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TR-1249

DESIGN REQUIREMENTS AND PROPOSAL FOR ARMY RESPIRATORS

Henrik H. Straub

22 June 1964

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22 June 1964

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CONTENTS

ABSTRACT

Civilian and military respirators must, for the most part, be functionally similar. However, the environments in which military respirators must operate, impose additional and more severe requirements on their mechanical design. The functional design requirements for military-type respirators are discussed in this report. Two fluid amplifier circuits, one for a pressure-cycled and the second for a volume-cycled respirator, are described and discussed. The results of the initial in vitro tests on the first prototypes suggest that they can satisfy the predicated design requirements.

1. INTRODUCTION

Existing automatic ventilators are designed to facilitate breathing in individuals during periods of inadequate respiration. Reference 1 presents a survey of the principal characteristics of the automatic respirators that are currently in use and the physiological parameters governing their design. Because of their size, weight, mechanical complexity, and fragility, the use of existing respirators for emergency and military field operation is impracticable. This report establishes functional and design requirements for military-type respirators and describes three prototypes that could meet military needs if further developed.

2. PROPOSED DESIGN REQUIREMENTS FOR ARMY RESPIRATORS

Army-type respirators are intended to be used primarily with adult subjects. Hence, the functional requirements of the respirators are established for the adult. The following requirements are based upon references 1 through 4.

2.1 Assistor and Controller Features

The respirator should control or assist the ventilation of the subject as necessary. During periods of complete respiratory failure of the patient, the respirator should automatically control ventilation, i.e., provide the proper flow rates, pressures, and cycling rates to ventilate the subject. The respirator should also be able to assist the patient in breathing when the subject shows any inspiratory attempt. The sensitivity of the trigger circuit should be variable from -0.5 to -10 cm H_2O.

2.2 Tidal Volumes

The ventilator should supply tidal volumes of gas ranging from 300 to 1000 cc to patients with normal and abnormal compliances and airway resistances. The tidal volume should be such that a maximum applied pressure of 50 cm H_2O is not exceeded for the pulmonary impedance present. Airway resistances range from 0.5 to 20 cm $H_2O/\ell/sec$

with a normal resistance of 2.5 cm H_2O/ℓ/sec. All resistances are calibrated at a flow rate of 0.5 ℓ/sec. Normal compliance is about 0.1 ℓ/cm H_2O but variations from 0.010 to 0.25 ℓ/cm H_2O have been measured.* For the present purpose, these averages and extremes of resistance and compliance are accepted as the load requirements.

2.3 Cycling Rates

The cycling rate of the respirator, when not patient-triggered, should always be fast enough to insure proper alveolar ventilation for resting condition. A continuously adjustable range from 6 to 40 cpm should adequately meet all ventilation needs for adult patients. Figure 1 shows the cycling rates and tidal volumes required for proper ventilation.

2.4 Minute Volumes

If a minute volume of 15 ℓ/min (ref 1) is accepted as the maximum requirement, and 5 ℓ/min as a minimum for adequate ventilation of a subject, the relationship between tidal volume and cycling rate is limited by the values in figure 1. For the loading conditions defined in paragraph 2.2, the respirator should operate in the shaded area of the curve without exceeding a maximum pressure of 50 cm H_2O.

2.5 Positive Pressures

The pressure developed in the lung during inspiration varies with compliance and tidal volume. Too much pressure can rupture the alveoli. The American Medical Association has adopted 14 mm Hg (19 cm H_2O) as the maximum safe pressure to which the lungs can be inflated (ref 2). Maximum pressures of 37 mm Hg (50 cm H_2O) are considered necessary to ventilate gas attack victims (ref 3). Therefore, in military respirators, it is necessary that the maximum pressures be adjustable continuously from 5** to 50 cm H_2O.

2.6 Negative Pressures

Negative pressure during the expiratory time reduces the mean positive pressure and increases the venous return to the heart. Caution has to be exercised, however, in applying too much negative pressure to the lung because some of the airways might collapse. Hence, the negative pressure during the expiratory period should be adjustable down to a minimum value of -6 cm H_2O. Lowering the negative pressure reduces the mean pressure at which other specified requirements can be satisfied.

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*Correspondence with Robert F. Hustead, M.D., University of Kansas, Medical Center, Kansas City, Kansas.

