AEROSPACE RECOMMENDED PRACTICE

ARP4259™ | **REV. A**

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Superseding ARP4259

Metabolic Simulator Testing Systems for Aviation Breathing Equipment

RATIONALE

ARP4259A has been reaffirmed to comply woth the SAE five-year review policy.

1. SCOPE:

This Aerospace Recommended Practice (ARP) describes test equipment and methods used for testing closed cycle or semiclosed cycle breathing devices of short duration that are designed to operate with a high partial pressure of oxygen in the breathing circuit. It is intended to supplement ARP1109 and ARP1398 for applications involving closed cycle or semiclosed cycle breathing equipment which may be evaluated to the requirements of AS8031 and/or AS8047.

1.1 Purpose:

This ARP recommends performance requirements for test equipment used to simulate human respiration in the testing of aviation protective breathing equipment (PBE). This ARP does not, however, preclude the need for human testing.

2. REFERENCES:

The applicable sections of the following documents shall be considered as integral parts of this recommended practice.

SAE:

AIR825	Oxygen Equipment for Aircraft
ARP1109	Dynamic Testing Systems for Oxygen Breathing Equipment
AIR1176	Oxygen System and Component Cleaning and Packaging
ARP1398	Testing of Oxygen Equipment
AS8010	Aviator's Breathing Oxygen Purity Standard
AS8031	Minimum Performance Standard for Personal Protective Devices for Toxic and Irritating Atmospheres, Air Transport Crew Members
AS8047	Performance Standard for Cabin Crew Portable Protective Breathing Equipment for Use During Aircraft Emergencies

2. (Continued):

Others:

MIL-O-27210	Oxygen Aviator's Breathing (ABO)
MIL-P-27401	Nitrogen, Type I
MIL-G-27617	Oxygen Lubricants
TSO C99	Protective Breathing Equipment
TSO C116	Crewmember Protective Breathing Equipment

3. GENERAL:

3.1 Human Respiration Simulation:

There are two primary requirements for simulation:

a. A breathing simulator with control of ventilation rate $(\dot{V}_E)$, respiratory frequency (f) and desirably, breathing waveform shape control

b. Gas-exchange metabolism simulation with control of the oxygen consumption $(\dot{V}O_2)$, carbon dioxide elimination $(\dot{V}CO_2)$, and temperature-humidity of the exhaled gas

3.2 Test Conditions Pertaining to Short Duration Breathing Devices of Rebreather Type:

As described in B.9, very elaborate respiration simulators with computerized monitoring of the different parameters have been designed to accurately simulate metabolic processes. Oxygen consumption is simulated by continuous gas removal sufficient to effect the desired rate of oxygen consumption, and replacement of the balance composition of the other gases. These systems allow accurate testing of any type of closed circuit breathing device and are particularly well suited to equipment which operates with oxygen concentrations that are less than 50%.

For breathing devices that operate with a high partial pressure of oxygen in the breathing circuit and are of short duration, much simpler simulators can allow reasonably accurate testing. Most of these breathing devices generally deliver an oxygen flow $\dot{V}_IO_2$ to the user largely in excess of the average metabolic O_2 consumption which results in a high O_2 concentration in the rebreather reservoir. Therefore the simulated O_2 consumption $(\dot{V}O_2)$ can be effectively achieved by direct volumetric removal of the breathing gas and a more complicated subsystem is not necessary. B.5 and B.10 describe functional installations of these simpler systems.

4. REQUIREMENTS:

Typical schematic diagrams of metabolic simulators are given in Figures 1 and 2.

4.1 Breathing Simulator or Artificial Lung:

It will be a mechanical breathing simulator of Type I or II, Class A as defined by ARP1109.

Use of a sinusoidal breathing waveform is acceptable.

Since high concentrations of oxygen will be encountered during testing, it is recommended that the equipment be cleaned for oxygen service in accordance with AIR1176. Test gases of the appropriate referenced standard are recommended to avoid contamination of the equipment.

