# BREATHING METABOLIC SIMULATOR

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## Introduction

The Breathing Metabolic Simulator (BMS) was developed by the IBM Corporation under the joint funding of NASA and the Office of Advanced Research and Technology (OART) and the Bureau of Mines. The BMS simulates man in the breathing and metabolic parameters required for evaluation and test of respiratory diagnostic, monitoring, support, and resuscitation equipment. For the first time, breathing and metabolic simulation are incorporated in a single device. Breathing rate, breathing depth, breath velocity contour, oxygen ($O_2$) uptake, and carbon dioxide ($CO_2$) release can be varied over wide ranges to simulate conditions from sleep to hard work, with respiratory exchange ratios ranging from hypoventilation to hyperventilation. Since the BMS can be remotely controlled in hostile environments, it can be used as a stand-in for humans in testing and validating respiratory equipment. In addition, it substantially reduces the cost of prolonged testing in cases where simulation chambers with human subjects would require three shifts of crews, including standby physicians. Perhaps, most important, it provides a calculated and reproducible test and validation facility.

The second-generation breathing metabolic simulator, currently under development, will be automated for computer control. Through a typewriter and paper tape the test sequence can be input into the computer which will then automatically adjust the BMS to simulate any desired sequence of metabolic activities for time durations up to 15 hours. The computer will also monitor the test procedures and provide printout of test results.

## BMS Design

Breathing Rate. The BMS contains a breathing rate adjustment that simulates human breathing rates, ranging from conditions of rest to hard work. However, this wide range would seldom be required in a single test.

Breathing Depth. The BMS breathing depth adjustment covers a range up to 3 liters per breath. Although an individual breath may exceed 3 liters under certain conditions, the breathing depth under continuous hard exercise should not exceed simulator capacity. Also, the BMS can simulate individual breath (tidal volume) which is normally 0.5-0.6 liter under rest conditions.

For special applications, the breathing depth can be expanded beyond 3 liters to simulate a full vital capacity, e.g., 6 liters.

Velocity-Time Waveform. A human breath velocity pattern is not generally represented by a true sine wave. It may vary from a slightly blunted sine wave to a drastic variation. To provide a true simulation, a waveform control is provided, allowing a wide range of variations from a basic sine wave.

Functional Residual Capacity (FRC). The FRC is the volume of air remaining in the lungs at the end of normal exhalation. To obtain an accurate simulation, the FRC must remain constant for breathing rate or depth changes. Also, the FRC must be variable to simulate individuals with different FRCs. Both of the conditions are provided by the BMS.

Exhaled Breath Temperature and Humidity. Exhaled breath, in humans, is at body temperature and, except for conditions of extremely hard breathing, at 100 percent relative humidity. Both of these conditions are simulated by the BMS.

Oxygen Consumption. The BMS provides a variable oxygen consumption rate to simulate the metabolic range between sleep and medium-hard work. For special applications, the BMS can simulate maximum oxygen consumption rates for the human undergoing maximum physical work.

Carbon Dioxide Production. The amount of $CO_2$ produced in the human is related to the amount of $O_2$ consumed. This $CO_2/O_2$ ratio is 0.707 if the fuel is fat and is 1.0 if the fuel is carbohydrates. This ratio, when referenced to tissue metabolic activity, is referred to as the respiratory quotient (RQ). When referenced to the ratio of gases in the exhaled breath (as in the BMS), it is referred to as the respiratory exchange ratio (R) (this differentiation is made because an individual may be underbreathing or overbreathing, markedly affecting the amount of $CO_2$ removed from the body and thus the value of R). To simulate these conditions, the BMS provides a range of $CO_2/O_2$ (R) wider than the normal range of 0.7 to 1.0.

## BMS Hardware

The BMS configuration consists of three subsystems:

1. Temperature/Humidity
2. Breathing
3. Metabolism

These subsystems are depicted in Figure 1.

Temperature/Humidity Subsystem (Fig. 2).