**Conversation with James O. Elam, M. D., Rosewell Park, Buffalo, N.Y. AMC Consultant.

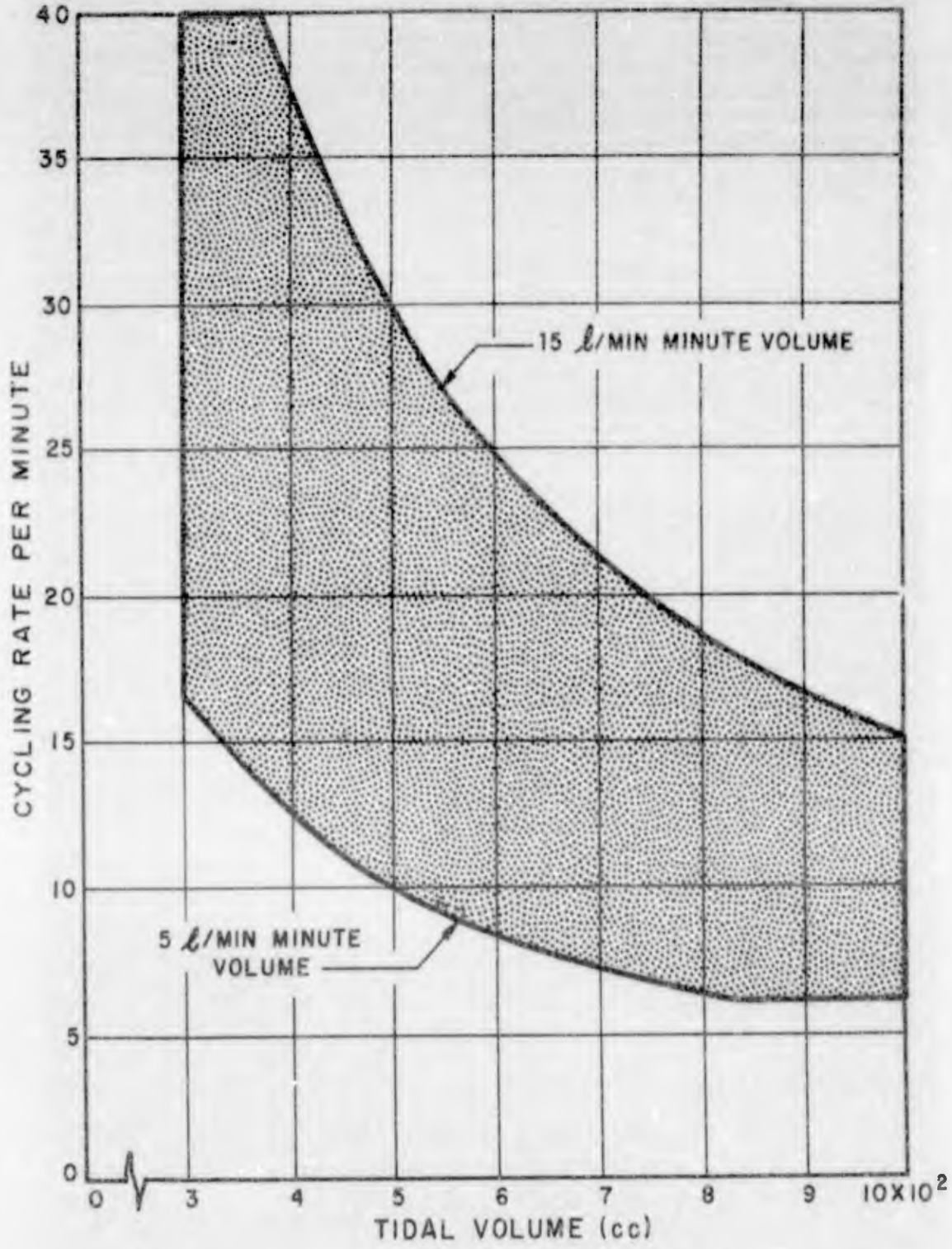

Figure 1. Design limits on tidal volumes and cycling rates.

2.7 Inspiratory Times

During the inspiratory phase, gas is delivered to the patient, inflating the lungs to the proper volume with corresponding pressures. Experience has shown that inspiratory times from 0.4 to 1.3 sec are required to achieve adequate ventilation. Figure 2 relates inspiratory time to expiratory time, which is described in paragraph 2.9.

2.8 Inspiratory Flow Rates

Inspiratory flow rates have to comply with the requirements set forth in paragraphs 2.4 and 2.7. These rates depend on the type of respirator involved. For volume-cycled respirators, the duration of inspiration time can be expressed as

$$t_{in} = V/Q_{in} \tag{1}$$

where

t_{in} = inspiratory time

V = tidal volume

Q_{in} = inspiratory flow rate

Since volume-cycled respirators are generally not load sensitive, the inspiratory time is not a function of airway resistance and chest compliance. Based on the equation (1) and the requirements of paragraphs 2.2 and 2.7, the maximum inspiratory flow rate should be 150 ℓ/min, while the minimum should be 13.8 ℓ/min for tidal volumes of 1000 cc and 300 cc, respectively, regardless of the loading conditions defined in paragraph 2.2. As shown in appendix A, equation (1) can also be applied to a pressure-cycled respirator provided the respirator's internal resistance to air flow is very high; then any change in the airway condition of the patient influences the total resistance only very slightly.

2.9 Expiratory Times

The duration of the expiration phase should be compatible with the cycling rates and inspiratory times specified in paragraphs 2.3 and 2.7. Expiratory time varies from 0.2 to 9.6 sec and is related to inspiratory time as shown in figure 2.

2.10 Typical Pressure-Flow Patterns

Figures 3 and 4 show typical gas pressure and flow patterns for volume-cycled and pressure-cycled respirators, respectively (ref 4).

3. PACKAGING AND OPERATIONAL REQUIREMENTS

3.1 Ease of Operation

A military-type respirator should be operable by individuals with a minimum of training. The control functions should be as independent

