

Low-Temperature Tests of Rescue Breathing Apparatus¹

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The U.S. Army Research Institute of Environmental Medicine tested two samples each of three different types of rescue breathing apparatus (RBA) to determine how long both could be worn by operators in sub-freezing temperatures. Phase-I tests were performed after overnight cold-soaking at the test temperature; Phase-II tests were performed after overnight storage at + 20°C. Successful performance was determined as proper operation for at least one-half of the certified duration of the oxygen supply without either exhaustion of the oxygen supply, increase of inspired CO₂ above physiologically acceptable levels, or increase in breathing resistance above tolerable levels. In Phase I, the Scott "Rescue Pak" operated successfully at - 20°C, while the Draeger 174-A, and the McCaa units operated successfully at - 10°C. In Phase II, the Scott unit operated successfully at - 25°C, the Draeger at - 20°C, and the McCaa at - 15°C. None of the RBA types appeared well designed for use in sub-freezing temperatures.

Introduction

The U.S. Army Research Institute of Environmental Medicine (USARIEM) is a research facility within the jurisdiction of the Medical Research and Development Command under the Surgeon General of the U.S. Army. USARIEM has been dedicated to the investigation of human medical, physiological and psycho-logical response to the stresses of heat, cold, altitude, and exercise since its inception in 1958. At the request of the U.S. Bureau of Mines (BuMines), USARIEM undertook to establish low-temperature performance limits of three types of currently certified rescue breathing apparatus (RBA) of closed-circuit, or recirculating, design. These three types of RBA have been certified for use by the U.S. Mine Safety and Health Administration, but only for environmental temperatures above the freezing point of water (0°C). BuMines needed to know the lowest environmental

temperatures down to - 30°C (- 22°F) in which each RBA design would function properly, in case the RBA needed to be used in colder temperatures during winter. Proper functioning was defined as providing a breathable air mixture containing at least 21% O₂ with CO₂ levels exceeding 3% for no more than 3 min and 4% for no more than 1 min, at inspiratory and expiratory breathing efforts tolerable to the subject. The minimum duration of proper operation was set at one-half of the certified duration for each RBA at above freezing temperatures.

¹ Originally published on July 1981, Bureau of Mines, contract report, under Working Fund Agreement JO188026, U.S. Army Research Institute of Environmental Medicine.

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Energy expenditures of the operators were to be varied cyclically from rest (105 W), through light work (350 W), to moderately heavy work (700 W) to simulate rates of O₂ consumption, CO₂ production and respiratory water vapor emission encountered in typical mine rescue operations. The environmental clothing was to be suitable for the testing temperatures.

Two types of pre-test storage conditions were required for each RBA. The more stringent condition was overnight storage at the testing temperature to simulate storage in unheated shelters followed by immediate use. The less stringent condition was storage overnight at room temperature (15–20°C) to simulate storage in heated spaces. O₂ bottles were to be filled to their specified pressures at room temperature and CO₂ scrubbers were to be in place, but not connected (if using replaceable canisters), prior to overnight storage. Fogging and frosting of facemask eyepieces were expected by BuMines and therefore were not criteria for failure of the RBA. USARIEM required that the eyepieces be kept clear for the personal safety of the test subjects. Hot air from industrial blower-types heat guns was used for this purpose and was very effective.

An experienced technician from BuMines assisted USARIEM personnel in training the test subjects, inspecting RBAs prior to and after each operational test and in cleaning, drying, reassembly and maintenance of RBAs between tests. In addition, distributor representative, from suppliers of currently marketed RBAs assisted in the training of personnel in operation, disassembly and maintenance of their products. In this way, failures of RBAs during operational test due to improper assembly, maintenance or operation were minimized.

