HDL-TM-69-20

AN AIR-OXYGEN MIXING VALVE FOR VOLUME-CYCLED RESPIRATORS

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U.S. ARMY MATERIEL COMMAND
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ABSTRACT

A valve that can deliver breathing gas of variable air-oxygen makeup to respirators has been designed, fabricated, and tested. Test results show that gas mixtures containing 20 to 100 percent oxygen can be obtained with good reliability. The maximum change in the makeup of gas leaving the valve caused by varying test conditions was about 5 percent oxygen.

The valve was designed to be used with a volume-cycled respirator being developed for the Army by the Harry Diamond Laboratories, but it could be used equally well with other respirators of the same general type.

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1. INTRODUCTION

Since 1962, the Harry Diamond Laboratories (HDL) in cooperation with the Walter Reed Army Institute of Research (WRAIR) have been developing several respirators for use by the Army. One such respirator is a volume-cycled type that uses a rubber bellows to deliver breathing gases to the patient.[1] As the design of this respirator progressed, the requirements for it were altered to broaden its capabilities. One of the added requirements was that the respirator be able to deliver breathing gases of variable oxygen concentration, and that the air used in the breathing gas must come from the ambient surroundings; i.e., only the oxygen can be supplied under pressure.

This report describes the air-oxygen mixing valve that has been designed, fabricated, and tested to satisfy these requirements. The equations governing the performance of the valve are presented along with experimental data to support them. Although the valve described herein was specifically designed for use with the volume-cycled respirator developed at HDL, it could easily be adapted for use with any similar type respirator.

2. OPERATIONAL DESCRIPTION

A brief discussion of the functioning of the HDL volume-cycled respirator will provide the basis for understanding the operation of the air-oxygen mixing valve. As shown in figure 1, the respirator consists primarily of a piston connected to a rubber bellows. As the piston is powered upward, the rubber bellows is compressed, and the gases contained in it are forced into the patient (inspiratory phase of the breathing cycle). When the inspiratory phase has been completed, the piston is powered downward, forcing the bellows to expand (in the axial direction), thereby creating negative (below ambient) pressure inside the bellows. This negative pressure draws in breathing gases supplied at ambient pressure through a one-way valve in the respirator intake manifold.

2.1 Description of Valve

The air-oxygen mixing valve designed for this respirator is shown schematically in figure 2. It consists of an air intake port, an oxygen intake port, a mixing chamber, and a single output port. Orifices are located in each intake port. Oxygen from a pressurized source is supplied to the unit from a demand-type regulating valve at a pressure slightly below atmospheric to prevent wasteful leakage of oxygen during those portions of the breathing cycle when the bellows is not refilling. Air is supplied from the ambient surroundings. The mixture leaving the unit will depend on the areas of the orifices, and the total flow leaving the valve will equal the flow into the respirator.

