high exhalation resistance, a duplicate 7/16 inch exhalation line bypassing the analyzer was provided. Both lines joined just upstream of the No. 2 or expiration mass flowmeter. Another thermister was located at the downstream end of this flowmeter. Just past the No. 2 flowmeter was located a three-way diverter valve so that exhaled gas could be directed either to the spirometer or to an electric hygrometer. Because of space limitations,

## SCHEMATIC OF THE PROTOTYPE RESPIRATION ANALYZER SYSTEM

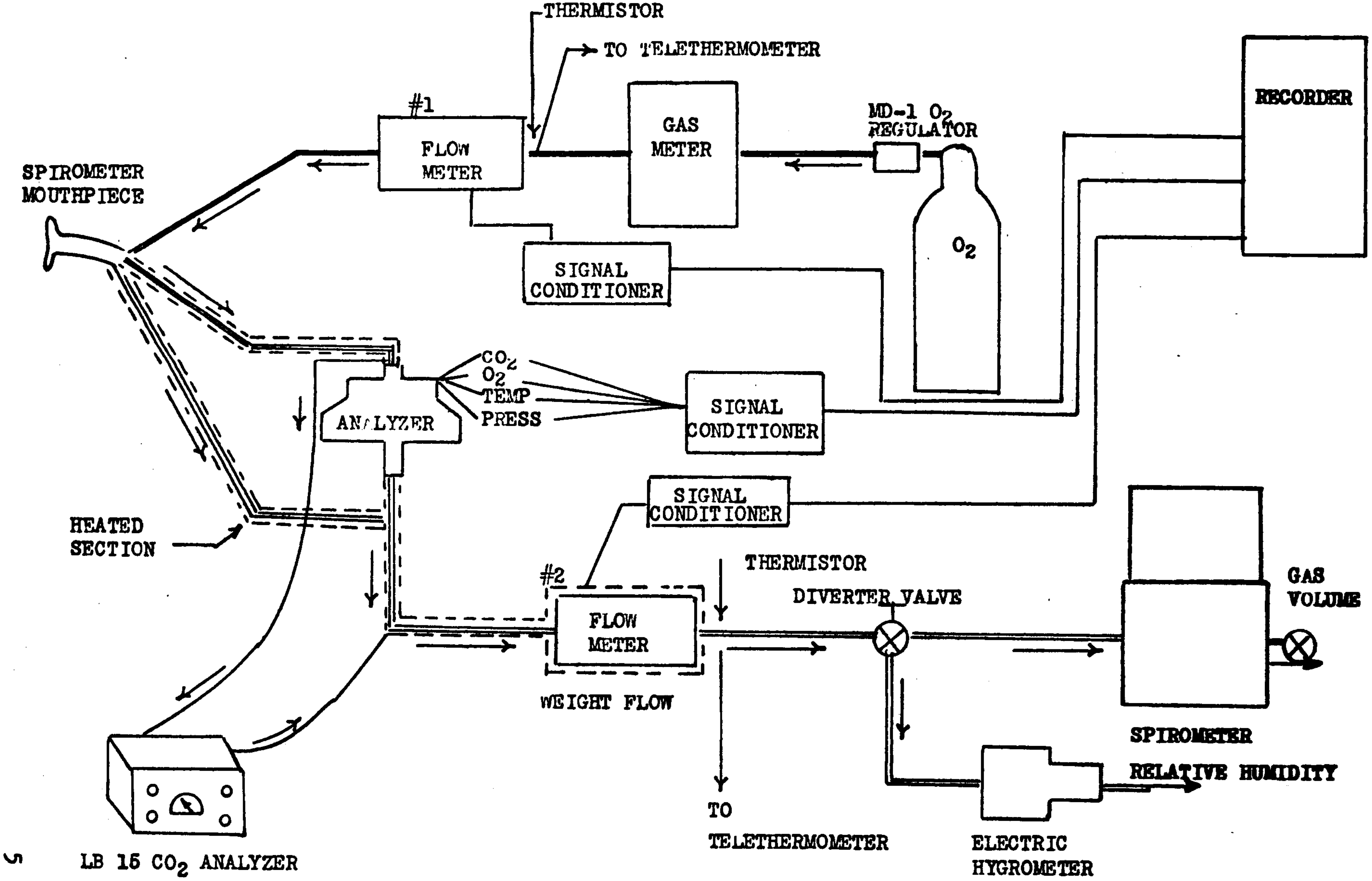

FIGURE I

the hygrometer was not utilized during the altitude runs, although all other apparatus, except for the LB-15 and the recorders, were located in the chamber.

Sample gas for the LB-15 $CO_2$ analyzer was drawn off just upstream of the prototype analyzer and returned to the exhaled air upstream of the No. 2 flowmeter. The LB-15 requires a sampling rate of approximately 300 cc/min.

To prevent condensation of moisture in the exhalation lines, Thermotape heaters were obtained and wrapped around these lines to an area downstream of the No. 2 flowmeter. The heaters were supposedly thermostated to maintain the flexible tubing at 100° to 100°F, but as seen from the results, much wider fluctuation was recorded. Moisture condensation did not, however, occur.

Although the respiration analyzer was located as close to the subject's face as possible, approximately 18 inches of flexible tubing (Tygon) was necessary to provide the freedom of movement required while walking on the treadmill. The analyzer was firmly installed on a shelf attached to the hose support bracket of the treadmill and, therefore, remained in the same relative position during all test runs. The two mass flowmeters were located adjacent to the analyzer while the spirometer, signal conditioners, gas meter, and teletherometer were located on a stand in front of the treadmill. Care was taken not to change the relative positions of any apparatus during the course of the experimental program.

Power for the respiration analyzer and the two mass flowmeters was supplied by a controlled power supply providing 28 volts dc. The LB-15 analyzer, F-3 oxygen analyzer, and all recorders were operated with normal 110 volt ac power. Sanborn hot stylus recorders were utilized for all parameters.

## RESULTS

Because of the large quantity of data colleted and the limited scope of the contract, reduction of all data was impossible. In order to provide the most meaningful sampling procedure, a decision had to be made as to which data samples provided the most pertinent information. Samples 5, 8, 9, 12, and 13 were chosen for the following reasons. Sample 5 was taken at the end of the 20-minute rest phase and was chosen on the assumption that the subject was equilibrated at this point and that the data would be very representative of the rest condition. Samples 8 and 9 were taken five minutes before the end and at the end of the 15-minute moderate exercise phase. They were chosen as representative of the respiratory response to moderate exercise. Samples 12 and 13 were taken five minutes before the end and at the end of the 15-minute heavy exercise phase and were chosen as being representative of respiratory response to heavy exercise.

A summary of test results derived from the chosen data samples is presented in Table I. All results with the exception of pressure transducer data are tabulated on this single sheet to facilitate comparative evaluation of the various sensors. Results of the system check runs are listed in Table V.

| RUN # | CO$_2$ MEASUREMENTS mm Hg pCO$_2$ |  |  |  |  |  |  |  |  |  | ANALYZER OXYGEN |  |  |  |  | INSPIRAT |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | LB-15 ANALYZER |  |  |  |  | PROTOTYPE ANALYZER |  |  |  |  | mm Hg pO$_2$ |  |  |  |  | #1 FLOW |  |  |
|  | SAMPLE 5 | SAMPLE 8 | SAMPLE 9 | SAMPLE 12 | SAMPLE 13 | 5 | 8 | 9 | 12 | 13 | 5 | 8 | 9 | 12 | 13 | 5 | 8 | 9 |
| #1 S.C. | 35 | 36 | 36 | 38 | 38 | 37.5 | 38 | 38 | 40 | 40 | 693 | 684 | 684 | 684 | 684 | 7.2 | 20.6 | 21.0 |
| #3 B.M. | 31.4 | 38 | 38 | 42 | 42 | 32 | 40 | 40 | 45 | 45 | 665 | 665 | 665 | 646 | 646 | 9.5 | 235 | 22.7 |
| #4 N.L. | 31.4 | 38 | 38 | 40 | 40 | 33.7 | 39.5 | 39.5 | 45 | 45 | 665 | 665 | 665 | 665 | 665 | 9.7 | 21.1 | 28.7 |
| #5 J.K. | 32.4 | 45.6 | 45.6 | 45.6 | 45.6 | 33.7 | 48 | 48 | 48 | 48 | 693 | 665 | 665 | 665 | 646 | 6.95 | 20.9 | 24.1 |
| #6 G.M. | 30.4 | 36 | 36 | 385 | 385 | 31 | 37.5 | 37.5 | 40 | 40 | 684 | 665 | 665 | 665 | 640 | 14.7 | 25.0 | 29.1 |
| #7 M.G. | 28 | 385 | 385 | 39 | 39 | 29 | 39.5 | 40 | 40 | 40 | 665 | 665 | 665 | 665 | 675 | 9.7 | 23.8 | 21.1 |
| #8 J.P. | 28.5 | 39 | 39 | 40 | 40 | 28.5 | 40 | 40 | 42 | 42 | 676 | 680 | 680 | 674 | 674 | 9.5 | 27.8 | 28.9 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| #9 B.M. | 20.5 | 27 | 27 | 28.5 | 28.5 | 21 | 27 | 27 | 28.5 | 285 | 215 | 215 | 215 | 215 | 215 | 9.1 | 22.2 | 22.6 |
| #15 J.K. | 20 | 32.4 | 32.4 | 38 | 38 | 22.5 | 33 | 33 | 38 | 38 | X | X | X | X | X | 5.7 | 22.2 | 25.5 |
| #16 S.C. | 21.5 | 23.8 | 23.8 | 24 | 24 | 20.5 | 23.5 | 23.5 | 24 | 24 | 218 | 218 | 218 | 207 | 207 | 7.4 | 17.6 | 21.0 |
| #17 J.P. | ?<br>10.7 | ?<br>15.2 | ?<br>15.2 | ?<br>18.5 | ?<br>18.5 | 19 | 22 | 22 | 23 | 23 | 210 | 190 | 210 | 210 | 210 | 12.5 | 22.2 | 25.6 |
| #18 M.G. | 20 | 21 | 21 | 23.8 | 23.8 | 21 | 22.5 | 22.5 | 245 | 245 | 210 | 210 | 210 | 200 | 200 | 8.5 | 19.9 | 22.2 |
| #19 N.L. | 18.5 | 21 | 21 | 21.7 | 217 | 20 | 21.5 | 21.5 | 22.5 | 225 | 200 | 210 | 210 | 200 | 200 | 6.4 | 22.7 | 22.2 |

TABLE 1

# SUMMARY SHEET — TEST RESULTS

| RY FLOW (LITERS/MIN) | | | | | | | EXPIRATORY FLOW (LITER/MIN) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ETER | | GAS METER | | | | | #2 FLOWMETER | | | | | SPIROMETER | | | | | AT |
| 12 | 13 | 5 | 8 | 9 | 12 | 13 | 5 | 8 | 9 | 12 | 13 | 5 | 8 | 9 | 12 | 13 | 5 |
| 24.4 | 23.2 | 7 | 17 | 18 | 18 | 23 | 8.7 | 19.3 | 20.9 | 24.0 | 23.0 | 7.2 | 16.2 | 16.3 | 22.2 | 24.2 | 73.5 |
| 26.8 | 27.6 | 7.3 | 18 | 19 | 23 | 23 | 9.6 | 22.6 | 20.8 | 26.1 | 27.6 | 9.7 | 21.0 | 25.4 | 28.4 | 25.4 | 75.5 |
| 28.1 | 33.5 | 8.4 | 22 | 23 | 26 | 26 | 8.3 | 23.3 | 29.6 | 28.9 | 34.1 | 8.3 | 23.3 | 27.9 | 27.3 | 31.7 | 76.7 |
| 25.9 | 27.6 | 6.5 | 15 | 18 | 20 | 22 | 7.0 | 19.4 | 24.1 | 26.1 | 28.0 | 7.8 | 20.3 | 24.1 | 25.4 | 25.4 | 73.5 |
| 38.6 | 37.3 | 10 | 25 | 24 | 30 | 29 | 14.8 | 27.6 | 29.6 | 39.8 | 38.3 | 15.9 | 29.2 | 31.7 | 43.4 | 40.6 | 75.5 |
| 26.4 | 24.0 | 8 | 19.8 | 20 | 21.5 | 24 | 9.6 | 24.4 | 21.8 | 27.4 | 24.6 | 9.1 | 21.0 | 21.1 | 26.0 | 24.8 | 72.4 |
| 32.9 | 33.5 | 8.9 | 22 | 24 | 27 | 28 | 9.2 | 28.5 | 28.5 | 33.7 | 33.5 | 9.2 | 23.5 | 26.5 | 29.2 | 31.7 | 73 |
| | | | | | | | | | | | | | | | | | |
| 28.5 | 28.5 | 7.7 | 12 | 18 | 22 | 25 | 8.8 | 21.7 | 22.3 | 28.1 | 28.1 | 8.1 | 19.8 | 20.4 | 26.4 | 28.3 | 71.2 |
| 25.0 | 25.0 | 8.1 | 16 | 17 | 19.6 | 18.6 | 5.9 | 21.1 | 24.6 | 24.6 | 24.6 | X | X | X | X | X | 75.7 |
| 22.7 | 27.3 | 6.8 | 18 | 18 | 24.4 | 26 | 7.6 | 18.2 | 21.1 | 21.7 | 27.0 | 7.2 | 17.6 | 23.7 | 23.7 | 26.4 | 74.3 |
| 27.8 | 30.7 | 8.0 | 19 | 20 | 24.6 | 27.4 | 12.5 | 22.9 | 25.6 | 27.5 | 30.5 | 13.2 | 26.4 | 26.4 | 33 | 33 | 71.5 |
| 24.4 | 27.9 | 6.3 | 17 | 16 | 21.2 | 20.6 | 8.8 | 19.9 | 22.9 | 24.6 | 26.4 | 7.7 | 19.8 | 21.7 | 22.7 | 24.4 | 73.0 |
| 24.4 | 26.7 | 6.7 | 20.2 | 20.4 | 26 | 25.4 | 6.5 | 22.9 | 21.1 | 24.0 | 27.6 | 6.7 | 22.8 | 23.1 | 26.6 | 28.7 | 72.6 |

## TEMPERATURE MEASUREMENTS (°F)

| #1 FLOWMETER | | | | AT ANALYZER | | | | | AT #2 FLOWMETER | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 9 | 12 | 13 | 5 | 8 | 9 | 12 | 13 | 5 | 8 | 9 | 12 | 13 |
| 74.0 | 74.0 | 74.5 | 74.5 | 91.5/88 | 89.7/89 | 88.8/88.8 | 88.8/88.8 | 88.8/88.8 | 93 | 91 | 91 | 91.7 | 91.7 |
| 75.5 | 75.5 | 75.7 | 75.7 | 105/84.4 | 106/87.1 | 106/87 | 102.4/88 | 97/85 | 99.5 | 102 | 102 | 103 | 103 |
| 77.5 | 77.5 | 77.5 | 77.5 | 107/88 | 101/89 | 104/95 | 90/87 | 93/89 | 98 | 105 | 106 | 106 | 106 |
| 74 | 74 | 74.5 | 74.5 | 117/97 | 119/98 | 119/99 | 118/101 | 116/102 | 99 | 104.5 | 105 | 107.5 | 107.5 |
| 75.5 | 75.5 | 76 | 76 | 110/97 | 106/98 | ? | 103/96 | 103/98 | 100 | 102 | 102 | 102 | 102 |
| 72.5 | 72.5 | 73 | 73 | 107/95 | 105/94 | 102/95 | 104/95 | 101/95 | 94 | 93.5 | 92 | 93 | 92 |
| 73.2 | 73.0 | 73.7 | 73.9 | 95/82 | 94/83 | 93/83 | 92/85 | 90/83 | 92 | 93 | 94 | 94 | 94 |
| | | | | | | | | | | | | | |
| 72.7 | 72 | 73.2 | 73.5 | 111/94 | 119/98 | 116/98 | 115/98 | 114/98 | 88.5 | 92.5 | 93 | 96.2 | 96.2 |
| 77 | 77 | 78.3 | 78.6 | 113/106 | 115/107 | 115/107 | 116/109 | 116/109 | 90 | 94.5 | 94.7 | 94.2 | 95 |
| 75.2 | 75.6 | 76.6 | 76.7 | 106/97 | 113/97 | 113/103 | 112/102 | 119/103 | 92.3 | 95.3 | 96 | 98.2 | 98.6 |
| 72.4 | 72.7 | 74.2 | 74.2 | X | X | X | X | X | 90.5 | 94 | 94.7 | 95.5 | 96.2 |
| 73.8 | 74.1 | 75.1 | 75.4 | X | X | X | X | X | 88 | 91.8 | 93 | 94.7 | 94.7 |
| 73.3 | 73.6 | 74.7 | 75.2 | X | X | X | X | X | 90.5 | 93.5 | 95.2 | 96.7 | 97.5 |

3

# FLOWMETER EVALUATION

## DESCRIPTION OF THE OPERATION OF THE TECHNOLOGY, INC., FLOWMETER

The operation of the Technology Inc. mass flowmeter is based on the fact that the amount of heat required to maintain a known temperature difference across the boundary layer indicates the heat transfer rate; this rate is a measure of the mass flow rate of the fluids.

The linear mass flowmeter uses basically the same sensing element as in the X-15 instrumentation package, that is, a thermistor operated in the self-heating region. Thermistors are resistive elements possessing a high negative temperature coefficient and a voltage-versus-current characteristic. Hence, when sufficient current is drawn, considerable heat is developed within the thermistor, causing the resistance to decrease at a faster rate than the current increases and, thereby, yielding a negative slope. The curve shifts upward with increased flow rates. This shift occurs because the increased airflow effectively increases the heat sinking capacity of the environment and carries away heat which would otherwise heat the thermistor and decreases the resistance. Therefore, the use of a thermistor and suitable allied electronics can produce a voltage output which is analogous to the rate of flow of the gas. This arrangement, in effect, is a flowmeter, but it lacks some of the characteristics essential to a linear flowmeter; for the output is nonlinear and is dependent on the temperature of the gas. These deficiencies are eliminated by using an analog variable attenuator. As the voltage input increases, the attenuation is decreased at certain specific points. The degree of attenuation for the straight-line segments preceding and following each of these points is controlled by using a second thermistor which is not self-heated to any extent. Therefore, this second thermistor reacts only to the temperature of the gas and, thereby, provides compensation for changes in gas temperature.

The function generator characteristic is adjusted so that its output is the inverse of the thermistor sensing element output for a linearly increasing voltage input. Hence, as the nonlinear output of the sensing element is fed into the function generator, the opposing nonlinearity of the function generator output has a cancelling effect which causes a single linear output. Because of the attenuation of the function generator and the relatively low input voltage to it, the output of the function generator is too small for most practical applications and, consequently, necessitates the use of an amplifier.

In order to obtain flow rate on a recorder from the flowmeter the output of the mass flowmeters was adjusted at the recorder so that one mm of paper equaled 144 millivolts. Because of the nature of the flowmeter output, it was necessary to integrate the area under the curves over a period of one minute to get an average voltage for this period. This voltage was then converted to pounds of gas per minute. Based on the perfect gas laws, conversion factors were derived to convert mass flow to liters per minute in accordance with figure 5 which will be discussed later in the report.

## DESCRIPTION OF THE OPERATION OF THE SPACELABS, INC. MODEL 210 GAS MASS FLOWMETER

The Spacelabs Mass Flowmeter is a flow transducer in which gas flow is accurately related to a small amount of heat injected elecrically into the fluid across the wall of the transducer tube. This heat which is carried away by the fluid flow is a well established function of the mass rate of flow of the fluid medium. By means of electronic feedback control, a balance is established and maintained between the quantity of heat injected and heat removed by the fluid transport. The electronic circuit produces an output voltage proportional to the quantity of heat injected and hence the mass flow rate.

The operating principle of the flowmeter is depicted in figure 2. Illustrated is a thin wall tube with temperature sensitive resistance elements wound around the outer diameter spaced axially apart by a distance of about four diameters. The direction of flow is indicated by an arrow. Wound in intimate contact with the downstream temperature sensor is a low power heater element. The tube wall material is high in thermal conductivity in the region of the sensing elements. Over short lengths between the sensors, and on both ends, the wall is constructed of material with good thermal insulating properties.

The other part of the flowmeter is a simple electronic controller which amplifies the unbalance signal from a 4-arm resistance bridge of which the two temperature sensing winding occupy two of the four positions. The bridge is so adjusted that balance is achieved when the downstream sensor temperature is 1°C above the temperature of the upstream sensor. The amplified error signal controls with high gain the power input to the heater located with the downstream sensor so as to maintain this 1°C

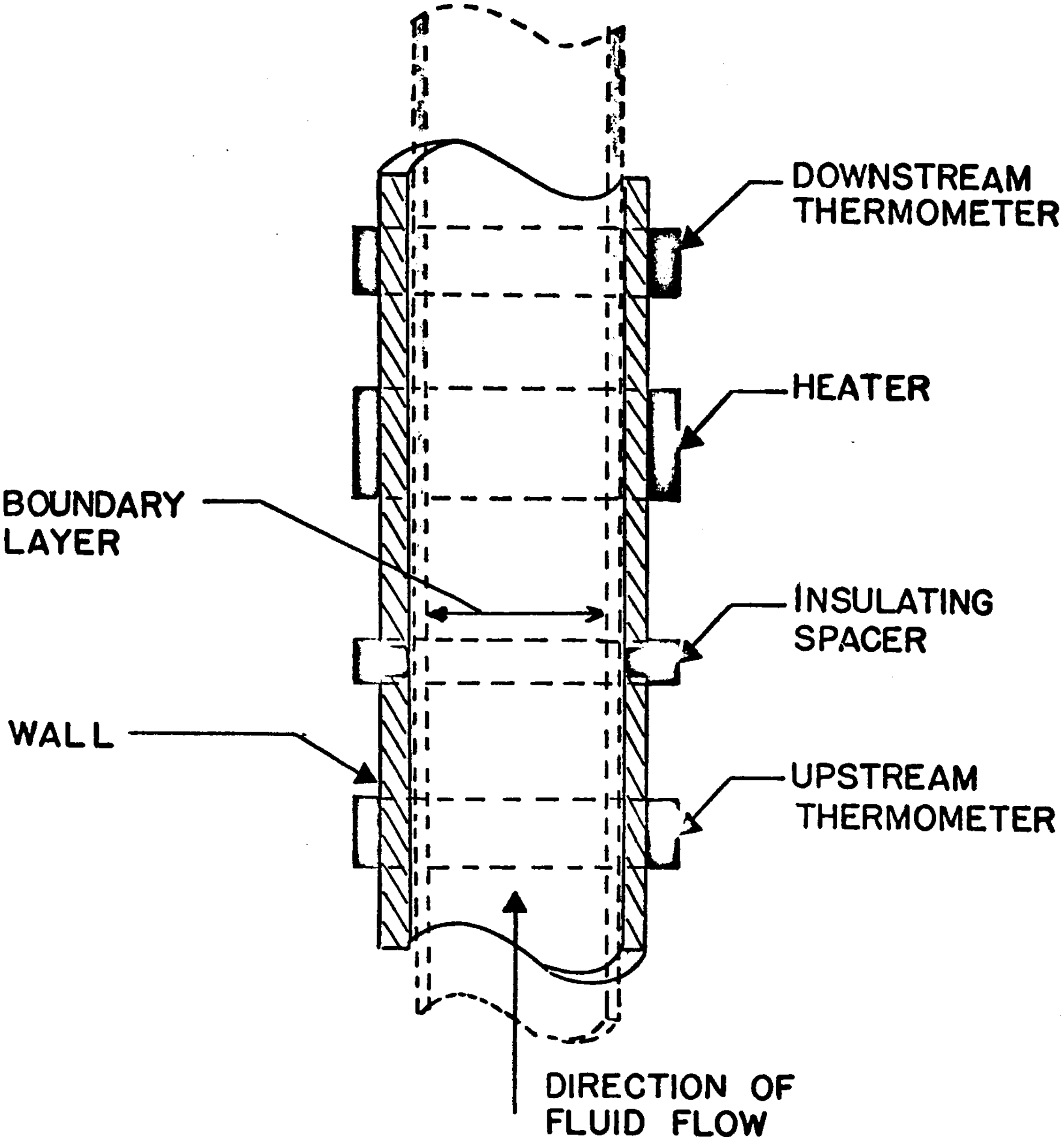

FIG. 2 BOUNDARY LAYER FLOWMETER

differential. In operation the, the power input to the heater becomes a measure of mass rate of flow. With zero flow the heater power input assumes quickly a small steady-state value just sufficient to maintain the required 1°C temperature differential in the face of losses to the external ambient and to the stagnant internal gas. In the presence of flow the heater power rises to hang up the heat carried away downstream by the flow. This transported heat is a function of the mass rate of flow. The significant facet of the heat transfer process is that the sensed temperature gradient between the temperature sensing elements exists almost entirely across the boundary layer between the moving gas and the tube wall.