Methods

1. Apparatus evaluated. Two samples of each of 3 types of commercially designed RBA were evaluated.*

a. RBA unit Type “D”. Draeger model BG-174A self-contained oxygen breathing

apparatus, distributed by National Mine Service Co., Pittsburgh, Pennsylvania. This unit has a certified 4-hour O₂ supply from replaceable bottles refilled to 3200 psi and disposable metal CO₂ scrubbing canisters using NaOH as the absorbent. The optional facemask with manually operated wiping device for the inner surface of the eyepiece was tested. This RBA is currently in production.

b. RBA unit Type “M”. McCaa 2 hour oxygen breathing apparatus, formerly distributed by Mine Safety Appliances Co., Inc., Pittsburgh, Pennsylvania. This unit is equipped with a certified 2-hour O₂ supply from replaceable bottles prefilled to 150 (atmospheres 2250 psi) and an integral compartment to hold the Cardoxide soda-lime scrubbing agent that requires recharge from pre-measured containers before each use. This unit is no longer in production; a large number are still in use throughout the mining industry, however.

c. RBA unit Type “S”. Scott model 900050-00 4 hour “Rescue Pak,” distributed by CSE Mine Service Co., Monroeville, Pennsylvania. This unit is equipped with a certified 4-hour O₂ supply from replaceable bottles filled to 1980 psi and a CO₂ scrubber containing LiOH in a disposable metal canister. This unit is currently in production.

2. Preparation prior to test. Preliminary testing showed that RBAs would not function properly in sub-freezing temperatures unless they were thoroughly dried after each use. After each use, RBAs were washed and rinsed thoroughly, disinfected with a water-based 1:1000 v/v solution of benzalkonium chloride, rinsed with 95% ethanol as a drying agent and dried with heated air from commercial hair driers. Particular attention was paid to the drying of sharp bends or water traps within the breathing circuit and all corrugated hoses, which were shaken out thoroughly and hung vertically while the hot air was blown through them.

O₂ bottles were pressurized to the specified levels at room temperature and installed in

* Reference to specific brands, equipment, trade names and manufactures in this report is for identification purposes only and does not imply endorsement by U.S. Bureau of Mines, the U.S. Army or the U.S. Department of Defense.

the RBA prior to overnight storage, but not turned on until the start of each test. CO₂ scrubbers for RBA Type-M were recharged prior to overnight storage; those for RBA Types D and S had replacement canisters installed prior to storage. However, the end caps were not removed until just before test when the scrubbers were connected into the breathing circuit.

3. Testing conditions. During Phase I, operations tests of all RBA units were conducted after overnight storage at the testing temperature. This phase was designed to simulate storage of RBAs in unheated buildings, followed by immediate use without re-warming. All facemasks were put on at +20°C, however, to prevent contact frostbite. All O₂ bottles were filled to the prescribed pressure at +20°C prior to overnight cold-soaking; their pressures were therefore reduced at each testing temperature according to the Gas Laws. This only affected pressure-operated functions, however, since the same quantity of O₂ was available for metabolic utilization. Figure 1 shows the planned sequence of testing temperatures for Phase I. In this experimental design, all units were first to be tested at -20°C, those that passed were to then be tested at -30°C, while those that failed were to be tested at -10°C. The subsequent test was then to be conducted at a temperature halfway between that of the last failed test and that of the last successful test (or 0°C, if no tests were passed).

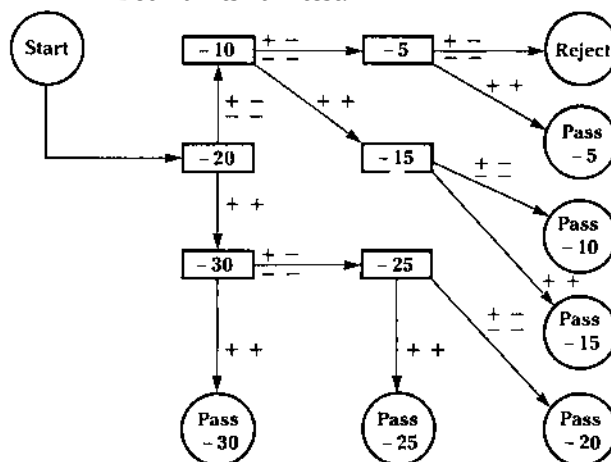
Phase II was begun after all tests in Phase I were completed. During Phase II, operational tests of all RBA units were conducted after