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

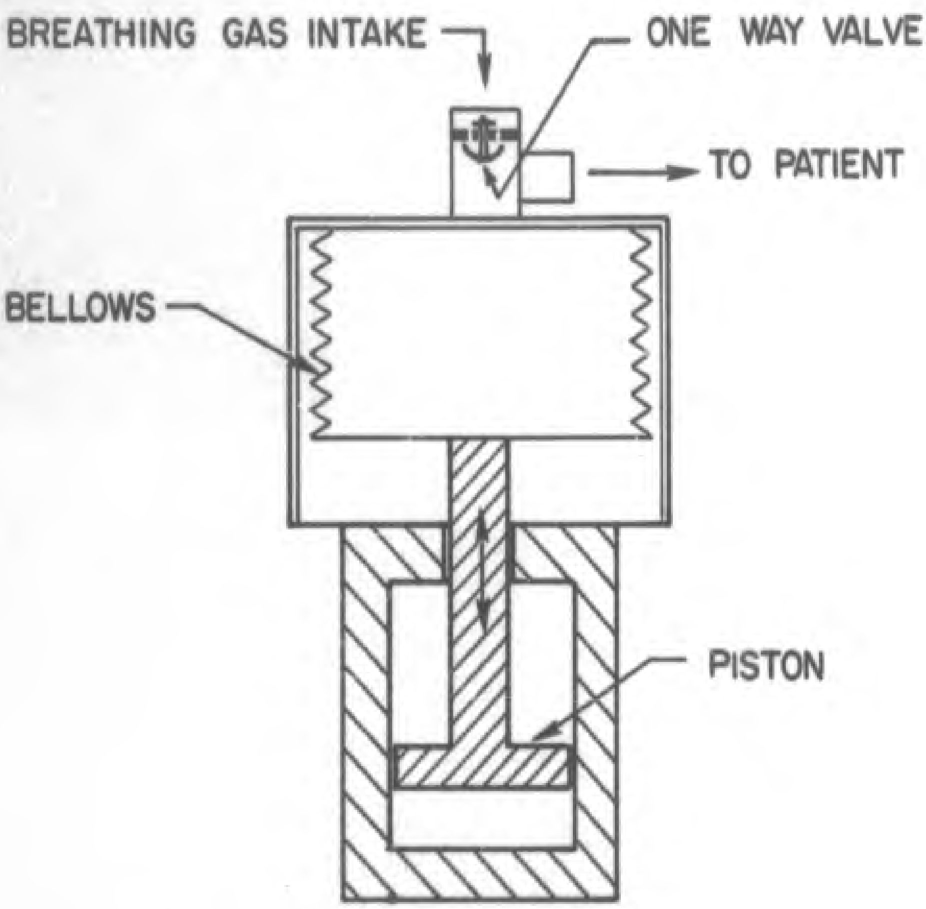

Figure 1. Simplified schematic diagram of volume-cycled respirator.

