AD

HDL-TM-7132

ENGINEERING PERFORMANCE EVALUATION OF ARMY FLUIDIC VOLUME-CYCLED RESPIRATOR, MODEL 4

by

Leland R. Jones

December 1971

U.S. ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
WASHINGTON, D.C. 20438

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Harry Diamond Laboratories
Washington, D. C. 20438

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
Engineering Performance Evaluation of Army Fluidic Volume-Cycled Respirator, Model 4

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*
Leland R. Jones

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1971	36	4

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. DA-3A062110A816.10	HDL-TM-71-32
c. AMCMS Code: 5910.21.63359	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d. HDL Proj: 31033	

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Surgical Directorate U. S. Army Medical R&D Command

13. ABSTRACT

The overall performance of the previous Army volume-cycled respirator models was satisfactory; however, the flow consumption (61 ℓ/min) was determined to be undesirably high. The Model 4 volume-cycled respirator was designed to reduce the required amount of flow while retaining the functions (volume- and pressure-cycling capabilities, assist and control) of the previous models by using low-power flueric components and combining the patient and power circuits. The maximum flow consumption of a breadboard model of this respirator was 21 percent of that required by the previous models, and general performance of this respirator exceeds that of the previous models.

DD FORM 1 NOV 68 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

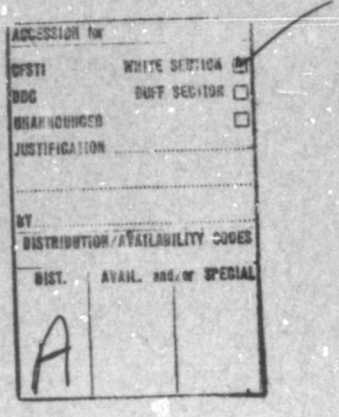
UNCLASSIFIED

Security Classification

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturers' or trade names does not constitute an official indorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.



AD

DA-3A062110A816.10
AMCMS Code: 5910.21.63359
HDL Proj: 31033

HDL-TM-7132

ENGINEERING PERFORMANCE EVALUATION OF ARMY FLUIDIC VOLUME-CYCLED RESPIRATOR, MODEL 4

by

Leland R. Jones

December 1971

U.S. ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
WASHINGTON, D.C. 20438

ABSTRACT

The overall performance of the previous Army volume-cycled respirator models was satisfactory; however, the flow consumption (61 ℓ/min) was determined to be undesirably high. The Model 4 volume-cycled respirator was designed to reduce the required amount of flow while retaining the functions (volume- and pressure-cycling capabilities, assist and control) of the previous models by using low-power flueric components and combining the patient and power circuits. The maximum flow consumption of a breadboard model of this respirator was 21 percent of that required by the previous models, and general performance of this respirator exceeds that of the previous models.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS–(continued)

1. INTRODUCTION

The fluidic volume-cycled respirator (figs. 1 and 2) is a joint effort of the Harry Diamond Laboratories and the Walter Reed Army Institute of Research. The breadboard of the Model 4 respirator is powered by the same gas that is supplied to the patient. The power supply and control system of this breadboard respirator were designed to operate with minimum power consumption. It is operated and controlled by two miniaturized bistable flueric amplifiers, a pneumatic timer, a trigger, and one interface valve. It has pressure-cycling as well as volume-cycling capabilities, and may assist or control the patient's breathing.

The power requirements of the earlier respirator models (1, 2, and 3) were determined to be too high. This problem was associated with the use of two large bistable flueric amplifiers that directly powered and controlled the respirator. The present breadboard of the Model 4 respirator employs miniature bistable flueric amplifiers as an indirect power source, and demonstrates reduced power requirements for this respirator. A complete engineering performance evaluation of this breadboard respirator has been conducted and is presented in this report.

2. DESIGN REQUIREMENTS

It is currently assumed that the respirator will be used primarily on adult Army patients. The requirements were accordingly defined by Joyce[1] as follows:

(1) The respirator should be able to assist or control the ventilation of a patient, and the change from one mode of operation to the other should take place automatically.

(2) In the assist mode of operation, the respirator should be able to sense an inspiratory effort by the patient of 1.0 cm (water) negative pressure. Sensitivity of the inspiration initiation trigger should, in addition, be variable at least to 4 cm (water) negative pressure.

(3) The respirator should have pressure-cycling capabilities. The switching pressures for the pressure-cycled mode of operation should be continuously variable between 10 and 60 cm (water).

(4) The respirator should have a continuously variable tidal volume capability from 300 to 2500 cc.

(5) The respirator should be able to deliver minute volumes from 5 to 20 ℓ/min.

(6) When operating in the control mode, the respirator should be able to cycle from 6 to 60 cpm.

(7) The inspiratory period of the respirator should be continuously variable from 0.4 to 2.0 sec.

(8) Expiratory periods achieved by the device should be compatible with the requirements for inspiratory times and cycling rates stated above.

(9) The respirator must be able to administer breathing gas of variable oxygen content.

---

[1] Joyce, J. W., "Revised Performance Evaluation of the Army Volume-Cycled Respirator, Model 2," HDL-TM-68-17, July 1968.

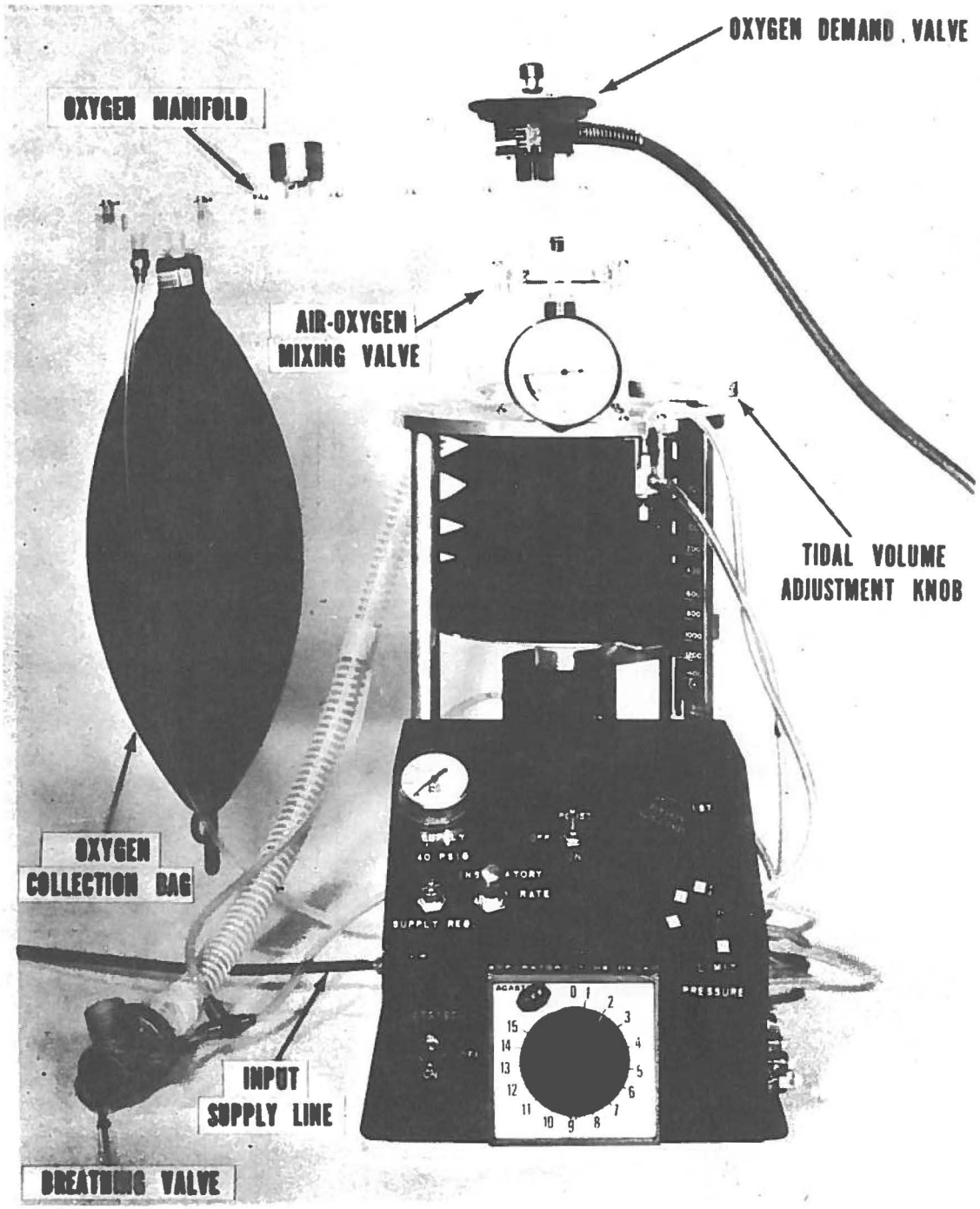


Figure 1. Breadboard of Model No. 4 respirator, front view.