overnight storage in the ante room of the climate-controlled chamber (approximately 20°C) to simulate storage in heated spaces. Operational tests that were successfully passed in Phase I were not repeated; the initial testing temperatures in Phase II were halfway between the lowest operational temperature achieved in Phase I and -30°C. The succeeding temperatures were then determined as in Figure 1. The temperatures investigated were in multiples of 5°C from -5° to -30°C; this range is to great to permit interpolation of endurance times between those investigated.

The controlled-temperature room was the central segment of a wind tunnel of

Code:

- ++ = Both units successfully complete test.
- + - = One unit successfully completes test.
- = Both units fail test.



**Figure 1. Test Schedule for Phases I & II:
Air Temperatures in Degrees Celsius.**

Table 1. Physical characteristics of test subjects.

RBA assigned	Age (yr)	Height (cm)	Weight (kg)	Body surface area (m ²)	Body fat (%)
D	19	179.4	74.7	1.93	20
	22	169.9	64.9	1.75	17
M	35	175.6	74.1	1.90	19
	23	170.5	66.5	1.77	16
S	22	177.0	83.6	2.01	19
	23	173.7	75.6	1.90	18
Alternate	22	175.7	74.6	1.90	15
	21	178.5	71.5	1.89	15

dimensions 18.3 x 4.6 x 3.3 m. Temperatures were controlled to within $\pm 0.4^{\circ}\text{C}$ and wind speed was controlled $1.8 \pm 0.2 \text{ m} \cdot \text{s}^{-1}$, as specified by BuMines. This low wind speed was used to insure that the temperature effect on equipment was the independent variable, rather than any wind-chill effect on the exposed skin of the operators.

4. Experimental subjects. Eight male volunteers were recruited from the military tests subject platoon available to USARIEM. All subjects signed statements of informed consent after being given a detailed explanation of the procedures and risks involved.* Their anthropometric characteristics are shown in Table 1.

Six subjects were each given random assignments to and trained on one of the RBA types, while the other 2 subjects were trained on all 3 types of devices. All subjects learned proper techniques for donning, doffing and cleaning the facemask, operating the bypass valve when needed and reading the O_2 pressure gauge. Replacement of O_2 cylinders and CO_2 scrubbing elements was done by experimenters rather than by subjects.

Subjects were issued the entire U.S. Army cold-weather clothing ensemble, which they selected the proper combination of garments for each specific test. Subjects were allowed to remove caps or mittens and unfasten garments for ventilation at will, with the exception that the RBA harness had to be left secured, as in the real-world situation.

5. Work rates. A cycle of work and rest was established to simulate energy expenditures approximating those that could be sustained during actual mine rescue operations requiring RBA. During the work cycle, subjects first walked for 20 min on a motor-driven treadmill at a speed which elicited an average oxygen uptake (VO_2) of $1 \text{ liter} \cdot \text{min}^{-1}$ (energy cost of 350 W, equal to light work), then walked for 10 min at a higher speed requiring VO_2 of $2 \text{ liters} \cdot \text{min}^{-1}$ (energy cost of 700 W, equal to moderately heavy work) and then sat on wooden benches

for a 10-min rest period. The 40-min work-rest cycle was repeated until failure of the RBA occurred or one-half its normal oxygen duration had elapsed. Treadmill walking speeds were established in advance of operational testing by having the 6 primary subjects walk on the treadmill while the walking speed was adjusted until their average oxygen uptake for the group was within 10% of the desired values of 1 and 2 $\text{liters} \cdot \text{min}^{-1}$. Subjects were dressed for -20°C and carried the RBA for weight, but breathed room air. Expired air from each individual was collected by timed Tissot spirometry. VO_2 was calculated from respiratory minute volume and the O_2 and CO_2 content of inhaled and expired air as determined by gas analysis using a zirconium oxide O_2 analyser (model S-3A, Applied Electrochemistry Inc., Sunnyvale, California) and an infra-red CO_2 analyser (Model LB-2, Beckman Instruments, Inc., Fullerton, California). Final treadmill speeds were 1.07 and $1.75 \text{ m} \cdot \text{s}^{-1}$ (3.85 and $6.30 \text{ km} \cdot \text{hr}^{-1}$), respectively. These speeds elicited average VO_2 values for the group of 1.10 ± 0.11 and $1.94 \pm 0.18 \text{ liter} \cdot \text{min}^{-1}$ (mean + S.D.).