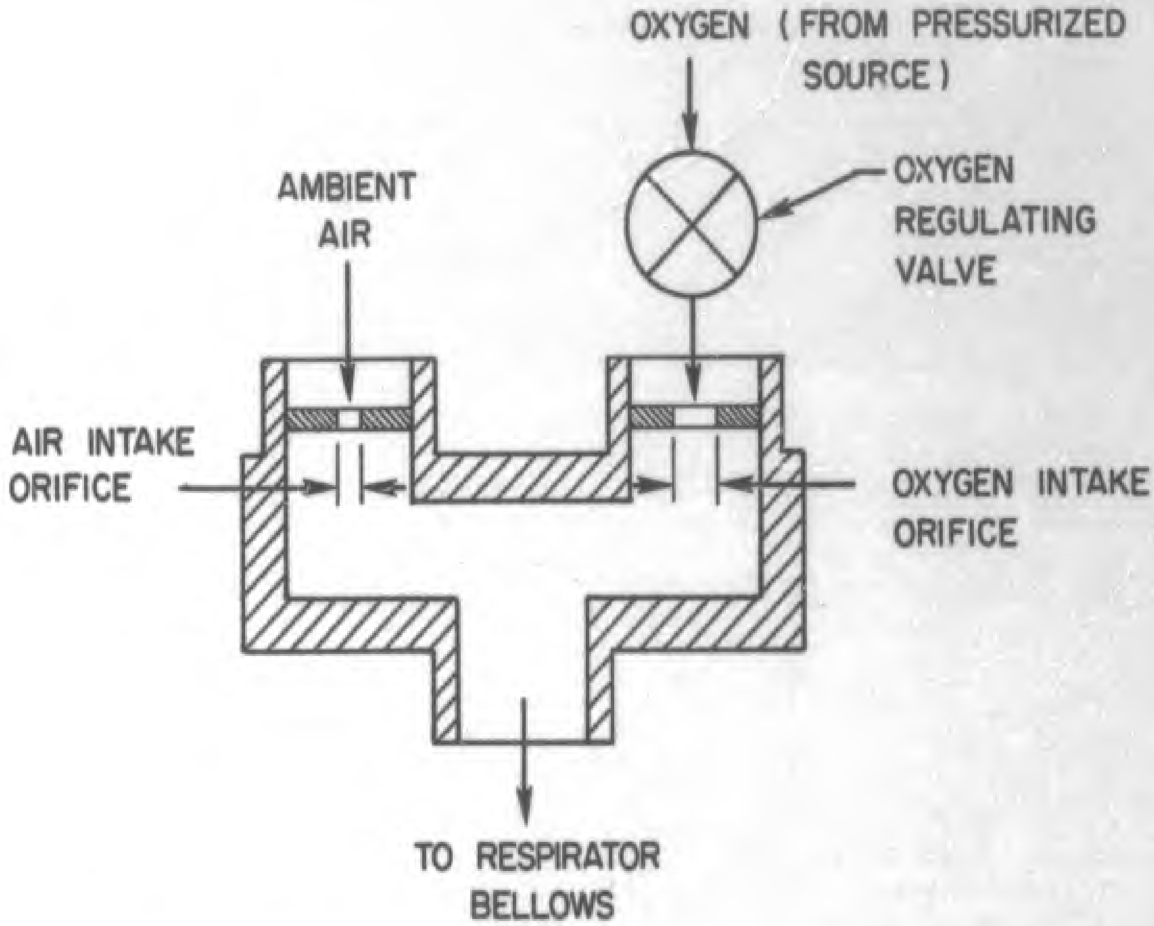

Figure 2. Schematic diagram of air-oxygen mixing valve.

2.2 Principles of Operation

For steady, incompressible flow, the two gas flows are described by equation (1).

$$Q = kD^2 \sqrt{\frac{\Delta P}{\rho}} \qquad (1)$$

The oxygen content in the gas mixture leaving the valve is shown in equation (2).

$$\%O_2 = \left[\frac{Q_o + 0.21\ Q_a}{Q_o + Q_a}\right] \times 100 \qquad (2)$$

Substituting equation (1) into equation (2) and simplifying yields equation (3).

$$\%O_2 = \left[\frac{\left(\frac{D_o}{D_a}\right)^2 \sqrt{\frac{\Delta P_o}{\Delta P_a}\left(\frac{\rho_a}{\rho_o}\right)} + 0.21}{\left(\frac{D_o}{D_a}\right)^2 \sqrt{\frac{\Delta P_o}{\Delta_a}\left(\frac{\rho_a}{\rho_o}\right)} + 1}\right] \times 100 \qquad (3)$$

Since the ratio of gas densities is known, equation (3) can be simplified to

$$\%O_2 = \left[\frac{0.95\left(\frac{D_o}{D_a}\right)^2 \sqrt{\frac{\Delta P_o}{\Delta P_a}} + 0.21}{0.95\left(\frac{D_o}{D_a}\right)^2 \sqrt{\frac{\Delta P_o}{\Delta P_a}} + 1}\right] \times 100 \qquad (3a)$$

If the pressure drops across the two orifices were equal, their ratio would become unity, and equation (3a) would reduce to equation (4).

$$\%O_2 = \left[\frac{0.95\left(\frac{D_o}{D_a}\right)^2 + 0.21}{0.95\left(\frac{D_o}{D_a}\right)^2 + 1}\right] \times 100 \qquad (4)$$

However, these pressure drops are not equal. Oxygen is supplied to the unit at pressures about 0.2 kN/m^2 below the ambient pressure at which air is supplied. Suction pressures in the bellows are limited to about 2 kN/m^2 (since greater suction pressures may cause the bellows to collapse or seriously retard the downward motion of the piston, fig. 1). Therefore, the differences between ΔP_o and ΔP_a are significant, and their ratio cannot be accurately approximated as being equal to unity.

3. DESIGN AND TESTING

3.1 Test Fixture

Based on the concept shown in figure 2, a test fixture consisting of a manifold and a series of interchangeable orifices was designed and fabricated. The purpose of the test fixture was to provide data for the final design of the air-oxygen mixing valve. To minimize the number of orifices needed in the final design, the test fixture data were specifically aimed at determining three pairs of orifices (each pair to be used twice by reversing the air and oxygen orifices) that could produce oxygen concentrations closely approximating 30, 40, 50, 60, 70, and 85 percent.

The test fixture was attached to the HDL respirator and tested with various combinations of orifices. The oxygen regulating valve (a commercially available unit) was attached to the mixing valve and connected to a pressurized oxygen source. For each set of orifices, the respirator was run, and samples of the gas in the bellows were subsequently fed into an instrument (an oximeter using a modified Clark-type electrode) that measured the partial pressure of oxygen in the mixture. From the measured partial pressures, oxygen concentrations could be calculated from equation (5)

$$\%O_2' = \left(\frac{P_{O_2}}{P_\infty - P_v}\right) \times 100 \qquad (5)$$

Pressure drops across the orifices were also measured using an appropriate transducer and an oscilloscope.