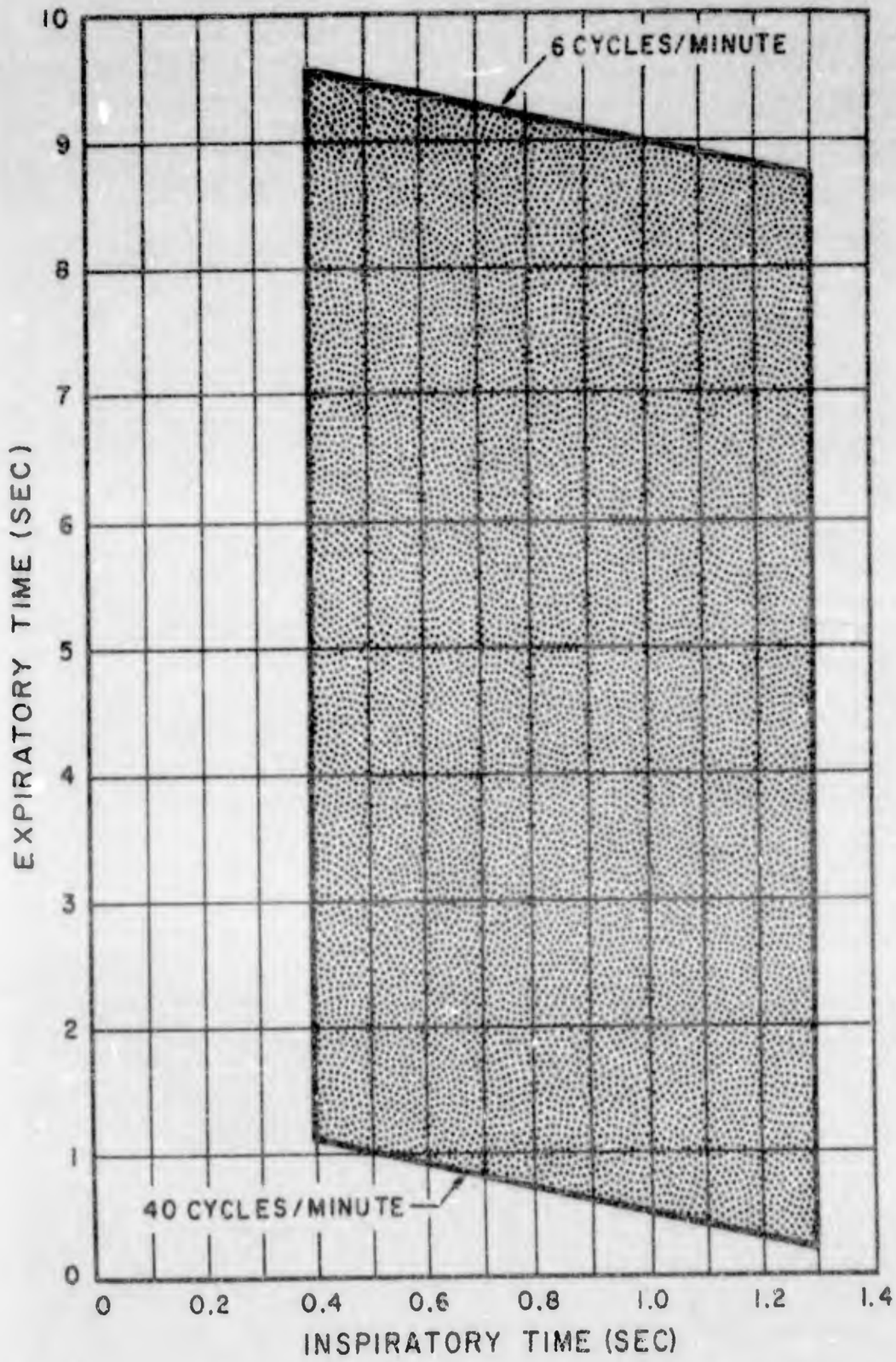

Figure 2. Design limits on inspiratory and expiratory time.

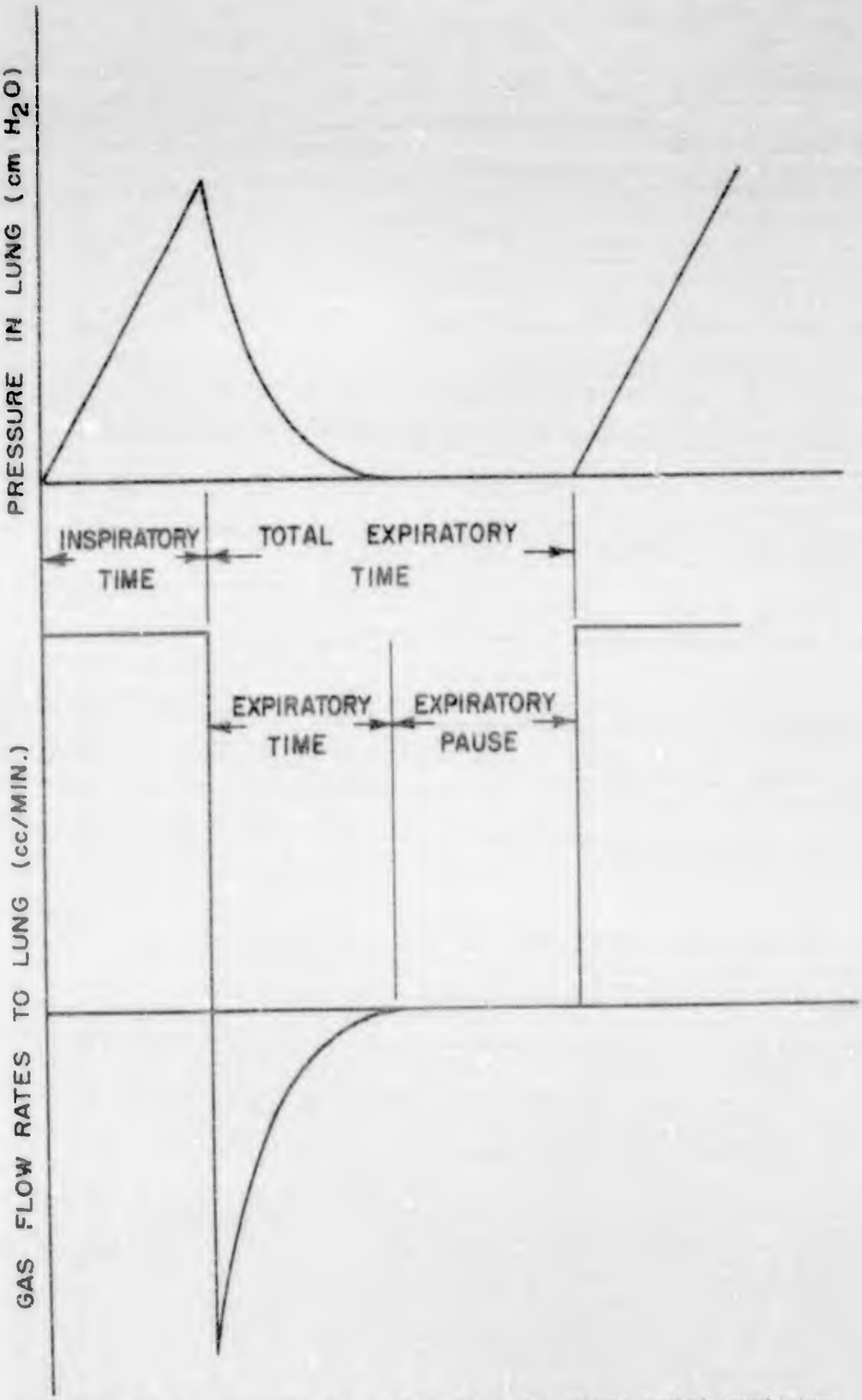

Figure 3. Gas pressure and flow patterns for volume-cycled respirator.