Functions. Incoming air from the aritificial trachea is fed into an exchange box, where it is blocked from entering the humidity chamber by a check valve. The air then passes through another check valve and enters the main connection to the top of the bellows during bellows expansion.

Outgoing (exhaled) air comes from the main connection to the top of the bellows during bellows contraction. The air passes through a check valve and enters the input end of the humidity chamber. The air entering the chamber displaces air from the output end of the chamber through a check valve, where it enters the exchange box and exits to the artificial trachea.

Features. The check valves and exchange box are used to control airflow direction and to permit a single connection to the artificial trachea.

The humidity chamber is used to add moisture to the exhaled air and to maintain temperature within specified limits. The moisture transfer media (surgical sponges) remain saturated with water from a separate reservoir (actual humidity is also affected by the dwell time of a breath inside the chamber). Temperature maintenance, accomplished by a heater blanket in the bottom of the chamber, is monitored by a thermistor placed in the path of the chamber output. Heater power is remotely controlled by the control unit.

This subsystem also contains sensors for monitoring the characteristics of the air to be exhaled. Wet and dry bulb thermistors placed in the output end of the chamber can be monitored by the digital voltmeter. A gas sample line, connected to the chamber input end, allows a sample pump to extract gas samples which are fed to the sensors of an $O_2$ analyzer and a $CO_2$ analyzer, and returned to the chamber. The readout of these analyzers is accomplished on the control unit.

Breathing Subsystem (Fig. 3).

Functions. The breathing subsystem controls bellows expansion and contraction to draw air from and expel air to the temperature/humidity subsystem. The bellows motion is independently variable in rate, magnitude of periodic motion, and volume remaining at the point of minimum periodic volume change. The periodic motion of the bellows is accomplished by a drive motor operating a crankshaft/connecting rod combination through a 30:1 gear reduction. The drive motor speed is varied by means of a motor controller. Long-term variations, greater than one crankshaft revolution, correspond to changes in breathing rate and are varied from the control unit. Short-term variations, within one crankshaft revolution, correspond to changes in breath waveform and are varied by the individual settings of 12 waveform controls on the control unit. Each control is effective during one-twelfth of a crankshaft revolution as determined by a 12-position read switch.

Connecting rod motion is transmitted to the bellows by a lever arm operating on a movable fulcrum. Fulcrum motion along the lever arm varies the lever-arm ratio corresponding to changes in breath depth. This motion is accomplished by means of a lead screw from the fulcrum drive motor which, in turn, is controlled by the bidirectional fulcrum switch on the control unit. Fulcrum motion normal to the lever arm, i.e., moving the position of the bottom of the bellows for a fixed crank position and lever arm ratio, will change the minimum bellows volume obtainable through periodic motion. This corresponds to a functional residual capacity adjustment and is controlled by a manual screw adjustment on the support for the fulcrum base. This adjustment has a scale calibrated in FRC volume in liters.

Features. The top of the bellows contains two separate gas lines to provide an output to the compressor of the metabolism subsystem and to receive the output of this subsystem.

Two separate magnetic flux-type sensors are mounted between the bottom of the bellows and the adjustable support for the fulcrum base. These sensors measure position and velocity between mountings (thus sensing breath characteristics independent of FRC adjustment) and are input to the oscilloscope in the control unit, where either may be selected for waveform display.

Metabolism Subsystem (Fig. 4).

Functions. This subsystem is used to control the simulated respiratory exchange ratio (R). Since R is a $CO_2$-to-$O_2$ ratio, metabolism is simulated by consuming $O_2$ and producing $CO_2$. This is accomplished by oxidizing propane and adding varying amounts of $CO_2$ in the following manner.