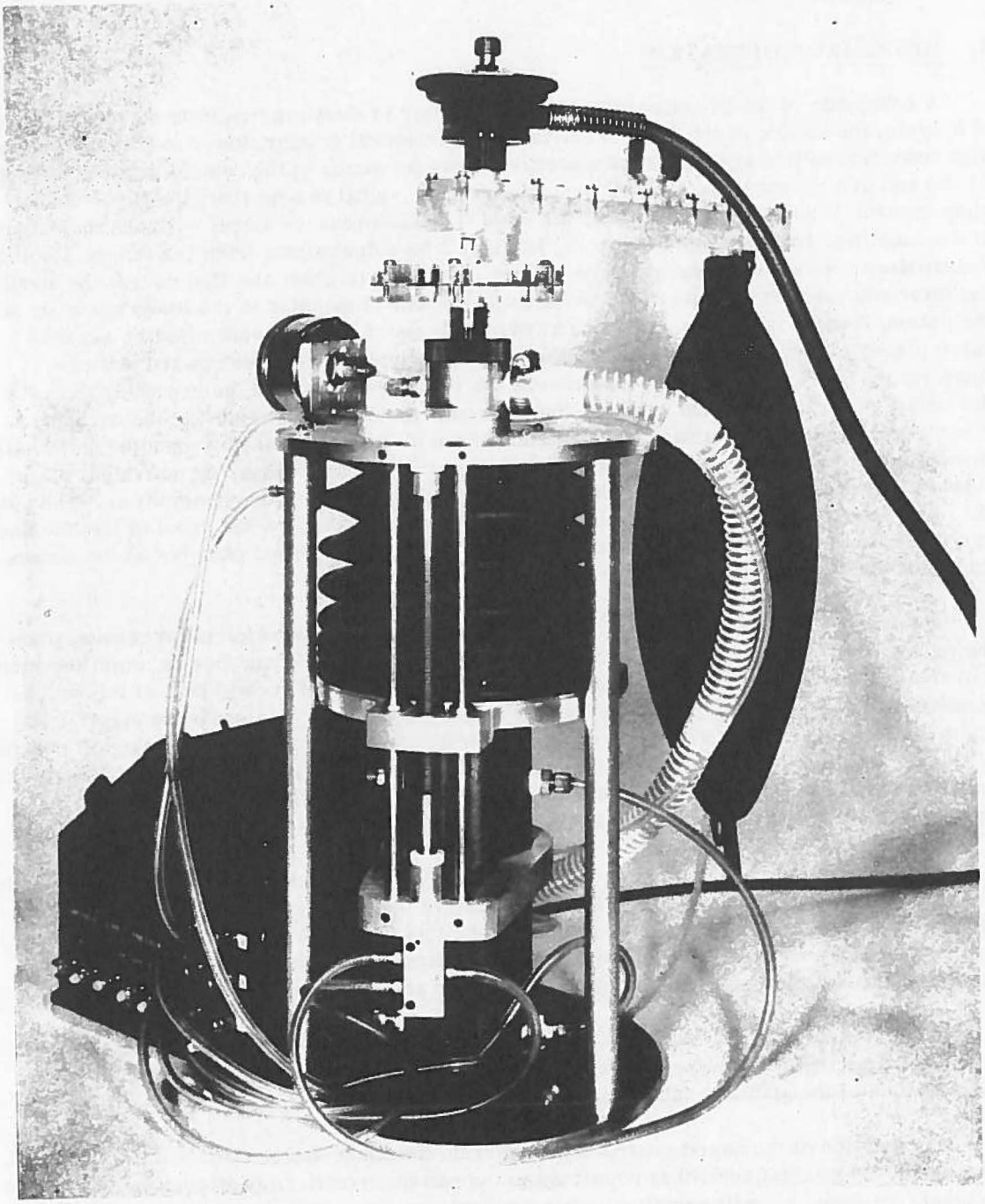


Figure 2. Breadboard of Model No. 4 respirator, rear view.

(10) The respirator should have a gas canister to filter contaminated incoming air when room air is used as the breathing gas.

(11) Provisions must be made to humidify the breathing gases being administered to the patient.

3. RESPIRATOR OPERATION

A schematic of the breadboard Model 4 respirator is shown in figure 3. At the beginning of a cycle, the bottom of the bellows activates a mechanical trigger (lower excursion trigger). The activation of this trigger sends a positive pressure signal to the control port of the timer. At the end of a preset time, a small positive pressure signal is sent from the timer to the right control of the first flueric amplifier (unit 1). This pressure signal switches the output of the amplifier from the right leg to the left leg. The output signal from the flueric amplifier pressurizes another mechanical trigger (upper excursion trigger) and also causes the spool of the interface valve to shift to a position such that power is supplied to the lower chamber of the piston, causing it to rise. The rate at which the piston rises is controlled by a needle valve placed in series with the input to the lower piston chamber. The upward motion (inspiratory phase) of the piston compresses the rubber bellows, and the breathing gas in the bellows is forced into the patient's lungs through the breathing valve. In the normal volume-cycle mode of operation, the upstroke of the piston is terminated when the bellows is completely compressed. When this occurs, the upper excursion trigger is activated. This activation sends a small pressure signal to the left control of the flueric amplifier. The output of this device is switched from the left leg to the right leg. Now the spool of the interface valve is shifted to a position such that power is supplied to the upper chamber of the piston, initiating the downstroke (expiratory phase) of the piston.

In the pressure-cycled mode of operation the upstroke of the piston is terminated when the pressure in the patient's circuit reaches a preset value. A second flueric amplifier (unit 2 of figure 3) is used as the pressure-cycling control. The right control port of this unit is connected to the patient circuit while the left control is biased with a pressure signal. The right output leg is open to atmosphere while the left output leg is connected to the left control of flueric amplifier, unit 1. When the pressure in the patient circuit exceeds the bias pressure, unit 2 is switched, and a positive pressure signal is supplied to the left control of unit 1, thereby terminating the upstroke as in the case when the bellows is fully compressed.

During the descent of the piston, the bellows is refilled with fresh breathing gas through a one-way valve in the gas intake located at the top of the respirator. The patient exhales to the surroundings through the breathing valve during this time. The exhaled gases cannot re-enter the bellows because of the design of the breathing valve. At the completion of the downstroke, the lower excursion trigger is activated and a new cycle is initiated.

In the control mode of operation, the onset of the inspiratory phase is controlled by the variable timer that is activated at the end of the downstroke. At the end of a preset time, the upstroke of the piston is initiated.

The function of the assist control is to override the timer and to initiate the upstroke of the piston. The assist control is connected to the patient circuit. Any attempt by the patient to inhale produces a small negative (below ambient) pressure signal which activates the assist control. The upstroke of the piston is then initiated before the delay time has elapsed.

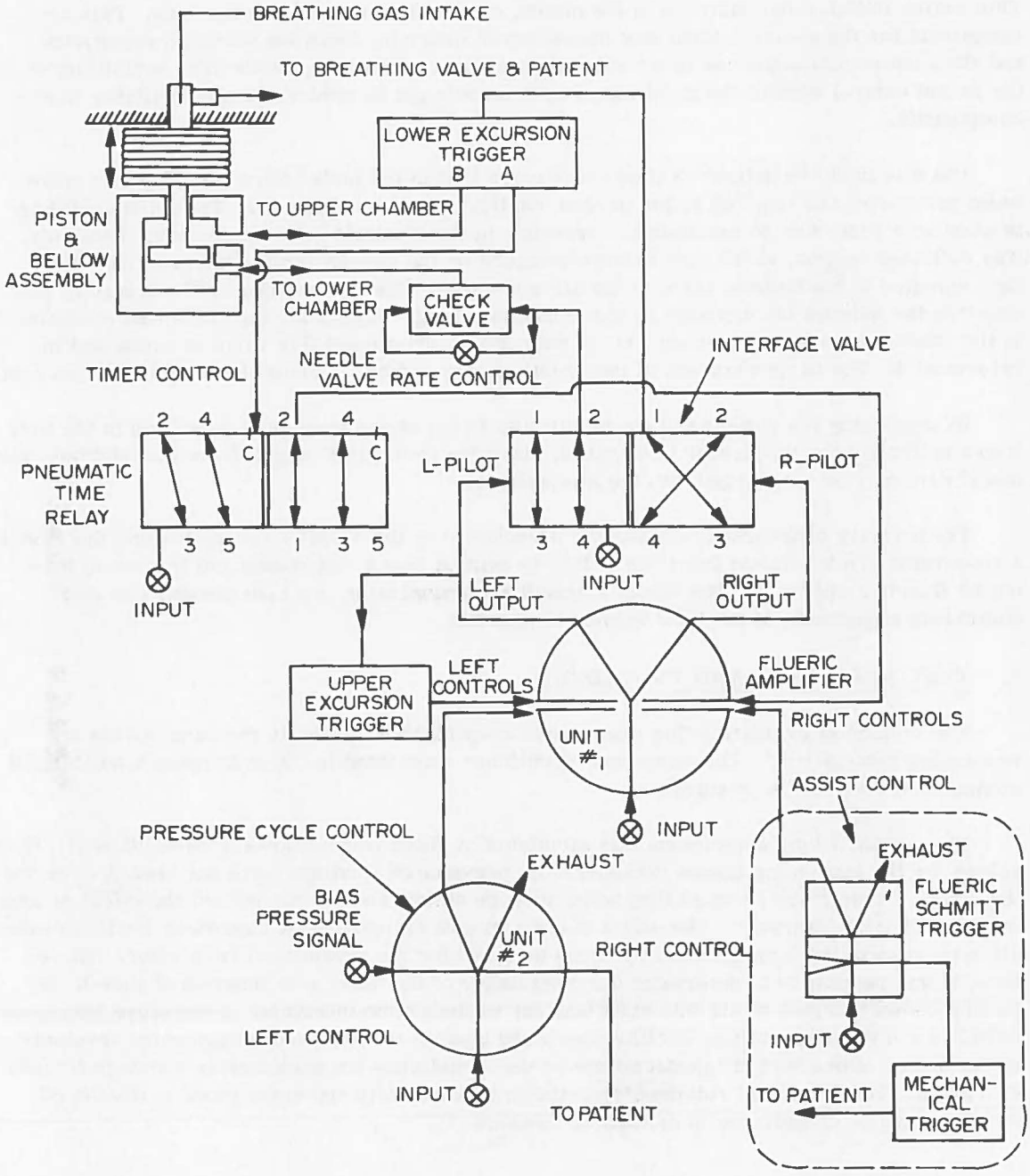


Figure 3. Schematic of breadboard respirator.

The assist control components include a Schmitt trigger and a spring-loaded diaphragm arrangement.[2] When the mechanical device is activated, the right control of the trigger is exposed to atmospheric pressure. The output of the trigger is then switched from the right leg to the left leg, which is connected to the right control of flueric amplifier, unit 1 (fig. 3). This action initiates the upstroke of the piston, overriding the preset delay time. This arrangement for the assist control was necessary in order to obtain the required sensitivity and does not preclude the use of a total flueric system. However, the desired sensitivity of the assist control without the mechanical device could not be achieved using available flueric components.