## COMPARISON OF DESIGN

As indicated in the preceding paragraphs on flowmeter operation two flowmeters have been considered for possible use in the respiratory analyzer system, the Technology, Inc. Model MFG-1012T which was used in the test runs of Phase I, and the Spacelabs Model 210 which was not used in the tests but is designed to serve similar functions. Since the latter model unit was unavailable for tests any comparison of the two units must be on a theoretical basis only. Also, due to the lack of information considered proprietary by both companies, only a very cursory evaluation could be made. However, the technical theory involved in making a rigorous heat transfer analysis and evaluation of the boundary layer phenomenon has been reviewed and applied to each of the flowmeters. This review may be found in the Appendix of this report.

One of the subtle problems which has been revealed in the use of either of these flowmeters results from the unsteady transient flow through the flowmeter due to the breathing cycle of the subjects. A review of the data taken during the Phase I tests indicates that the volume flowrates were in a range of zero to 80 LPM. From a plot of volume flowrate vs Reynolds Number for each flowmeter based on internal diameter of the flow passage (see figures 3 and 4) it can be seen that the flow characteristics would be laminar, then turbulent, and then laminar again, with corresponding influences on the boundary layer and heat transfer. The transition from laminar to turbulent to laminar flow would affect the Spacelabs flowmeter by a hysteresis which according to Spacelabs Personnel, has not been fully evaluated as yet. Such flow characteristics may not affect the Technology Inc. flowmeter to as great an extent since the thermistor beads utilized in this unit are located in the core of the flow where the boundary layer

FORM 1002-X (FORMERLY ED147)

| | | |
|---|---|---|
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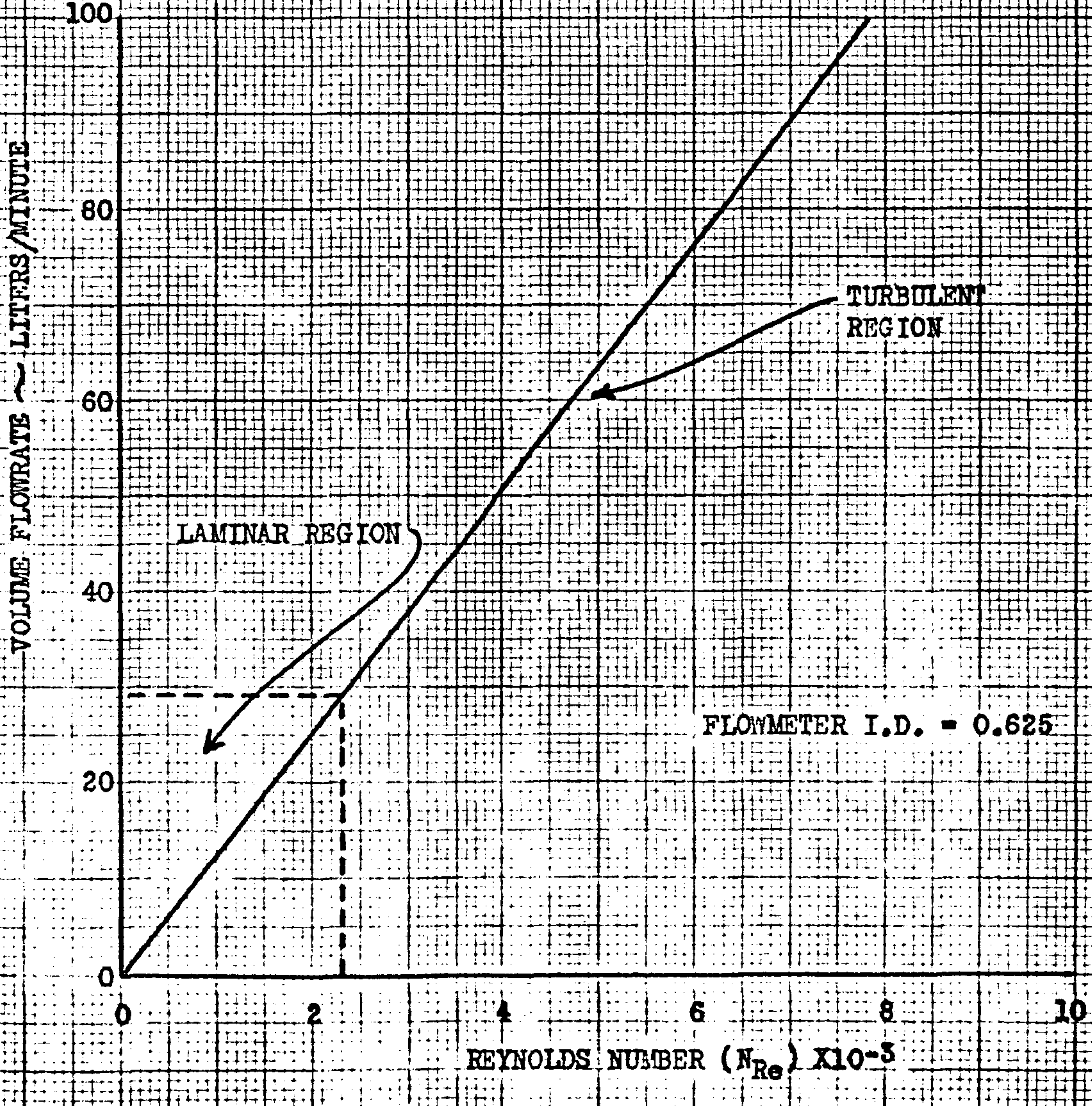
| CHECKED BY: | FLOWRATE vs. REYNOLDS NUMBER | REPORT NO. NA-65-22 |
| DATE: | FIGURE #3 | MODEL NO. |

DATA FOR TECHNOLOGY FLOWMETER

ASSUMED MAXIMUM FLOWRATE = 80 LPM



FORM 1002-X (FORMERLY ED147)

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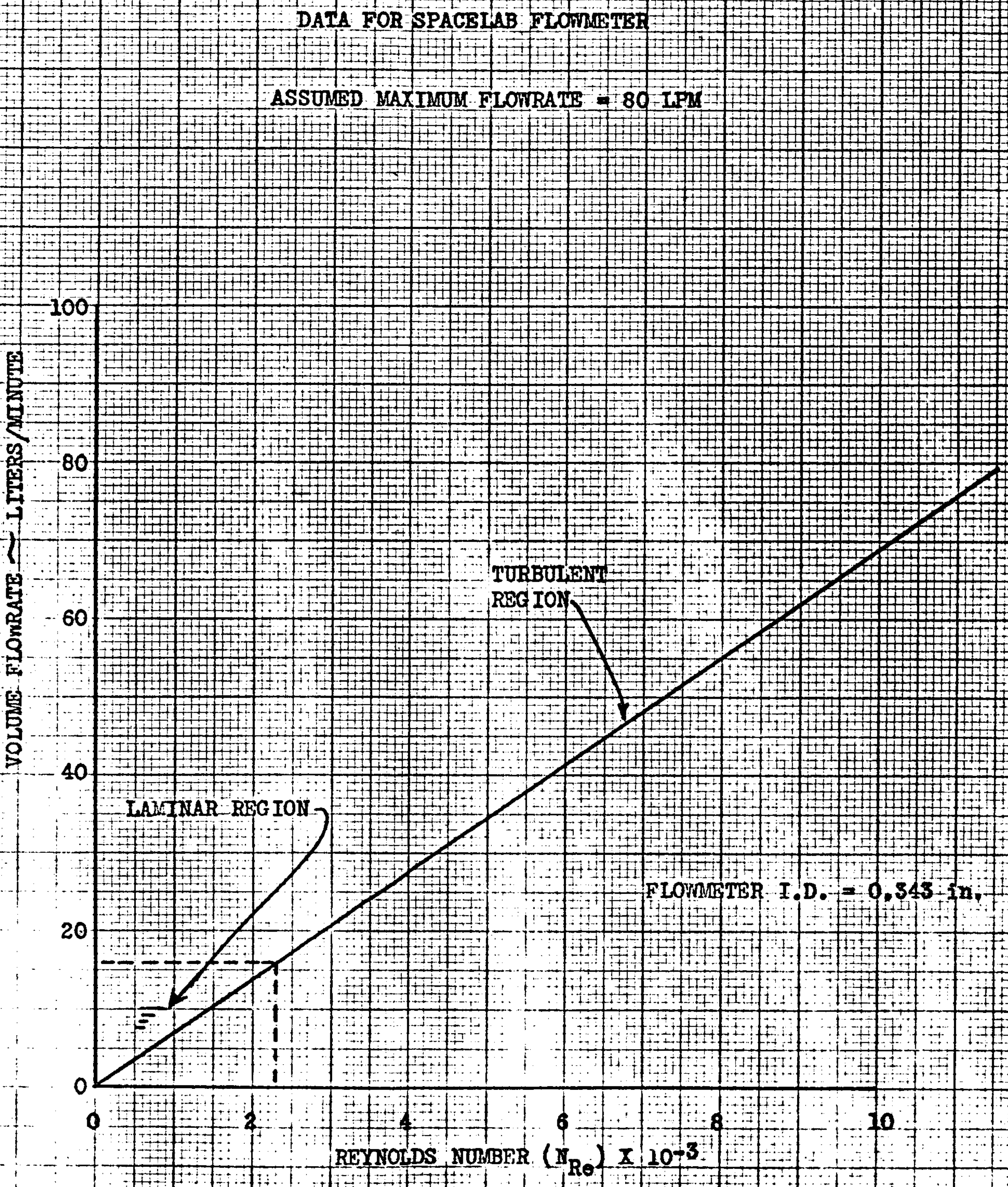
| CHECKED BY: | FLOWRATE vs. REYNOLDS NUMBER | REPORT NO. NA-65-22 |
| DATE: | FIGURE #4 | MODEL NO. |


DATA FOR SPACELAB FLOWMETER

ASSUMED MAXIMUM FLOWRATE = 80 LPM

(hence velocity and thermal gradients) effects around the small beads are negligible compared with the thermal and velocity gradients in the core.

An examination of the Technology, Inc. flowmeter located on the exhalation side of the system showed that considerable residue was deposited on the protective screen located in the unit inlet. These deposits would alter the flow of gas over the thermistor beads in an unknown way and possibly effect the meter output. A test made of voltage output of both meters used in the Phase I tests indicated a 20 percent difference in output during final closed system checks, which could have been caused by the residue according to Technology, Inc. personnel. A discussion of the closed system checks may be found in a later section of this report.

It is not possible to make a final recommendation as to which flowmeter (Spacelabs or Technology, Inc.) should be used in the analyzer system at this time, due to the lack of definitive information, particularly on the Spacelabs flowmeter. It is recommended that the follow-on respiratory analyzer feasibility studies should include a simultaneous effort to make a laboratory study of the two flowmeters. This would include a calibration of each unit, a response time check, cyclic flows of saturated gas mixtures, and an error analysis based on the overall determination of flow rate. The instrument readout for both meters should be digitized and integrated over given time intervals (i.e., one minute, five minutes, etc.) as desired for the study.

## FLOWMETER CORRECTED CONVERSION FACTORS

In order to convert the mass flow rate data obtained from the Standard Air Calibration Curve furnished by the flowmeter manufacturer (figure 5) to corrected volume flow rates for the real gases used, correct conversion factors had to be calculated.

The correction factors are based on the assumption that 100 percent oxygen is inhaled by the subject and that the expired gases consist only of oxygen, carbon dioxide ($CO_2$), and water vapor.

An examination of the ranges of data from the selected data shown in Table I are as follows:

| | |
|---|---|
| Oxygen Partial Pressure ($P_{O_2}$) | 640-693 mm Hg |
| $CO_2$ Partial Pressure ($P_{CO_2}$) | 28.8-48 mm Hg |
| *Water Vapor Partial Pressure ($P_{H_2O}$) (By Difference) | 30-66 mm Hg |

TABLE II

BAROMETRIC PRESSURE MEASUREMENTS

| Run Number | Inches Hg | Millimeters Hg |
|---|---|---|
| 1 | 30.05 | 763 |
| 2 | 30.02 | 762 |
| 3 | 30.04 | 763 |
| 4 | 29.98 | 761 |
| 5 | 30.03 | 762 |
| 6 | 29.96 | 761 |
| 7 | 30.01 | 762 |
| 8 | 30.02 | 762 |

* See Table for Barometric Pressures Measured

| | |
|---|---|
| Inhalation Gas Temperature Range (At flowmeter) | 72-78°F |
| Exhalation Gas Temperature Range (At flowmeter) | 91-108°F |

For calculation of the corrected conversion factors the following average values were used:

| | |
|---|---|
| $P_{O_2}$ - 675 mmHg | $\text{Temp}_{\text{Inhalation}}$ - 75°F |
| $P_{CO_2}$ - 38 mmHg | $\text{Temp}_{\text{Exhalation}}$ - 100°F |

The inhalation gas, oxygen need only be corrected for temperature, molecular weight difference from air and converted to liters (28.3 Liters/Ft$^3$) therefore for oxygen:

$$\text{Corrected Conversion Factor} = F_{O_2} = \frac{M_{O_2}}{M_{Air}} \frac{28.3}{P_{Air}}$$

$$P_{Air} \text{ at } 75° = \frac{P x 144}{R_{air} T}$$

$$P_{Air} = \frac{14.7 \times 144}{53.3 \times 535} = 0.0742 \text{ Lbs/Ft}^3$$

$$F_{O2} = \frac{32}{29} \frac{28.3}{.0742} = 422$$

The exhalation gases must be corrected for the gas mixture average molecular weight, temperature, and conversion to Liters per minute: the average molecular weight of the gas mixture is determined from the mole fraction of each gas:

$$\text{Mole Fraction } X_1 = \frac{P_i}{P_{mix}} = \frac{P_i}{P_T}$$

and

$$M_{Mix} = \frac{P_{O2}}{P_T}(M_{O2}) + \frac{P_{CO_2}}{P_T}(M_{CO_2}) + \frac{P_{H_2O}}{P_T}(M_{H_2O})$$

Using average values from data

$$M_{Mix} = \frac{675}{760}(32) + \frac{38}{760}(44) + \frac{47}{760}(18)$$

$$M_{Mix} = 31.71$$

The density of the air at 100°F

$$P_{air} = \frac{Px144}{R_T} = \frac{14.7x144}{53.3x560} = 0.0710 \text{ Lbs/Ft}^3$$

Therefore the corrected conversion factor for the exhaled gases ($F_{Ge}$)

$$F_{Ge} = \frac{M_{Mix}}{M_{air}} \quad \frac{28.3}{P_{air}}$$

$$F_{Ge} = \frac{31.71}{29} \quad \frac{28.3}{.0710}$$

$$= 435$$

For the altitude runs which were at approximately the same temperature conditions only the addition of the pressure ratio term is necessary for conversion of the altitude (25,000 feet) runs.

$$F_{O_2} \text{ at } 28{,}000 \text{ Ft} = \frac{29.92}{11.10} \times 422 = 1138$$

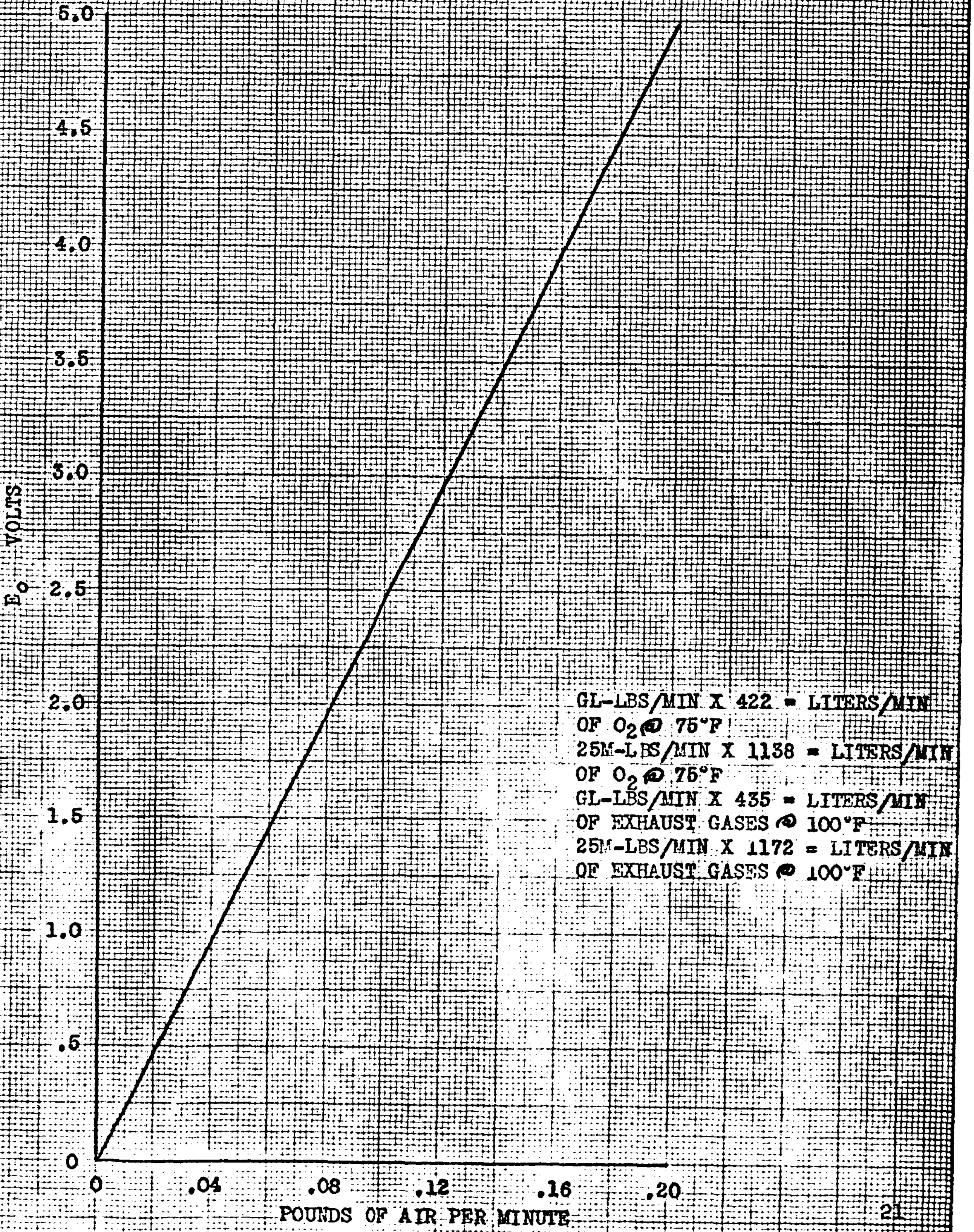
$$F_{Ge} \text{ at } 25{,}000 \text{ Ft} = \frac{29.92}{11.10} \times 435 = 1172$$

The corrected conversion factor are also shown on the calibration curve of figure 5 .

FORM 1021-8

|  |  |  |
|---|---|---|
| PREPARED BY: | NORTH AMERICAN AVIATION, INC. | PAGE NO. OF |
| CHECKED BY: | FLOWMETER CALIBRATION | REPORT NO. NA-65-22 |
| DATE: | FIGURE #5 | MODEL NO. |

AIR MASS FLOW vs. OUTPUT
TECHNOLOGY INC. FLOWMETER



GL-LBS/MIN X 422 = LITERS/MIN OF $O_2$ @ 75°F
25M-LBS/MIN X 1138 = LITERS/MIN OF $O_2$ @ 75°F
GL-LBS/MIN X 435 = LITERS/MIN OF EXHAUST GASES @ 100°F
25M-LBS/MIN X 1172 = LITERS/MIN OF EXHAUST GASES @ 100°F

The deviations in the mass flowmeter readings converted to volume flow-rates are shown in figures 6 and 7 for sea level and altitude runs. Although the deviations appear to be random in nature they are well within the expected error (except for a few cases) in determining a flow measurement by planimetry. Planimetry was required in making an integration of the flow traces to determine a one minute average flow rate. Table III and IV contain the differences between the flowmeters, gas meter and spirometer for both sea level and altitude runs. The significance of the deviations in the flowmeter reading will be discussed later in the report under feasibility.