The results of these tests are summarized in table I. For each set of orifices, the respirator tests were conducted at two filling rates.

Using the data from table I, the theoretical and experimental oxygen concentrations were calculated from equations (3a) and (5). These results are presented in table II. The error given in table II is defined in equation (6)

$$\text{Error} = \frac{|\%O_2 - \%O_2'|}{\%O_2} \times 100 \qquad (6)$$

Table I. Prototype Test Results

Q_T (ℓ/sec)	D_o (mm)	D_a (mm)	P_{O_2} (mm Hg)	ΔP_o (cm H_2O)	ΔP_a (cm H_2O)
1.0	7.77	2.95	615	3.7	5.2
1.4	7.77	2.95	630	8.3	10.2
1.0	2.95	7.77	207	3.4	4.8
1.4	2.95	7.77	215	7.9	9.1
1.0	6.58	4.16	523	4.2	5.7
1.4	6.58	4.16	520	9.1	11.1
1.0	4.16	6.58	292	4.1	5.6
1.4	4.16	6.58	290	8.7	10.2
1.0	6.18	5.36	438	3.6	5.1
1.4	6.18	5.36	443	7.8	9.7
1.0	5.36	6.18	355	3.6	5.1
1.4	5.36	6.18	360	7.6	9.1

P_v = 47 mm Hg
P_∞ = 765 mm Hg
P_i = 210 kN/m^2 (30 psig)

Table II. Comparison of Theoretical and Experimental Results

D_o (mm)	D_a (mm)	$\%O_2$ (Theory) (%)	$\%O_2'$ (Experiment) (%)	Error (%)
7.77	2.95	88.0	85.7	2.6
7.77	2.95	88.7	87.8	1.0
2.95	7.77	29.2	28.8	1.4
2.95	7.77	29.9	30.0	0.3
6.58	4.16	74.0	72.8	1.6
6.58	4.16	74.8	72.5	3.1
4.16	6.58	40.4	40.7	0.7
4.16	6.58	41.5	40.4	2.7
6.18	5.36	61.6	61.0	1.0
6.18	5.36	62.8	61.7	1.8
5.36	6.18	50.7	49.5	2.4
5.36	6.18	52.3	50.2	4.0

and indicates that the experimental and theoretical values are in good agreement. The maximum error is 4 percent, and in all but two cases the error is less than 3 percent.

The results also show that three pairs of orifices are able to produce oxygen concentrations of approximately 30, 40, 50, 60, 70, and 85 percent. This performance was the basis for the final design of the air-oxygen mixing valve.

3.2 Final Design

The final design of the air-oxygen mixing valve is shown in figures 3 and 4. It consists of a plastic housing and a metal disk into which the three pairs of orifices from table II have been cut. All orifices are located on a common center line diameter, and the orifices in each pair are diametrically opposite each other. The mixture leaving the valve is determined by which pair of orifices lines up with the two intake ports. A fourth "pair" has a through hole at one end, but no hole at the other, so that either room air or pure oxygen is obtained from this pair of settings. The valve is calibrated in values rounded to the nearest 5 percent oxygen (fig. 3). The valve assembly is shown mounted on the HDL volume-cycled respirator in figure 5.

Three units of the type shown in figure 3 have been fabricated, and each was tested to check its calibration. The test procedure was the same as described earlier, with the respirator operating at the slower filling rate (1.0 ℓ/sec). The results shown in table III indicate that all measured values are within 3 percent oxygen of the calibration values. The variation in data from one unit to another is small.

Table III. Calibration Data for Final Design Units

Setting ($\%O_2$)	Actual $\%O_2$ Unit 1	Unit 2	Unit 3
100	99.3	97.6	98.2
85	85.6	84.0	85.3
70	72.0	70.7	73.0
60	60.2	59.5	60.2
50	49.0	49.0	50.4
40	40.3	39.5	40.6
30	28.3	29.1	29.0
20	21.3	21.0	21.3

$P_1 = 210$ kN/m² (30 psig)

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Figure 3. Air-oxygen mixing valve.