The circuit shown in figure 3 allows the oxygen that is exhausted from the interface valve to be recovered and supplied to the oxygen manifold as shown in figure 1. The collapsable bag is used as a reservoir to maintain the pressure in the manifold near atmospheric pressure. The collected oxygen, which may be supplemented by the oxygen demand valve as shown, is then supplied to the bellows through the air mix valve. The composition of the breathing gas entering the bellows is regulated by the setting of the air-oxygen mixing valve that is attached to the intake of the respirator (fig. 1). A detailed description of this valve is presented in reference 3. The oxygen content of the breathing gas can be regulated from 20 to 100 percent.

By combining the patient and power circuits in the above manner, a reduction in the flow consumption for the respirator is obtained, since the recovered oxygen from the interface valve would normally be discharged into the atmosphere.

The primary differences between the breadboard of the Model 4 respirator and the Model 3 respirator are the use of interface valves to control flow to the piston and the use of low-power flueric amplifiers. The Model 4 breadboard respirator was also designed so that continuous adjustment of the tidal volume is possible.

4. TEST APPARATUS AND PROCEDURE

The method of evaluating this breadboard respirator is basically the same as the for respirator models.[1,2,3] The same test conditions[4] were used in order to make a meaningful comparison between the respirators.

The patient's lung compliance was simulated by fixed volume tanks of three sizes.[2] Those values for the tank compliances obtained from previous evaluations were not used to evaluate the Model 4 respirator because they were average values and did not reflect the effect of long inspiratory time intervals. The effect of time on tank compliance is important for this evaluation because of the long inspiratory times obtained for the breadboard respirator. Therefore, it was necessary to determine the compliance of the tanks as a function of time by injecting known volumes of air into each tank for various time intervals. A pressure transducer (± 70.377 cm H_2O) and storage oscilloscope were used to record the peak pressure developed in the tanks. The effect of injection time on the compliance for each tank is shown in figures 4, 5 and 6. The functional relationship between tank capacity and compliance is developed in reference 2. Compliance is defined by equation (1),

---

[1] Joyce, J. W., "Revised Performance Evaluation of the Army Volume-Cycled Respirator, Model 2," HDL-TM-68-17, July 1968.

[2] Joyce, J. W., "The Development of a Volume-Cycled Respirator," HDL-TM-65-14, 24 March, 1965.

[3] Joyce, J. W., "An Air-Oxygen Mixing Valve for Volume-Cycled Respirators," HDL-TM-69-20, August 1969.

[4] Joyce, J. W., "Engineering Performance Evaluation of Army Volume-Cycled Respirator, Model 3," HDL-TM-69-34, October 1969.

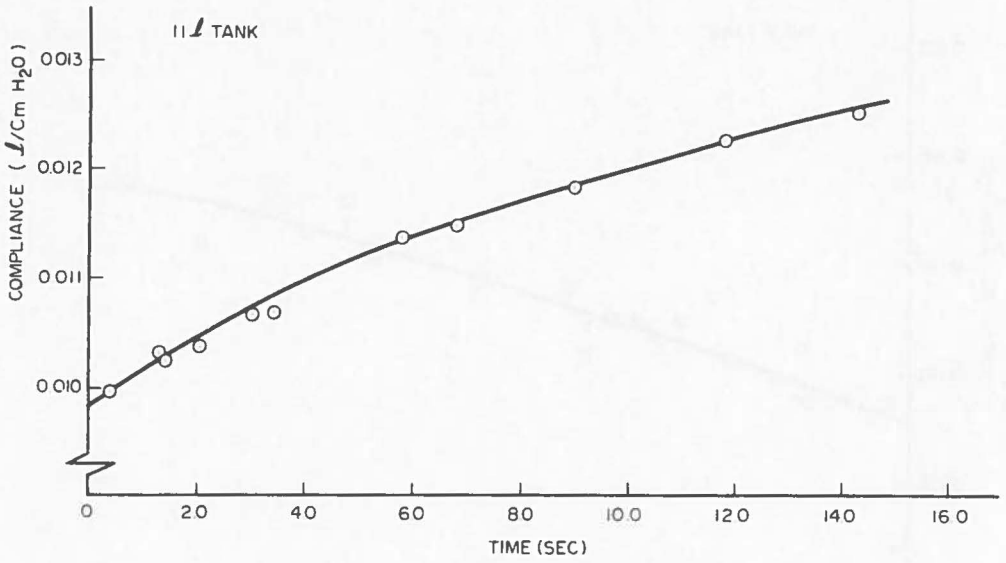


Figure 4. Effect of time on time compliance.

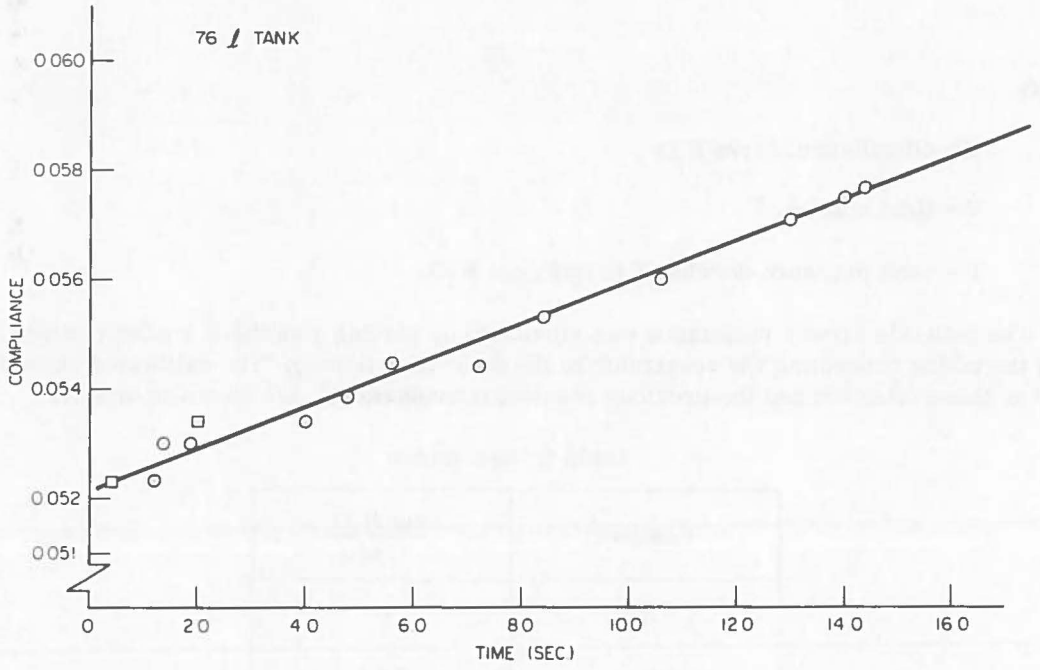


Figure 5. Effect of time on time compliance.

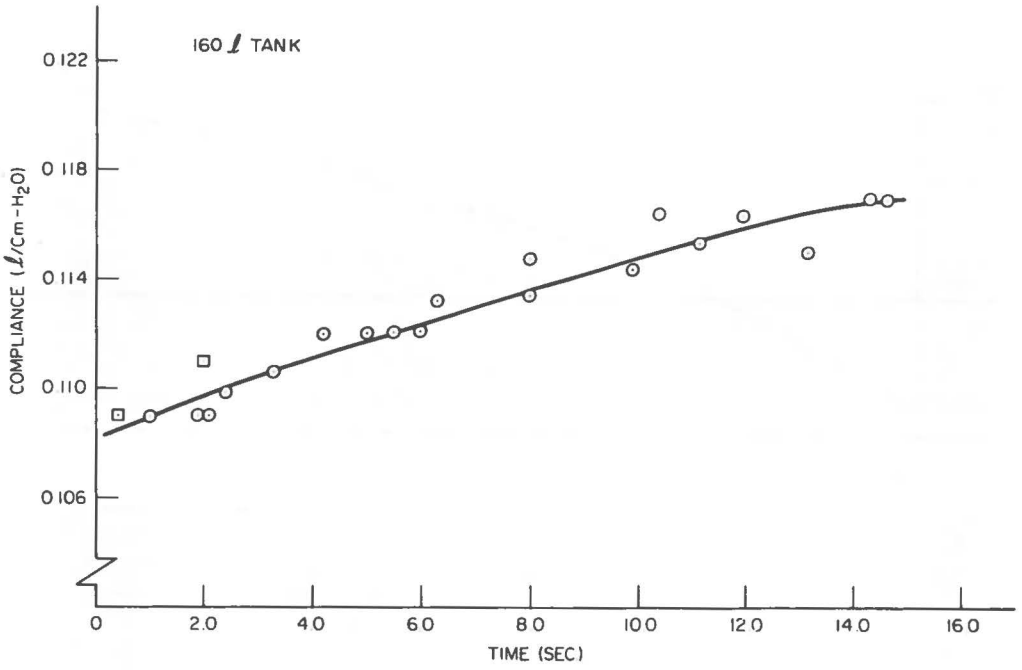


Figure 6. Effect of time on time compliance.

$$c = \frac{V}{P} \tag{1}$$

where

c = compliance, ℓ/cm H_2O

V = tidal volume, ℓ

P = peak pressure developed in tank, cm H_2O.

The patient's airway resistance was simulated by placing a variable resistor in series with the tubing connecting the respirator to the tank (compliance). The calibrated resistances used in this evaluation and the previous respirator evaluations[4] are shown in table I.

Table I. Resistance

Resistor	$\frac{\text{cm } H_2O}{\ell/\text{sec}}$
R_0	0
R_1	19.1
R_2	44.0

[4]Joyce, J. W., "Engineering Performance Evaluation of Army Volume-Cycled Respirator, Model 3," HDL-TM-69-34, October 1969.