For each workload to be simulated, the artificial lung will be set to a given ventilation rate (minute volume $\dot{V}_E$) for a given respiratory frequency (f) in breaths per minute (BPM) according to the procedures described in Section 5.

4.2 Metabolic Simulation:

4.2.1 Body CO_2 Simulated Production ($\dot{V}CO_2$): A steady flow of CO_2 simulating $\dot{V}CO_2$ will be injected into the simulator, preferably directly into the artificial lung for better mixing of the breathing gases. $\dot{V}CO_2$ will be in accordance with the values determined in Section 5 for the given workload. Note that expiratory $CO_2(\dot{V}_ECO_2)$ must be the sum of $\dot{V}CO_2$ and of inspiratory residual CO_2 leaving the breathing device.

A CO_2 analyzer will allow measuring the CO_2 contents in expired gases prior to their entry into the breathing device.

Accurate control of the CO_2 flow is essential to establish the proper loading on the breathing device CO_2 scrubbing component. CO_2 average input can be manually adjusted by means of a needle valve and an appropriate rotameter or equivalent, with a flexible bag and a check-valve upstream of the artificial lung to allow for cyclic discharge into the upper chamber of the lung.

4.2.2 Body O_2 Simulated Consumption ($\dot{V}O_2$): A metered flow of inspired gas will be withdrawn from the inspired gas circuit to simulate O_2 consumption. A length of withdrawal tubing will isolate the withdrawal gas stream from the circuit as it is diverted to a series of analyzers (O_2, CO_2, CO, etc.) and then discharged to ambient. This will allow for measuring the mean gas concentrations in the mixture.

An auxiliary lung synchronized with the artificial lung can be used to simulate cyclic withdrawal of the gases. Alternatively, a small volumetric pump can be used in a continuous mode.

4.2.2 (Continued):

For simplicity, the volume/time of gas withdrawn to simulate $\dot{V}O_2$ may be set equal to $\dot{V}CO_2$, establishing a respiratory quotient (RQ) of 1. This will have the advantage of maintaining a constant mass balance within the simulator and the breathing device. If more accurate volumetric control of the gas exchange is desired, a detailed procedure is described in Annex 1.

4.2.3 Temperature and Humidity Control: Expired gases from the simulator shall be water saturated at body temperature (37 °C or 98 °F).

Humidification can be achieved by means of an appropriate humidifier located between the artificial lung and the expired gases interface to the breathing device.

An alternate method is to circulate water at 37 °C into the upper chamber of the breathing simulator by means of a small volumetric pump.

Temperature control of the gas within the simulator, or volumetric compensation, is required to prevent gas volume changes in $\dot{V}_E$ resulting from changing temperatures in the output of the device under test. Subsequent rewarming of the gases to body temperature prior to entering the breathing device during expiration phase is required. This rewarming can also be achieved at the same time as humidification.

A water trap may be needed to remove condensation in the tubing circuits.

4.2.4 Simulator Dead Volume: A metabolic simulator and human anatomy will never be identical. However it is essential that:

a. The dead volume above the breathing simulator piston and that of the different hoses and accessories up to simulator/device interface should not exceed the average human functional residual capacity (FRP), i.e., 2.3 to 2.4 L.

b. The simulated tracheal dead volume should not exceed 150 cm^3.

c. If it is necessary to extend the functional interface of the simulator for remote operation within an altitude or environmental chamber, separation of inspiration and expiration circuits shall be maintained to minimize the dead volume effects.

4.2.5 Breathing Device/Simulator Interface: Protective Breathing Equipment (PBE) for Air Transport Cabin Crew to the requirements of AS8047 generally consists of closed cycle breathing hoods sealing around the neck of the user.