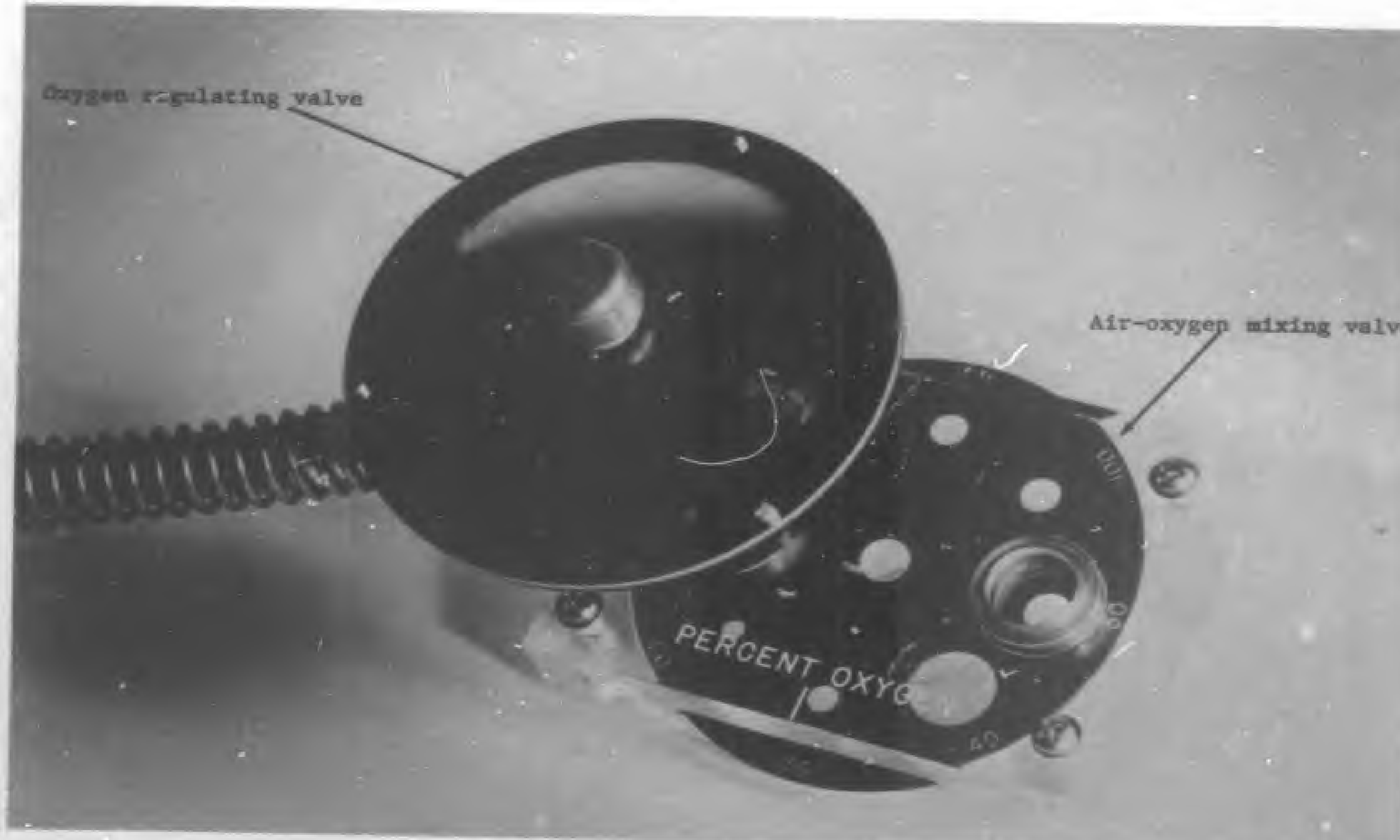

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Figure 4. Air-oxygen mixing valve assembly.