Air is drawn from the top of the bellows by a compressor. The compressed air output is then fed to an accumulator used to eliminate surging caused by bellows motion. The accumulator output is connected to an adjustable orifice used to preset the flow rate for more than sufficient air for all oxidation conditions; the accumulator is then connected to a gas line input to the oxidation chamber. A size-D tank of CP-grade propane is fitted with a manual regulator (set to 15 psi). The regulator output is connected to a solenoid shutoff valve controlled by the manual switch on the control unit (and the series safety circuitry discussed later). The solenoid valve output is connected to a remotely adjustable metering valve (controlled by the valve enable and $CO_2$ adjustment on the control unit). The metering valve output is connected to a flowmeter sensor (the flowmeter is located on the control unit panel) and finally to the oxidation chamber input line. A size-D $CO_2$ tank is fitted with a duplicate of the propane controls (except safety circuit not required) and also connected to the oxidation chamber input line.

The oxidation chamber is an expanded line area (made of quartz) containing a probe input for a chamber thermocouple and surrounded by an encased insulated heating element. Power to the heater is manually controlled (ON/OFF only) from the control panel combustion heater switch and maintains the chamber's temperature above that required for oxidation of propane. In operation, complete oxidation occurs with the chamber output having a $CO_2/O_2$ ratio which is variable, dependent upon the $CO_2$ and propane flow rates into the chamber (air input is a constant). The chamber output is fed to a radiant series cooler to reduce temperature to a safe level and then is returned to the top of the bellows.

Features. A safety circuit (Fig. 5) used to control propane flow will not allow the solenoid valve to be opened unless the proper oxidation conditions exist. The conditions monitored are the $O_2$ output level in the Temperature/Humidity subsystem, the compressor output pressure at the accumulator, and the chamber temperature.

The chamber thermocouple output can be monitored by the digital voltmeter to determine temperature during preheating or other conditions as desired.

The following expendables are required for operation:

| | | |
|---|---|---|
| 1. | $CO_2$ | Air Products size-D tank (4 in. by 17 in.) |
| 2. | Propane (CP) | Air Products size-D tank (4 in. by 18 in.) |
| 3. | Distilled water | Reservoir capacity (approximately 2.33 quart) |
| 4. | Surgical sponge | Part-Davis gauze (approximately 4 in. by 8 in.) |