The hood will interface with the simulator by means of a dummy head (medium size) provided with a smooth neck surface compatible with the device neck seal. The dummy head will be equipped with a pipe connecting the mouth area with the simulator. An alternative is shown in Figures 2 and 3 with a concentric pipe connector separating the inhaled gases from the exhaled gases. Each branch of this connector is alternatively isolated from the simulator by means of a check valve or solenoid valve activated by the artificial lung. Solenoid A opens at the beginning of the inspiration phase and closes at the end of this phase. Solenoid B opens at the beginning of the expiration phase and closes at the end of this phase. The advantages of this system are:

a. Reduction of the dead volume simulating the trachea
b. Reduction of the rebreathing between inhaled and exhaled gases

4.2.6 Directional Valves: A set of directional valves (C and D Figure 2) located at the lung outlet will allow for proper transfer of the breathing gases throughout the simulator.

5. OPERATING PARAMETERS:

Simulator set point parameters for different workloads may be empirically derived from equivalent human subject testing, or calculated from physiological relationships. A sample sequence for calculating parameters for a known workload is discussed in this section.

5.1 Determination of $\dot{V}O_2$:

The relationship of $\dot{V}O_2$ to work is well defined and is generally considered linear for submaximal work. B.7 details methods for relating external workload to oxygen equivalents. For purposes of this derivation, the external workload of a bicycle ergometer is used. Referring to the procedures of AS8047 to determine the external workload from the subject weight, a 95th percentile 220 lb (100 kg) male exercising at a workload of 0.5 w/lb is chosen for illustration.

External workload requirement:

$$220 \text{ lb} \times 0.5 \text{ w/lb} = 110 \text{ w} \qquad \text{(Eq. 1)}$$
$$(100 \text{ kg} \times 1.1 \text{ w/kg} = 110 \text{ w})$$

5.1 (Continued):

For a bicycle ergometer, the total oxygen uptake includes a resting basal metabolism component dependent upon the individual's body weight, plus the external work requirement that is independent of body weight. This is frequently expressed by the following equation (where w = power in kilopond meter/minute (kpm/min), wt = subject weight in kg, and $\dot{V}O_2$ = ml/min):

$$\dot{V}O_2 = 3.5\text{ wt} + 2\text{ w} \quad \text{(Eq. 2)}$$

Applying the conversion factor of 1 w = 6.12 kpm/min

$$\dot{V}O_2 = 3.5 \times (220\text{ lb} / 2.2\text{ lb/kg}) + (2 \times 110 \times 6.12) \quad \text{(Eq. 3)}$$

$$(\dot{V}O_2 = 3.5 \times 110\text{ kg} + (2 \times 110 \times 6.12))$$

$$\dot{V}O_2 = 1{,}696\text{ ml/min} = 1.696\text{ lpm}$$

5.2 Determination of $\dot{V}_E$:

Although $\dot{V}_E$ is normally a function of $\dot{V}O_2$, it is significantly altered by increased inspiratory levels of CO_2. These effects over the range of 0 to 40 mmHg P_ICO_2 are documented in B.6 and shown graphically in Figure 4 for male subjects of average 71 kg bodyweight. Accordingly, the equation closest to the known, or anticipated, inspiratory CO_2 level should be chosen for determination of $\dot{V}_E$.

P_ICO_2 = 0 mmHg (0 kPa)

$$\dot{V}_E = 6.588 + 10.72\,\dot{V}O_2 + 6.226\,\dot{V}O_2{}^{\wedge 2} \quad \text{(Eq. 4)}$$

P_ICO_2 = 10 mmHg (1.3 kPa)

$$\dot{V}_E = 6.277 + 20.60\,\dot{V}O_2 + 4.923\,\dot{V}O_2{}^{\wedge 2} \quad \text{(Eq. 5)}$$

P_ICO_2 = 20 mmHg (2.7 kPa)

$$\dot{V}_E = 6.680 + 33.95\,\dot{V}O_2 + 1.744\,\dot{V}O_2{}^{\wedge 2} \quad \text{(Eq. 6)}$$

P_ICO_2 = 30 mmHg (4.0 kPa)

$$\dot{V}_E = 12.20 + 50.71\,\dot{V}O_2 - 2.532\,\dot{V}O_2{}^{\wedge 2} \quad \text{(Eq. 7)}$$

P_ICO_2 = 40 mmHg (5.3 kPa)

$$\dot{V}_E = 26.99 + 59.60\,\dot{V}O_2 - 5.879\,\dot{V}O_2{}^{\wedge 2} \quad \text{(Eq. 8)}$$