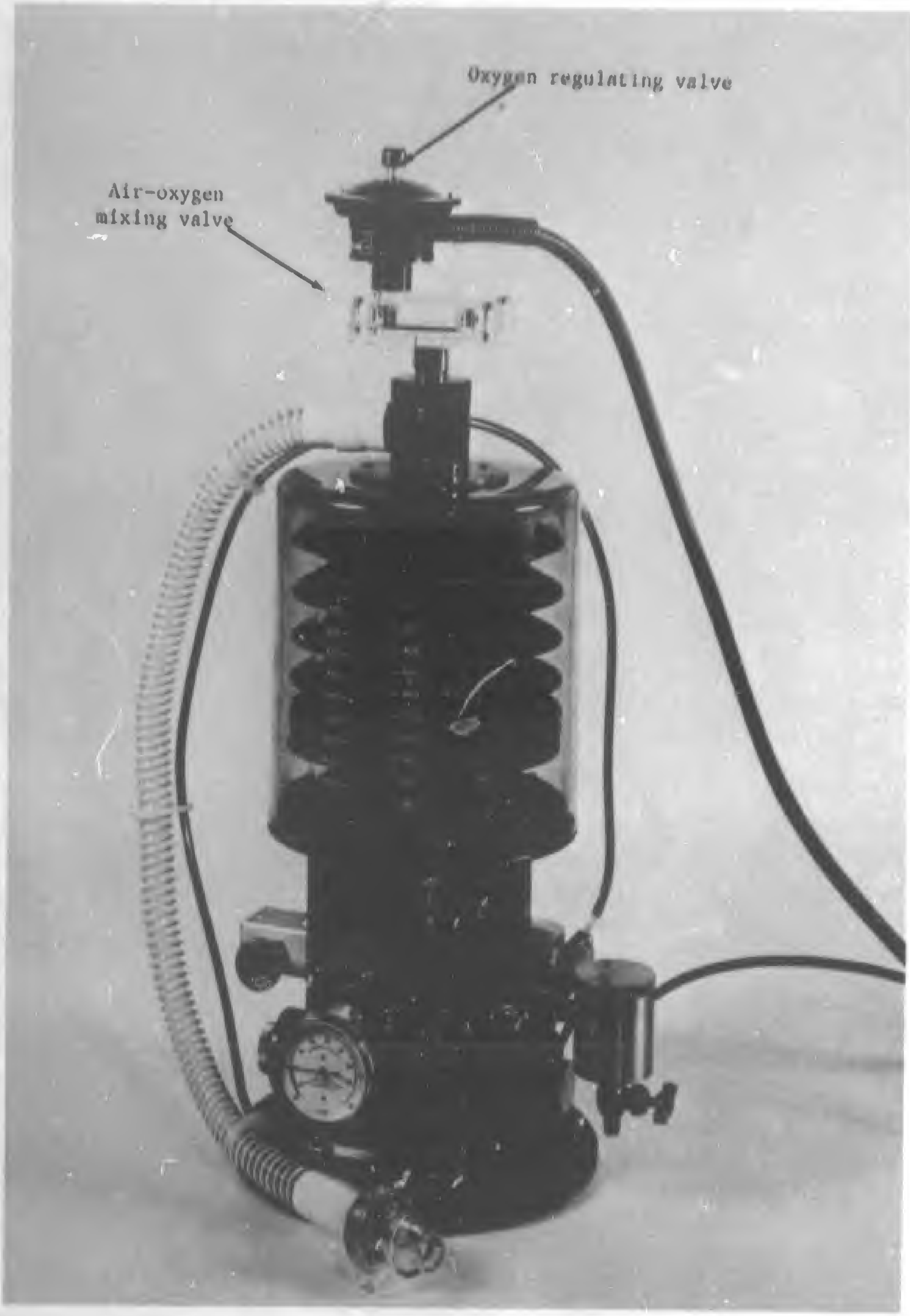

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Figure 5. Volume-cycled respirator with air-oxygen mixing valve assembly.

A more thorough performance evaluation of the air-oxygen mixing valve was made using unit 3 (table III). In this test, the respirator was operated to produce filling flow rates of 1.0 and 2.5 ℓ/sec, which represent the maximum range of conditions that would be encountered in actual use. Additionally, the input pressure to the oxygen regulator was varied from 70 to 350 kN/m² (10-50 psig). The upper limit of 350 kN/m² (50 psig) was selected because it is the value at which wall oxygen is supplied in many hospitals. Data were recorded as before, and oxygen concentrations were determined. The results of these tests are shown in table IV.