FORM 1021-8

**PREPARED BY:** R.K.B.

**CHECKED BY:**

**DATE:**

## NORTH AMERICAN AVIATION, INC.

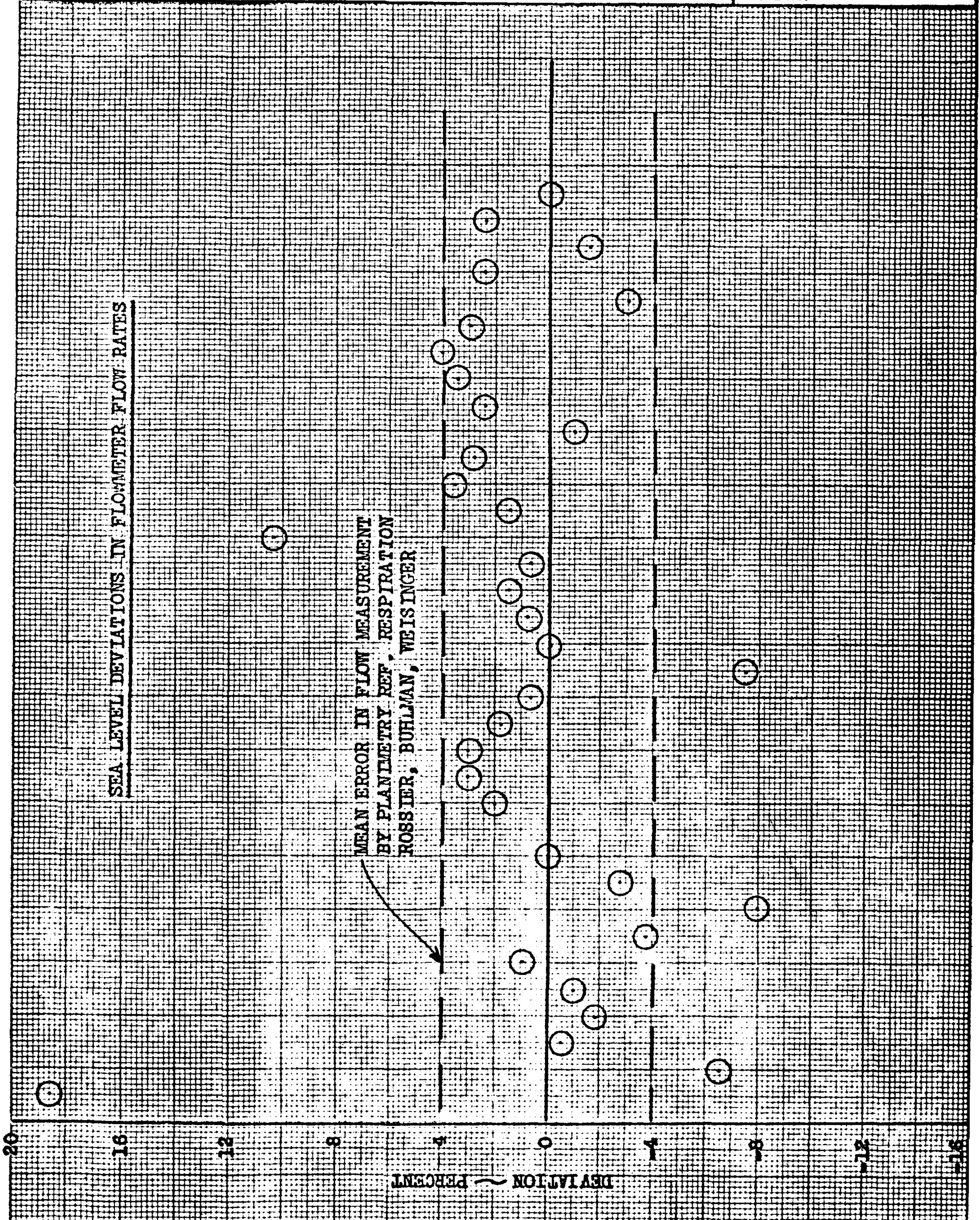
DEVIATIONS IN FLOWMETER DATA
FOR SELECTED RUNS

FIGURE #6

**PAGE NO.** OF

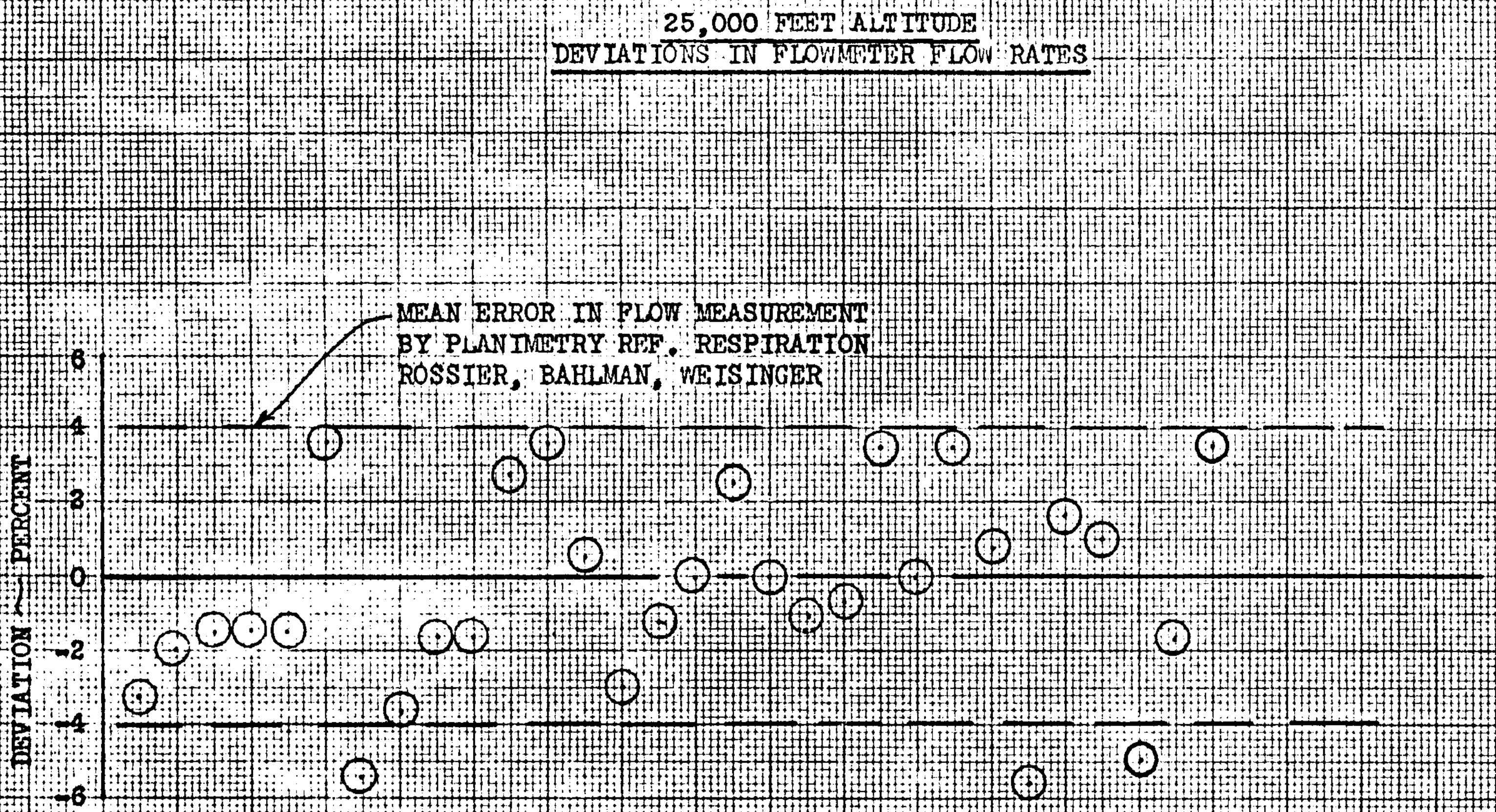
**REPORT NO.** NA-65-22

**MODEL NO.**



FORM 1021-B

| | | |
|---|---|---|
| PREPARED BY: R.K.B. | **NORTH AMERICAN AVIATION, INC.** | PAGE NO. OF |
| CHECKED BY: | DEVIATION IN FLOWMETER DATA<br>FOR SELECTED RUNS | REPORT NO. NA-65-22 |
| DATE: | FIGURE #7 | MODEL NO. |



### Table III
### SUMMARY OF FLOW DEVIATIONS
### SEA LEVEL RUNS

| $\Delta W$ | | $\Delta W$ | | $\Delta W$ |
|---|---|---|---|---|
| #1 Flowmeter-Gas Meter | | #1 Flowmeter-#2 Flowmeter | | #2 Flowmeter-Spirometer |
| Run #1 S.C. | | | | |
| #1 Flowmeter will be the Basic Number (#2 Flowmeter is Base) | | | | |
| 5 | - .2 | + 1.5 | 18.7 % + | - 1.5 |
| 8 | - 3.6 | - 1.3 | 6.5 % - | - 3.1 |
| 9 | - 3.0 | - .1 | 0.5 % - | - 4.6 |
| 12 | - 6.4 | - .4 | 1.8 % - | - 1.8 |
| 13 | - .2 | - .2 | 1.0 % - | + 1.2 |
| Run #3 B.M. | | | | |
| 5 | - 2.2 | + .1 | 1.0 % + | + .1 |
| 8 | - 5.5 | - .9 | 3.8 % - | - 1.6 |
| 9 | - 3.7 | - 1.9 | 8.0 % - | + 4.6 |
| 12 | - 3.8 | - .7 | 2.8 % - | + 2.3 |
| 13 | - 4.6 | 0 | 0 % | - 2.2 |
| Run #4 N.L. | | | | |
| 5 | - 1.3 | - 1.4 | 15.5 % - | 0 |
| 8 | + .9 | + .4 | 2.0 % + | + 1.8 |
| 9 | - 5.7 | + .9 | 3.0 % + | - 1.7 |
| 12 | - 2.1 | + .8 | 3.0 % + | - 1.6 |
| 13 | - 7.5 | + .6 | 1.8 % + | - 2.4 |

|  | W<br>#1 Flowmeter-Gas Meter | W<br>#1 Flowmeter-#2 Flowmeter |  | W<br>#2 Flowmeter-Spirometer |
|---|---|---|---|---|
| Run #5 J.K. |  |  |  |  |
| 5 | - .45 | + .05 | 0.7 % + | + .8 |
| 8 | - 5.9 | - 1.5 | 7.5 % - | + .9 |
| 9 | - 6.1 | 0 | 0 % - | 0 |
| 12 | - 5.9 | + .2 | 0.8 % + | - .7 |
| 13 | - 5.6 | + .4 | 1.5 % + | - 2.6 |
| Run #6 G.M. |  |  |  |  |
| 5 | - 4.7 | + .1 | 0.7 % + | + 1.1 |
| 8 | 0 | + 2.6 | 10.4 % + | + 1.6 |
| 9 | - 5.1 | + .5 | 1.5 % + | + 2.1 |
| 12 | - 8.6 | + 1.2 | 3.5 % + | + 3.6 |
| 13 | - 8.3 | + 1.0 | 2.8 % + | + 1.7 |
| Run #7 |  |  |  |  |
| 5 | - 1.7 | - .1 | 3 % - | - .5 |
| 8 | - 4.0 | + .6 | 2.5 % + | - 3.4 |
| 9 | - 1.1 | + .7 | 3.5 % + | - .7 |
| 12 | - 4.9 | + 1.0 | 4.0 % + | - 1.4 |
| 13 | 0 | + .6 | 3.0 % + | + .2 |
| Run #8 |  |  |  |  |
| 5 | - .6 | - .3 | 3 % - | 0 |
| 8 | - 5.8 | + .7 | 2.5 % + | - 5.0 |
| 9 | - 4.9 | - .4 | 1.5 % - | - 2.0 |
| 12 | - 5.9 | + .8 | 2.5 % + | - 4.5 |
| 13 | - 5.5 | 0 | 0 % | - 1.8 |

% Deviation in Flowmeter corrected and converted flowrates.

$$\frac{W_{f_1} - W_{f_2}}{W_{f_1}} \times 100 = \% \text{ Deviation}$$

Where flowmeter No. 1 is the base

$W_{f_1}$ = Vol. Flow Rate Flowmeter No. 1, Liters/Min.

$W_{f_2}$ = Vol. Flow Rate Flowmeter No. 2, Liters/Min.

## Table IV
## SUMMARY OF FLOW DEVIATIONS
## 25,000 FEET RUNS

(#1 Flowmeter will be the Basic Number) (#2 Flowmeter is Basic)

| | $\Delta W$<br>#1 Flowmeter-Gas Meter | $\Delta W$<br>#1 Flowmeter-#2 Flowmeter | | $\Delta W$<br>#2 Flowmeter-Spirometer |
|---|---|---|---|---|
| Run #9 B.M. | | | | |
| 5 | - 1.4 | - .3 | 3.8 % - | - .7 |
| 8 | - 10.2 | - .5 | 2.0 % - | - 1.9 |
| 9 | - 4.6 | - .3 | 1.5 % - | - 1.9 |
| 12 | - 6.5 | - .4 | 1.5 % - | - 1.7 |
| 13 | - 3.5 | - .4 | 1.5 % - | + .2 |
| Run #15 J.K. | | | | |
| 5 | + 2.4 | + .2 | 3.6 % + | No Data |
| 8 | - 6.2 | - 1.1 | 5.5 % - | |
| 9 | - 8.5 | - .9 | 3.6 % - | |
| 12 | - 5.4 | - .4 | 1.6 % - | |
| 13 | - 6.4 | - .4 | 1.6 % - | |
| Run #16 S.C. | | | | |
| 5 | - .6 | + .2 | 2.8 % + | - .4 |
| 8 | - .4 | + .6 | 3.6 % + | - .6 |
| 9 | - 3.0 | + .1 | 0.5 % + | + 2.6 |
| 12 | + 1.7 | - .8 | 3.0 % - | + 1.8 |
| 13 | - 1.3 | - .3 | 1.2 % - | - .6 |

| | W<br>#1 Flowmeter-Gas Meter | W<br>#1 Flowmeter-#2 Flowmeter | | W<br>#2 Flowmeter-Spirometer |
|---|---|---|---|---|
| Run #17 | | | | |
| 5 | - 4.5 | 0 | 0 % 0 | + .7 |
| 8 | - 3.2 | + .7 | 2.5 % + | + 3.5 |
| 9 | - 5.6 | 0 | 0 % 0 | + .8 |
| 12 | - 3.2 | - .3 | 1.1 % - | + 5.5 |
| 13 | - 3.3 | - .2 | 0.7 % - | + 2.5 |
| Run #18 | | | | |
| 5 | - 2.2 | + .3 | 3.5 % + | - 1.1 |
| 8 | - 2.9 | 0 | 0 % - | - .1 |
| 9 | - 6.2 | + .7 | 3.5 % + | - 1.2 |
| 12 | - 3.2 | + .2 | 0.8 % + | - 1.9 |
| 13 | 7.3 | - 1.5 | 5.6 % - | - 2.0 |
| Run #19 NL | | | | |
| 5 | + .3 | + .1 | 1.6 % + | + .2 |
| 8 | - 2.5 | + .2 | 1.0 % + | - .1 |
| 9 | - 1.8 | - 1.1 | 5.0 % - | + 2.0 |
| 12 | + 1.6 | - .4 | 1.7 % - | + 2.6 |
| 13 | - 1.3 | + .9 | 3.5 % + | + 1.1 |

## PERFECT GAS LAW APPLICATION

According to Reference 7 the perfect gas equation of state applies (in theory) only for the condition when the pressure approaches zero. However, it has been shown that this equation,

$$H = U + PV$$

can be used with reasonably high accuracy whenever H or U (enthalpy or internal energy) is nearly a function of temperature only. The perfect - gas region, for any medium, is defined on any diagram as that region in which the enthalpy and internal - energy lines are parallel to the temperature lines, and it is incorrect to use perfect - gas relationships except when this condition is closely approached. The use of these relationships introduces a negligible error. A check of the correction factors which indicate the deviation from the perfect gas condition provides a comparatively simple means of checking the application of the perfect gas law to a given problem or condition.

The deviation of a medium from the perfect - gas condition is indicated by its compressibility (Z), which is determined from experimental data substituted in the relation

$$PV = ZRT$$

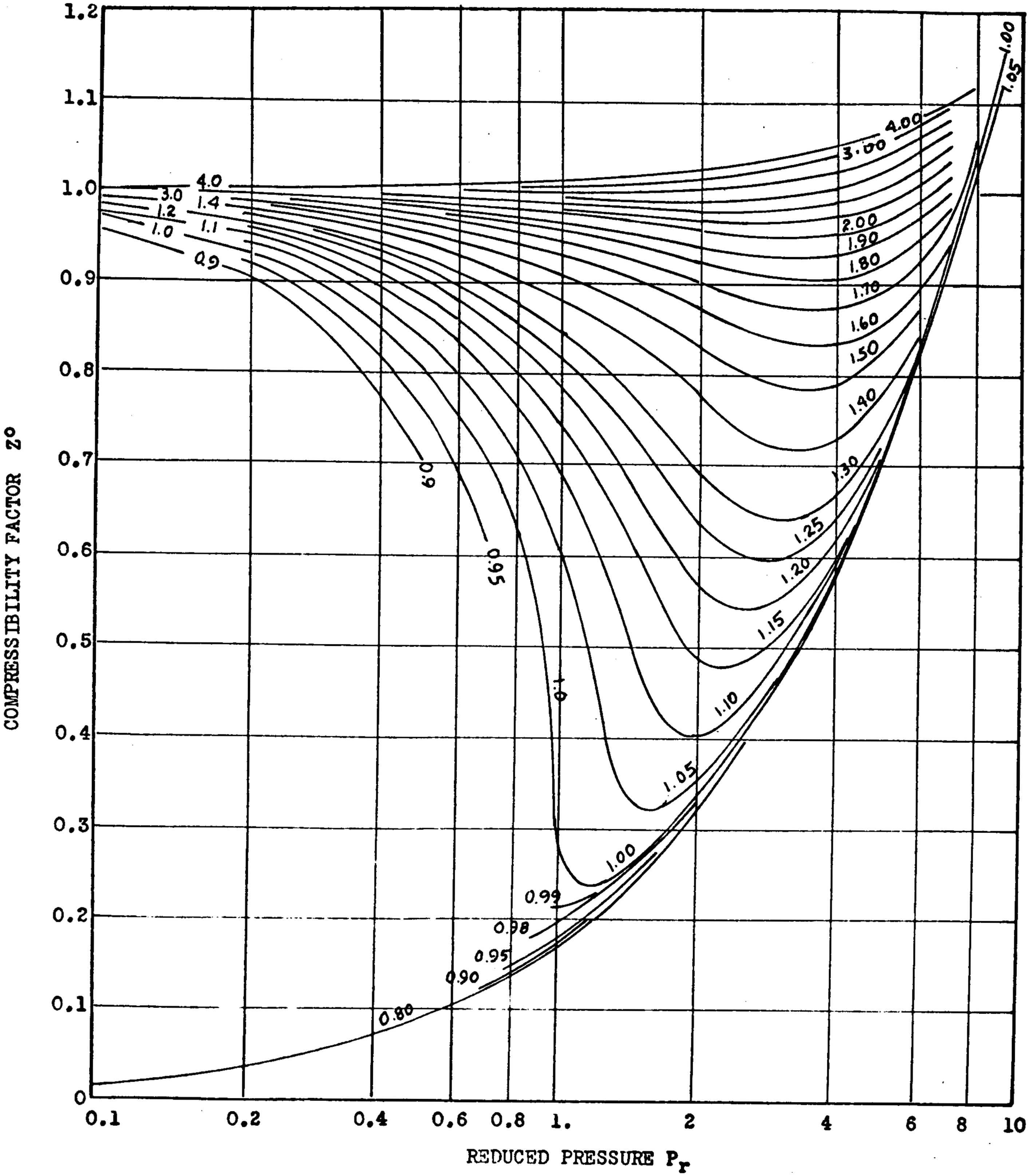
or

$$Z = \frac{PV}{RT}$$

The compressibility factor (Z) has been plotted against reduced pressure with reduced temperature as a parameter. This plot (figure 8 ) which can be found in various forms in any good thermodynamics text book including Reference 7, is applicable to any gas through the Law of Corresponding States. The Law of Corresponding States is that gases at the same reduced coordinates have

COMPRESSIBILITY FACTORS (Z)

FIGURE #8



approximately the same properties. The reduced coordinate is the ratio of the actual coordinate to the critical value for that coordinate. Thus

$$T_r = \frac{T}{T_c}, \quad P_r = \frac{P}{P_c} \quad \text{and} \quad V_r = \frac{V}{V_c}$$

Where subscripts r and c indicate reduced and critical values respectively. Usually $P_r$ and $T_r$ are used, since only two of the three elementary coordinates are required to define the state.

The critical values for the gases of interest in the inhalation and exhalation of the test subjects are as follows:

| GAS | CRITICAL PRESSURE $P_r$ (PSIA) | CRITICAL TEMPERATURE $T_r$ (°F) |
|---|---|---|
| Oxygen | 730.6 | -181.8 |
| Nitrogen | 485 | -232.8 |
| Carbon Dioxide | 1071 | 87 |
| Water Vapor | 3206.2 | 705.34 |

The reduced temperature $T_r$ for oxygen was calculated in the following manner:

$$T_r = \frac{T}{T_c} = \frac{460 + 72}{460 - 181.8} = 1.91$$

For assumed laboratory temperature of 72°F

The reduced pressure $P_r$ for oxygen was calculated in the following manner:

$$P_r = \frac{P}{P_c} = \frac{14.7}{730.6} = 0.0201$$

A summation ~~of the~~ reduced pressures and temperatures, and corresponding values of (Z) are shown in the following table:

| GAS | REDUCED PRESSURE $P_r$ | REDUCED TEMPERATURE $T_r$ | COMPRESSIBILITY FACTOR (Z) |
|---|---|---|---|
| Oxygen | .0201 | 1.91 | 1 |
| Nitrogen | .0299 | 2.34 | 1 |
| Carbon Dioxide | .0137 | 0.973 | .96 |
| Water Vapor | .0046 | 0.456 | .95 |
| Gas Mixture | .0162 | 1.52 | 1 |

The critical temperature and pressure was calculated for the gas mixture utilizing the "KAY" method based on molal averaging. This technique is satisfactory for conditions which are far removed from the critical such as those which exist in the respiration analyzer system.

$$(T_c)_{\text{Mixture}} = (T_c)_a\, y_a + (T_c)_b\, y_b + (T_c)_c\, y_c +$$

$$(P_c)_{\text{Mixture}} = (P_c)_a\, y_a + (P_c)_b\, y_b + (P_c)_c\, y_c +$$

For the three gas mixtures ($O_2$, $CO_2$, and $H_2O$ vapor) expected in the respired gases from the subjects

$(T_c)_a$ is the critical temperature of the pure component

$(P_c)_a$ is the critical pressure of the pure component a, etc., and $y_a$ is the mol fraction of component a, etc. The gaseous mixture is handled on the compressibility charts the same as the pure single gases.