5.2 (Continued):

For this example, an inspiratory P_ICO_2 = 20 mmHg (2.7 kPa) will be assumed

$$\dot{V}_E = 6.680 + 33.95\,\dot{V}O_2 + 1.744\,\dot{V}O_2{}^{\wedge 2} \quad \text{(Eq. 9)}$$

$$\dot{V}_E = 6.680 + (33.95 \times 1.696) + (1.744 \times 1.696 \times 1.696)$$

$$\dot{V}_E = 69.3 \text{ lpm}$$

5.3 Determination of Respiratory Frequency (f):

Although there is a high degree of individual variation in f, B.8 establishes a general relationship to $\dot{V}O_2$ that is useful for obtaining a guide to anticipated values.

$$f = 6.7\,\dot{V}O_2 + 17.4 \quad \text{(Eq. 10)}$$

For this example,

f = (6.7 × 1.696) + 17.4
f = 28.8

5.4 Determination of Tidal Volume (V_T):

$$V_T = \dot{V}_E / f \quad \text{(Eq. 11)}$$

For this example,

V_T = 69.3 lpm/28.8 bpm
V_T = 2.4 L

5.5 Alternative Procedures for Fixed Tidal Volume:

As an alternative simplification, a specific midrange tidal volume may be chosen for a test sequence, and changes in ventilation ($\dot{V}_E$) achieved by adjusting the breathing frequency (f) to obtain desired values. Because of the wide range in individual tidal volumes and breathing frequencies, this simplification has little impact on the accuracy of the test set up. The following Table 1 summarizes the calculations of 6.2 to determine $\dot{V}_E$ for a 220 lb (100 kg) subject:

TABLE 1

Watts (EXT)	LPM O_2 & CO_2	0 mmHg 0 kPa	10 mmHg 1.3 kPa	20 mmHg 2.7 kPa	30 mmHg 4.0 kPa	40 mmHg 5.3 kPa
40	0.84	20	27	36	53	73
50	0.96	23	31	41	59	79
60	1.08	26	34	46	64	85
70	1.21	29	38	50	70	90
80	1.33	32	42	55	75	96
90	1.45	35	47	60	80	101
100	1.57	39	51	64	86	106
110	1.70	43	55	69	91	111
120	1.82	47	60	74	96	116
130	1.94	51	65	79	101	121
140	2.06	55	70	84	106	125
150	2.19	60	75	89	111	129
160	2.31	65	80	94	116	133
170	2.43	69	85	100	121	137
180	2.55	75	91	105	125	141
190	2.68	80	97	110	130	144
200	2.80	85	102	115	134	148

5.6 Summary of Calculated Parameters:

For this example, simulating a 220 lb (100 kg) subject exercising at 110 w external workload with P_ICO_2 = 20 mmHg (2.7 kPa).

a. VENTILATION ($\dot{V}_E$) = 69.3 lpm
b. FREQUENCY (f) = 28.8 bpm
c. TIDAL VOLUME (V_T) = 2.40 L
d. O_2 CONSUMPTION = 1.696 L
e. CO_2 PRODUCTION = 1.696 L (RQ = 1 assumed)

6. TESTING AT ALTITUDE:

It may be necessary to run altitude tests with the simulator in an altitude chamber (as an example, 8000 ft (2438 m) cabin simulation for TSO C116).

$\dot{V}O_2$ as a function of $\dot{V}_E$ at altitude is given in Figure 3 of B.3 in Appendix B.

To simplify compensation for changes in altitude, CO_2 contents in the inspired gases shall be stated in partial pressure, i.e., P_ICO_2 (kPa or mmHg).