6. Operational test procedures. Subjects reported to the laboratory in sufficient time to be harnessed, dressed and ready to start the operational tests by 0815 or, in the case of some tests of Type-M units, by 1030. These starting times were dictated by the time required after test to inspect, disassemble, clean, dry and reassemble the RBAs prior to overnight cold-soaking. After reporting, subjects inserted a 7-cm rectal thermistor temperature probe, and donned an 8-point skin temperature thermocouple harness. Over this, they dressed in selected items of the U.S. Army standard cold-weather clothing ensemble which were appropriate for the testing temperature and vapor barrier insulated boots. This clothing is similar to standard commercial cold-weather work clothing for weight, bulk and warmth. However, it is more durable and designed as an integrated system in many layers for extreme cold-weather protection. The first subject to finish dressing reported to the ante room of the environmental chamber, where he donned and adjusted the facemask. The operator then put on the RBA, either after

* Human subjects participated in this study after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on use of Volunteers in Research.

entering the environment chamber if the unit was cold-soaked, or before entering the chamber if the unit was not. The mask was connected to the RBA by the experimenters and the operator then turned on the O₂ supply and cleared the mask. As soon as the RBA was functioning properly the operator went to his assigned place on the treadmill and sat down on a wooden bench while the temperature monitoring harnesses, the inspired air sampling lines and the facemask pressure measuring lines were connected. When the first subject was completely connected, recording began and then the RBA donning and connected procedure was repeated with the next subject while the first subject remained seated at rest. When the last subject had been connected, the benches were removed from the treadmill, and the first work cycle was begun. At this time, the endurance time clock for measuring was started.

7. Parameters measured. The endurance time of each RBA until failure was recorded and parameters indicating performance of the RBA, the subjective responses of the operators were measured during each experimental test. The body core and selected skin temperatures of the subject were measured only for safety reasons and will not be reported.

a. Endurance time. The endurance time of each RBA to failure or to at least one-half of its certified endurance time was measured from the start of the first work-rest cycle. Up to 30 min could have elapsed from the time the first subject's O₂ bottle was turned on until the first work cycle began. This time was taken up in preparing the second (or second and third) subjects for testing (donning mask, connecting air hoses, turning on O₂, clearing mask and connecting sensors to recording instruments). During this period, the first operator sat quietly at rest, consuming O₂ at a rate of about 0.3 liter · min⁻¹, or about 9 liters over a 30-min period. This was equivalent to walking at the slow speed for 9 min, and represented only a small portion of the total O₂ capacities of 150-300 liters.

Endurance time was terminated when the O₂ supply became depleted, when the CO₂ levels exceeded tolerance limits, or when the

inspiratory or expiratory resistance to breathing became too great. If the RBA has functioned properly for at least one-half its nominal duration, the subject was requested to continue as long as possible thereafter, to gain a measure of the unit's actual endurance. However, some tests were terminated before failure of the RBA because of the need to prevent foot blisters which would interfere with the subject's participation in subsequent tests.