The calculation of $(T_c)_{mix}$ and $(P_c)_{mix}$ was made using the following average data which approximates the conditions of the tests of Phase I.

$P_{O_2}$ = 685 mm Hg

$P_{CO_2}$ = 38 mm Hg     Total Pressure $P_T$ = 760 mm Hg

$P_{H_2O}$ = 47 mm Hg

The critical temperature of the gas mixture is

$$(T_C)_{mix} = (T_{C_{O_2}}) \left(\frac{P_{O_2}}{P_T}\right) + (T_{C_{CO_2}}) \left(\frac{P_{CO_2}}{P_T}\right) + (T_{C_{H_2O}}) \left(\frac{P_{H_2O}}{}\right)$$

$$(T_C)_{mix} = (278.2) \left(\frac{685}{760}\right) + (547) \left(\frac{38}{760}\right) + (1165.34) \left(\frac{97}{760}\right)$$

$$(T_C)_{mix} = 350.5°R$$

The reduced temperature is

$$T_r = \frac{T}{T_{C_{mix}}} = \frac{460 + 72}{350.5} = 1.52$$

For assumed laboratory temperature of 72°F

The critical pressure of the gas mixture is

$$(P_C)_{mix} = (P_{C_{O_2}}) \left(\frac{P_{O_2}}{P_T}\right) + (P_{C_{CO_2}}) \left(\frac{P_{CO_2}}{P_T}\right) + (P_{C_{H_2O}}) \left(\frac{P_{H_2O}}{P_T}\right)$$

$$(P_C)_{mix} = (730.6) \left(\frac{685}{760}\right) + (1071) \left(\frac{38}{760}\right) + (3206) \left(\frac{47}{760}\right)$$

$$(P_C)_{mix} = 909.8 \text{ PSIA}$$

The reduced pressure is:

$$P_r = \frac{P}{P_{C_{mix}}} = \frac{14.7}{909.9} = 0.0162$$

The value of (Z) determined from figure 8 and the computed values of $(T_r)_{mix}$ and $(P_r)_{mix}$ indicate a close approximate to 1.0.

It can readily be seen from the above calculations and table of data that there will be very little error introduced in the use of the perfect gas law for computations regarding volume of mass flow rates of the constituents in the exhalation gases. This is particularly true in light of the fact that the carbon dioxide and the water vapor, only make up about 5 to 6 percent each of the expired gases.

The percentage of deviation in flow rates determined between the inhalation and exhalation mass flowmeters readings is indirectly a verification of the applicability of the perfect-gas law. The maximum deviation between the volume flow rates computed for the two flowmeters is in the order of plus or minus four percent. This apparent agreement with calculations made based on the perfect-gas law gives credence to the assumption.

## ISOTHERMAL SYSTEM REQUIREMENT

The best information available indicates that the present state-of-the-art in the design of mass flow transducers precludes the development of a mass flow transducer which is completely impervious to the flow of $H_2O$ vapor. However, the previous section of the report which concerns the application of the perfect-gas law shows that if the moisture produced by the subjects remains in the vapor phase it may be treated as any other gas with regard to computations of mass flow rate of the various constituents and in its effect on the accuracy of the flow indicated by the flowmeter.

As a result of poor flow rate data measured with the exhalation gases flowmeter during very early runs in Phase I, a heater tape was wrapped around the exhalation lines and flowmeter in order to prevent condensation of water vapor prior to the measurement of the mass flow rate. Again during the closed system check runs of Phase I as shown in Table V the heaters were not utilized and again large differences in inspiratory and expiratory flow data was indicated by the meters. This discrepancy was attributed to moisture condensation in the expiratory gas flowmeter.

With regard to the effects on the flowmeter indication of mass flow as a function of the difference in thermal conductivity between water vapor and oxygen and nitrogen, it can be noted from figures 9 and 10 that the thermal conductivity of carbon dioxide differs from oxygen and nitrogen more than does the water vapor at essentially body temperature. Although the carbon dioxide has a lower thermal conductivity its partial pressure is measured and its effects, therefore, considerably more predictable than those of water vapor, whose quantity will vary to a greater degree, and its partial pressure is not measured directly.

TABLE V. PHASE I - SYSTEM CHECK

| RUN NO. | $CO_2$ (mm Hg) | | | | $O_2$ Uptake (cc/min) | | INSPIRATORY FLOW (L/M) | | | | EXPIRATORY FLOW (L/M) | | | | TEMPERATURE (°F) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LB-15 | | Prototype | | | | #1 Flowmeter | | Gas Meter | | #2 Flowmeter | | Spirometer | | #1 Flowmeter | | #2 Flowmeter | |
| | Rest | Work | Rest | Work | Rest | Work | Rest | Work | Rest | Work | Rest | Work | Rest | Work | Rest | Work | Rest | Work |
| 20 GM | 26.8 | 32.9 | 22.6 | X | 269.3 | X | 15.6 | 44.7 | 12.6 | X | 14.2 | 38.2 | 7.7 | X | 74.5 | | 77.2 | X |
| 21 GM | 23.7 | 34.5 | 24.0 | 34.0 | 189.0 | 954.7 | 15.4 | 35.4 | 12.3 | 29.8 | 12.6 | 26.1 | 10.2 | 28.0 | 75.6 | 75.5 | 80.5 | 78.6 |
| 22 SC | 27.8 | 36.5 | 29.0 | 37.5 | 153.9 | 770.7 | 9.5 | 24.0 | 9.4 | 17.4 | 8.5 | 15.6 | 7.7 | 17.6 | 75.2 | 76.2 | 75.5 | 80.7 |

FORM 1021-S

| | | |
|---|---|---|
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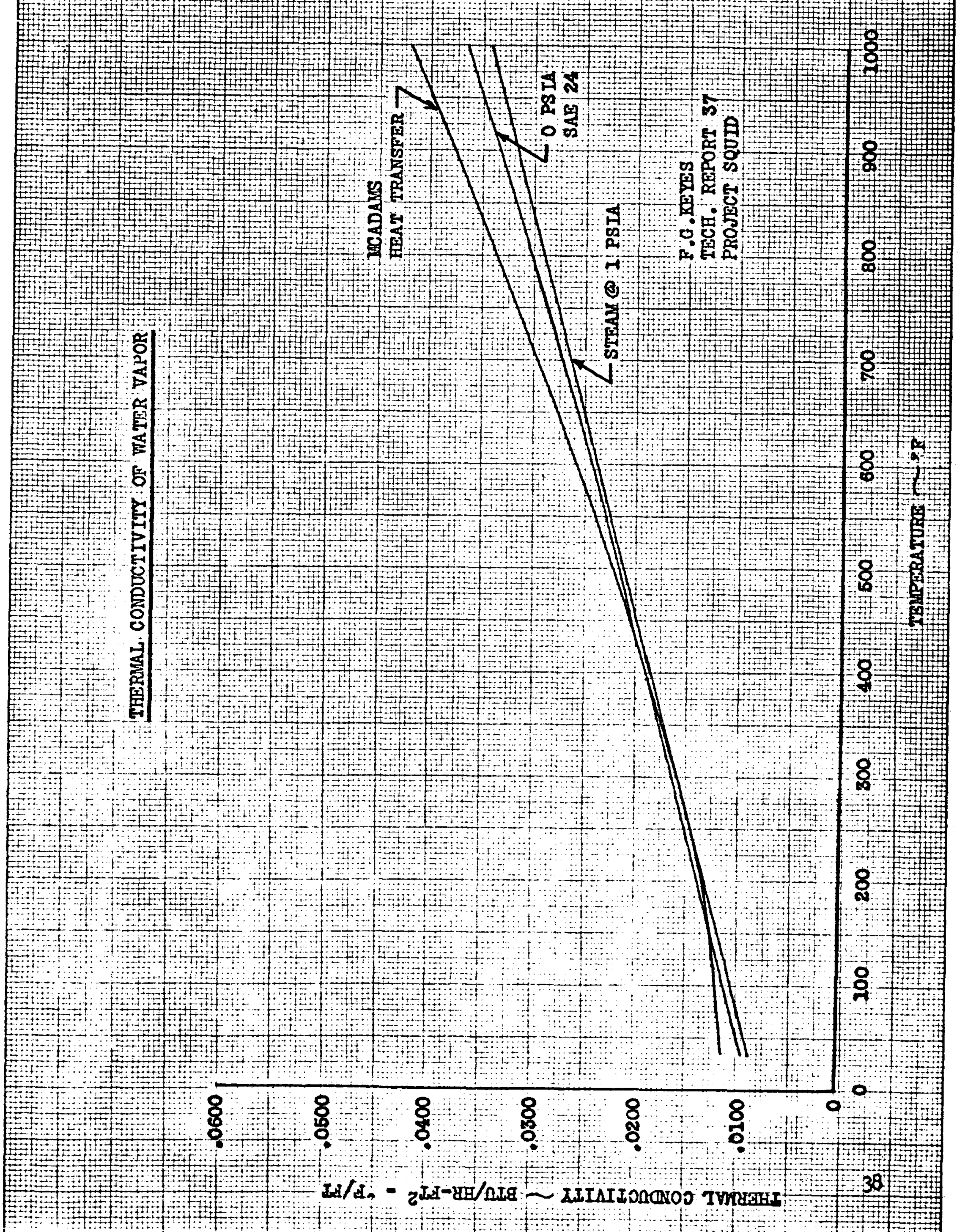
| CHECKED BY: | | NA-65-22<br>REPORT NO. |
| DATE: | FIGURE #9 | MODEL NO. |



THERMAL CONDUCTIVITY OF WATER VAPOR

FORM 1021-S

| | | |
|---|---|---|
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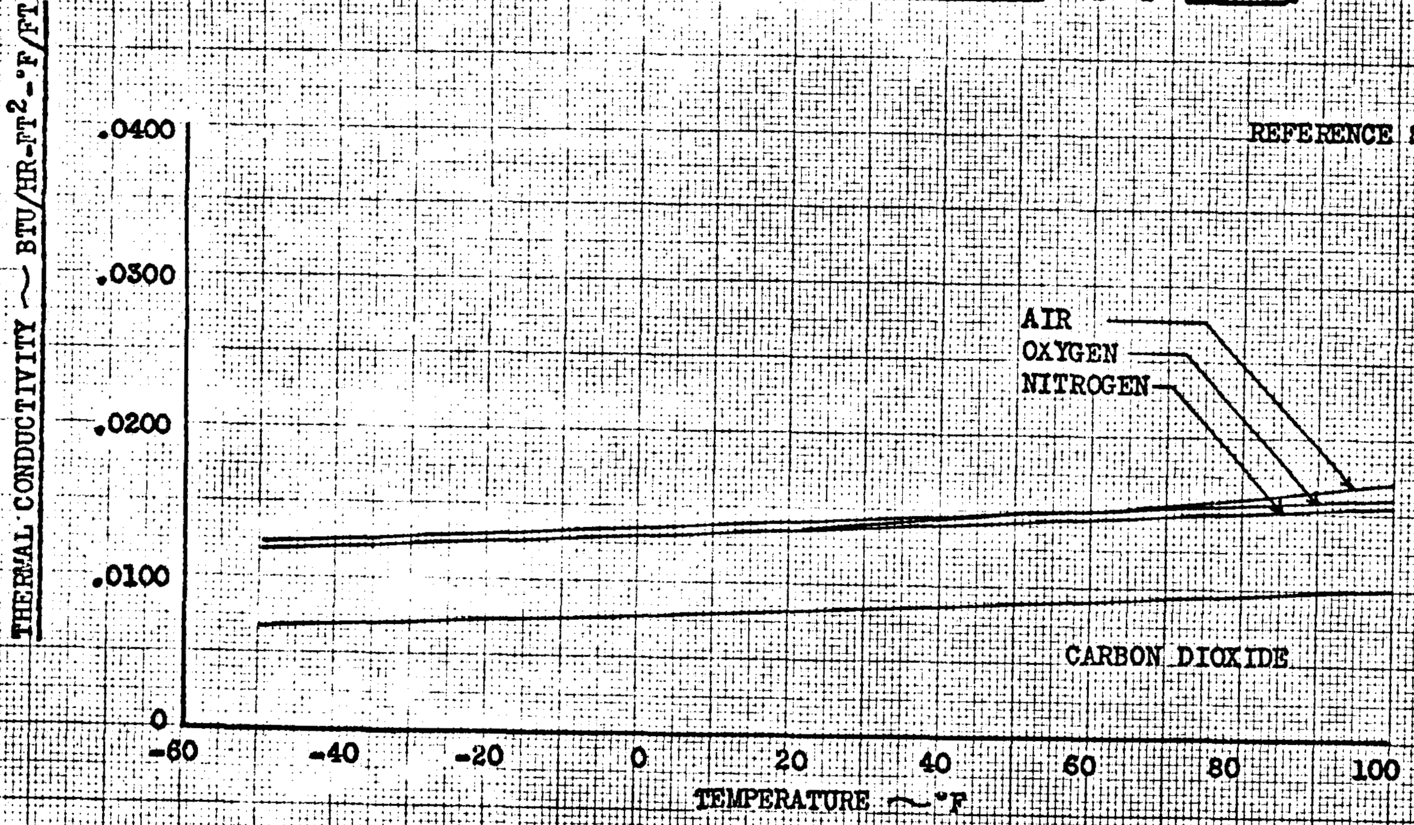
| CHECKED BY: | | NA-65-22<br>REPORT NO. |
| DATE: | FIGURE #10 | MODEL NO. |

THERMAL CONDUCTIVITY OF AIR, $O_2$, $N_2$, AND $CO_2$

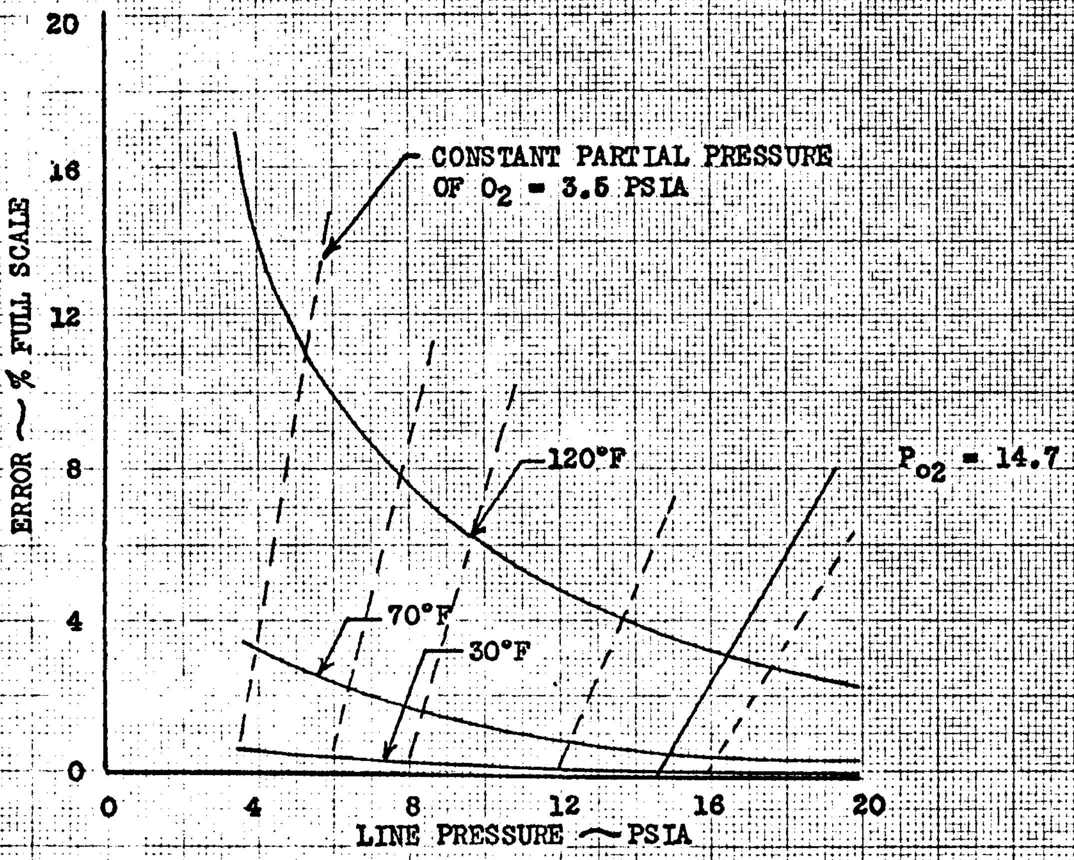


The theoretical effect of water vapor on the Spacelab's mass flowmeter has been determined by that company for maximum flow conditions for the flowmeter and gases at 99 percent relative humidity. The results are presented in figure 11 for error as a percent of full scale versus line pressure. For sea level conditions and low temperatures the errors in absolute flow values is not significantly large.

FORM 1021-S

| | | |
|---|---|---|
| PREPARED BY: R.K.B. | **NORTH AMERICAN AVIATION, INC.** | PAGE NO. OF |
| CHECKED BY: | EFFECT OF WATER VAPOR ON<br>SPACELABS, INC. FLOWMETER | NA-65-22<br>REPORT NO. |
| DATE: | FIGURE #11 | MODEL NO. |

ERROR IN INDICATED MASS FLOW RATE vs.
LINE PRESSURE AT MAX. FLOW AND 99% R.H.



VENDOR SUPPLIED DATA

## OXYGEN CONSUMPTION

One of the principal objectives of the overall respiratory analyzer feasibility study is the determination of oxygen consumption. Accurate measurements of inspiratory and expiratory mass flow rates, partial pressures of oxygen, carbon dioxide, total pressure, and temperatures of the inspiratory and expiratory gases, theoretically are sufficient data for calculating oxygen consumption.

The following method may be used to calculate oxygen consumption assuming that the inspiratory gas is 100 percent dry oxygen and the expiratory gas consists of oxygen carbon dioxide, and water vapor, only. Any other gases are negligible.

The mass flow rate of inspired oxygen is represented by ($W_{O_{2in}}$) and the total expired gas flow rated by ($W_{G_{out}}$).

Then

$$W_G = W_{O_2} - W_{CO_2} - W_{H_2O}$$

Where

$W_{O_2}$, $W_{CO_2}$, and $W_{H_2O}$ are the mass flow rates of the individual constituents of the expired gas.

If the volume flow rate is determined from the mass flow rate and a temperature measurement of the total expired gas, then the individual constituents may be determined from the partial pressure of each constituent and the total volume flow rate as indicated in the following relationships:

$$P_{O_2} V = W_{O_2} R_{O_2} T$$

$$P_{CO_2} V = W_{CO_2} R_{CO_2} T$$

$$P_{H_2O} V = W_{H_2O} R_{H_2O} T$$

Also the following:

$$W_{O_2} = \frac{P_{O_2}}{R_{O_2} T} (V)$$

$$W_{CO_2} = \frac{P_{CO_2}}{R_{CO_2} T} (V)$$

$$W_{H_2O} = \frac{P_{H_2O}}{R_{H_2O} T} (V)$$

For these relationships the partial pressure of the water vapor is the difference between the total pressure and the sum of the partial pressures of oxygen and carbon dioxide:

$$P_T - (P_{O_2} - P_{CO_2}) = P_{H_2O}$$

The oxygen consumption is the difference between the mass flow of inspired oxygen and the mass flow of oxygen expired, as follows:

$$W_{O_{2in}} - W_{O_2} = \text{Oxygen Consumed}$$

The principal difficulties in calculating oxygen consumption in this manner utilizing the measured data is due to the inaccuracy of determining the mass flow rates. The error in mass flow rate determination comes from two areas of interest, the meter inaccuracies (±2%) and from the planimeter work utilized in the graphical integration of the flowmeter output data (±4%). The magnitude of this error is twice the percentage that the oxygen consumption is to the total respiratory flow rate as shown in diagram of figure 2. A complete error analysis showing the required accuracy of the flowmeters and other instrumentation may be found in the feasibility discussion section of this report.