For a given combination of compliance and resistance, the respirator was operated at various tidal volumes. For each tidal volume setting, the supply pressure to the interface valve was fixed at a constant value (275 kN/m^2 or 40 psig), and the piston was operated at its minimum and maximum upstroke times. The upstroke and downstroke times were measured by means of two microswitches and a battery. The microswitches were located so that the elapsed time for the upstroke and downstroke could be accurately determined with the use of an oscilloscope.

The tank pressures and pressures ahead of the airway resistances were measured by a pressure transducer (±70.377 cm H_2O). The transducer outputs were displayed on an oscilloscope.

5. PERFORMANCE RESULTS

5.1 Calibration of Tidal Volumes

As previously mentioned, this respirator was designed so that the tidal volume can be continuously adjusted by a knob (fig. 1). The calibration of tidal volumes was performed in the following manner: (1) the respirator was connected to a 76 liter tank with no airway resistance; (2) for various tidal volumes (200 - 1500 cc), the corresponding pressure in the tank was calculated using equation (1) with c = 0.053 ℓ/cm H_2O for a 2-sec upstroke time); (3) the bellows displacement was adjusted so that the peak pressure in the tank would correspond to the calculated value; (4) the stroke of the piston was then measured and from the tabulated values of stroke measurements, the tidal volume settings were engraved on a grid attached to the respirator.

Figure 7 shows the relationship for stroke length (cm) versus tidal volume.

5.2 Inspiratory Time

The inspiratory time (piston upstroke time) can be varied by adjusting the input pressure to the lower chamber of the piston. This may be accomplished by adjusting the needle valve shown in figure 1. Increasing (decreasing) the pressure at this point increases (decreases) the driving force of the piston and therefore decreases (increases) the inspiratory time. Increasing the tidal volume setting increases the inspiratory time since a longer stroke must be completed. This is illustrated in figures 8 and 9. These curves also indicate that inspiratory time increases as compliance decreases (fig. 8), and as airway resistance increases (fig. 9). Generally, the minimum inspiratory times for this respirator and the previous respirator are the same. However, the maximum inspiratory times for this respirator are about five times greater than those obtained for previous models.

The complete data for inspiratory times are given in appendix A, table A-1.

5.3 Expiratory Time

The expiratory time for this respirator is a function of the piston downstroke time and the delay time during which the bellows pauses at the end of the downstroke. The rate at which the piston descends is dependent upon the input pressure to the upper chamber of the piston and volume setting. Figure 10 illustrates the effect of volume setting on the downstroke time of the piston (where supply pressure is 275 kN/m^2 or 40 psig). By comparison, the downstroke times are smaller than the minimum and maximum upstroke times. For the assist mode of operation, it is desirable to have the downstroke times at a minimum, because a new cycle cannot be initiated until the downstroke is completed.

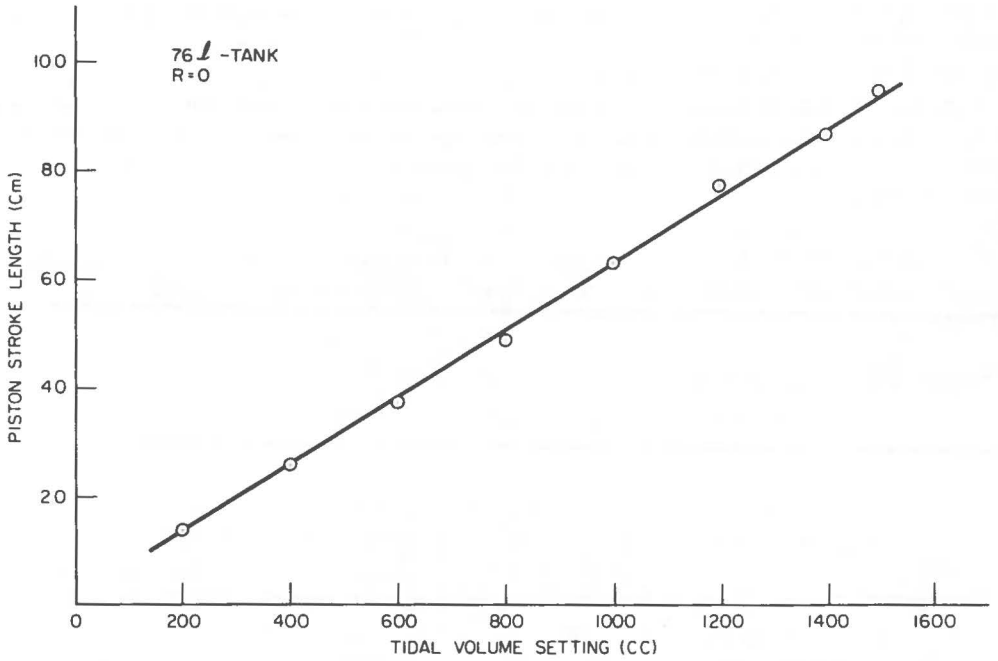


Figure 7. Tidal volume calibration.

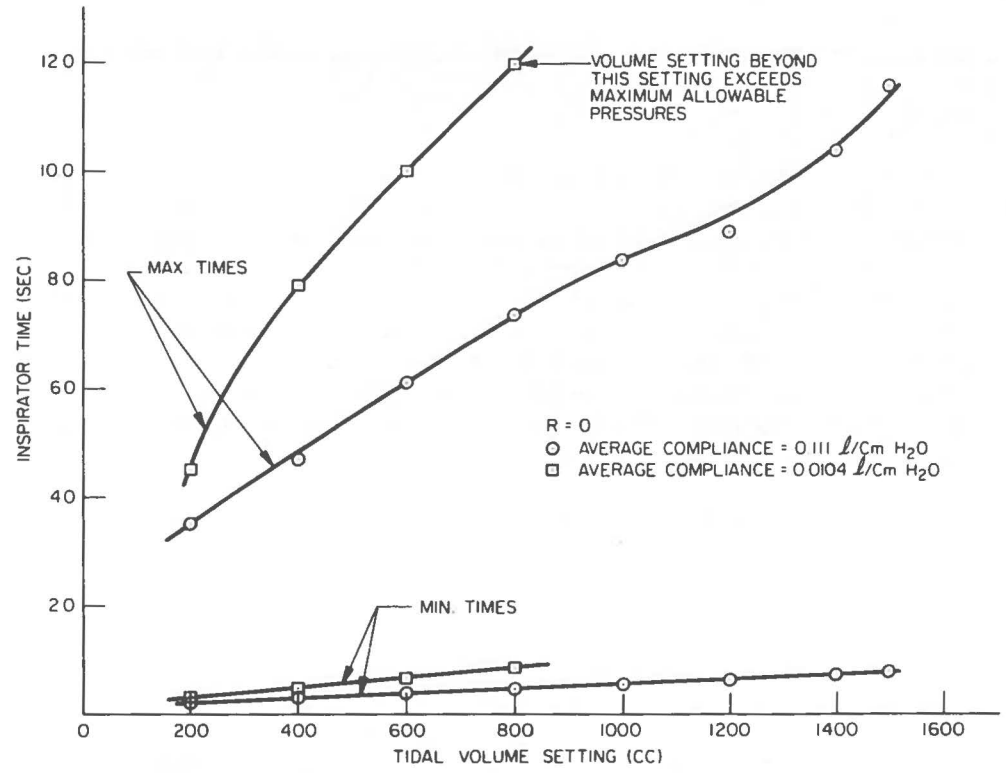


Figure 8. Effect of compliance on inspiratory time.

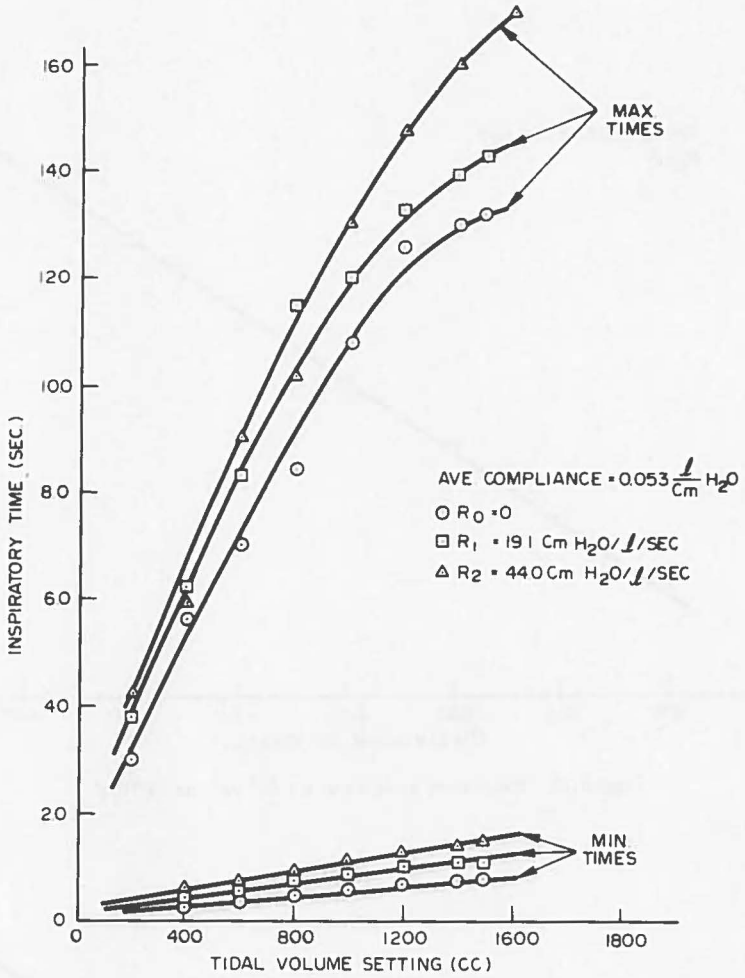


Figure 9. Effect of airway resistance on inspiratory time.