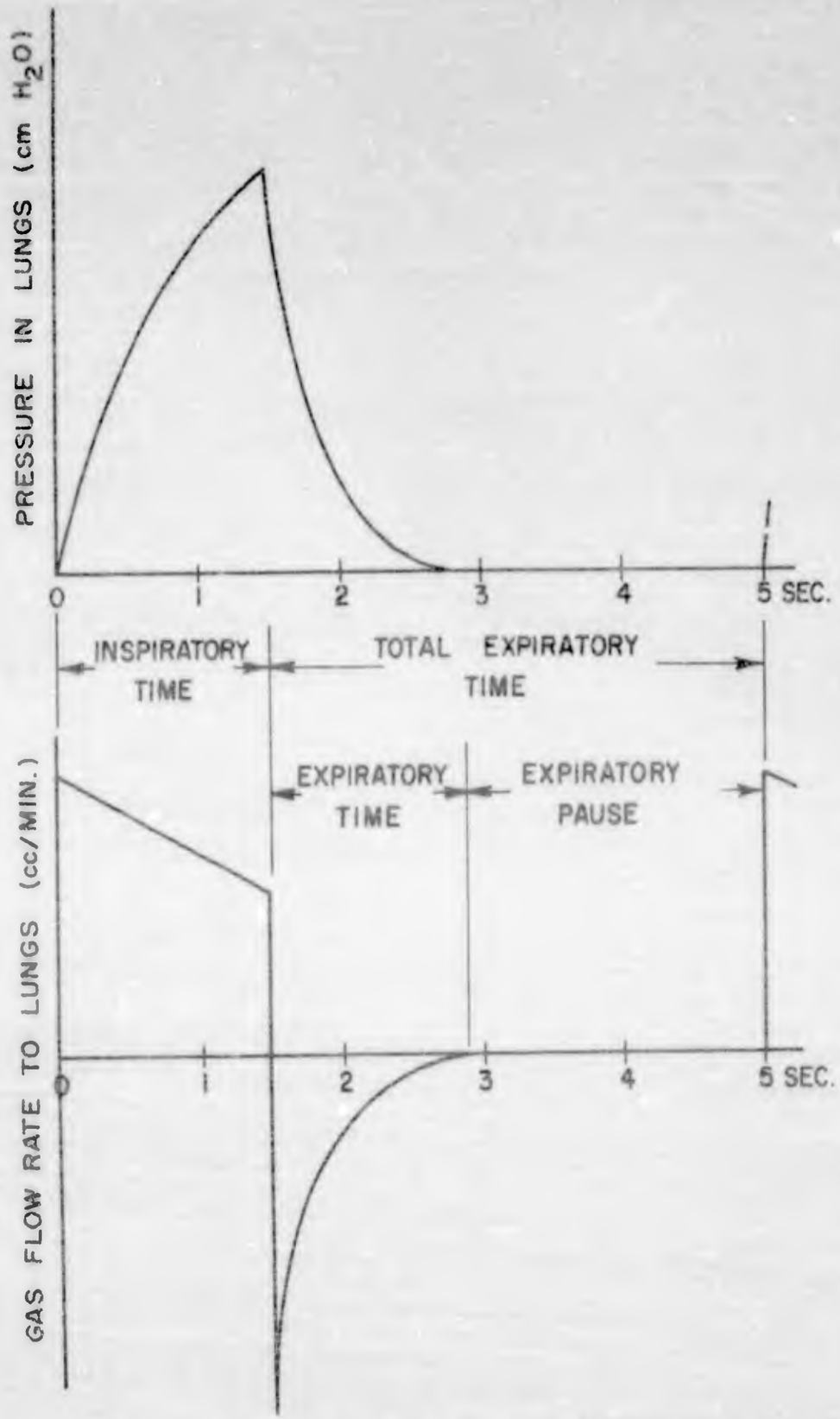

Figure 4. Gas pressure and flow patterns for pressure-cycled respirator.

as possible, and control knobs should be clearly identified to indicate function.

3.2 Cleaning

All parts of the respirator that might be contaminated by the breath of the patient should be constructed for easy cleaning and, possibly, sterilization. Normally, sterilization would be restricted to the face mask, breathing valve, and connecting tubing.

3.3 Life

The mechanical design construction must be suitable for continuous operation up to three months. Maintenance should be a minimum.

3.4 Power

The respirator should be capable of being powered with contaminated gas, if necessary. Preferably the unit should require driving pressures not higher than 50 psig with low, gas flow rates so that bottled gas could serve as a power supply.

3.5 Noise Level

The operating noise of the artificial ventilator should be low enough to be tolerated comfortably by both operator and patient over extended periods of use. The operation should be audible, however, to serve as a check on the proper functioning of the respirator.

3.6 Size and Weight

A military-type respirator should be small, light in weight, portable, and rugged in mechanical design. It should be designed to be carried easily by one person to the patient. The operation should not be significantly affected by slight movements or vibration, to permit use in moving vehicles.

3.7 Storage

The respirator should meet the following military standards: Temperature and Humidity - Mil Std 304 (28-day cycle), Transportation Vibration - Mil Std 353, and Aircraft Vibration - Mil Std 202 A, Method 204, Test Condition C.

4. DESCRIPTION AND OPERATIONAL PRINCIPLES OF PROPOSED ARMY VENTILATORS

The advent of pure fluid amplifiers (ref 5) has introduced a new control technique for pneumatic systems. High energy jet streams can now be controlled by low energy streams without moving parts. Fluid amplifiers incorporated into the proper pneumatic circuits can be used as oscillators with characteristics suited to the need of ventilators. Two prototype ventilators using fluid amplifiers, one pressure-cycled

and the other volume-cycled, have been designed, and early test results indicate that the devices amply satisfy the design requirements for Army respirators. Each has been tested against a 0.034-ℓ/cm H_2O compliance (a 34-ℓ tank), and it appears that they provide adequate control over flow rates, tidal volumes, pressures, and breathing rates. The ventilators can be made to operate either as controllers or assistors.