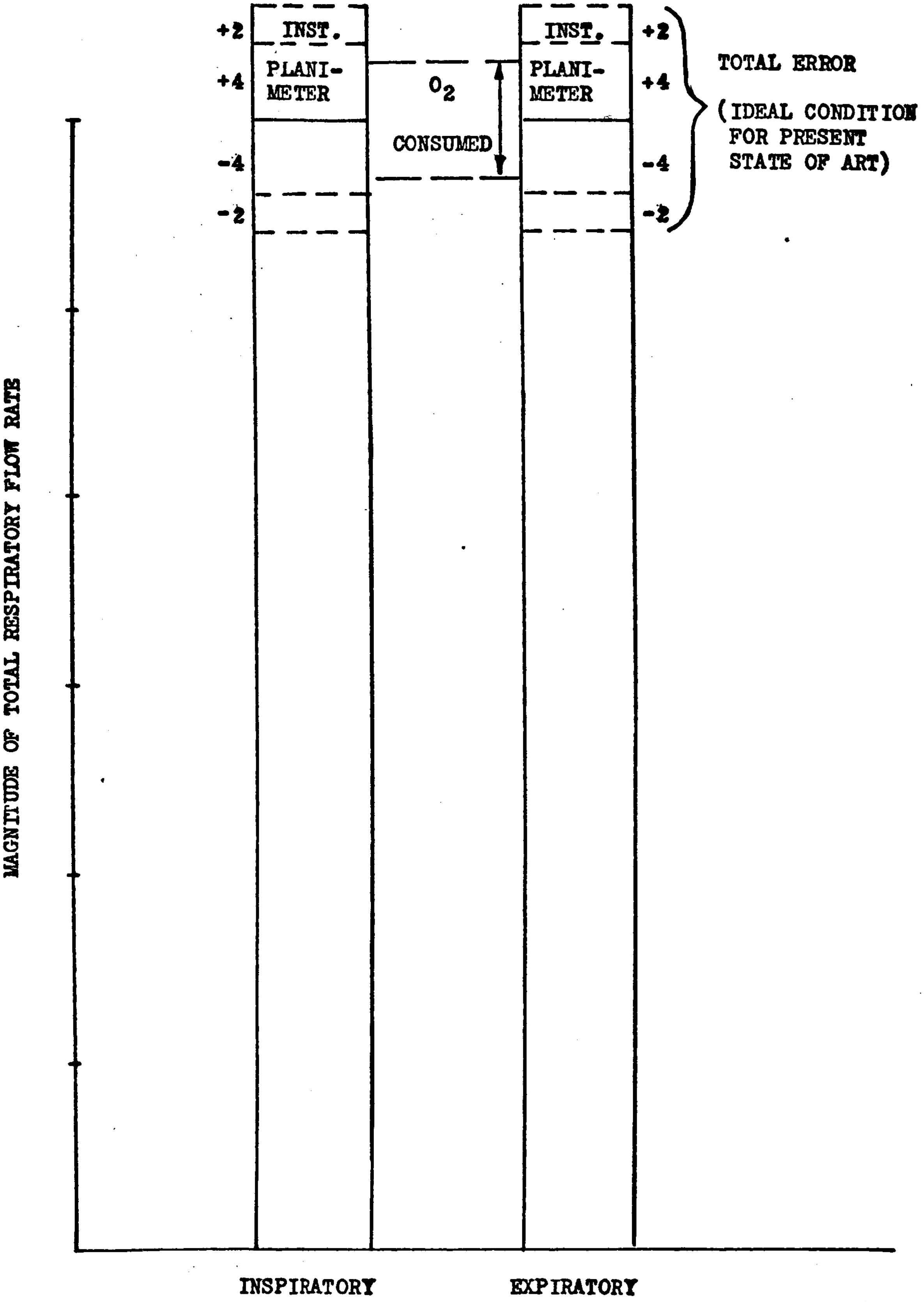


FIGURE #12 ILLUSTRATION OF FLOWMETER ACCURACY PROBLEM

In order to compute the oxygen consumption based on the measured data of the Phase I tests certain assumptions were necessary because of the random deviations in reading between the inspiratory and expiratory flowmeters. The basic assumption is that the inspiratory and expiratory volume flow rates are equal. This was confirmed by physiological data in Reference 9. An average value of the inspiratory and expiratory flowmeter calculated volume flow rates was used for calculating the oxygen consumption values shown in figure 13. It can readily be seen that the oxygen consumption rates calculated are considerably higher than the "standard" data taken from the Journal of Applied Physiology. Further doubt is cast on the calculated values as seen in figure 14 where the carbon dioxide production rate is plotted against oxygen consumption and compared to an average $\frac{W_{CO_2}}{W_{O_2}}$ for an average respiratory quotient (R.Q.). Calculations for the oxygen consumption at altitude were made in a similar manner and are presented in figures 15 and 16. The results are the same as for the sea level runs.

Generally, oxygen consumption is determined by the use of a spirometer in a "closed loop" system. The spirometer is filled with oxygen gas. As the subject breathes into the closed system, oxygen is depleted in the spirometer and the $CO_2$ produced is removed by a $CO_2$ absorber within the system or in the spirometer itself. The inspired gas is saturated and the expired gas is saturated so that there is only a small amount of water vapor increase in the expired gas. In the test setup of Phase I, dry oxygen was inspired and saturated gas was expired. All the moisture for saturating the gas at body temperature was added during the respiratory cycle.

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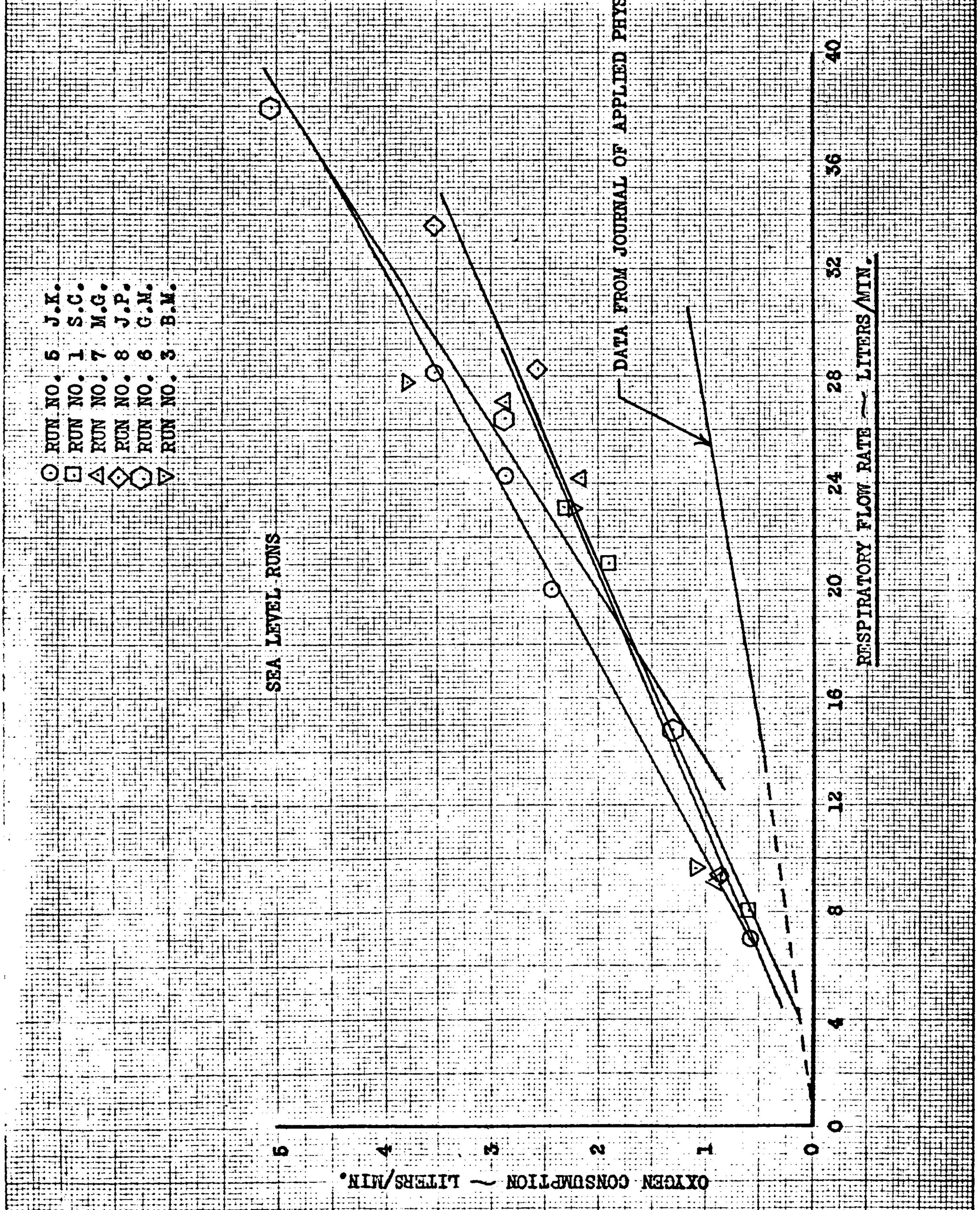
| CHECKED BY: | OXYGEN CONSUMPTION<br>BASED ON AVERAGE OF BOTH FLOWMETERS | NA-65-22<br>REPORT NO. |
| DATE: | FIGURE #13 | MODEL NO. |



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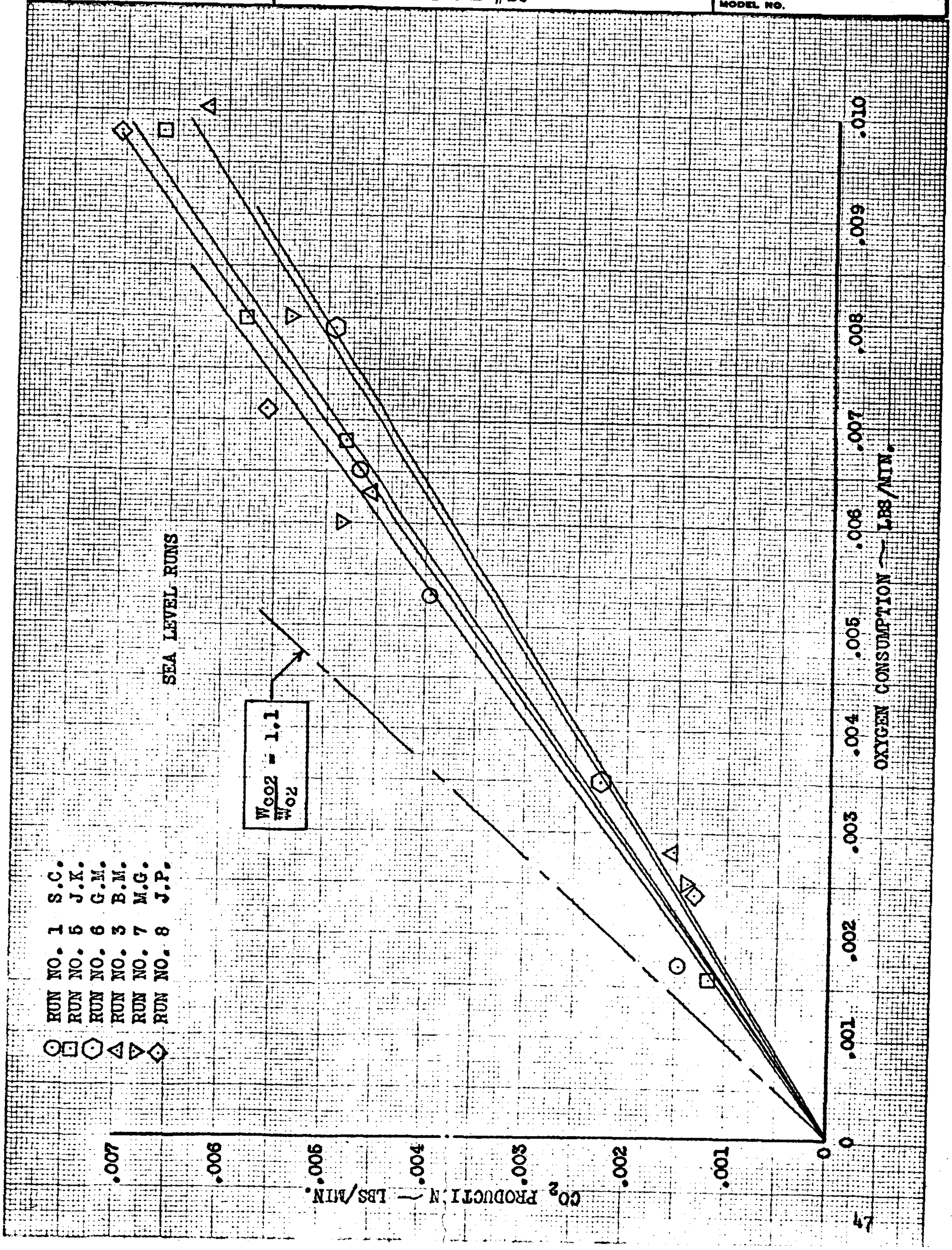
| CHECKED BY: | $CO_2$ PRODUCTION vs $O_2$ CONSUMPTION | REPORT NO. NA-65-22 |
| DATE: | FIGURE #14 | MODEL NO. |



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## $CO_2$ PRODUCTION vs $O_2$ CONSUMPTION

FIGURE #15

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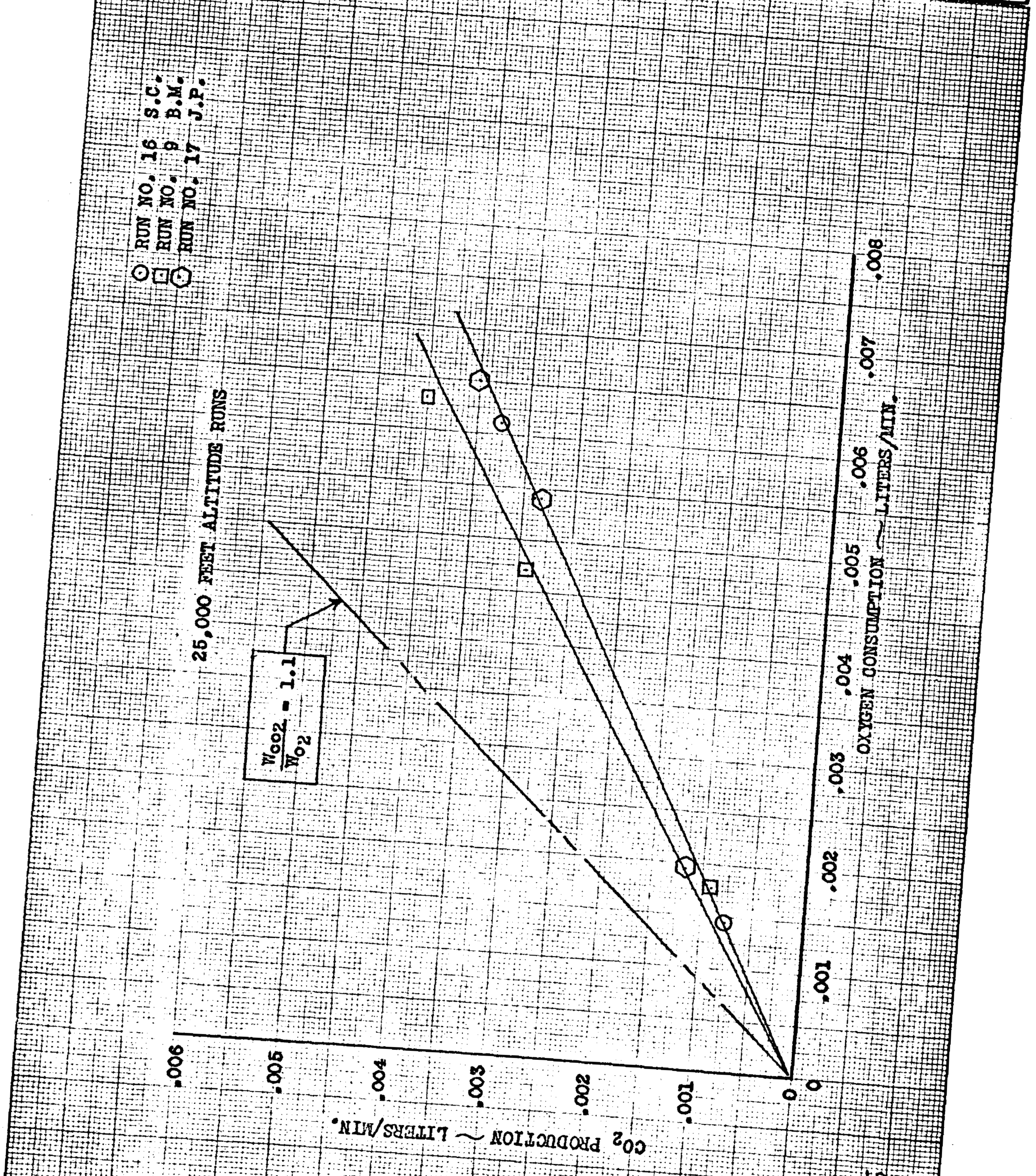
MODEL NO.



FORM 1002-X (FORMERLY ED147)

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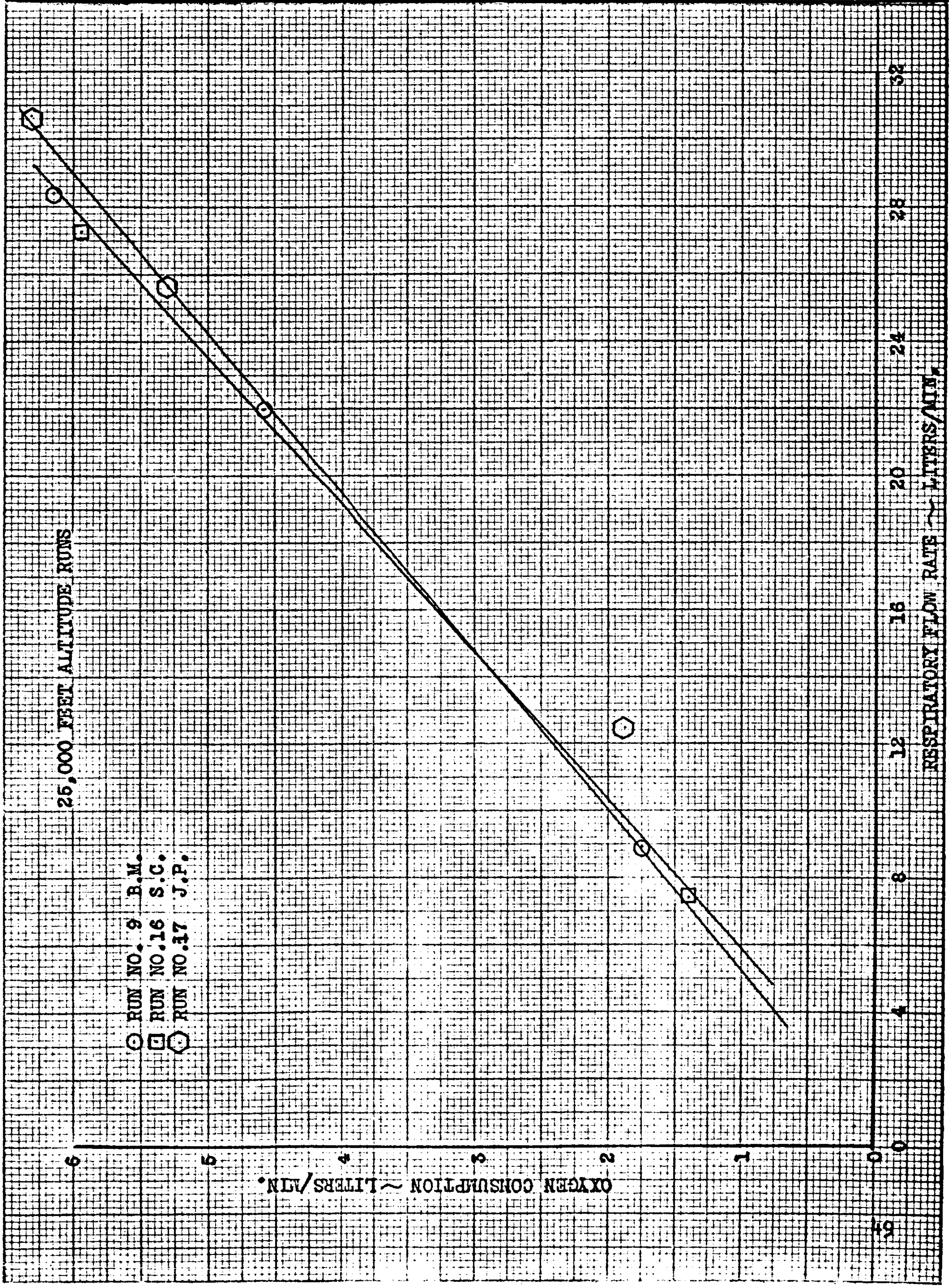
| DATE: | FIGURE #16 | MODEL NO. |



A diagram of the respiratory gas exchange is shown in figure 17. Therefore, in an attempt to improve the calculation method the assumption was made that the inspiratory flow rate was less than the expiratory flow rate by an amount equal to the water vapor added in the respiratory cycle. The oxygen consumption was calculated and again plotted against respiratory flow rate as shown in figure 18. The R.Q. for these calculations was assumed to be 1.0, where the volume of $CO_2$ produced is equal to the volume of oxygen consumed. Although the assumptions introduce errors, the agreement with standard data is considerably better. However, the question remains as to the validity of the assumptions in view of the fact that the gas meter and spirometer checks of the flowmeter readings do not agree with the flowmeters. Other "closed system" check runs were made during Phase II and these are discussed in the section in Closed System Check Runs.