The delay time of the respirator is controlled by a commercial pneumatic timing relay. This timing relay combines a pneumatic timing mechanism with a floating spool valve assembly. The timing head recirculates air under controlled pressure through a variable orifice to provide linearly adjustable timing. The desired delay time is obtained by setting the time dial, which is calibrated in seconds (fig. 1); maximum delay time is about 16 sec. Figure 11 is the calibration of the timer used with this respirator.

5.4 Cycling Rates

The cycling rates of the respirator are a good indicator of the respirator's capabilities. The minimum and maximum cycling rates can be obtained from the inspiratory and expiratory data. The minimum cycling rate for all test conditions is less than 6 cycles per minutes because a 9-second delay time was used for each case. The cycling rates are a function of the loading conditions and the volume setting, since the inspiratory and expiratory times of the respirator are affected by these parameters. Figures 12 and 13 show that the maximum cycling rate decreases as compliance decreases, as airway resistance increases, and as the volume setting increases.

The complete set of data for maximum cycling rates is given in appendix A, table A-2.

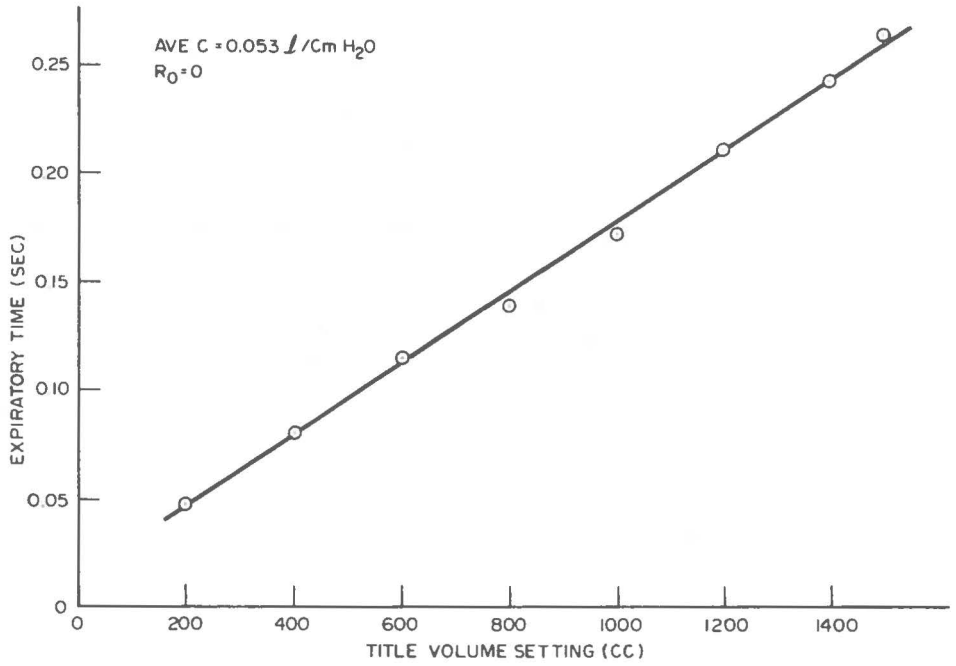


Figure 10. Expiratory time versus tidal volume setting.

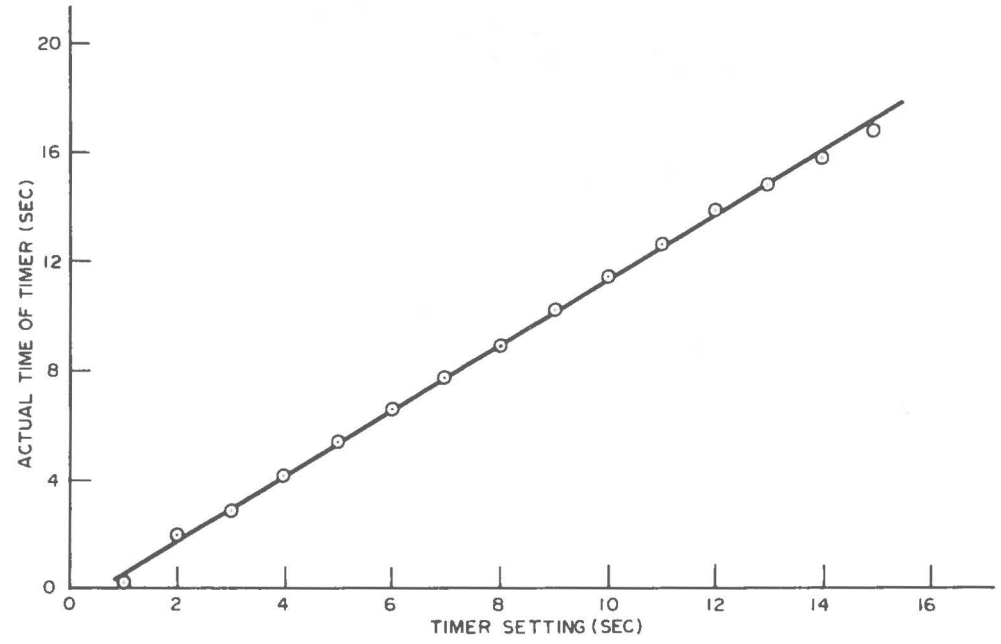


Figure 11. Calibration of respirator timer.

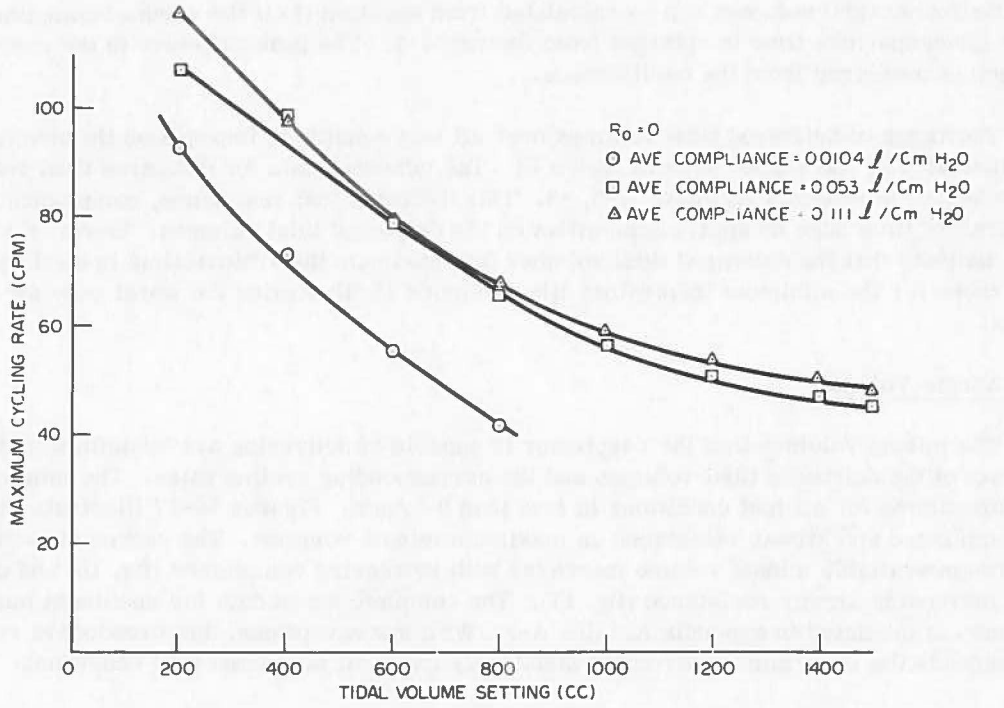


Figure 12. Effect of compliance on maximum cycling rate.

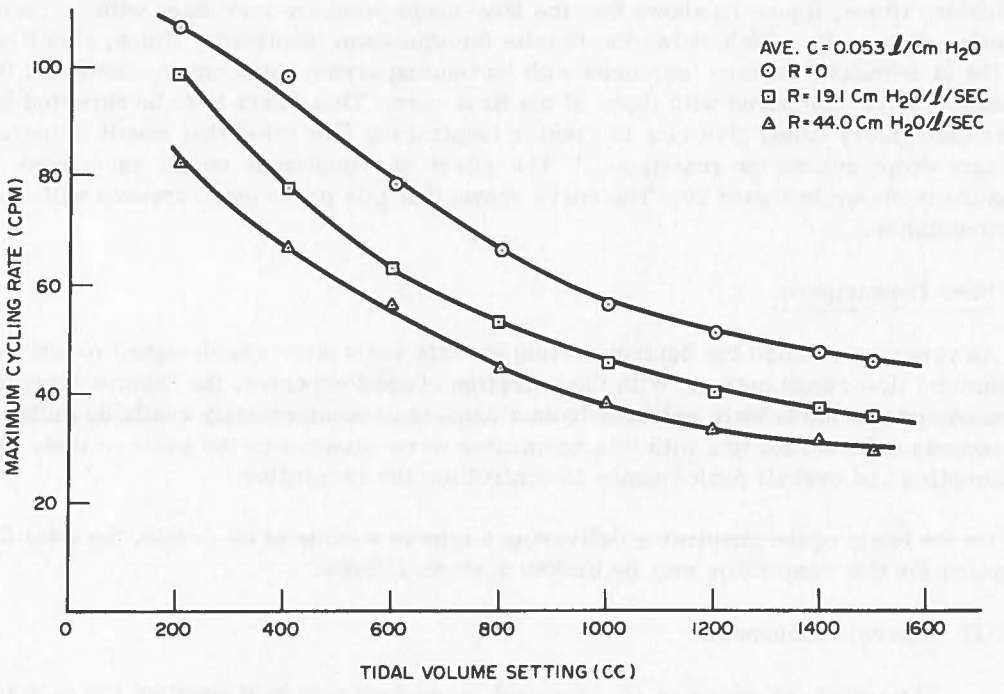


Figure 13. Effect of airway resistance on maximum cycling rate.

5.5 Delivered Tidal Volumes

Delivered tidal volumes can be calculated from equation (1) if the value of compliance for a given upstroke time is obtained from figures 4-6. The peak pressure in the compliance is measured from the oscilloscope.