4.1 Volume-Cycled Respirator

A respirator that can satisfy most of the requirements set forth in section 2 is shown in figure 5. It is essentially a pump, controlled by a fluid amplifier. A flexible rubber bellows is compressed, and air is forced into the lungs of the patient. Expiration occurs through a breathing valve and is governed by the pulmonary impedance of patient and valve.

The pneumatic circuit is similar to that of the Army artificial heart pump (ref 6). Compressed gas enters the power orifice of the fluid amplifier. The power jet then exhausts to the left receiver since at the beginning of a stroke the trigger switch is open, but the port to the feedback line is closed. The pressurized gas delivered to the cylinder forces the piston upward. The speed of the upward moving piston depends on the pressure delivered to the amplifier and the subject's resistance and compliance. As the rubber bellows moves away from the trigger, the trigger switch closes immediately. When the port to the feedback line becomes uncovered as the piston reaches the upward limit of travel, entrainment from the left control of the fluid amplifier becomes possible, switching the power jet from the left to the right receiver. The pressure in the left receiver and cylinder drops below atmospheric pressure due to entrainment of the amplifier, and the piston descends at a rate governed by the setting of the expiratory time control. Once the bellows opens the trigger switch, the air entrained through the right control switches the power jet to the left receiver, thus starting a new cycle.

In vitro tests of the prototype have demonstrated adequate control of inspiration rate, tidal volume, cycling frequency, and expiratory time. Contaminated gas may be used to power and control the unit, which is quite important for a military respirator.

The above description presented the respirator operating as a controlling ventilation device. This respirator can also be used as an assistor by substituting the circuit shown in figure 6 for the trigger switch which requires a feedback line from the face mask or tracheal tube of the patient. The inspiratory effort of the patient lowers the pressure within the mask and feedback line, and moves the rubber diaphragm toward the left, uncovering the nozzle. Air from the atmosphere enters the nozzle and supplies air to the right control of the fluid amplifier, and the power jet is switched to the left receiver (fig. 5). The needle valve in the assistor circuit adjusts the amount of effort the patient has to exert to initiate inspiration of the ventilator.

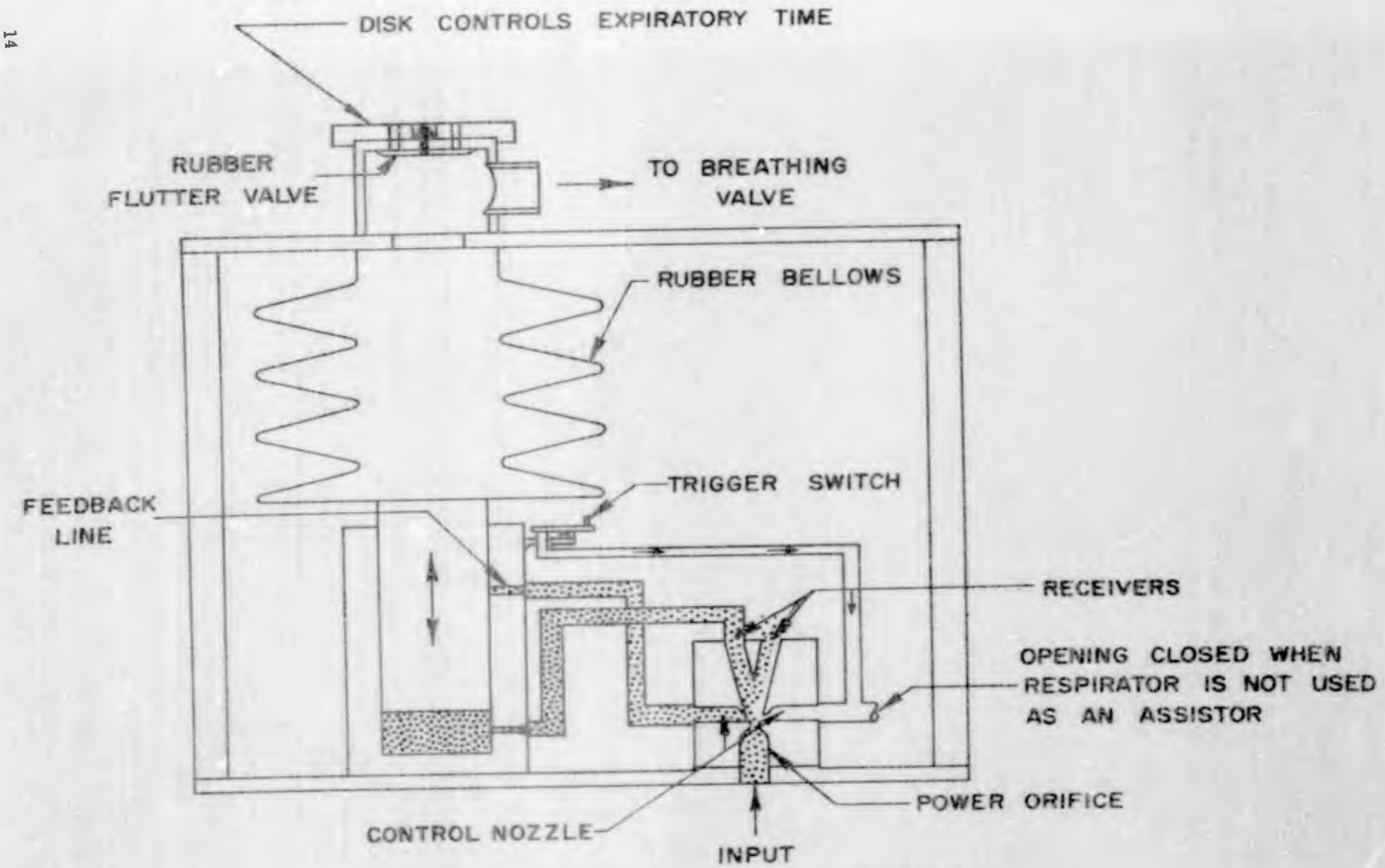

Figure 5. Volume-cycled fluid-amplifier respirator.