b. Inspired O₂ and CO₂ concentrations. The air in the inspired air hose to the facemask was continuously sampled to monitor inspired O₂ and CO₂ concentration. Sampled air was returned to the expired air hose to maintain volume within the breathing circuit. Sampling and return ports were established by fitting the mid-point of each inspired and expired air hose with a nylon tubing connector 4.25 inches long and 1 inch i.d., made air-tight with screw-locking hose clamps, which lengthened the air hoses by approximately 2 inches. The tubing connectors each were drilled, tapped, fitted with a single 1.8 inch i.d. threaded brass Luer-lock^R male nipple and reinforced with epoxy. A mating female Luer-lock fitting was attached to a short length of 3/16 inch i.d. Tygon^R tubing to provide attachment to the female gas-seal portion of a 1.8 inch i.d. quick-disconnect Swagelok^R coupling. These couplings were used to connect the sampling ports to 3/16 inch i.d. Thyon air sampling lines leading to the gas analysers located outside the climate-controlled chamber. A combined pump and flowmeter (Flow controller model R-1, Applied Electrochemistry Inc., Sunnyvale, California) continuously sampled inspired air and circulated it, in turn, through a CaSO₄ drying tube, the O₂ analyser, the CO₂ analyser and back to the expired air hose of the RBA. Warm air from heat guns was used to de-ice the sampling port and fittings whenever flow resistance was observed to increase.

At a flow rate of 500 ml · min⁻¹, stepwise changes of CO₂ concentration fed into the sampling ports showed the combined time for line flushing and meter stabilization to vary between 45 and 65 sec, depending on which of the 4 pairs of sampling and return lines was being evaluated. Thus the lag in reading

the inspired gas concentrations was approximately one min. When a CO₂ concentration above 3% which was increasing at a rate greater than 1% each min was observed, it was considered to have already reached 4% and thus had exceeded the criterion for termination. This occurred during the Phase-I test of unit D-1 at - 15°C.

O₂ and CO₂ indicator readings were read visually and recorded every 2-3 min, unless termination criteria were being approached. Subsequent to the experiment, the recorded data were digitized and graphed on the HP-9825 data acquisition and plotting system. Two separate gas analysis systems were used, which permitted gas sampling and analysis to be continuous in all experiments where only two RBA units were tested simultaneously. To permit testing of 3 RBA units at once during the initial Phase-I tests at - 20°C, a manifold system was used to alternately switch the air sampling and return lines of two RBA units into one of the gas analysis systems. Gas concentration data from these units was recorded every 3-4 min rather than every 2 min.

c. Breathing circuit temperatures.

Temperatures of the CO₂ scrubber surface and at 5 points within the closed breathing circuit were monitored. Copper-constantan thermocouples were soldered to the mid-point of the surface of the CO₂ scrubbers (permanently in the case of the Type-M units and just after installation of the disposable canister for the Type-D and -S units). Thermocouples for monitoring air temperature were positioned in the approximate center of the air passages just up-stream of the inlet to and down-stream of the outlet from the facemask, at the CO₂ scrubber inlet and outlet and at the outlet of the breathing bag. The thermocouples were referenced and recorded on a data acquisition and plotting system based on the model HP-9825 programmable calculator (Hewlett-Packard Inc., Lexington, Massachusetts). This system consisted of an HP-9825A programmable calculator, and HP-3455A digital voltmeter, and HP-3495A scanner, and HP-59308A timing generator, and HP-59309 digital clock, and HP-9866A line printer, and HP-9872A x-y plotter, and a model UTR-AS 32 channel thermocouple reference junction

(Kaye Instruments Inc., Bedford, Massachusetts). Breathing circuit temperatures were printed out every minute for visual inspection and real-time plots were made of environmental temperatures and test subject body temperatures to monitor progress of each experiment. Breathing circuit temperatures were recorded on magnetic tape and later used to construct the final temperature plots on the same time scale and the facepiece inspiratory and expiratory pressures.