The range of delivered tidal volumes over all test conditions imposed on the respirator is illustrated by the shaded area of figure 14. The tabulated data for delivered tidal volumes is presented in appendix A, tables A-3, -4. This indicates that resistance, compliance, and inspiratory time have no appreciable effect on the delivered tidal volumes. However, the data does indicate that the delivered tidal volumes for maximum inspiratory time is slightly less than those for the minimum inspiratory time. Figure 15 illustrates the worst case for this effect.

5.6 Minute Volumes

The minute volumes that the respirator is capable of delivering are by definition the product of the delivered tidal volumes and the corresponding cycling rates. The minimum minute volume for all test conditions is less than 9 ℓ/min. Figures 16-17 illustrate the effect of compliance and airway resistance on maximum minute volumes. The curves show that the maximum available minute volume increases with increasing compliance (fig. 16) and decreases with increasing airway resistance (fig. 17). The complete set of data for maximum minute volumes is tabulated in appendix A, table A-5. With few exceptions, this breadboard respirator exceeds the 20 ℓ/min requirement (section 2) under all simulated load conditions.

5.7 Pressures Ahead of Airway Resistances

The pressure ahead of the airway resistance is often called the face-mask pressure, and is a function of the airway resistance and the flow rate through the resistance. For maximum inspiratory times, figure 18 shows that the face-mask pressure increases with increasing resistance. Figure 19, which shows the results for minimum inspiratory times, also illustrates that the face-mask pressure increases with increasing airway resistance. However, the variations are small compared with those of the first case. This effect is to be expected because faster inspiratory times give rise to greater inspiratory flow rates that result in increased pressure drops across the resistance.[1] The effect of compliance on the face-mask pressure is shown in figure 20. The curve shows that this pressure decreases with increasing compliance.

5.8 Flow Consumption

As previously stated the control system for this respirator was designed to function with a minimum flow consumption. With the exception of one component, the Schmitt trigger, all of the component parts were selected from a number of commercially available units. The components selected for use with this respirator were selected on the basis of their low flow consumption and overall performance in controlling the respirator.

On the basis of the respirator delivering a minute volume of 20 ℓ/min, the total flow consumption for this respirator may be broken down as follows:

(1) Flueric Components

The power jet pressure (P_J) for each component was held constant for each test, and the flow rates (Q_N) were measured by means of a volo-flowmeter.

[1] Joyce, J. W., "Revised Performance Evaluation of the Army Volume-Cycled Respirator, Model 2," HDL-TM-68-17, July 1968.

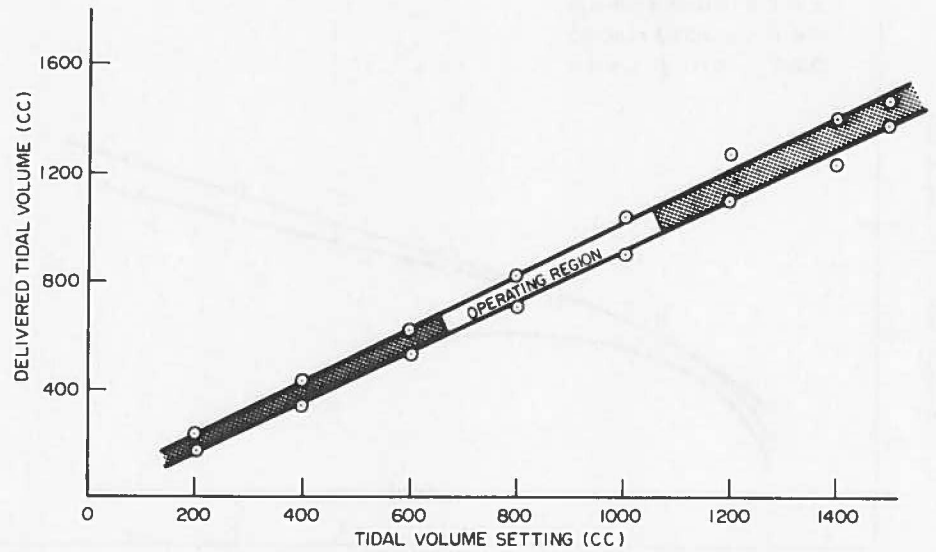


Figure 14. Range of delivered tidal volume.

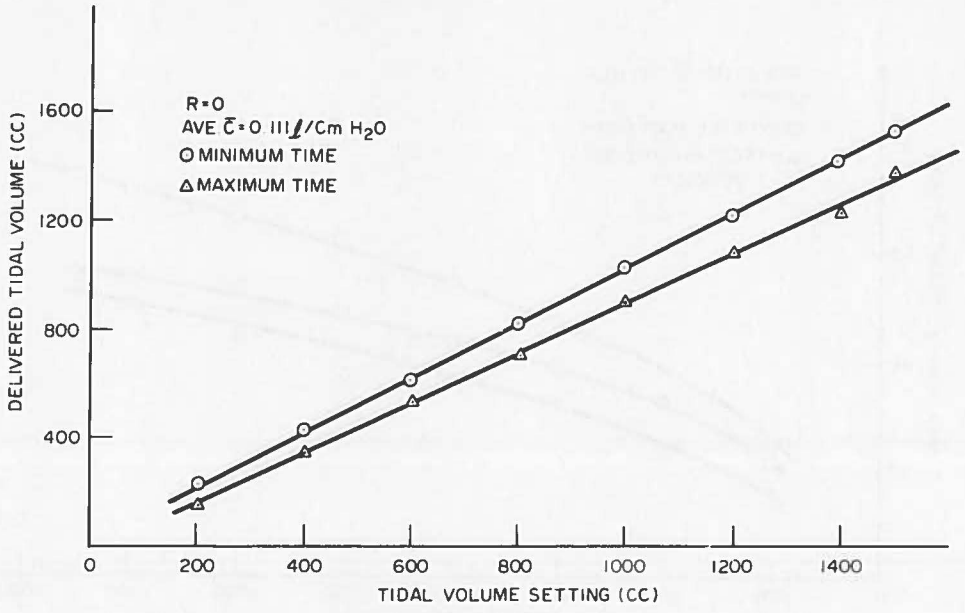


Figure 15. Effect of inspiratory time on delivered tidal volume.

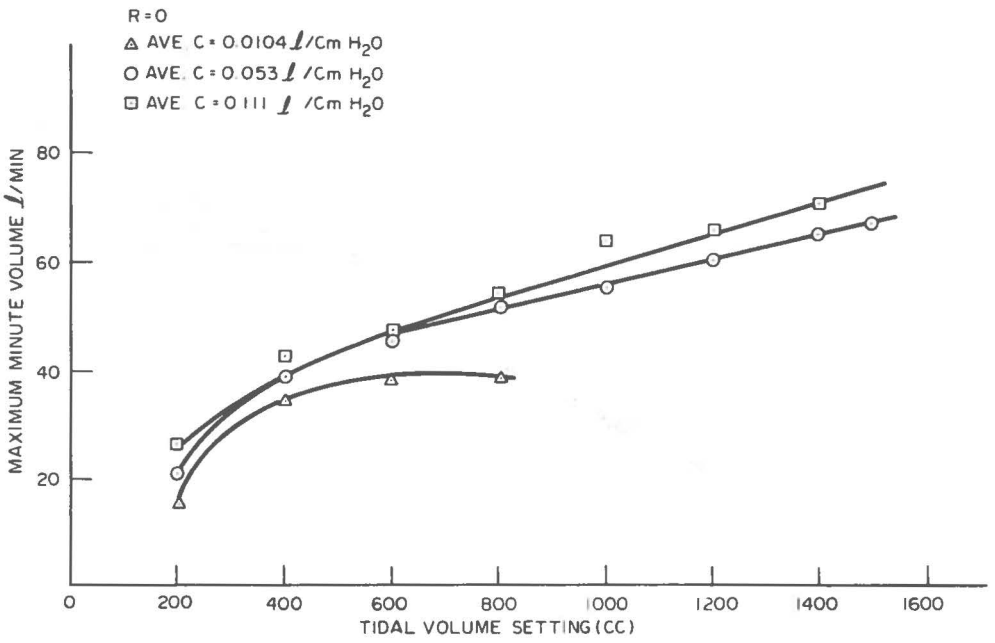


Figure 16. Effect of compliance on maximum minute volume.

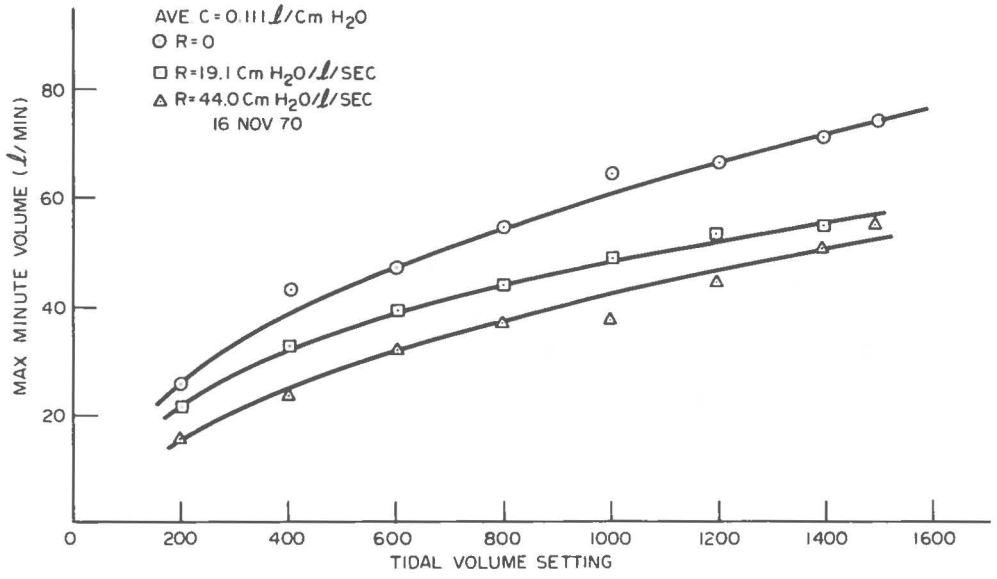


Figure 17. Effect of airway resistance on maximum minute volumes.