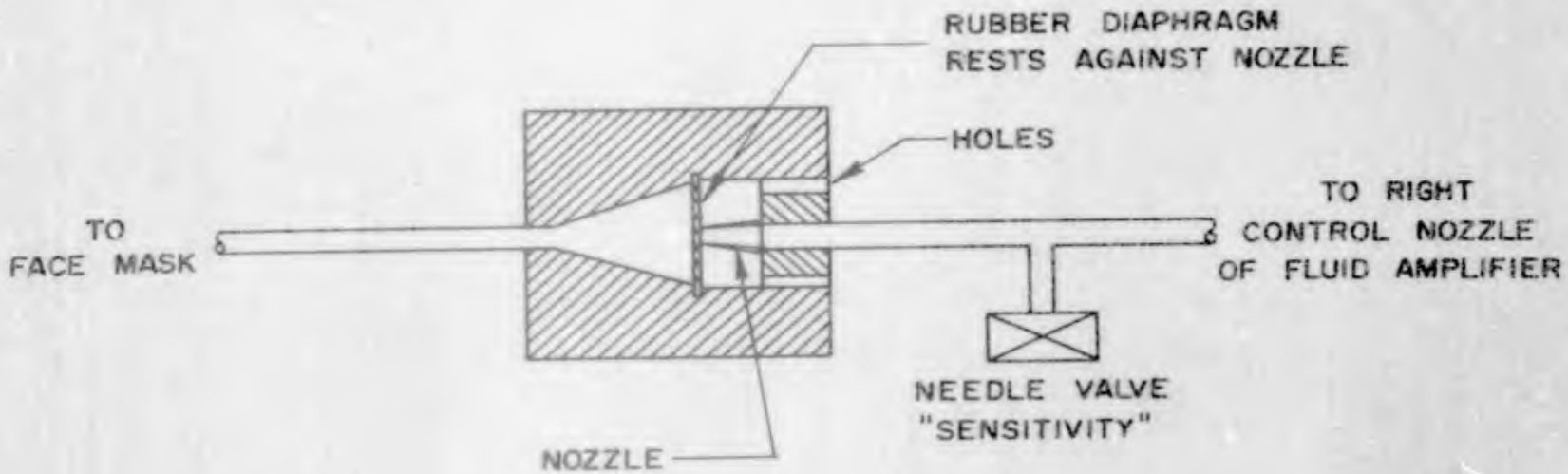

Figure 6. Assistor circuit.

4.2 Pressure-Cycled Respirator

Fluid amplification principles can also be applied in the design of an extremely simple pressure-cycled respirator. The nature of the design prevents the use of a contaminated gas. Hence, its application for the Army field use might be limited because of breathing-gas supply problems, but its simplicity, reliability and small size promise application for emergency situations where such supply problems do not exist.

A schematic diagram of the pressure-cycled respirator is shown in figure 7. In this design, gas flows from the fluid amplifier are used to ventilate the patient directly. When the power jet locks to the left receiver, air pressure builds up in the casualty circuit to the subject in accordance with the time constant of the load. Valve I controls the amount of air fed back to the left control nozzle. This feedback flow increases with the pressure in the casualty circuit. When the flow becomes large enough to satisfy the entrainment needs of the power jet, the amplifier switches to the right receiver. The patient can now exhale through the breathing valve directly to atmosphere.

The pressure levels in the casualty circuit can be controlled by adjusting valve I. Valve II controls the expiratory phase by controlling the differential control pressures across the power stream. The small plastic bag provides a reservoir of air to prolong the expiratory phase. Flow rate to the subject is adjusted by changing the input pressure to the fluid amplifier.

This unit can be used as an assistor by replacing valve II with the assistor circuit (fig. 6) whose operation was described earlier.

4.3 Pressure-Cycled Emergency Respirator

Figure 8 shows a miniaturized prototype of the circuit shown in figure 7 without the expiratory pause capacitor. A face mask is shown attached directly to the left receiver. The fluid amplifier (fig. 8) functions now as a pressure-sensitive valve. Operation of this particular unit is similar to that for the circuit previously discussed in paragraph 4.2. A difference between the two exists in the control of the expiratory phase. In this respirator, the patient exhales through the amplifier, assisted by a controlled negative pressure resulting from power stream entrainment. The inspiratory phase of the cycle is initiated as soon as a low enough pressure has been reached in the left leg of the fluid amplifier. In this case the respirator functions as a controller. Should the patient attempt to inhale, he creates a negative pressure in the left receiver of the respirator, switching the unit from expiration to inspiration and the respirator cycles as an assistor.

Setscrews A and B adjust the maximum positive and negative pressure respectively. Setscrews A and B could be locked after these adjustments are made; the adjustment of the gas flow rate to the power nozzle would alter the cycling pressure levels and frequencies.