d. Inspiratory and expiratory pressures. Respiratory pressures exerted by the operator to overcome resistance within the breathing circuit were measured with a variable-reluctance type differential pressure transducer (Model MP-45, Validyne Engineering Corp., Northridge, California) equipped with a stainless-steel diaphragm for the ± 50 cm-H₂O range. The transducer served as the variable impedance arm of the two-arm bridge operating at 3 kHz. Each transducer was paired with a carrier-demodulator unit (Validyne Model CD-19) whose dc output was proportional to the impedance mismatch of the two current arms. Each transducer-demodulator pair was calibrated against a water manometer by adjusting the signal gain to yield an output of 5V dc at 40 cm-H₂O. The calibration for all units was linear throughout this range. Bridge imbalance could be achieved with no differential pressure across the transducer by inserting a shunt resistance in parallel to the transducer arm. Five shunt resistors were chosen to produce the same demodulated voltage output at no differential pressure as were obtained with differential water manometer pressures of +5, ± 10 , ± 15 , ± 25 , and ± 40 cm. The gain thus could be checked for all signal channels before and after each operational test without the need for applying a known hydrostatic pressure. All transducer calibrations were validated after installation against hydrostatic pressure on two occasions 3 weeks apart, however, to insure validity of the easier method.

Four pressure-sensing transducers were isolated from vibration by mounting on a cushioned rack which was suspended from the ceiling of the environmental chamber above the treadmill. Each was connected to a

facemask through a 6 foot length of Teflon tubing (1/4 inch i.d.) which terminated at the facemask with a quick disconnect Swagelok fitting, which the gas lock on the facemask side.

The pressure-sensing tube was connected to the interior of the nose-cup of each facemask by attachment to a 1/4 inch i.d. threaded brass pipe nipple which penetrated the mask. For the Type-M and -S masks, the rubber outer shell and inner nose-cup were punctured with a slightly undersized cork borer. The fully threaded nipple was screwed in just far enough to permit installation of a brass washer and brass nut on the inside. Self-vulcanizing rubber (SVR) compound was used as a gasketing material. And identical washer and nut were installed from the outside and tightened to make an air-tight seal after the SVR cured. For the Type-D facemask, the voice-transmission diaphragm was removed and the louvered metal diaphragm cover was drilled out to accept the 1/4 inch i.d. brass nipple. The nipple was mounted in the approximate center of a 1/8 inch thick aluminum disc which replaced the diaphragm in the mask. SVR, washers and nuts were used to make an air-tight seal. The gas-sealing portion of Swagelok quick-disconnect couplings were installed on the outer ends of the nipples. Mating portions were installed on the end of the Teflon pressure-sensing lines.

Carrier-demodulator units were powered by a 10-channel transducer control system (Model MC-10, Validyne Engineering Corp.). The pressure-signal voltages from each carrier-demodulator unit fed 3 high-impedance input channels. One channel provided input to a 10-channel strip-chart recorder (Model 7 Polygraph, Grass Medical Instrument Co., Quincy, Massachusetts) for visual monitoring during the study, another to the input channels of a Honeywell model 5600C tape recorder/reproducer for later data processing and the third to a 10-channel (HP Model 3495A) to provide a programmable switching network for data sampling from each subject. The HP data-acquisition system (scanner, voltmeter, timer, plotter) was used to interrupt and switch subjects at one-minute intervals and sample the pressure signal every 50 msec. Maximum inspiratory and

expiratory pressures were determined by comparison of the magnitudes of successive voltmeter signals until phase reversal occurred. Maximum and minimum values for each respiratory cycle were stored and averaged over successive 1-min periods; the standard deviations were calculated and the results stored on tape for later graphing on the HP-9872 x-y plotter.

The treadmill capacity was 4 subjects. Although 4 identical systems for gas sampling and temperature and pressure measuring were available, generally only the two RBAs of the same design were evaluated at the same time. The exceptions were that the initial tests at -20°C in Phase I were performed on two successive testing days; one of each of the 3 types of RBA was tested each day. This procedure insured that at least one entire measuring system was available for use at all times as a back-up. In the single case of equipment failure, the subject was re-connected to an operating pressure transducer with only 10 sec loss of data.

e. O₂ bottle pressures. The pressure in each O₂ supply bottle was read visually at the end of each portion of the work cycle. Pressures below 100 psi or 6.5 atm were used as a termination criterion.