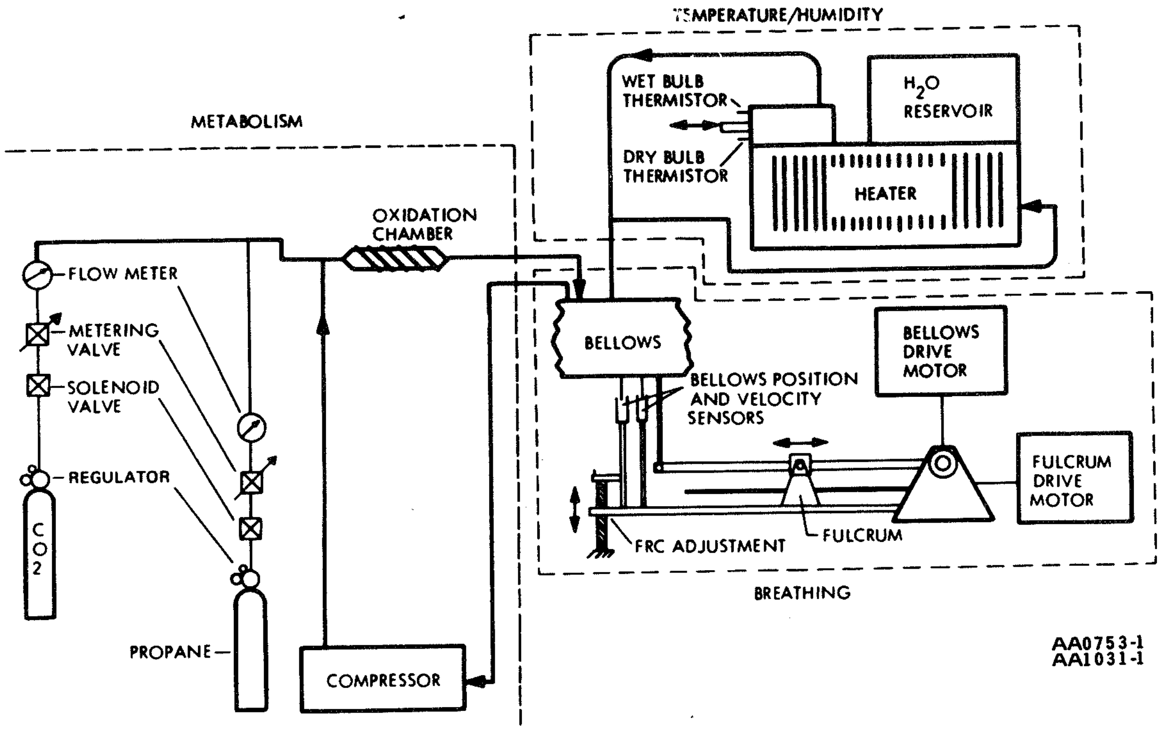


Figure 1. BMS subsystems.

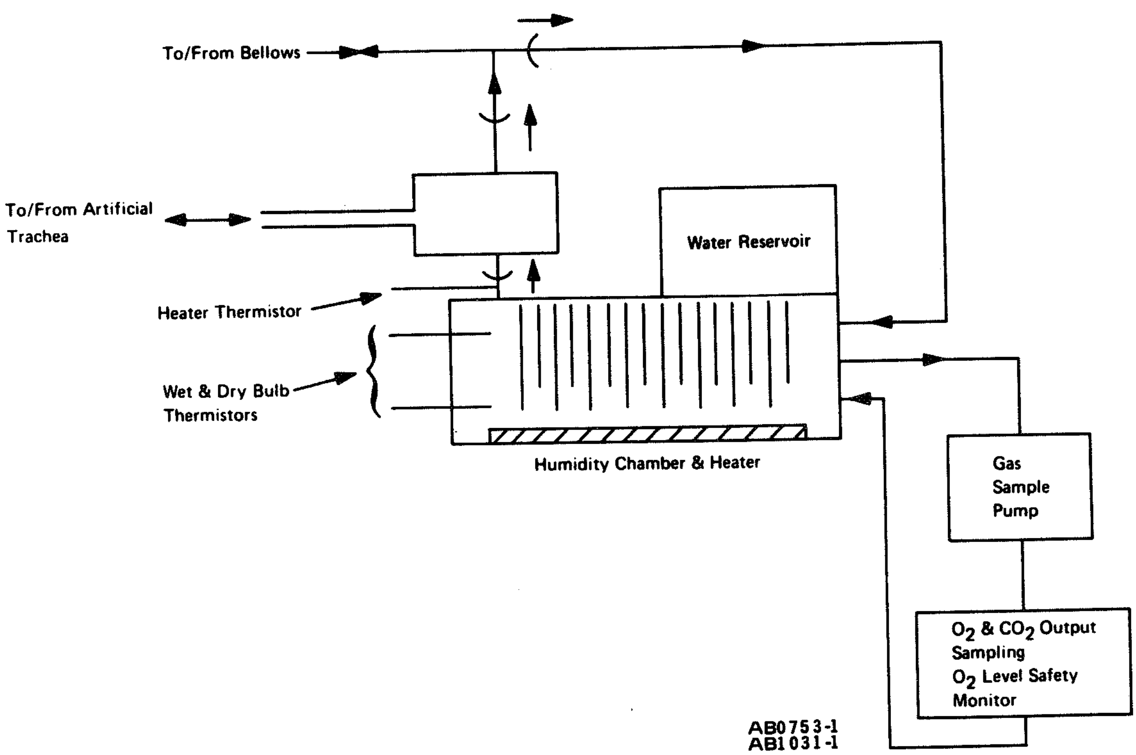


Figure 2. Temperature/Humidity subsystem.