## RESPIRATION

## GAS EXCHANGE DIAGRAM

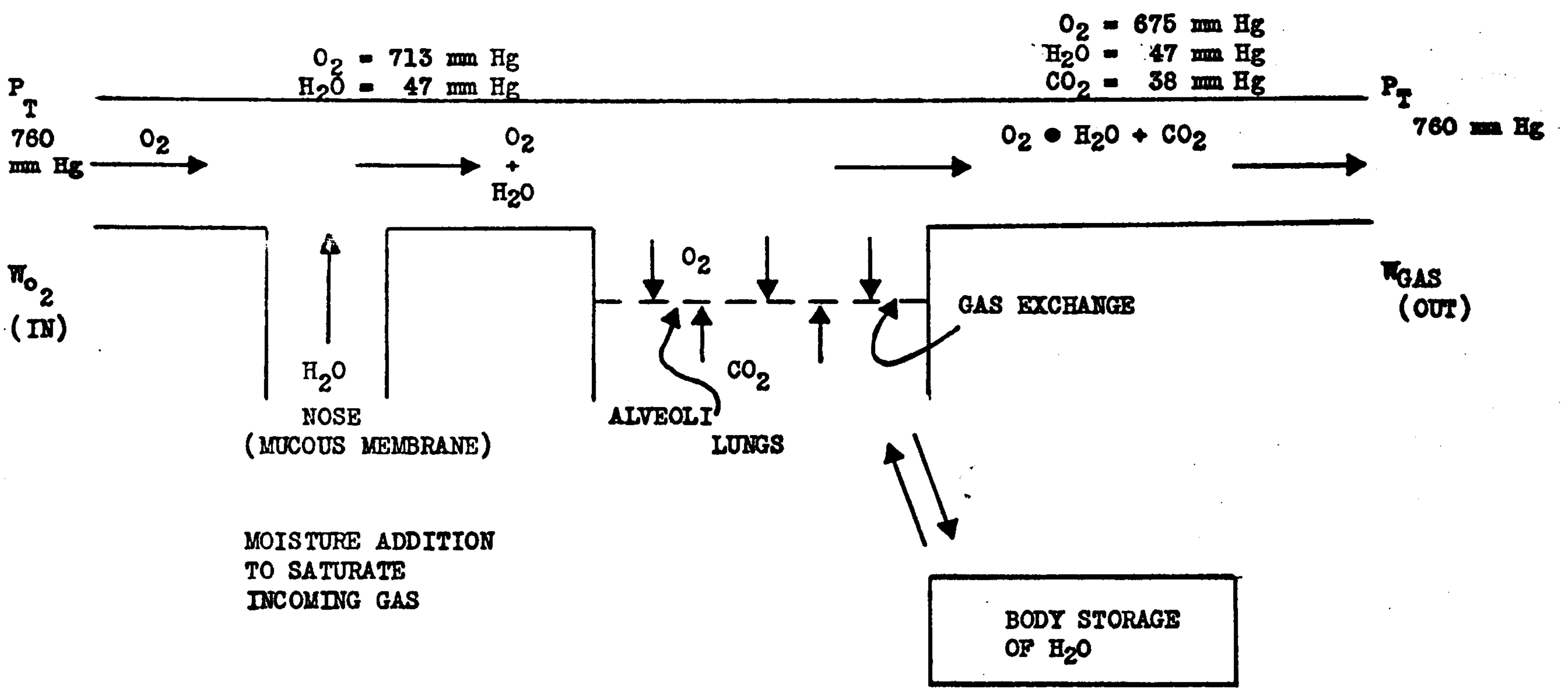


FIGURE #17

FORM 1021-8

| | | |
|---|---|---|
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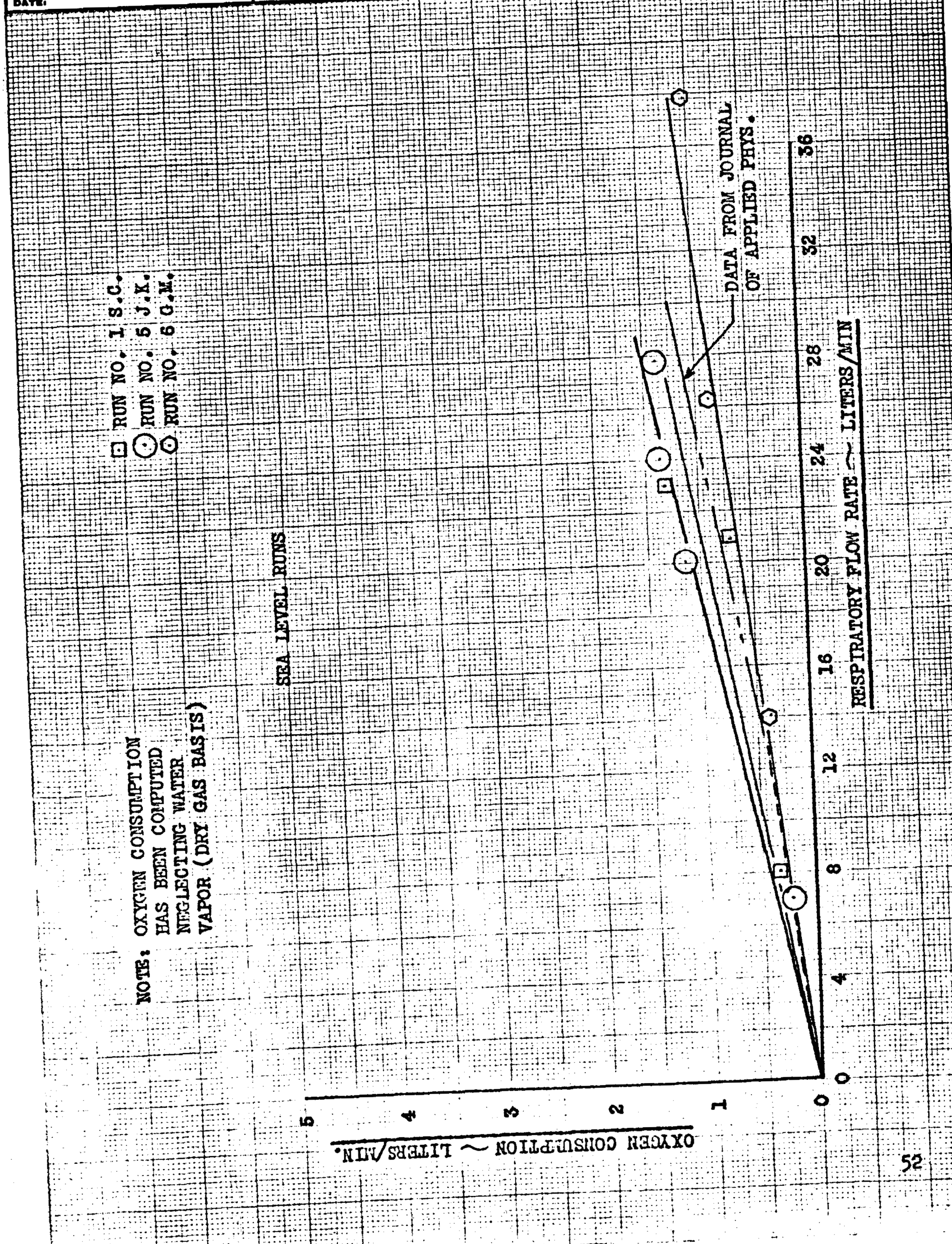
| DATE: | FIGURE #18 | MODEL NO. |



NOTE: OXYGEN CONSUMPTION HAS BEEN COMPUTED NEGLECTING WATER VAPOR (DRY GAS BASIS)

## SYSTEM FEASIBILITY

The evaluation of the Respiratory Analyzer System, the magnitude of the deviations in mass flow measurements, the error analysis as given in the latter part of this section of the report, and the lack of a positive system check, all tend to indicate that the feasibility of the system for determining oxygen consumption from direct measurements has not as yet been satisfactorily proven. Further work including modifications to the equipment will be necessary to prove feasibility. Some of the areas of interest where improvements must be made are as follows:

1. The method by which the data is utlized to calculate oxygen consumption.
2. The methods of data reduction (i.e., utilization of machine programs and digital analogs, etc.)
3. Modifications to the sensors and flowmeters.
4. Addition of gas collection system such as Douglas Bags, for system checkout.
5. New approaches to the problem of measuring oxygen consumption under airborne conditions.

The modifications to the equipment will consist of reconditioning of the absolute pressure transducer so that small changes in total pressure due to breathing can be measured, reconditioning of the oxygen sensors and production of additional oxygen sensors, the replacement of the temperature transducer and modification of the breath cell to increase the cross-sectional area. The quality of the $CO_2$ sensor signal must be improved for accuracy and noise reduction and increased sensing range to read from 0 to 80 mm Hg $P_{CO_2}$. Also, in order to improve the quality of the data, it will be necessary to modify the electronic signal conditioning equipment to allow for significant zero offset and scale expansion for both the oxygen channel and the absolute pressure channel.

A correction factor for the $CO_2$ partial pressure for the altitude condition which is not fully understood, although the phenomenon has been measured, has been labeled "Pressure Broadening" by Beckman, Inc. Scientists. A curve of the instrument output versus partial pressure of $CO_2$ as shown in figure 19 indicates the effect of this phenomenon on signal output. Further study is required to better understand this effect and the application of correction factors to the data taken.

If the oxygen consumption by the human subjects is to be calculated by the difference in the mass flow of inspired oxygen and mass flow of expired oxygen and other data such as the partial pressure of expired oxygen, to within 20 percent accuracies, then the measured data must fall within the necessary accuracy tolerances as determined by the following error analysis.

| | | |
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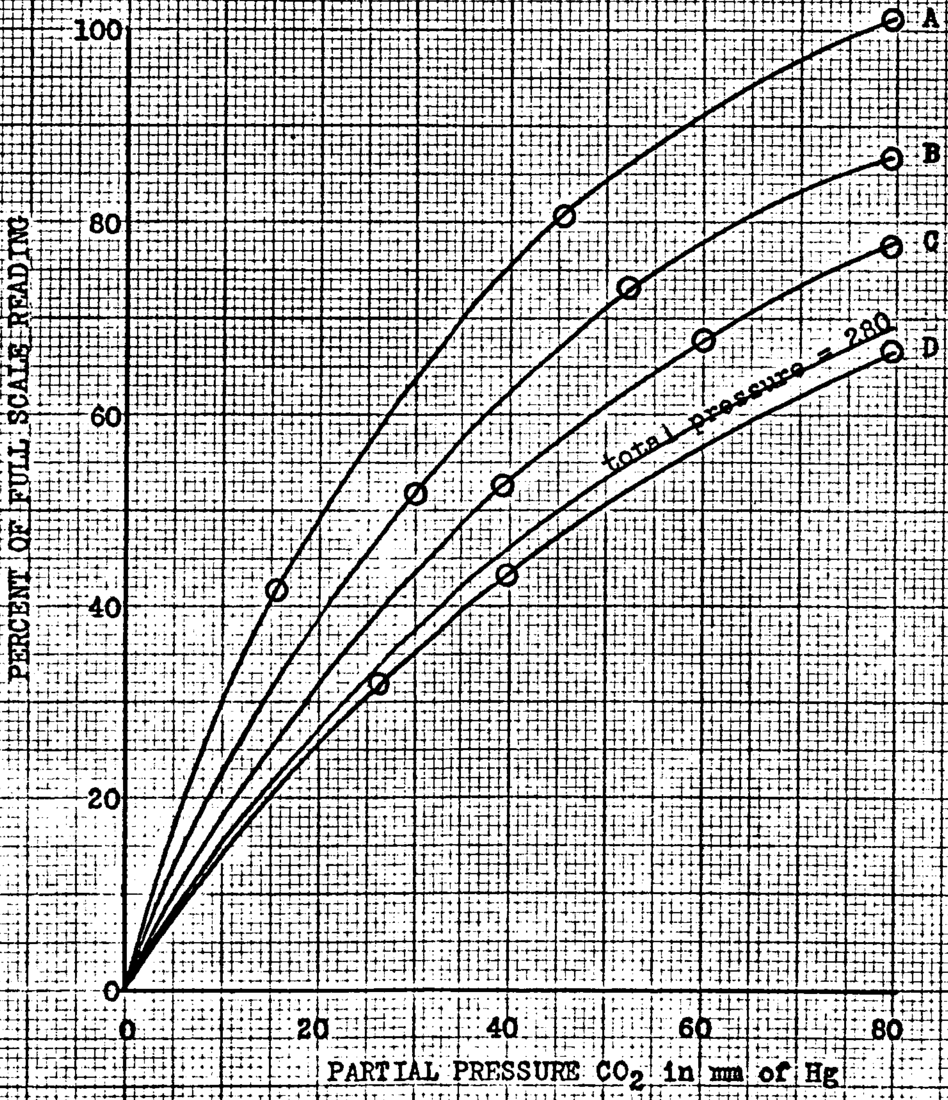
| CHECKED BY: | IR "PRESSURE BROADENING" EFFECTS | REPORT NO. NA-65-22 |
| DATE: | FIGURE #19 | MODEL NO. |



A: 0-80 mm $CO_2$ at 760 mm Total Pressure
B: 0-80 mm $CO_2$ at 500 mm Total Pressure
C: 0-80 mm $CO_2$ at 375 mm Total Pressure
D: 0-80 mm $CO_2$ at 250 mm Total Pressure

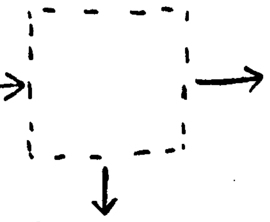
# ERROR ANALYSIS OF RESPIRATION ANALYZER

## General

**Intake:**

**Pure $O_2$ at**

| | |
|---|---|
| **Pressure** | $P_1$ |
| **Temperature** | $T_1$ |
| **Mass Flow Rate** | $M_1$ |



**Uptake:**

Pure $O_2$ at Mass uptake rate U

**Output:**

Gaseous mixture of $O_2$, $CO_2$, $H_2O$

| | |
|---|---|
| Pressure | $P_2$ |
| Temperature | $T_2$ |
| Mass Flow Rate | $M_2$ |
| Volumetric Flow Rate | $V_2$ |
| Partial Pressure $O_2$ | $P_{02}$ |
| Partial Pressure $CO_2$ | $P_{CO_2}$ |
| Partial Pressure $H_2O$ | $P_{H_2O}$ |
| Mass Fraction $O_2$ | $Y_{02}$ |
| Average $M_W$ | $M_W$ |

Measured quantities used in calculations:

$M_1$, $M_2$, $P_2$, $P_{02}$, $P_{CO_2}$

Desired quantity:

U

Constants:

$M_{W_{02}} = 32$, $M_{W_{CO_2}} = 44$, $M_{W_{H_2O}} = 18$ ($M_W$ = Molecular Weight)

Conservation of mass (assuming steady flow):

$$M_1 - U = Y_{02} M_2$$

$$= \frac{M_{W_{02}}}{R} \cdot \frac{P_{02}}{T_2} \cdot V_2$$

$$= \frac{M_{W_{02}}}{\overline{M_W}} \cdot \frac{P_{02}}{P_2} \cdot M_2$$

$$= \frac{M_{W_{O2}} P_{O2}}{M_{W_{O2}} P_{O2} + M_{W_{CO_2}} P_{CO_2} + M_{W_{H_2O}} P_{H_2O}} \cdot M_2$$

$$= \frac{M_{W_{O2}} P_{O2}}{M_{W_{O2}} P_{O2} + M_{W_{CO_2}} P_{CO_2} + M_{W_{H_2O}}(P_2 - P_{O2} - P_{CO_2})} \cdot M_2$$

$$= \frac{32 \quad P_{O2}}{32 \, P_{O2} + 44 \, P_{CO_2} + 18 \, (P_2 - P_{O2} - P_{CO_2})} \cdot M_2$$

Define $f = U/M_1$

Then

$$Y_{O2} M_2 = M_1 \, (1-f) = M_1 - U$$

$$32 \, P_{O2} + 44 \, P_{CO_2} + 18 \, (P_2 - P_{O2} - P_{CO_2}) = \frac{M_2}{M_1} \cdot \frac{32 \, P_{O2}}{1 - f}$$

EFFECT OF MEASUREMENT ERRORS

In following, assume there are no errors other than that being examined.

$\epsilon$ indicates absolute value of fractional error.

a) Mass-flowmeter errors

Assume $\epsilon_{M_1} = \epsilon_{M_2} = \epsilon_M$

$$\epsilon_u = \frac{\Delta U}{U} = \frac{\pm \epsilon_m M_1 \overset{\pm}{\underset{\mp}{\mathrm{or}}} \epsilon_m Y_{O2} M_2}{M_1 - M_2 Y_{O2}} = \pm \epsilon_m \cdot \frac{1 \overset{\pm}{\underset{\mp}{\mathrm{or}}} (1 - f)}{f}$$

b) Effluent-pressure error

$$\epsilon_u = \frac{\Delta U}{U} = \frac{1}{U} \left\{ \frac{-32 \, P_{O2} M_2}{32 \, P_{O2} + 44 \, P_{CO_2} + 18 \left[ (1 \pm \epsilon_2) P_2 - P_{O2} - P_{CO_2} \right]} + (M_1 - U) \right.$$

$$= \frac{1}{M_1 f} \left[ \frac{-32 \, P_{O2} M_2}{\frac{M_2}{M_1} \cdot \frac{32 \, P_{O2}}{1 - f} \pm 18 \, P_2 \epsilon_2} + M_1 \, (1 - f) \right]$$

$$= \frac{1 - f}{f} \left[ 1 \pm \frac{32}{18 \, (1 - f) \epsilon_2} \cdot \frac{P_{O2}}{P_2} \cdot \frac{M_2}{M_1} \right]^{-1}$$

c) $P_{CO_2}$ error

$$\epsilon_u = \frac{\Delta U}{U} = \frac{1}{f\,M_1}\left\{\frac{-32\,P_{02}\,M_2}{32\,P_{02}+44\,(1\pm\epsilon_{CO_2})P_{CO_2}+18\left[P_2-P_{02}-(1\pm\epsilon_{CO_2})P_{CO_2}\right]}+M_1(1-f)\right\}$$

$$= \frac{1}{M_1 f}\left[\frac{-32\,P_{02}\,M_2}{\frac{M_2}{M_1}\cdot\frac{32P_{02}}{1-f}\pm(44-18)\,P_{CO_2}\,\epsilon_{CO_2}}+M_1\,(1-f)\right]$$

$$= \frac{1-f}{f}\left[1\pm\frac{32}{(44-18)(1-f)\epsilon_{CO_2}}\cdot\frac{P_{02}}{P_{CO_2}}\cdot\frac{M_2}{M_1}\right]^{-1}$$

d) $P_{02}$ error

$$\epsilon_u = \frac{\Delta U}{U} = \frac{1}{M_1 f}\left\{\frac{-32\,(1\pm\ {}_{02})\,P_{02}\,M_2}{32(1\pm\epsilon_{02})P_{02}+44\,P_{CO_2}+18\left[P_2-(1\pm\epsilon_{02})P_{02}-P_{CO_2}\right]}+M_1(1-f)\right\}$$

$$= \frac{1}{M_1 f}\left[M_1\,(1-f)-\frac{32\,(1\pm\epsilon_{02})\,P_{02}\,M_2}{\frac{32}{1-f}\cdot P_{02}\cdot\frac{M_2}{M_1}\pm(32-18)\epsilon_{02}\,P_{02}}\right]$$

$$= \frac{1-f}{f}\left[1\pm\frac{1\pm\epsilon_{02}}{{}_{02}}\cdot\frac{1}{\frac{32-18}{32}\cdot\frac{M_1}{M_2}(1-f)-1}\right]^{-1}$$

Numerical - calc$^{\underline{ns}}$

Parameters:

$P_{02}\,/\,P_2 = 675/760$

$P_{02}\,/\,P_{CO_2} = 675/38$

$M_2\,/\,M_1 = 1.08307685$

(the above imply f = 0.03)

a) Mass flow error

$$\text{Max }\epsilon_u = \frac{2-f}{f}\epsilon_m$$

$$= \frac{1.97}{0.03}\epsilon_m = (65+2/3)\epsilon_m$$

b) $P_2$ error

$$\epsilon_u = \frac{1-f}{f}\left[1 \pm \frac{32}{18\epsilon_2(1-f)}\cdot\frac{P_{02}}{P_2}\cdot\frac{M_2}{M_1}\right]^{-1}$$

$$= \frac{0.97}{0.03}\left(1 \pm \frac{32}{18}\cdot\frac{1}{0.97}\cdot\frac{675}{760}\cdot\frac{1.083_{07685}}{\epsilon_2}\right)^{-1} = (32+1/3)\left(1 \pm \frac{1.763_{01169}}{\epsilon_2}\right)^{-1}$$

$$-\max\epsilon_u = (+32+1/3)\left(\frac{1.763_{01169}}{\epsilon_2} - 1\right)^{-1}$$

c) $P_{CO_2}$ error

$$\epsilon_u = \frac{1-f}{f}\left[1 \pm \frac{32}{(44-18)\,\epsilon_{CO_2}(1-f)}\cdot\frac{P_{02}}{P_{CO_2}}\cdot\frac{M_2}{M_1}\right]^{-1}$$

$$= \frac{0.97}{0.03}\left(1 \pm \frac{32}{26}\cdot\frac{1}{0.97}\cdot\frac{675}{38}\cdot\frac{1.083_{07685}}{\epsilon_{CO_2}}\right)^{-1} = (32+1/3)\left(1 \pm \frac{24.41_{093108}}{CO_2}\right)^{-1}$$

$$-\max\epsilon_u = (+32+1/3)\left(\frac{24.41_{093108}}{\epsilon_{CO_2}} - 1\right)^{-1}$$

d) $P_{02}$ error

$$\epsilon_u = \frac{1-f}{f}\left[1 \mp \frac{1 \pm \epsilon_{02}}{\epsilon_{02}}\cdot\frac{1}{1-\frac{(32-18)(1-f)}{32}\cdot\frac{M_1}{M_2}}\right]^{-1}$$

$$= \frac{0.97}{0.03}\left(1 \mp \frac{1\pm\epsilon_{02}}{\epsilon_{02}}\cdot\frac{1}{1-\frac{14}{32}\cdot\frac{0.97}{1.083_{07685}}}\right)^{-1} = (32+1/3)\left(1 \quad \frac{1\pm\epsilon_{02}}{\epsilon_{02}} \times 1.644_{25961}\right)^{-1}$$

$$\max\epsilon_u = (32+1/3)\left(1 + 1.644_{25961}\,\frac{1-\epsilon_{02}}{\epsilon_{02}}\right)^{-1}$$

| ① | (B2) | (C2) | (D2) | (D3) | (A2) | (B3) | (C3) | (D4) |
|---|---|---|---|---|---|---|---|---|
| i | $\frac{1.763_{01169}}{1}$ | $\frac{24.41_{093108}}{1}$ | $\frac{1}{1} - 1$ | $1.644_{25961}$ D2 | (65+2/3) 1 | $\frac{32+1/3}{B2 - 1}$ | $\frac{32+1/3}{C2 - 1}$ | $\frac{32+1/3}{D3 + 1}$ |
| 0.001 | 1763.01169 | 24410.93108 | 999 | 1642.6153504 | 0.0656667 | 0.01835024 | 0.0013245975 | 0.01967208 |
| 0.002 | 881.505845 | 12205.46554 | 499 | 820.4855454 |  | 0.0367213 | 0.0026493035 | 0.0393595888 |
| 4 | 440.752922 |  |  |  | (Straight Line) |  |  |  |
| 6 | 293.835281 | 4068.48851 | 165+2/3 | 272.399008778 |  | 0.1104147 | 0.0079492132 | 0.1182642668 |
| 8 | 220.376461 |  |  |  |  |  |  |  |
| 0.010 | 176.301169 | 2441.093108 | 99 | 162.7817014 |  | 0.184444 | 0.01325086 | 0.1974172514 |
| 0.012 | 146.9176408 | 2034.244256 | 82+1/3 | 135.37737455 |  | 0.221586185 | 0.015902336 | 0.2370872252 |
| 14 | 125.9294064 | 1743.637934 | 70.4285714 | 115.892855343 |  | 0.25881283 | 0.0185542462 | 0.2768197168 |
| 16 | 110.1882306 | 1525.683192 | 61.5 | 101.121966015 |  | 0.2961247 | 0.02120659 | 0.3166148733 |
| 18 | 97.9450938 |  |  |  |  |  |  |  |
| 0.020 | 88.1505845 | 1220.546554 | 49. | 80.56872089 | 1.31333 | 0.371005 | 0.026512586 | 0.396393776 |

It is clearly shown in figure 20 that the accuracy required for the measurement of the mass flow rates far exceeds the accuracy stated by the manufacturer of the flowmeter (±2 percent). This accuracy limitation when coupled with a planimeter method of data integration which has an error of ±4 percent simply indicates that this method of computing oxygen consumption (by difference) is impractical. Data Processing can be improved by Digital Analog and Machine Program Techniques, but these will not improve the meter accuracy to within the required limits. Other methods for utilizing the measured data to determine oxygen consumption must be developed.