Table IV. Air-Oxygen Mixing Valve Performance

Setting ($\% O_2$)	Q_T (ℓ/sec)	Actual $\% O_2$, P_i (kN/m²): 70 (10 psig)	140 (20 psig)	210 (30 psig)	280 (40 psig)	350 (50 psig)
100	1.0	95.2	98.6	98.2	98.0	95.8
85		86.1	84.7	85.3	85.4	82.7
70		73.3	73.0	73.0	73.0	71.4
60		61.1	60.4	60.2	59.7	58.3
50	1.0	51.2	50.7	50.4	49.0	48.9
40		40.0	40.0	40.6	39.7	38.3
30		29.2	29.2	29.0	28.5	28.2
20		20.8	20.8	20.8	20.8	20.8
100	2.5	89.6	95.2	97.6	99.3	98.6
85		77.1	87.5	86.4	86.1	86.8
70		70.1	75.3	73.6	74.0	74.0
60		62.5	62.8	62.8	62.2	61.8
50	2.5	52.8	52.5	52.5	52.2	52.2
40		41.3	41.3	40.6	40.6	41.4
30		29.6	29.4	29.2	29.2	29.2
20		20.8	20.8	20.8	20.8	20.8

Table IV shows that the performance of the mixing valve was only slightly affected by varying the input pressure to the oxygen regulator, allowing only a small decrease in the percent oxygen out of the valve as regulator input pressure increased over the range tested. The one exception was that for the high flow rate; oxygen concentrations were well below the calibration settings of 100 and 85 percent when the input pressure to the oxygen regulator was 70 kN/m² (10 psig). Consequently, input pressures should be maintained between 140 and 350 kN/m² (20-50 psig) when using this type oxygen regulator with the mixing valve.

The effect of respirator filling flow rate on oxygen concentration was more noticeable, with the higher flows resulting in somewhat higher concentration values. The combined effects of oxygen regulator input pressure and respirator filling flow rate (excluding the data for 70 kN/m^2 regulator input pressure) are illustrated in figure 6 and indicate that the total variation in performance is relatively small over the range of test conditions used. In all case, the difference between the maximum and minimum values is less than 5 percent oxygen. Such accuracy is quite acceptable for this application.[2]

4. SUMMARY

An air-oxygen mixing valve designed for use with the HDL volume-cycled respirator has been fabricated and tested. The test data show that the valve can deliver preset air-oxygen mixtures to the respirator with good accuracy over a wide range of oxygen regulator input pressures and respirator filling rates. If percent oxygen being administered to the patient can be selected and reliably maintained within 5 percent oxygen, a device of this type will very probably be acceptable to medical personnel concerned with its use. The unit described in this report can easily satisfy these requirements.

The general applicability of this valve is not confined to the HDL respirator alone. It can be used with any respirator that has a bellows, bag or piston that alternately forces out and draws in the breathing gas during each cycle. For respirators that have a fixed filling flow rate, the orifices for the mixing valve could be selected for a more accurate calibration of oxygen concentration than on the valve described herein. The simplicity of design and operation, the easy adaptability to different makes of respirators, and the efficient use of oxygen should make this valve a useful piece of respiratory equipment.

5. ACKNOWLEDGEMENT

The author wishes to express his appreciation to Lyndon S. Cox for his efforts in helping to conceive and design the air-oxygen mixing valve described in this report.

[2]Personal communication with medical team at WRAIR.