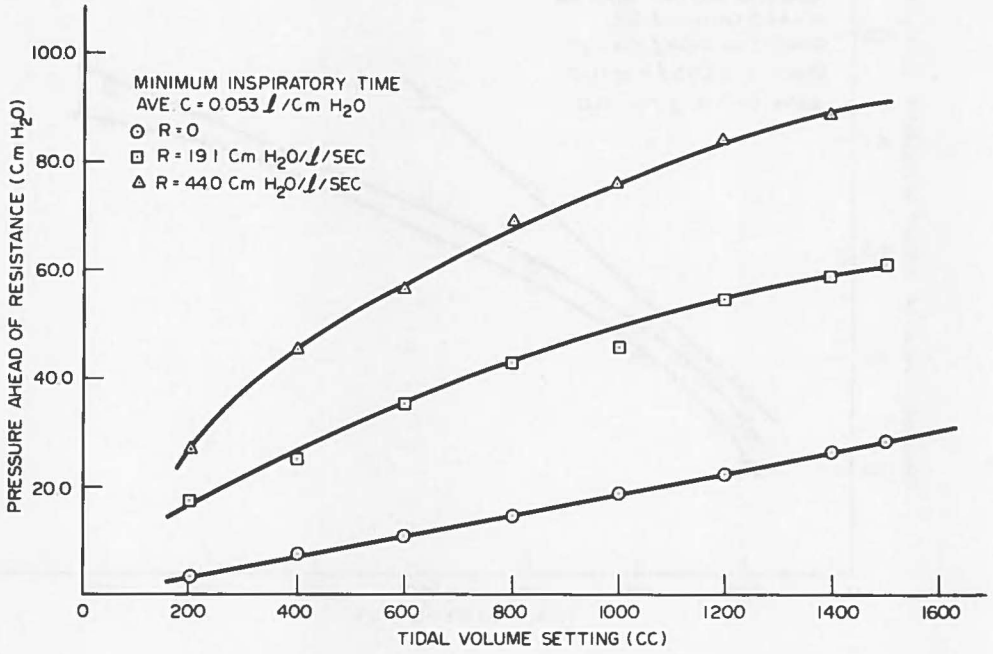


Figure 18. Effect of airway resistance on face-mask pressure (minimum inspiratory times).

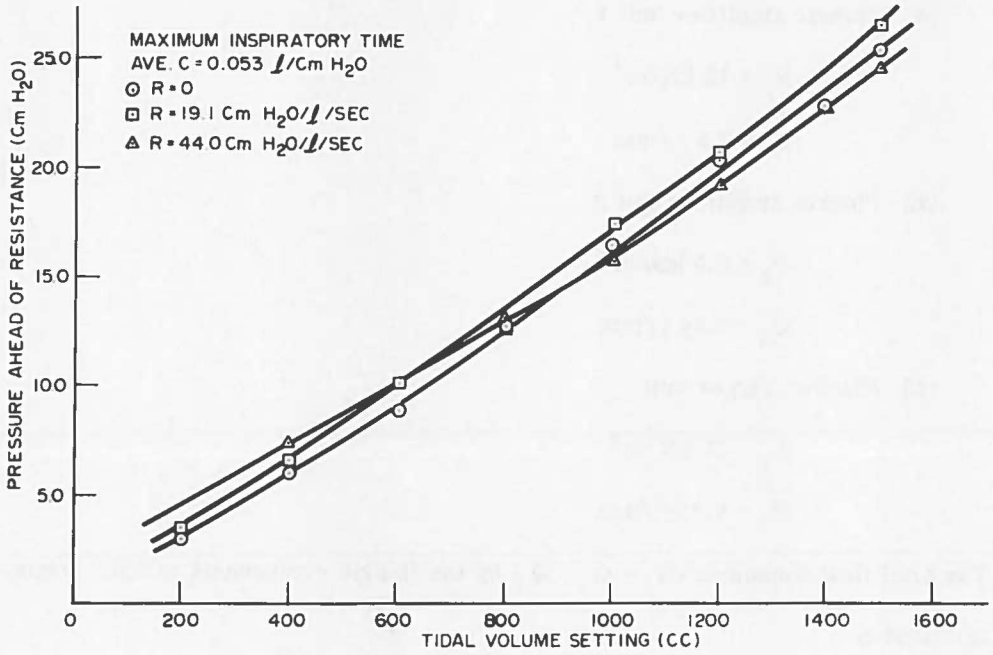


Figure 19. Effect of airway resistance on face-mask pressure (maximum inspiratory times).

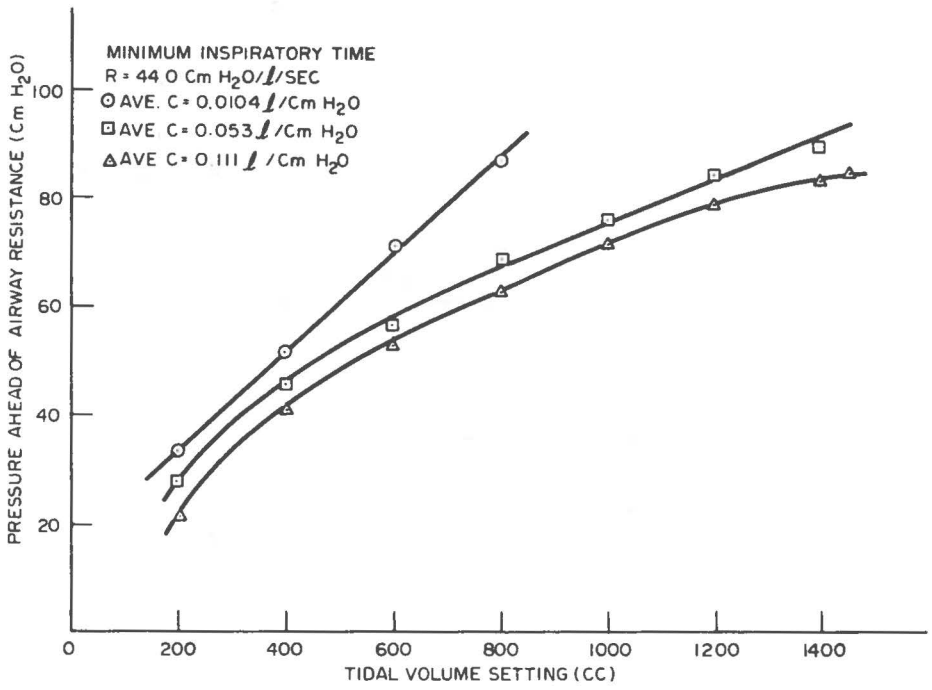


Figure 20. Effect of compliance on face-mask pressure.

(A) Flueric amplifier unit 1

$P_J = 12\ kN/m^2$

$Q_1 = 1.3\ \ell/min$

(B) Flueric amplifier unit 2

$P_J = 5.5\ kN/m^2$

$Q_2 = 0.94\ \ell/min$

(C) Flueric trigger unit

$P_J = 20\ kN/m^2$

$Q_3 = 0.73\ \ell/min$

The total flow consumed ($Q_1 + Q_2 + Q_3$) by the flueric components is 2.97 ℓ/min.

(2) Piston

Conventional flowmeters could not be used to measure the input air flowrate to the piston; however, because the flow consumption of the piston is a function of the piston's cycling rate and geometry, its flow consumption can be determined analytically. The cycling rate can

be determined from the relationship for minute volume (section 5.6). For a minute volume of 20 ℓ/min and a tidal volume of 1.5 ℓ(corresponding to a cycling rate of 13.3 cpm), we may proceed as follows to determine the flow consumption of the piston.

$$\text{Volume per cycle} = V = hA_1 + hA_2 = h(A_1 + A_2) \tag{2}$$

$$V_c = \frac{P_{max} V}{P} \tag{3}$$

$$Q_4 = V_c \,(\text{Rate})$$

where

V_c = corrected volume per cycle

P_{max} = maximum piston driving pressure

P = atmospheric pressure

h = piston stroke length

A_1 = effective piston area for upstroke

A_2 = effective piston area for downstroke

Q_4 = flow consumption for piston

For the given operating conditions and geometry, $Q_4 = 6.55$ ℓ/min.

(3) Leakages

The air consumption of the piston and pressure regulators due to leaks was experimentally determined to be about 2.5 and 1.06 ℓ/min, respectively, or a total of 3.56 ℓ/min.

The maximum flow consumption for the respirator can be obtained by adding the flow consumption for each component in addition to the losses due to the leakages. The maximum flow consumption is then 13.08 ℓ/min. For minute volumes less than 20 ℓ/min, the flow consumption would be reduced. The maximum flow consumption of the previous respirator models (1-3) was about 61 ℓ/min of free air at an input pressure of 30 psig. Therefore, this respirator consumes about 21% of that required by the previous models.

5.9 Assist Sensitivity

The sensitivity of the assist control is varied by turning the inspiratory sensitivity knob. The range of negative pressures required to provide a patient assist for the two extremes of the assist control was found to be 0.4 to 5.0 cm H_2O. These sensitivities are within the design requirement of the respirator.