Pressures were normally read from the operator's O₂ pressure gauge, except for the Type-S apparatus which became defective early in the study. The pressures in the Type-S units were read from the O₂ bottle gauge.

f. Subjective responses of users.

Subjects were asked to rate their difficulty in breathing and seeing and the comfort of their facemask and RBA backpack during each period of the work cycle. "Difficulty" was judged on a 5-point scale ranging from "not difficult" to "very difficult"; "comfort" was rated on a 5-point scale ranging from "quite comfortable" to "quite uncomfortable." The data on difficulty of seeing were invalidated early in each operational test by the necessity for defogging the defrosting the facemask eyepieces with heat guns for the safety of the operators. The different RBA types varied little in this regard: defogging and defrosting were initially required during the first slow or fast walk and frequently thereafter throughout each test. The eyepiece wiping mechanism in the Type-D facemask, which was not wetted,

helped reduce fogging. It was of no help when frosting began 5-10 min later, however.

During each rest period, leaks in and around the facepiece were tested for using isoamyl acetate. Three cardboard boxes of 1-m³ volume, with suitable cut-out in the bottom, were placed one at a time over the head of the seated subject. One of the three boxes contained a pad of 4 x 4 inch gauze sponges saturated with the testing agent; the location of the box containing the agent was varied with each trial. The box with the agent was readily identified during preliminary tests with the facemask seal disrupted by placing a pencil beneath the mask. No leaks were ever detected during any of the operational tests.

g. Test subject body core and skin temperatures. Rectal temperature was monitored by thermistor probe and skin temperatures by thermocouple at 8 locations (center forehead, right cheek, earlobe, chest, forearm, little finger nailbed, calf, and big toe nailbed), using the HP data-acquisition/recording system. Rectal temperatures at or below 35°C or any skin temperature below 4°C were the predetermined criteria for termination of the study for the test subject so affected, but were never achieved. Subjective reports of skin irritation and impending blisters due to treadmill walking for prolonged periods in the Army standard vapor-barrier boots were also used as a termination criterion, but only after the expected "half-life" of the particular RBA had been achieved. Long experience has shown that feet must be conditioned slowly to permit prolonged walking in vapor-carrier boots, due to the macerating effect of accumulated sweat which cannot evaporate. To help prevent foot blistering, subjects walked for progressively longer periods on the treadmill each day during training and preliminary check-testing of the experimental systems. During the operational tests, once the RBA units had successfully operated for one-half their nominal endurance time, subjects were asked to continue testing as long as possible. They were cautioned not to induce any foot blisters which, *ipso facto*, would have prevented them from any further testing until they had resolved. Successful tests were terminated for this reason alone, despite the RBA unit being fully operational at that time. This was an

unfortunate by necessary requirement to preserve the health of the subjects and to insure completion of the study

Results

1. Endurance time. The three types of RBA differed from each other not only in their ability to function in the cold but also in their manner of failure. In addition, each RBA type responded differently when tested in the cold after cold-soaking (Phase I) that after overnight storage at 20°C (Phase II).

a. Phase-I testing. The endurance times achieved by each type of RBA during the Phase-I operational tests are shown in Table 2. Of the 3 types of apparatus, only Type S was able to function for at least one-half its nominal endurance time at -20° after cold-soaking. Unit S-2 operated for 141 min at which time the O₂ supply was reduced to the predetermined safety level of 100 psi. Unit S-1 operated for 200 min, at which time testing was discontinued to prevent foot blisters. The O₂ pressure remaining at termination was 220 psi.

The Type-S units did not operate properly at temperatures below -20°C because of failures within the O₂ supply system which caused venting to the atmosphere, prematurely exhausting the O₂ supply. At -25°C, unit S-1 ran out of O₂ after only 70 min. Post-test inspection did not reveal a definite cause for the failure, but the rapid O₂ depletion was consistent with the hypothesis that the O₂ by-pass valve never closed properly after initial purging of the breathing circuit. O₂ could have been constantly released into the circuit and thence to ambient air by escaping outward beneath the seal of the facemask. Unit S-2 operated properly for 190 min at which point the O₂ supply had been reduced to 100 psi.