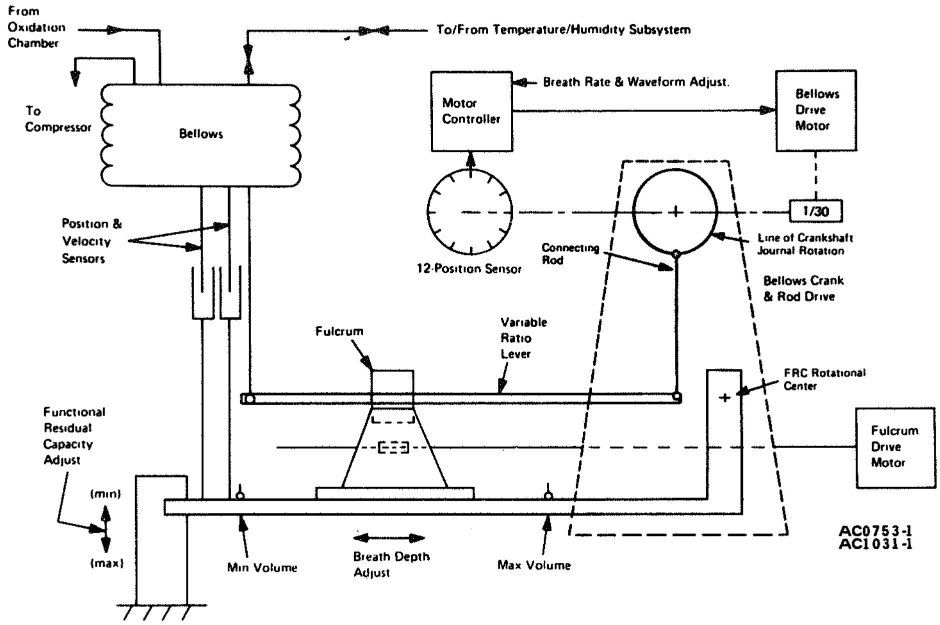


Figure 3. Breathing subsystems.

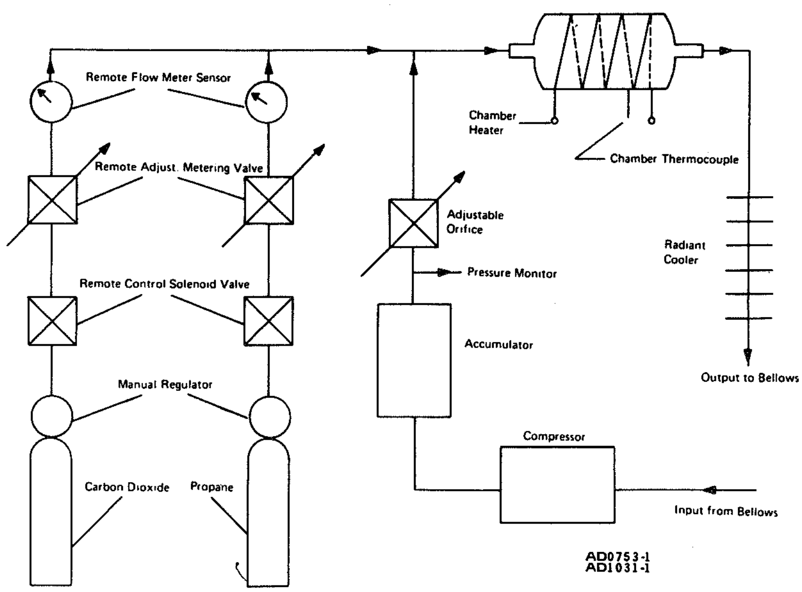


Figure 4. Metabolism subsystem.

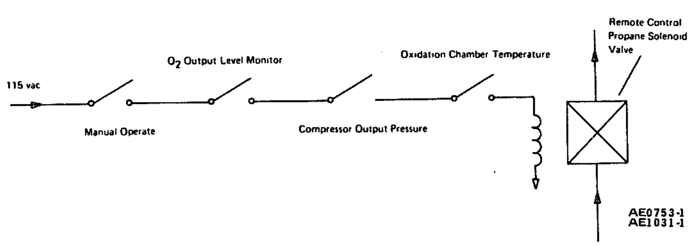


Figure 5. Metabolism subsystem's safety circuit.