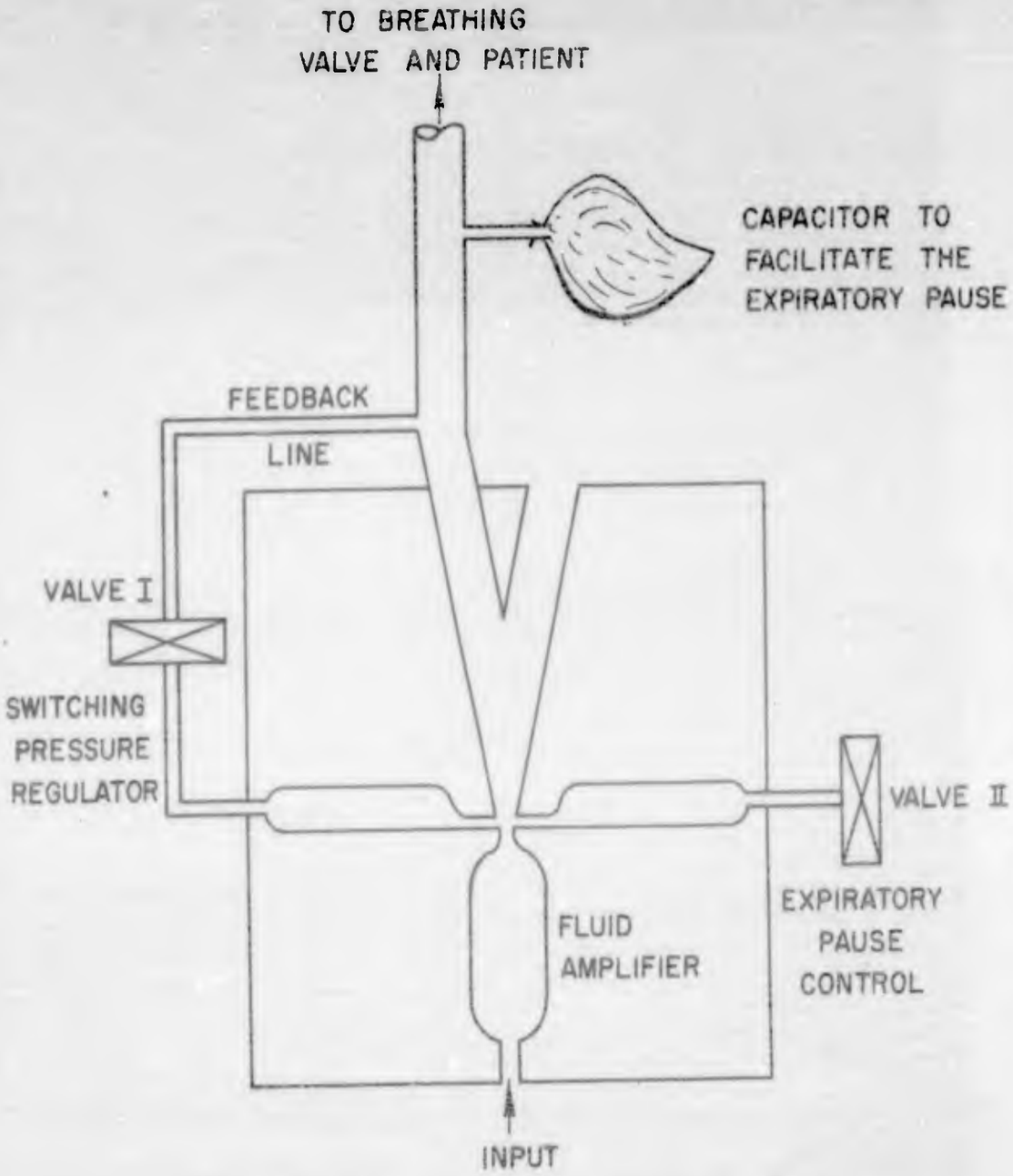

Figure 7. Pressure-cycled fluid-amplifier respirator.