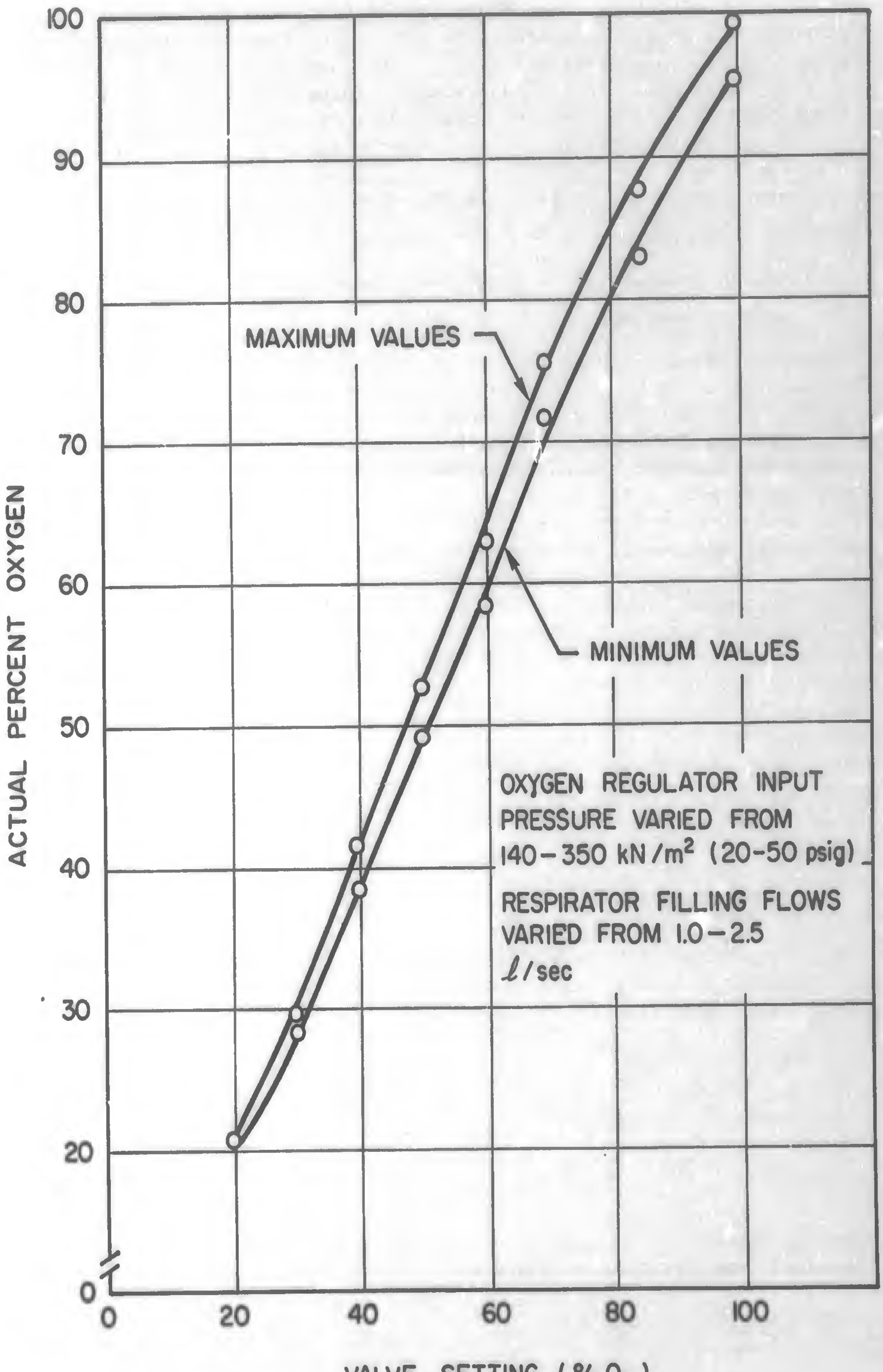

Figure 6. Air-oxygen mixing valve performance.

NOMENCLATURE

D = orifice diameter

k = constant

ΔP = pressure drop across orifice

P_i = input pressure to oxygen regulator

P_{O_2} = partial pressure of oxygen in breathing gas (from respirator)

P_v = vapor pressure of water at 37°C (temperature of the gas analyzer)

P_∞ = ambient pressure

ρ = density

Q = volume flow rate

Q_T = filling flow rate for respirator = flow rate out of air-oxygen mixing valve

$\% O_2$ = theoretical percent oxygen in gas mixture

$\% O_2'$ = experimental percent oxygen in gas mixture

Subscript o = oxygen

Subscript a = air

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Mixing valve	8	3				
Respirators	8	3				