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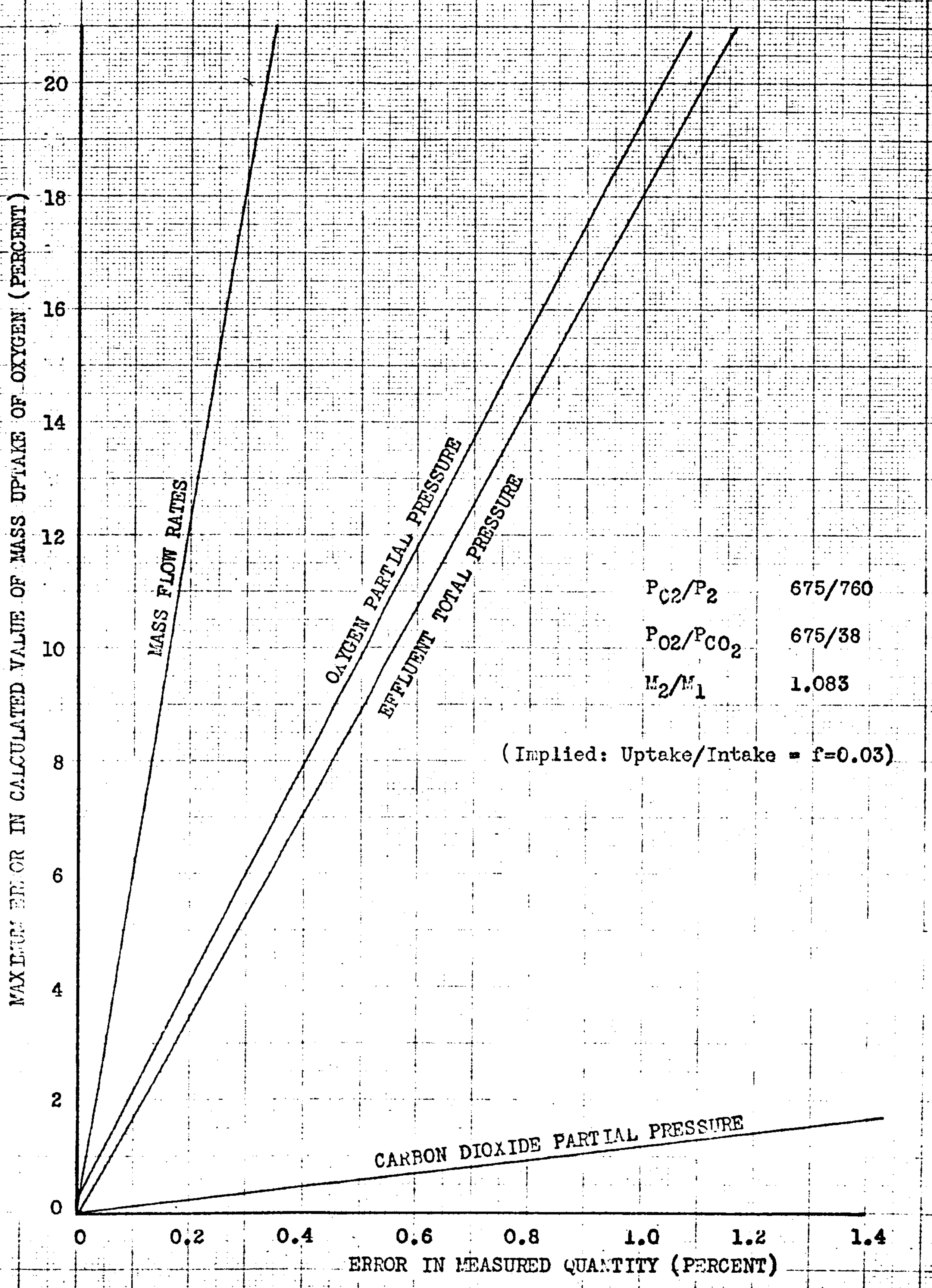
| CHECKED BY: | ERROR ANALYSIS, RESPIRATION ANALYZER | REPORT NO. NA-65-22 |
| DATE: | FIGURE #20 | MODEL NO. |



| | |
|---|---|
| $P_{O2}/P_2$ | 675/760 |
| $P_{O2}/P_{CO_2}$ | 675/38 |
| $M_2/M_1$ | 1.083 |

(Implied: Uptake/Intake = f=0.03)

## SYSTEM PACKAGING

At the present time it is not possible to make any final recommendations for system packaging since the number of components for the system has not been fixed. While the flowmeter mass flow measuring accuracy precludes the determination of oxygen consumption by the difference in inspiratory and expiratory mass flows rates of oxygen, the number of flowmeters necessary in the system has yet to be determined. However, it would appear that only one flowmeter will be necessary if other techniques are used to calculate oxygen consumption whereby a known or assumed R.Q. is used. Such a system would utilize one flowmeter to measure the mass flow rate of expiratory gases. The accuracy range within ±2 percent and machine techniques of data handling will provide the necessary overall accuracy for flow rate determination.

North American Aviation, Inc. will work with Beckman, Inc. to develop a minimum size and weight package when the feasibility of the analyzer system has been proven and the number of components fixed. The objective will be to assemble all of the components into a single package for easy installation and removal for maintenance and/or replacement of individual components.

## CLOSED SYSTEM TESTS OF PHASE II

In an effort to check the Prototype Respiratory Analyzer System, in addition to the check runs of Phase I, additional "Closed System" runs were made during Phase II for the basal or rest condition. The test equipment was arranged as shown in the schematic diagram of figure 21.

### Test Procedure

Subjects were seated in reclining chair and preoxygenated on 100 percent $O_2$ for 30 minutes to eliminate all pulmonary and some tissue nitrogen. During this time, $O_2$ and $CO_2$ sensors were calibrated, thermal tape heaters were turned on and the spirometer flushed and filled with 100 percent $O_2$. Subjects then moved to a hospital bed and assumed a supine position while breathing 100 percent $O_2$ from a portable oxygen source. Subjects then held breath and transferred from $O_2$ mask to spirometer mouthpiece. The spirometer recording motor was started and traces were recorded continuously during the test period. $CO_2$, $O_2$, inspiratory flow and expiratory flow were recorded for periods of one minute at five minute intervals. Tests were continued for periods of 20-30 minutes.

The results of the tests were inconclusive due to problems with the prototype equipment. A check of the voltage output from the mass flowmeters at the conclusion of the tests, (when the flowmeters were connected in series and the same flow of gas passed through both meters) showed a 20 percent difference, which is indicative of one or both meters malfunctioning. The readings of the partial pressure of oxygen were all too low by 100 to 150 mm Hg, as shown in Table VI. Initially, it was thought that a large portion of this error was due to the partial pressure of nitrogen because the subjects had not been completely denitrogenated. However, a

SCHEMATIC OF THE PROTOTYPE RESPIRATION
ANALYZER FOR CLOSED SYSTEM CHECK

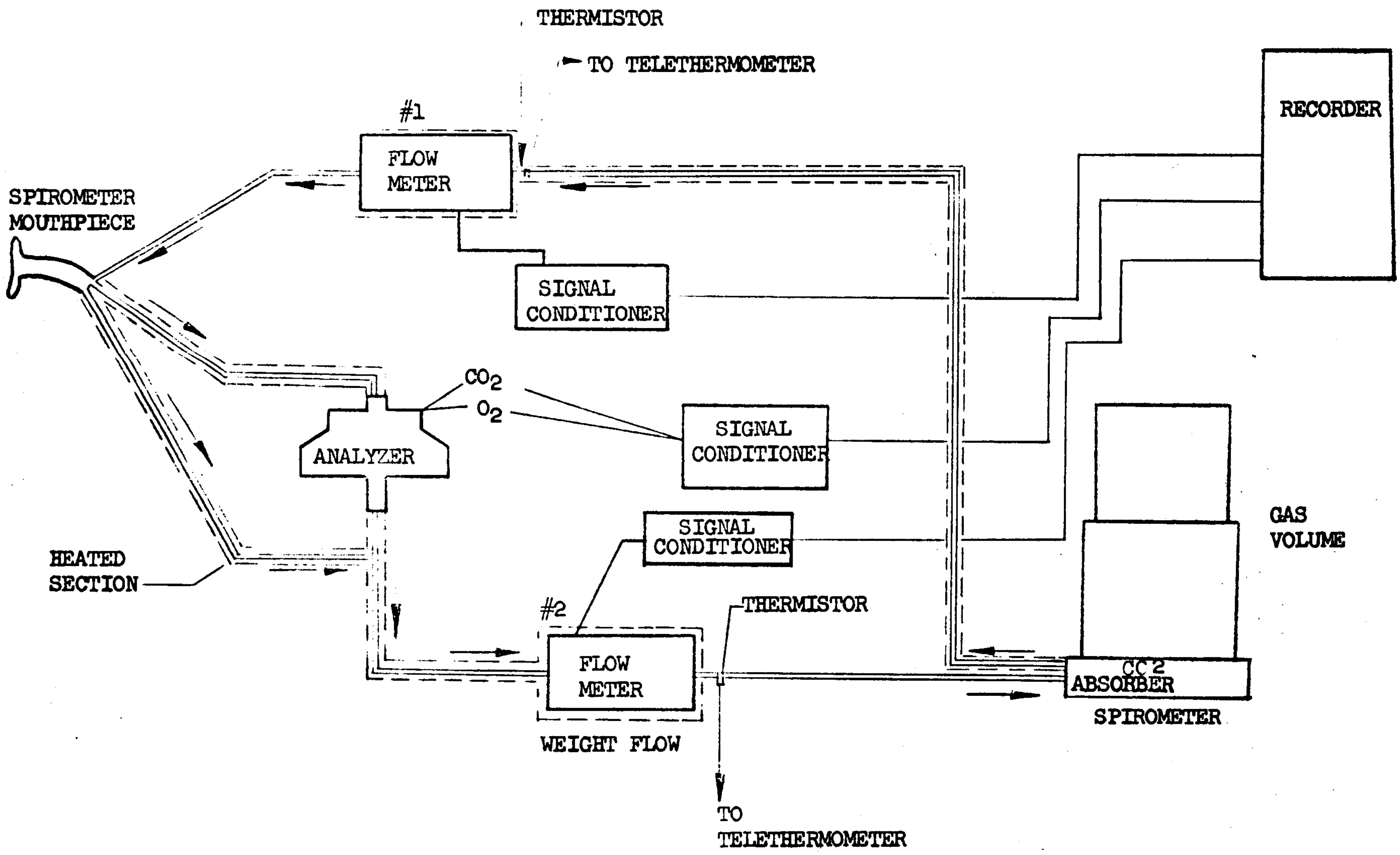


FIGURE #21

### Table VI
### DATA SUMMARY - SUPPLEMENTARY CLOSED SYSTEM RUNS

| RUN | SUBJ. | TIME | SPIROMETER | | | ANALYZER | | FLOW METERS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | FLOW METER #1 | | FLOW METER #2 | |
| | | | TEMP | MIN VOL | $O_2$ | $P_{O2}$ | $P_{CO_2}$ | FLOW | AIR TEMP | FLOW | AIR TEMP |
| 1 | GM | 2:10 | 22°C | | | 551 | | | 86°F | | 94°F |
| | | 2:15 | 22° | | | 500 | | | 86°F | 7.38 | 95°F |
| | | 2:20 | 22° | 10 L/M | 333cc/M | 472 | 28 Min | | 86°F | | 96°F |
| | | 2:25 | 22.5° | | | 460 | | | 87°F | 6.0 | 96°F |
| | | 2:30 | 22.5° | | | 440 | | | 87.5°F | | 96.5°F |
| 2 | MG | 2:40 | 22.5° | | | 588 | | | 87.5°F | | 94°F |
| | | 2:45 | 22.5° | | | 567 | | | 88°F | 5.48 | 93.5°F |
| | | 2:50 | 23.0° | 6 L/M | 200cc/M | 546 | 29 Min | | 88°F | | 93.5°F |
| | | 2:55 | 23.0° | | | 525 | | | 88.5°F | 5.4 | 94°F |
| | | 3:00 | 23.5° | | | 525 | | | 88.5°F | | 93.5°F |
| 3 | JK | 2:50 | 21.5° | | | 520 | | | 87.5°F | | 91°F |
| | | 2:55 | 21.5° | | | 510 | | | 87.5°F | 2.95 | 91.5°F |
| | | 3:00 | 21.5° | 4.8 L/M | 233cc/M | 504 | 29 Min | | 88.0°F | | 91.5°F |
| | | 3:05 | 22° | | | 500 | | | 88.0°F | | 91.5°F |
| 4 | GM | 3:10 | 21.5° | | | 572 | | | 86°F | | 93°F |
| | | 3:15 | 21.5° | | | 567 | | | 85.5°F | 7.38 | 93.5°F |
| | | 3:20 | 22.0° | 7.5 L/M | 280cc/M | 539 | 29 Min | | 85.0°F | | 91°F |
| | | 3:25 | 23.0° | | | 528 | | | 85.5°F | 6.33 | 91°F |
| | | 3:30 | 23.0° | | | 517 | | | 85.5°F | | 91°F |

check of the data shown in figure 22 indicated that only a very small quantity of nitrogen would be liberated during the 20-minute run because of the oxygen prebreathing which had been accomplished prior to the test run. The basic error was then assumed to be caused by a malfunctioning in the partial pressure sensing equipment.

The data taken with the spirometer was used to determine minute volume, tidal volume, respiratory flow rate, and oxygen consumption. A plot of oxygen consumption versus time is shown in figure 23 for three test subjects. A calculation of the required partial pressure of oxygen in the respired gases was made to obtain the mass flow rate which would agree with the spirometer data. The corresponding partial pressure of $CO_2$ was determined and found to agree very closely with the $P_{CO_2}$ which was measured during the test runs.

FORM 1021-B

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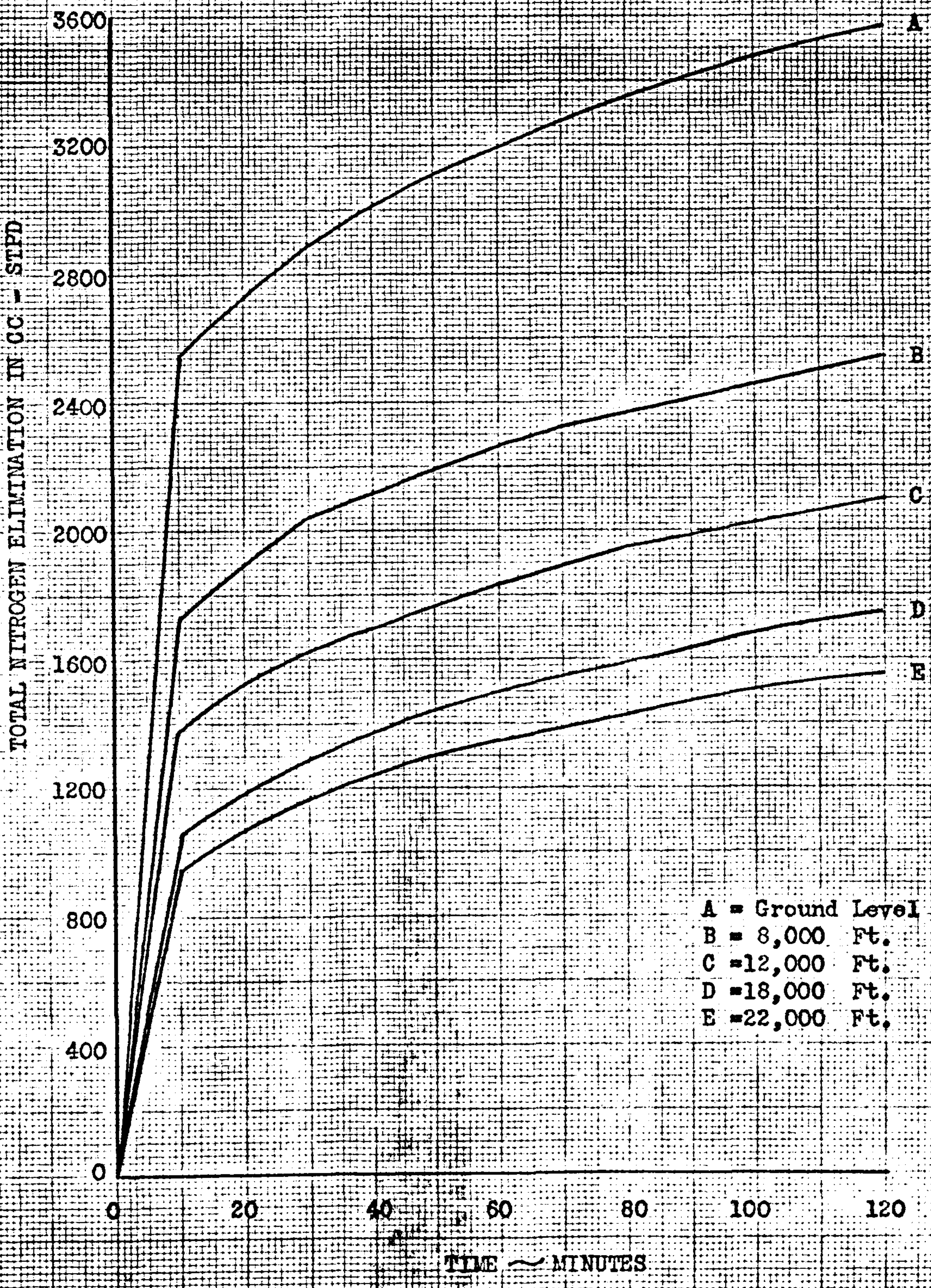
|---|---|---|
| PREPARED BY: | **NORTH AMERICAN AVIATION, INC.** | PAGE NO. OF |
| CHECKED BY: | TOTAL NITROGEN ELIMINATION (ACCUMULATED)<br>DURING 2 HOURS BREATHING OXYGEN | REPORT NO. NA-65-22 |
| DATE: | EACH POINT IS AN AVERAGE OF 33 SUBJECTS | MODEL NO. |

FIGURE #22

REFERENCE:
SCHOOL OF AVIATION MEDICINE, USAF
RANDOLPH AFB, TEXAS
REPORT 55-73



FORM 1021-S

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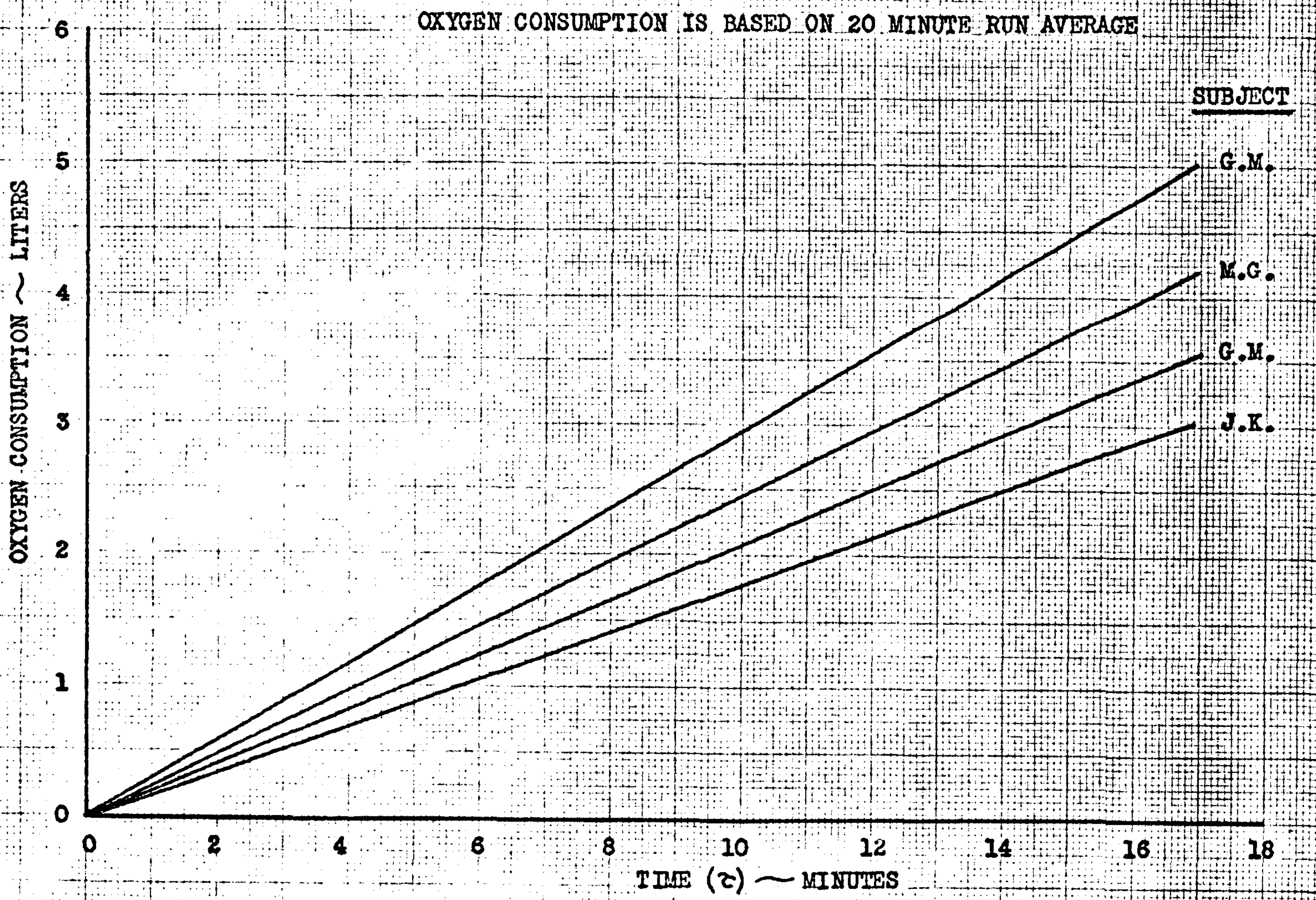
|---|---|---|
| PREPARED BY: R.K.B. | **NORTH AMERICAN AVIATION, INC.** | PAGE NO. OF |
| CHECKED BY: | CLOSED SYSTEM DATA SPIROMETER | REPORT NO. NA-65-22 |
| DATE: | FIGURE #23 | MODEL NO. |



As an illustration of an indirect method of computing oxygen consumption data is selected from Run No. 4 (Subject G. M.). The spirometer Data yielded a minute volume of 7.5 Liters/Minute. Oxygen consumption based on the Spirometer was 280 CC/Minute BTPS, or 250 CC/Minute STPD. The flow rate of expired gases determined from the flowmeter was 7.38 Liters/Minute. The measured value of $P_{CO_2}$ by the Beckman Sensor was 29 mm Hg.

From the ratio of the partial pressure of $CO_2$ and the total pressure, utilizing an assumed R.Q. of 0.82 for resting conditions the $O_2$ consumed is calculated.

$$O_2 \text{ Consumed} = \frac{29}{760} \times 7380 \times .82$$

$$= 231 \text{ CC/Minute}$$

Percent Deviation from Spirometer Data

$$\frac{250-231}{\frac{250+231}{2}} \times 100 = \frac{19}{240} \times 100 - 8\% \text{ Deviation}$$

## RECOMMENDATIONS FOR FURTHER RESEARCH TO DETERMINE FEASIBILITY

The follow-on research work recommended within this report section is commensurate with the areas discussed in the section on Feasibility. These recommendations will be further amplified in an unsolicited proposal to do follow-on work to determine the feasibility of the respiratory analyzer to yield data fromwhich oxygen consumption by the human subjects can be determined.