7. GLOSSARY:

$\dot{V}_I$ = total inspiratory volume/time (liters per minute)
$\dot{V}_IN_2$ = inspiratory N_2 volume/time (liters per minute)
$\dot{V}_IO_2$ = inspiratory O_2 volume/time (liters per minute)
$\dot{V}sub$ = pumped (subtracted) total volume/time (liters per minute)
$\dot{V}N_2$ = pumped and added N_2 volume/time (liters per minute)
$\dot{V}O_2$ = simulated O_2 consumption (= pumped O_2 liters per minute)
$\dot{V}add$ = total added volume/time (liters per minute)
$\dot{V}CO_2$ = simulated CO_2 production (= added CO_2 liters per minute)
$\dot{V}_E$ = ventilation rate volume/time (liters per minute)
$\dot{V}_EN_2$ = expiratory N_2 volume/time (liters per minute)
$\dot{V}_EO_2$ = expiratory O_2 volume/time (liters per minute)
$\dot{V}_ECO_2$ = expiratory CO_2 volume/time (liters per minute)
F_IO_2 = inspiratory O_2 concentration (Percent)
F_ICO_2 = inspiratory CO_2 concentration (Percent)
f = respiratory frequency (Breaths per minute)
FRP = Functional Residual Capacity: Volume of gas remaining in the lungs following a normal expiration (liters)
P_ICO_2 = inspiratory CO_2 partial pressure (kPa or mmHg)
RQ = $\dot{V}CO_2/\dot{V}O_2$ = respiratory quotient (dimensionless)