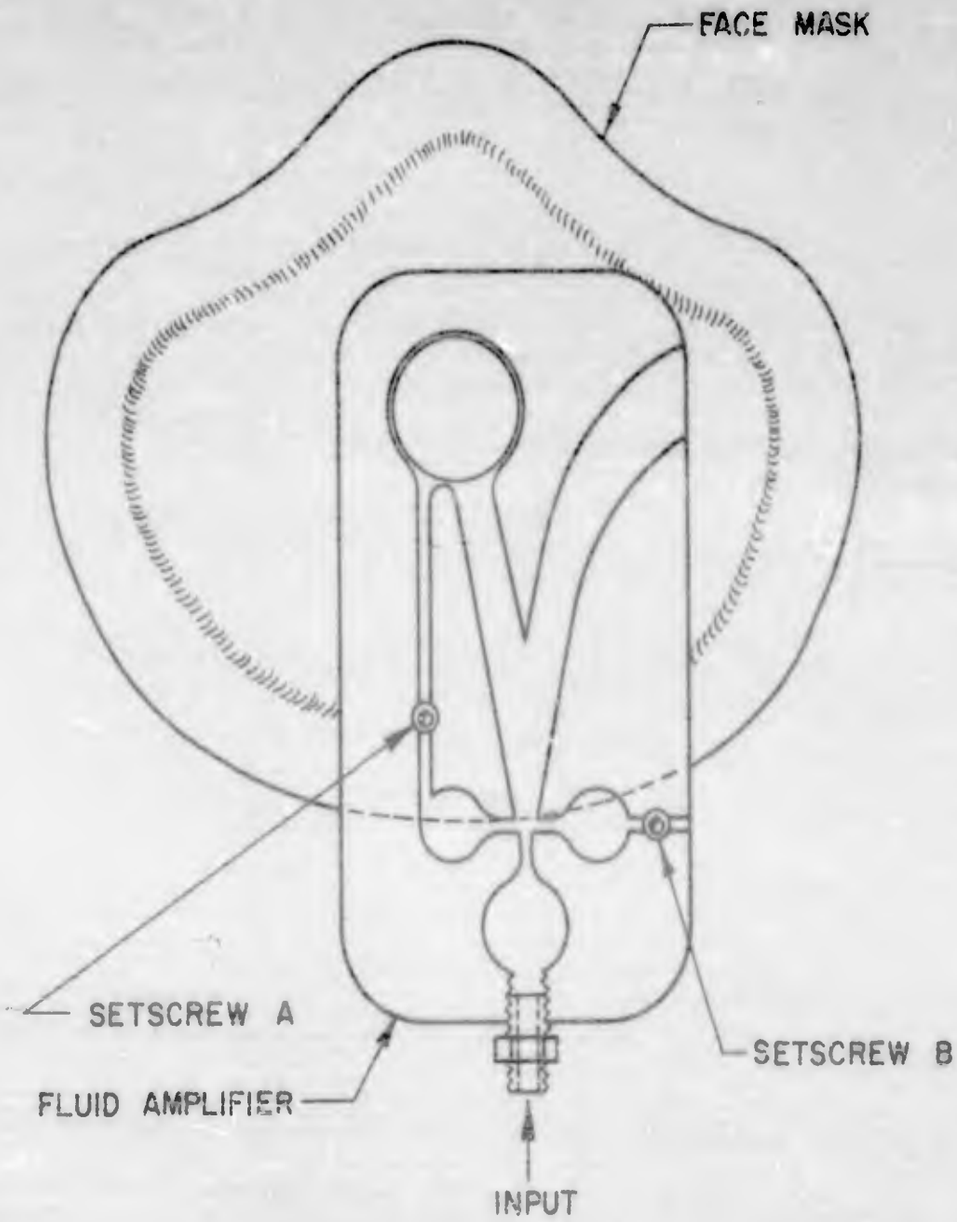

Figure 8. Pressure-cycled emergency respirator.

It should be realized that the extreme simplicity of this design limits the control over the respiratory cycle. During all phases of operation the performance of this small respirator is, in part, dependent on the condition of the patient. Changing airway resistances and lung compliances can alter the performance. It is anticipated, therefore, that the design requirements established in paragraph 2 can only be partly realized. However, this respirator presents a real advantage over other pressure-cycling types in that no moving parts are required, facilitating rapid and low cost manufacturing techniques. It is conceivable that the respirator might become a throw-away item for the ventilation of patients with contageous diseases.

4.4 Discussion of Prototypes under Development

Each of the ventilators is being tested in vitro in the laboratory. The purpose of the tests is to demonstrate control over flow rates, frequencies, and pulse shapes. In preliminary tests conducted thus far, adequate control either exists or can be obtained. The other design characteristics of the ventilators, it is believed, can be tailored to satisfy the requirements stated earlier.

5. CONCLUSIONS

The proposed automatic respirators, controlled and powered by fluid amplifiers, show promise of being functionally equal to existing respirators found to be medically acceptable. That the fluid amplifier respirators are physiologically superior to existing types is not implied. The significant advantages of the proposed ventilators are related to cost, reliability, life, and ruggedness under extreme environments. Each of these factors is favorably affected because of the unique and desirable characteristics of pure fluid amplifiers.

6. ACKNOWLEDGMENTS

The writer expresses his appreciation to Raymond Warren for proposing the application of the basic pneumatic circuit for use in the pressure-cycled respirators and demonstrating its practicability. He wishes to thank Kenneth E. Woodward for his suggestions in the construction of the respirators. The patience and care exercised by James Britt in fabricating the prototypes are recognized and greatly appreciated.

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APPENDIX A

Equation 3 (ref 1) describes the volume of gas delivered to the subject as follows:

$$V = PC\ (1 - e^{-t/RC}) \tag{A1}$$

where

V = volume delivered to lungs (tidal volume)
P = total pressure supplied by the respirator
C = pulmonary compliance
R = linear resistance to airflow
t = time elapsing during inspiration

Equation A1 can be slightly modified to include the internal airflow resistance of the respirator:

$$V = PC\ (1 - e^{-t/C(R_i+R_p)}) \tag{A2}$$

where

R_p = linear resistance of patient to airflow
R_i = linear resistance of respirator to airflow

The instantaneous gas flow rate to the subject can be found by differentiating (A2)

$$\frac{dV}{dt} = Q = \frac{P}{R} e^{-t/R_T C}$$

where

$$R_T = R_p + R_i$$

At the initiation of the inspiratory phase t = 0, and

$$Q = \frac{P}{R_T}$$

This Q is the maximum instantaneous flow rate during the inspiratory phase since any value of $t > 0$ will result in lower flows. Hence

$$Q_{max} = \frac{P}{R_T} \tag{A3}$$

Substituting (A3) into (A4)

$$Q/Q_{max} = e^{-t/C(R_i+R_p)} \tag{A4}$$

letting $k = R_i/R_p$ equation (A4) becomes:

$$Q/Q_{max} = e^{-t/(k+1)\,RC} \qquad (A5)$$

The ratio Q/Q_{max} can be examined at the end of the inspiratory time for various values of k. Typical values for (A5) are

$$t = t_{in} = 1 \text{ sec}$$

$$C = 0.10\ \ell/\text{cm } H_2O$$

$$R_p = 2.5 \text{ cm } H_2O/\ell/\text{sec}$$

Hence

$$Q/Q_{max} = e^{-4/k+1}$$

For values of $k > 100$, $Q/Q_{max} > 0.960$. For different values of t_{in}, C, and R_p, the ratio Q/Q_{max} can be held close to 1 by choosing the appropriate magnitude for k. This suggests that, during the inspiratory time, the gas flow rate is very nearly equal to Q_{max}. Equation A3 indicates that Q_{max} is independent of time, and, therefore, the inspiratory flow rate is constant. Thus pressure-cycled respirators with a suitable high internal resistance can achieve inspiratory flow rates that are not affected by the changes of airway resistance of patients.

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DESIGN REQUIREMENTS AND PROPOSAL FOR ARMY RESPIRATORS -- Henrik H. Straub

TR-1249, 22 June 1964, 10 pp text, 8 illus., Department of the Army Proj MIPR-R-63-1-MD, AMCMS Code 5010.21.71201, HDL Proj 31033, UNCLASSIFIED Report

Civilian and military respirators must, for the most part, be functionally similar. However, the environments in which military respirators must operate, impose additional and more severe requirements on their mechanical design. The functional design requirements for military-type respirators are discussed in this report. Two fluid amplifier circuits, one for a pressure-cycled and the second for a volume-cycled respirator, are described and discussed. The results of the initial in vitro tests on the first prototypes suggest that they can satisfy the predicated design requirements.

Army respirator design

Respirator requirements

Fluid amplifier

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