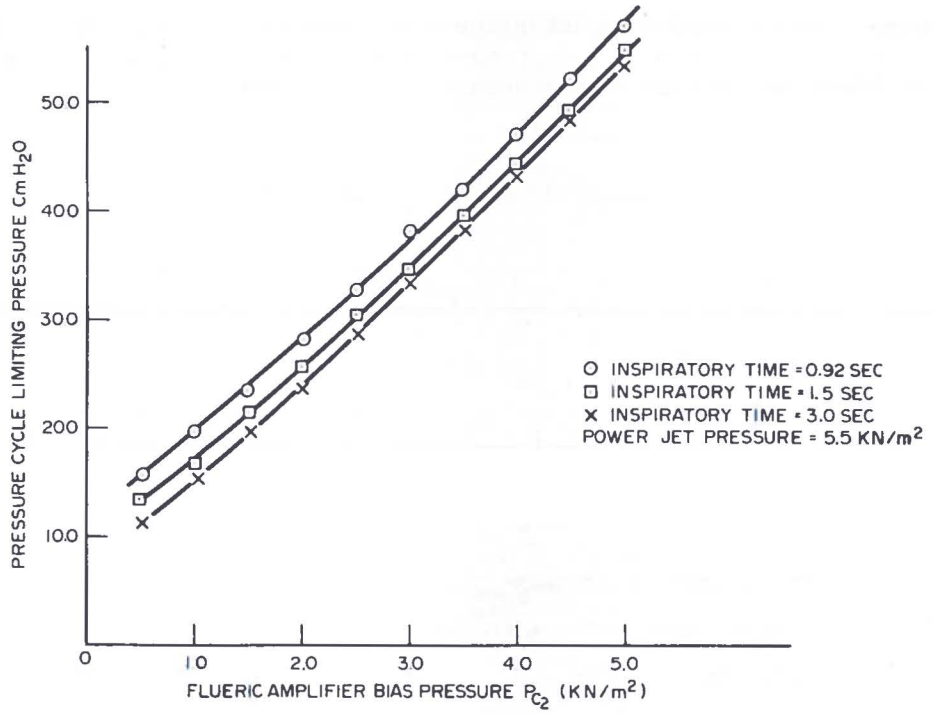


Figure 21. Flueric amplifier bias pressure versus pressure-cycle limiting pressure.

5.10 Pressure Cycle Sensitivity

The pressure cycle sensitivity is a function of the bias pressure supplied to one of the controls of fluid amplifier unit 2 as explained in section 3. Figure 21 illustrates this functional relationship, where the pressure-cycle limiting pressure increases as the bias pressure increases and decreases for increasing inspiratory times.

The pressure cycling capability for this breadboard respirator is variable between 10 and 60 cm H_2O as prescribed in the design requirements.

6. SUMMARY AND RECOMMENDATIONS

The engineering evaluation of the breadboard of the Model 4 respirator shows conclusively that the high flow consumption (61 ℓ/min) associated with the previous respirators has been greatly reduced (13 ℓ/min). These results also show that the general performance of the breadboard respirator exceeds that of the previous models.

Combining patient and respirator power circuits in the breadboard unit reduces the flow requirements so that it is practicable to operate from bottled breathing gas alone. Previous respirators required the use of breathing gas as well as a compressor to operate the respirator. Other design features include a continuously adjustable tidal volume selector, and a control system that is packaged separately from the piston-bellows assembly.

This breadboard Model 4 respirator will be made available for medical evaluation to determine its overall effectiveness. Should the results of this evaluation warrant further development, there are a number of design improvements that can be made including a leakproof piston to further reduce power consumption, a total flueric assist control with the desired sensitivity, and improved overall packaging.

LITERATURE CITED

1. Joyce, J. W., "Revised Performance Evaluation of the Army Volume-Cycled Respirator, Model 2," HDL-TM-68-17, July 1968.

2. Joyce, J. W., "The Development of a Volume-Cycled Respirator," HDL-TM-65-14, 24 March 1965.

3. Joyce, J. W., "Engineering Performance Evaluation of Army Volume-Cycled Respirator, Model 3," HDL-TM-69-34, October 1969.

4. Joyce, J. W., "An Air-Oxygen Mixing Valve for Volume-Cycled Respirators," HDL-TM-69-20, August 1969.

Appendix A. Performance Data

Table A-I. Inspiratory Times

C	V	$(t_0)_{max}$	$(t_0)_{min}$	$(t_1)_{max}$	$(t_1)_{min}$	$(t_2)_{max}$	$(t_2)_{min}$
0.010	200	4.5	0.32	4.2	0.36	4.0	0.44
	400	7.9	0.45	8.1	0.54	8.4	0.60
	600	10.0	0.66	10.8	0.74	10.4	0.88
	800	12.0	0.92	12.0	1.00	13.6	1.15
0.053	200	3.0	0.26	3.8	0.30	4.2	0.42
	400	5.6	0.28	6.2	0.44	5.9	0.55
	600	7.0	0.40	8.3	0.58	9.0	0.70
	800	8.4	0.51	11.5	0.74	10.2	0.95
	1000	10.8	0.64	12.0	0.88	13.0	1.10
	1200	12.6	0.70	13.3	1.04	14.8	1.30
	1400	13.0	0.77	14.0	1.10	16.0	1.40
	1500	13.2	0.80	14.3	1.12	17.0	1.50
0.111	200	3.5	0.20	3.4	0.30	4.5	0.35
	400	4.7	0.28	4.2	0.42	5.2	0.57
	600	6.1	0.40	5.5	0.56	6.0	0.73
	800	7.4	0.50	7.0	0.72	7.9	0.90
	1000	8.4	0.59	7.7	0.87	8.7	1.10
	1200	8.9	0.65	8.2	0.98	10.8	1.20
	1400	10.4	0.72	9.6	1.08	12.0	1.40
	1500	11.6	0.75	10.0	–	14.0	1.45

C = compliance, ℓ/cm H_2O (average value obtained for 2-sec injection time

V = volume setting, cc

t_0 = inspiratory times for $R_0 = 0$, sec

t_1 = inspiratory times for $R_1 = 19.1 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, sec

t_2 = inspiratory times for $R_2 = 44.0 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, sec

Table A-2. Maximum Cycling Rates

C	V	f_0	f_1	f_2
0.010	200	92.2	90.3	79.5
	400	73	67.8	61.2
	600	55.6	52.2	44.9
	800	42	40.8	35.7
0.053	200	107.5	99.2	82.4
	400	98.4	77.9	67.1
	600	78.4	63.2	56.1
	800	66.7	53.3	44.6
	1000	56.4	46	38.7
	1200	51.7	40.1	33.5
	1400	47.8	37.7	31.0
	1500	45.6	36.3	29.3
0.111	200	117.7	98.4	92.3
	400	97.6	80.0	71.0
	600	78.4	64.5	55.1
	800	67.4	54.1	46.5
	1000	59.7	46.5	39.6
	1200	54.3	41.8	36.4
	1400	50.4	38.5	31.8
	1500	48.0	–	30.5

C = compliance, ℓ/cm H_2O (average value obtained for 2-sec injection time)

V = volume setting, cc

f_0 = cycling rates for $R_0 = 0$, cpm

f_1 = cycling rates for $R_1 = 19.1 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, cpm

f_2 = cycling rates for $R_2 = 44.0 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, cpm

Table A-3. Delivered Tidal Volumes for Maximum Inspiratory Times

C	V	V_0	V_1	V_2
0.010	200	156	167	168
	400	328	329	301
	600	505	526	494
	800	691	722	703
0.053	200	163	192	164
	400	332	361	361
	600	492	565	556
	800	706	721	743
	1000	936	1001	903
	1200	1163	1185	1121
	1400	1312	1321	1337
	1500	1460	1470	1453
0.111	200	170	180	171
	400	340	399	314
	600	516	569	543
	800	693	749	752
	1000	907	984	990
	1200	1108	1161	1211
	1400	1233	1404	1319
	1500	1393	–	1406

C = Compliance, ℓ/cm H_2O (average value obtained for 2-sec injection time)

V = volume setting, cc

V_0 = delivered volume for $R_0 = 0$, cc

V_1 = delivered volume for $R_1 = 19.1 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, cc

V_2 = delivered volume for $R_2 = 44.1 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, cc

Table A-4. Delivered Tidal Volumes for Minimum Inspiratory Times

C	V	V_0	V_1	V_2
0.010	200	164	179	153
	400	337	357	332
	600	512	539	516
	800	686	616	674
0.053	200	197	240	197
	400	394	427	396
	600	591	631	592
	800	790	819	792
	1000	989	1033	992
	1200	1186	1275	1191
	1400	1384	1410	1392
	1500	1483	1599	1491
0.111	200	219	221	194
	400	440	416	332
	600	609	609	583
	800	809	821	806
	1000	1030	1055	946
	1200	1221	1279	1225
	1400	1421	1424	1282
	1500	1555	–	1483

C = compliance, ℓ/cm H_2O (average value obtained for 2-sec injection time

V = volume setting, cc

V_0 = delivered volume for $R_0 = 0$, cc

V_1 = delivered volume for $R_1 = 19.1 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, cc

V_2 = delivered volume for $R_2 = 44.0 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, cc

Table A-5. Maximum Minute Volumes

C	V	Q_0	Q_1	Q_2
0.010	200	15.2	16.1	12.2
	400	24.6	24.2	20.3
	600	28.5	28.1	23.2
	800	29.2	25.2	24.1
0.053	200	21.2	23.8	16.3
	400	38.8	33.3	26.5
	600	46.4	39.8	33.2
	800	52.7	43.7	35.4
	1000	55.8	47.5	38.4
	1200	61.4	51.2	39.9
	1400	66.2	53.2	43.2
	1500	67.7	58.0	43.7
0.111	200	25.7	21.8	18.0
	400	42.9	33.3	23.6
	600	47.7	39.3	32.1
	800	54.6	44.4	37.5
	1000	64.5	49.1	37.5
	1200	66.3	53.5	44.6
	1400	71.7	54.8	40.8
	1500	74.4	–	45.3

C = compliance, ℓ/cm H_2O (average value obtained for 2-sec injection time)

V = volume setting, cc

Q_0 = minute volume for $R_0 = 0$, ℓ/min

Q_1 = minute volume for $R_1 = 19.1 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, ℓ/min

Q_2 = minute volume for $R_2 = 44.0 \frac{\text{cm } H_2O}{\ell/\text{sec}}$, ℓ/min