8. KEY WORDS:

Testing, simulator, metabolic

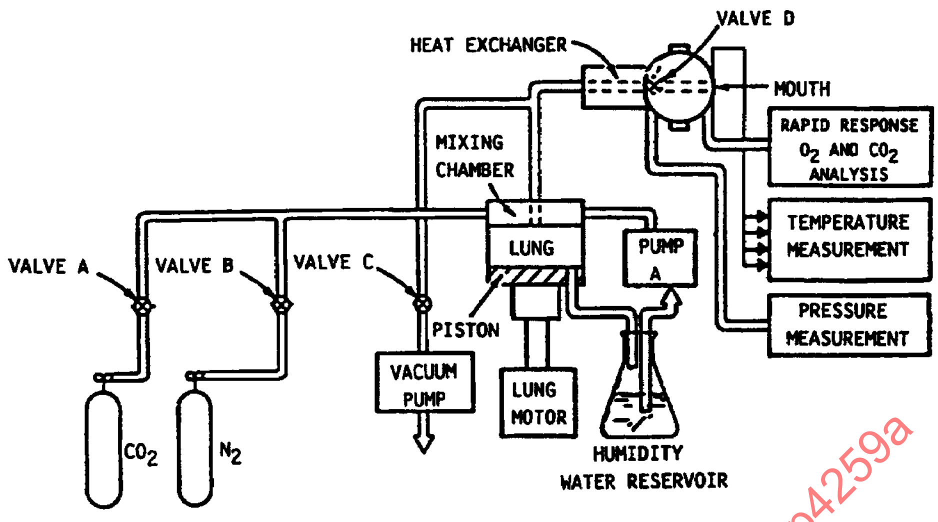

FIGURE 1 - General Schematic Diagram

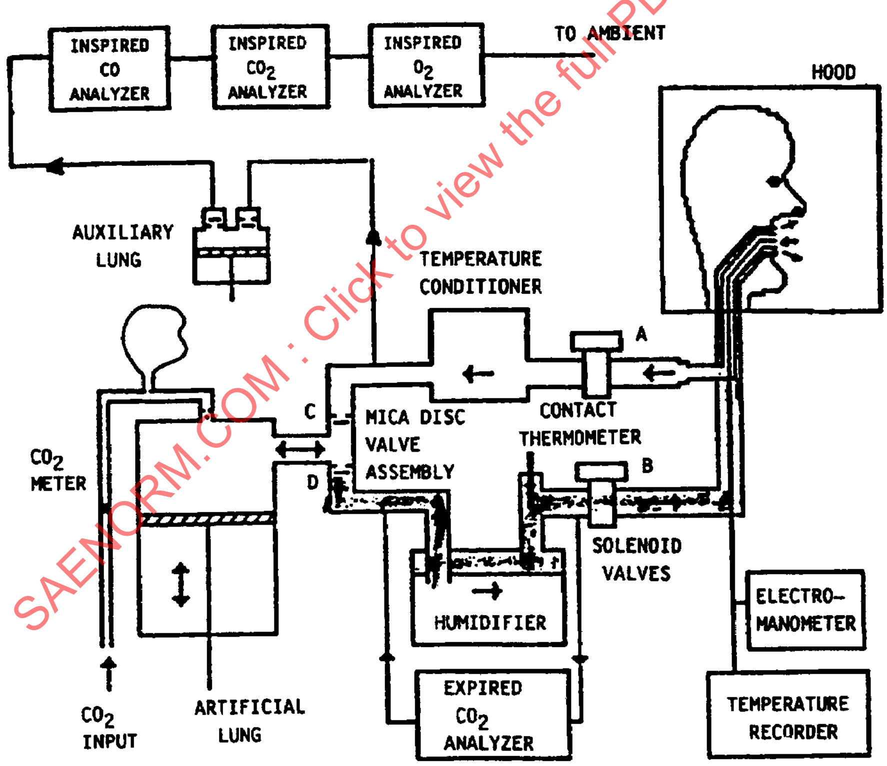

FIGURE 2 - Schematic Diagram (Alternate)

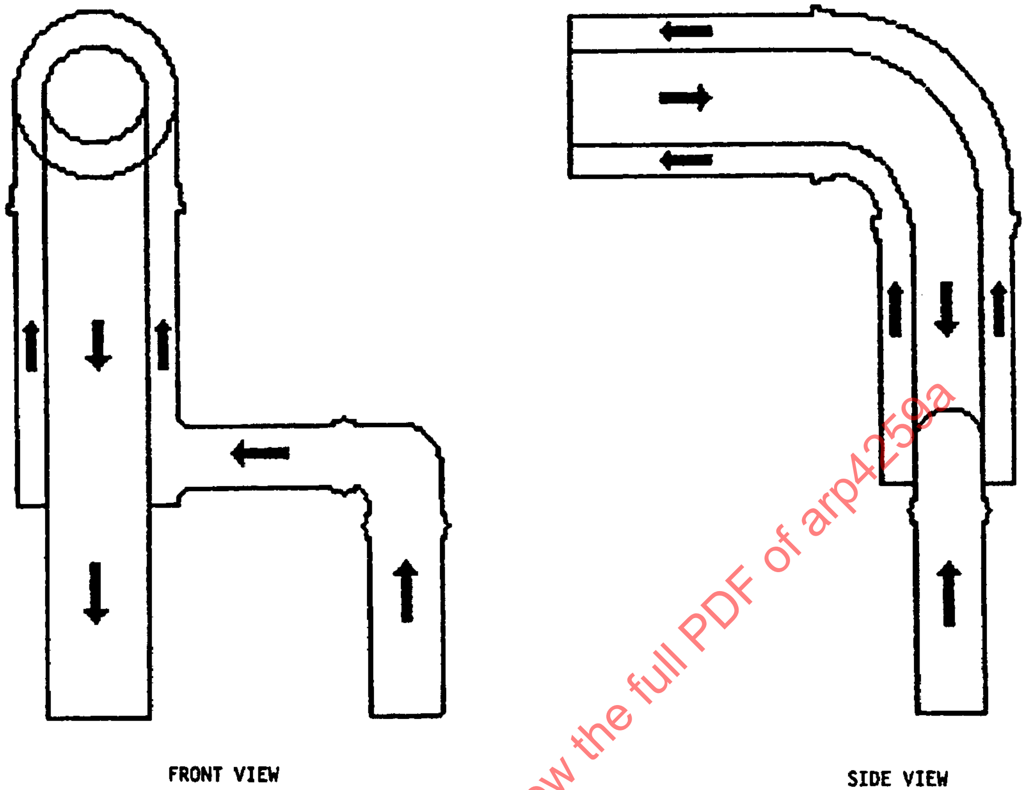

FIGURE 3 - Concentric Pipe Connector