Th e recommendations for the follow-on program, for improvements to the equipment and for data processing and interpretation are as follows:

1. Flowmeters:

   Laboratory comparison of the Technology, Inc. Flowmeter and the Spacelabs, Inc. Flowmeter to determine which meter has the best potential advantages to the system.

   Run a flow check on each meter to obtain an accurate calibration curve - Do this with real gases, with varying humidity levels (0-100%)

   Check Response Time during calibration with cyclic flow rates.

2. $P_{O_2}$, $P_{CO_2}$, $P_T$, Temperature Sensor by Beckman

   Expand the range of the scale on the oxygen partial pressure and total pressure channels.

   Increase breath-cell cross-sectional area to alleviate restriction to expired gas flow.

3. Addition of "Douglas Bags" to collect expired gases for analysis of expired gases to check sensors.

4. Modification of system to a closed system to check methods of determining oxygen consumption.
5. Develop methods of determining oxygen consumption from data taken and estimates of maximum error in using these methods.
6. Develop machine programs and utilize digital methods for data handling to increase accuracy and efficiency.
7. Investigation of other ways of determining oxygen consumption by human subjects considering application to airborne systems.

# CONCLUSIONS

The conclusions presented here as a result of the Thermodynamic Analysis of the Respiration Analyzer differ slightly from those presented in the Phase I Final Report in that the emphasis has been directed toward the goal of determining oxygen consumption rather than an indication of total respiratory function. Also, several important factors considering the method of approach and design of the system were brought out during the Phase II program which were not apparent during the first phase.

The important conclusions are:

1. This is the first time that breath-by-breath analysis of expired air has been accomplished with such rapid response instrumentation.
2. It has been determined that oxygen consumption by measurement of the mass flow of inspired oxygen and mass flow of expired gas differences is not as yet feasible because of state-of-the-art inaccuracies of measurement.
3. The accuracy required to determine oxygen consumption by direct differences in mass flow measurement, $P_{CO_2}$, $P_{O_2}$, etc., has been determined.
4. Although the analyzer gives satisfactory indication of the total respiratory function, improvements are indicated which will improve this ability.
5. The application of the "Perfect-Gas" law for the pressure and temperature ranges involved in this work, is considered satisfactory.

6. Sufficient information has been obtained to show the need for maintaining a heated (ideally isothermal) situation from the subject to a point downstream of the exhalation flowmeter.
7. The results of the analysis to compare the Spacelabs and Technology, Inc. Mass Flowmeter is inconclusive as to which flowmeter is most applicable to the analyzer system. However, both flowmeters should be calibrated with saturated gases simulating human expiration gases in a manner simulating the breathing cycle.
8. The work accomplished during Phase I and Phase II in studying the feasibility of the respiration analyzer yielded much valuable information by way of giving direction to the follow-on work that is necessary to attain the desired goal.

## REFERENCES

1. NA-64-1298, "Development and Testing of a Prototype Respiration Analyzer," by J. W. Raeke and D. M. Walton, dated 14 December 1964
2. Spacelabs, Inc. 1164-34, Model 210 Gas Mass Flowmeter, 4 November 1964
3. Technology, Inc., "A Linear Pneumotachometer," by R. S. Scranton, 5 November 1962
4. Temperature, Its Measurement and Control in Science and Industry, V Vol. III, Part II, Paper 29, "Thermistor for Temperature Measurement," by C. R. Droms
5. Boundary Layer Theory - Schlichting
6. Heat, Mass and Momentum Transfer, Roshnow, H. Choi, 1961 Edition
7. Thermodynamics, Lichty, L. C., Second Edition McGraw-Hill Publication
8. "Handbook of Physiology", Section III Respiration Volume I, American Physiological Society, Washington, D. C., 1964
9. "Methods in Pulmonary Physiology," Translated by John M. Workman, Hafner Publishing Company, Inc., 1963
10. Respiration, Edited and Translated by P. C. Luchinger, MD, and K. M. Moser, MD, Publisher C. V. Mosby Co., 1960, page 155

# APPENDICES

1. Evaluation of the Mass Flowmeters

SPACELABS GAS MASS FLOWMETER

## Equations of Motion of a Viscous Fluid

The continuity equation is given by

$$\frac{\partial \rho}{\partial t} + \rho \operatorname{div.} \bar{V} + \bar{V} \cdot \operatorname{grad} \rho = 0 \tag{1}$$

The vector $\bar{J} = \rho \bar{V}$ is called the mass flux density. Its direction is that of the motion of the fluid while its magnitude equals the mass of fluid flowing in unit time through unit area perpendicular to the velocity.

The momentum equation is given by

$$\frac{\partial}{\partial t}\left(\rho v_i\right) = - \frac{\partial \pi_{ik}}{\partial x_k} \tag{2}$$

where the tensor $\pi_{ik}$ is defined as

$$\pi_{ik} = p\delta_{ik} + \rho v_i v_k$$

where $\delta_{ik}$ is the unit tensor, i.e.

$$\begin{aligned} \delta_{ik} &= 1 \quad \text{for } i = k \\ &= 0 \qquad\quad i \neq k \end{aligned}$$

to see the meaning of (2), we can integrate over some volume:

$$\frac{\partial}{\partial t}\int \rho v_i \, dV = -\int \frac{\partial \pi_{ik}}{\partial x_k} \, dV$$

The integral on the right is transformed into a surface integral by Green's formula (the surface element $ds_i$ is replaced by the operator $dV \cdot \frac{\partial}{\partial x_i}$ and applied over the whole of the integrand)

$$\frac{\partial}{\partial t}\int \rho v_i \, dV = -\oint \pi_{ik} \, dS_k \tag{3}$$

The left hand side of (3) is the rate of change of the i - component of the momentum contained in the volume. The surface integral on the right is therefore the amount of momentum flowing out through the bounding surface in unit time. Thus, $\Pi_{ik}$ is the momentum flux density tensor.

The equation of motion of a viscous fluid is obtained by adding to the "ideal" momentum flux, a term $-\sigma'_{ik}$ which gives the "viscous" transfer of momentum in the fluid. The momentum flux density tensor in a viscous fluid becomes

$$\Pi_{ik} = p\delta_{ik} + \rho v_i v_k - \sigma'_{ik} = -\sigma_{ik} + \rho v_i v_k \qquad (4)$$

The tensor

$$\sigma_{ik} = -p\,\delta_{ik} + \sigma'_{ik}$$

is called the stress tensor and $\sigma'_{ik}$ the viscosity stress tensor.

It is usual practice to define $\sigma'_{ik}$ in terms of a viscosity coefficient, $\mu$, , and add to the right hand side of the Euler equation to obtain

$$\rho\left[\frac{\partial \bar{v}}{\partial t} + (\bar{v}\cdot \mathrm{grad})v\right] = -\mathrm{grad}\, p + \mu\Delta\bar{v}_i + \left(\zeta + \frac{1}{3}\mu\right) \mathrm{grad}\,\mathrm{div}\,\bar{v} \qquad (5)$$

for an incompressible fluid, $\mathrm{div} = 0$. Thus the equation motion for an incompressible fluid are

$$\frac{\partial \bar{v}}{\partial t} + (\bar{v}\cdot \mathrm{grad})\, v = \frac{1}{\rho}\mathrm{grad}\, p + \frac{\mu}{\rho}\bar{\nabla}^2\bar{v} \qquad (6)$$

where

$$\bar{\nabla}^2 v_i \equiv \partial^2 v_i / \partial x_k \partial x_k$$

is the Lapacion operator.

## ENERGY DISSIPATION

The presence of viscosity results in the dissipation of energy, which is transformed into heat.

The total kinetic energy of an incompressible fluid is

$$E_{KIN} = \frac{1}{2} \rho \int v^2 dV \tag{7}$$

If we take the time derivative of this energy, writing

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2\right) = \rho v_i \frac{\partial v_i}{\partial t}$$

and substituting for $\frac{\partial v_i}{\partial t}$ the expression for it given by the Navier-Stakes equation (6).

$$\frac{\partial v_i}{\partial t} = -v_K \frac{\partial v_i}{\partial x_K} - \frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{1}{\rho}\frac{\partial \sigma'_{iK}}{\partial x_K}$$

The result is

$$\begin{aligned}\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2\right) &= -\rho\bar{v}\,(\bar{v}\cdot grad)\bar{v} - \bar{v}\cdot grad\, p \\ &\quad + v_i \frac{\partial \sigma'_{iK}}{\partial x_K} \\ &= -\rho(\bar{v}\cdot grad)\left(\frac{1}{2}v^2 + \frac{P}{\rho}\right) + div\,(\bar{v}\cdot\bar{\sigma}') \\ &\quad - \sigma'_{iK}\frac{\partial v_i}{\partial x_K}\end{aligned}$$

where $\bar{v}\cdot\bar{\sigma}'$ denotes the vector whose components are $v_i\,\sigma'_{iK}$. Since $div\ \bar{v} = 0$ for an incompressible fluid, we can write the first term on the right as:

$$\begin{aligned}\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2\right) = -div\left[\rho\bar{v}\left(\frac{1}{2}v^2 + \frac{P}{\rho}\right) - \bar{v}\cdot\bar{\sigma}'\right] - \\ - \bar{\sigma}'_{iK}\frac{\partial v_i}{\partial x_K}\end{aligned} \tag{8}$$

The expression in the brackets is the energy flux density in the fluid. The term, $\bar{v} \cdot \bar{\sigma}'$ , is the energy flux due to internal friction.

If Equation (8) is integrated over some volume V, we obtain

$$\frac{\partial}{\partial t}\int \frac{1}{2}\rho v^2 dV = -\oint \left[\rho v\left(\frac{1}{2}v^2 + \frac{p}{\rho}\right) - \bar{v}\cdot\bar{\sigma}'\right]\cdot d\bar{s} - \int \sigma'_{ik}\frac{\partial v_i}{\partial x_k} dV \quad (9)$$

The first term on the right gives the rate of change of kinetic energy of the fluid in V due to the energy flux through the surface bounding V. The integral in the second term is consequently the decrease per unit time in kinetic energy due to dissipation.

If the integration is extended to the whole volume of fluid, the surface integral vanishes (since the velocity vanishes at infinity) and the energy dissipated per unit of time is:

$$E_{KIN} = -\int \sigma'_{ik}\frac{\partial v_i}{\partial x_k}\, dV \quad (10)$$

For incompressible fluids the tensor $\sigma'_{ik}$ is given by

$$\sigma'_{ik}\frac{\partial v_i}{\partial x_k} = \mu\frac{\partial v_i}{\partial x_k}\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i}\right) = \frac{1}{2}\mu\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i}\right)^2$$

Thus the energy dissipation becomes

$$\dot{E}_{KIN} = -\frac{1}{2}\mu\int\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i}\right)^2 dV \quad (11)$$

## FLOW IN A PIPE

Take the axis of the pipe as the X-axis. The fluid velocity is along the X-axis as a function of y and z only. The equation of continuity is satisfied identically, while the y and z components of the Navier-Stokes equation give $\frac{\partial P}{\partial y} = \frac{\partial P}{\partial z} = 0$, i.e., the pressure is constant over the cross-section of the pipe. The X-component of Equation (6) gives

$$\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} = \frac{1}{\mu}\frac{dP}{\partial x} \qquad (12)$$

If the pressure is constant, we can write the gradient as $\frac{\Delta P}{L}$ where $\Delta P$ is the pressure difference between the ends of the pipe and L is the length of the pipe.

The velocity distribution in the pipe is determined by a two-dimensional equation of the form

$$\nabla^2 v = CONST.$$

For a circular pipe with the origin at the center and using polar coordinates, we have by symmetry v = v (r). Using the expression for the Lapacian in polar coordinates, we have

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dv}{dr}\right) = -\frac{\Delta P}{\mu L}$$

Integration yields

$$v = -\frac{\Delta P}{4\mu L} r^2 + a \log r + b$$

the constant a must be zero since the velocity must remain finite at the center of the pipe.

The constant b is determined by the fact that v = 0 when r = R, where R is the radius of the pipe. The velocity distribution becomes

$$v = \frac{\Delta P}{4\mu L}\left(R^2 - r^2\right) \tag{12}$$

The mass flow $\dot{m}$ is determined by the fact that a mass

$$\rho \cdot 2\pi r v\, dv$$

passes each second through an annular element $2\pi r dr$ of the cross-sectional area. Therefore,

$$\begin{aligned} \dot{m} &= 2\pi\rho \int_0^R r v\, dr \\ &= \frac{\pi \Delta P}{8 v L} R^4 \end{aligned} \tag{13}$$

where

$$v = \frac{\mu}{\rho}$$

THERMAL CONDUCTION

For an ideal fluid, the conservation of energy was given by Equation (6)

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \rho\epsilon\right) = -\operatorname{div}\left[\rho\bar{v}\left(\frac{1}{2}v^2 + h\right) - \bar{v}\cdot\bar{\sigma}'\right] \tag{14}$$

where $\epsilon$ = internal energy per unit mass and w is the fluid enthalpy

$$dw = T ds + \left(\frac{1}{\rho}\right) dp$$

with s = entropy per unit mass. The term on the left is the rate of change of energy in unit volume of fluid and the term on the right is the divergence of the energy flux density. Besides the flux $\rho\bar{v}\left(\frac{1}{2}v^2 + h\right)$ due to transfer of mass by motion of the fluid there is also the flux due to internal friction. If the temperature of the fluid is not constant throughout its volume, there will be an energy transfer by heat called thermal conduction.

The heat flux $q$ is given by

$$\bar{q} = -\kappa \, grad \, T \tag{15}$$

where k is called the thermal conductivity. The total energy flux is therefore given by

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \rho \epsilon\right) = -div\left[\rho \bar{v}\left(\frac{1}{2} v^2 + h\right) - \bar{v}\cdot\bar{\sigma}' - \kappa \, grad \, T\right] \tag{16}$$

If this equation is combined with the Navier-Stokes Equation (8) the general equation of heat transfer is obtained

$$\rho T\left(\frac{\partial s}{\partial t} + \bar{v}\cdot grad \, s\right) = \sigma'_{ik}\frac{\partial v_i}{\partial x_k} + div(\kappa \, grad \, T) \tag{17}$$

The quantity $ds/dt$ gives the rate of change of entropy of a unit mass of fluid and T ds/dt is the quantity of heat gained by this mass in unit time so that $\rho$ T ds/dt is the quantity of heat gained per unit volume. The amount of heat gained by unit volume of fluid is therefore

$$\sigma'_{ik}\frac{\partial v_i}{\partial x_k} + div(\kappa \, grad \, T)$$

The first term is the energy dissipated into heat by viscosity and the second is the heat conducted into the volume of fluid.

The general equation of thermal conduction (17) can be simplified for an incompressible fluid

$$\frac{\partial s}{\partial t} = \left(\frac{\partial s}{\partial T}\right)_p \frac{\partial T}{\partial t}, \quad grad s = \left(\frac{\partial s}{\partial T}\right)_p grad \, T$$

and since $T\left(\frac{\partial s}{\partial T}\right)_p$ is by definition the specific heat, Cp, we obtain

$$T\frac{\partial s}{\partial t} = C_p \frac{\partial T}{\partial t}, \quad T \, \mathrm{grad}\, s = C_p \, \mathrm{grad}\, T$$

Equation (17) becomes

$$\rho C_p\left(\frac{\partial T}{\partial t} + \bar{v}\cdot \mathrm{grad}\, T\right) = \mathrm{div}\left[K \, \mathrm{grad}\, T\right] + \sigma'_{ik}\frac{\partial v_i}{\partial x_k} \tag{18}$$

Expanding the term $\sigma'_{ik}\frac{\partial v_i}{\partial x_k}$ as in Equation (11) and defining

$$\chi = \frac{K}{\rho C_p} \tag{19}$$

Equation (18) becomes

$$\frac{\partial T}{\partial t} + \bar{v}\cdot \mathrm{grad}\, T = \chi \bar{\nabla} T + \frac{v}{2C_p}\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i}\right)^2 \tag{20}$$

## DIMENSIONLESS PARAMETERS

It is convenient to introduce several dimensionless parameters

Reynolds Number, $R_e = \frac{\rho U L}{\mu} = \frac{U L}{v}$

Prandtl Number, $P_r \quad \frac{C_p \mu}{K} = \frac{v}{\chi}$

Heat Transfer Coefficient, $\alpha = \frac{q}{T_1 - T_0}$

Nusselt Number, $N_L = \frac{\alpha L}{K} =$

Stanton Number, $S_T = \frac{\alpha}{\rho g C_p U} \quad \frac{N_L}{R_e P_r}$

## THE BOUNDARY LAYER

It is well known that viscosity dissipation effects take place in a very thin layer adjoining the wall. This layer is called the boundary layer. The nature of the boundary, laminar or turbulent, depends upon the disturbances in the boundary layer. In a laminar boundary layer, the fluid particles flow in an orderly fashion in smooth lamina. In contrast, the turbulent boundary layer is characterized by "turbulent bursts" or disturbances. Momentum change is by macroscopic transport and so the fluid particles no longer flow in lamina but move in a "jagged" - nonuniform manner. Thus, the processes of heat transfer in laminar and in turbulent flow are fundamentally different.

For laminar flow the equations of motion (6) and (20) give

$$v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} = \chi \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \qquad (21)$$

On the right hand side, the derivative

$$\frac{\partial^2 T}{\partial x^2} << \frac{\partial^2 T}{\partial y^2}$$

and can be dropped since gradients across the boundary layer are larger than an AXIAL GRADIENT.

Thus
$$v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} = \chi \frac{\partial^2 T}{\partial y^2} \qquad (22)$$

If the Prandtl Number is on the order of unity, then the order of magnitude $\delta$ of the boundary layer thickness and the thermal boundary layer will be the same and will be inversely purportional to $\sqrt{R_e}$. The heat flux $q = -k \frac{\partial T}{\partial r}$ is equal, in order of magnitude, TO $k(T_1 - T_0)/\delta$. Hence $q$ and therefore the Nusselt Number, are purportional to $\sqrt{R_e}$. It follows that the heat transfer coefficient $\alpha$ is inversely purportional to the square root of the dimension L of the pipe.

To determine the temperature distribution in a fluid moving in Poiseuille flow along a pipe when the temperature of the walls varies linearly along the pipe we assume that the conditions of the flow are the same at every cross-section of the pipe, and take the temperature distribution in the form

$$T = Az + f(r)$$

where AZ is the wall temperature. We use cylindrical coordinates with the Z-axis along the axis of the pipe. The velocity is given by Equation (12) and (13).

$$v_z = v = 2\, v_{MAX} \left(1 - \frac{r^2}{R^2}\right)$$

Substituting into (20) $\frac{\partial}{\partial t} = 0$ gives

$$\bar{v}_0 \, grad \, T = \chi \, \bar{\nabla} T$$

$$\frac{1}{r} \frac{d}{dr}\left(r \frac{df}{dr}\right) = \frac{2\, v_{MAX} A}{\chi} \left[1 - \left(\frac{r}{R}\right)^2\right]$$

solution is

$$f(r) = - \frac{v_{MAX} A r^2}{2\chi} \left[\frac{3}{4} - \left(\frac{r}{R}\right)^2 + \frac{1}{4}\left(\frac{r}{R}\right)^4\right] \qquad (23)$$

The heat flux is

$$q = K \left[\frac{\partial T}{\partial r}\right]_R = \frac{1}{2} \rho \, C_P \, v_{MAX} R A \qquad (24)$$

Writing (24) in terms of $\dot{m}$ using Equation (13) yields

$$q = C_P R \dot{m} \qquad \text{(Poiseville Flow)} \qquad (25)$$

Hence, the heat flux, $q$, is seen to be purportional to the mass flow rate, $\dot{m}$, the specific heat, $C_P$, and the pipe radius. It follows that for a different velocity distribution and/or temperature distribution, the heat flux will have a different dependency on mass flux. It also follows that this mass flux dependency will be a function of the nature of the boundary layer, i.e. laminar or turbulent.

In the design of a mass flowmeter, one would have to know the nature of the velocity and thermal distributions in order to determine the relationship between mass flux and heat flux. Reference (2) assumes a fully developed pipe flow and then applies an empirical correlation of experimental data for the Nusselt Number to determine mass flux as a function of heat flux. This technique is inaccurate when applied to biomedical measurements since the breathing process is highly transient in nature and it is doubtful if fully developed flow is ever developed in the breathing tube. Therefore, it is doubtful if the equations and procedure of Reference 2 could be used to accurately determine mass flow rates for biomedical purposes.

## TECHNOLOGY INCORPORATED PNEUNOTACHOMETER

The mass flowmeter of Reference 3 is based on the use a thermistor operates in the self-heating region. Thermistors are a class of semiconductors, having electrical properties between those of conductors and insulators. The resistance of thermistors varies rapidly with temperature which suggests an obvious use as a temperature measuring device.

The equation which approximates the resistance of a thermistor as a function of temperature is

$$R_T = R_\infty e^{B/T} \tag{1}$$

where

$R_T$ = Thermistor resistance at temperature T degrees.

$R_\infty$ = Thermistor resistance as temperature becomes infinite

$\beta$ = Work function

The work function is expressed as

$$\beta = E/K$$

where

E - Electron volt energy level

K - Boltzmann's constant $(8.625 \times 10^{-5}\ eV/°K)$

As voltage is applied to the thermistor heat is developed and according to Equation (1) the resistance decreases. If the thermistor is immersed in a tube and exposed to several different airflows, the variation of volts with current would vary so as to form a family of curves with airflow as a parameter. Thus, volts applied to the thermistor can be interpreted as a flowmeter, providing suitable electronics is used to interpret the voltage output. Reference 3 uses a function generator to shape the thermistor output.

The degree of success of using therm stors as flowmeters depends entirely on electronic shaping of the thermistor output. From the fluid dynamic standpoint, the thermistor bead, being immersed in the core of the pipe flow, will respond to the conditions of the flow. Since the bead is small, any boundary layer and hence thermal and velocity gradients measured in the core. Of course, the thermistor only detects flow conditions at the location of the thermistor. This fact allows the thermistor to be located at the "most probable" location for mean flow. If there is some question as to the location for mean flow, two or more thermistors could be used and their output integrated as the root-mean-square to determine average output.

In conclusion, the system designed by Technology Incorporated does not have the fluid mechanic problems of Reference 2 and by virture of the nature of thermistors appears to be much more flexible in operation and more compatible with measuring transient mass flows.