At -30°C, unit S-1 sounded its O₂ pressure alarm after 52 min, at a tank pressure of 500 psi. The alarm did not shut off properly, but continued to sound for 8 min, at which time that tank pressure had been reduced to 200 psi. The test was terminated at a tank pressure of 100 psi after a total endurance

time of 80 min. The inspired air sampling lines to unit S-2 were not assembled properly before the test at -30°C , which invalidated the test. Since unit S-1 failed at that temperature, unit S-2 was not retested. There were no CO_2 scrubber failures or impending failures observed during any of the Phase-I tests of the Type-S apparatus.

The Type-D apparatus operated properly at -10°C for 160 min, at which time testing was discontinued to prevent foot blisters. The remaining O_2 pressure was 450 and 750 psi in units D-1 and D-2, respectively. At -15° and -20°C , the Type-D apparatus failed because of inability to remove CO_2 properly at the start of the tests; at -10°C the initial CO_2 scrubbing action was marginal, but became effective after about 45 min. The lower the testing temperature, the poorer the initial scrubbing action until, at -20°C , unit D-2 failed to scrub CO_2 at all at the start of the test while unit D-1 lasted only 4 min.

The Type-M apparatus also experienced failures due to inadequate CO_2 scrubbing. These units scrubbed adequately at the start of each test but the length of time the

scrubbers were effective was inversely related to the testing temperature. Throughout each test, the CO_2 concentration of the inspired air progressively increased until the upper tolerance levels were reached, usually during the fast walk portion of the work cycle. At -10°C , units M-1 and M-2 lasted 75 and 67 min, respectively thus achieving the minimum duration of one hour for the Type-M apparatus. At -15°C , the scrubbers on M-1 and M-2 were able to maintain acceptable CO_2 concentrations for only 30 and 28 min, respectively; at -20°C , the corresponding endurance times were 23 and 27 min.

b. Phase-II testing. The endurance times achieved by each type of RBA during the Phase-II operational tests are shown in Table 3. Again, the types of RBA differed in their ability to function and their manner of failure. The Type-S apparatus operated at -25°C for more than 2 hours. Unit S-1 operated until the O_2 supply unexpectedly became exhausted at 187 min with the tank gauge still reading 400 psi. Unit S-2 was still operating at 211 min when the test was terminated to prevent foot blisters; the

Table 2. Endurance time and condition of each RBA at end of low temperature operational tests. Phase I: overnight storage at temperature of subsequent operational test.

Test temperature ($^{\circ}\text{C}$)	RBA unit no.	Endurance time (min)	Pass/Fail test	Condition at end of test
-10	D-1	160	P	operational
	D-2	160	P	operational
	M-1	75	P	CO_2 too high
	M-2	67	P	CO_2 too high
-15	D-1	12	F	CO_2 too high
	D-2	10	F	CO_2 too high
	M-1	30	F	CO_2 too high
	M-2	28	F	CO_2 too high
-20	D-1	4	F	CO_2 too high
	D-2	0	F	CO_2 too high
	M-1	23	F	CO_2 too high
	M-2	27	F	CO_2 too high
-25	S-1	200	P	operational
	S-2	141	P	out of O_2
	S-1	70	F	out of O_2
	S-2	0	P	operational
-30	S-1	80	F	out of O_2
	S-2	(improper test, not repeated)		

remaining O₂ pressure was 400 psi. At - 30°C, unit S-2 failed at 71 min when the breathing effort became too great for the operator. No signs of blockage were observed when the unit was inspected. The constant-flow valve was suspect, as, prior to failure, the breathing bag did not inflate fully, no hissing sound was heard and banging the hoses to the facemask did not relieve the breathing effort. The unit was retested at - 30°C the next day and failed after 101 min due to high breathing effort; frost and ice were discovered obstructing the inlet to the CO₂ scrubber. At - 30°C, unit S-1 operated properly for 2 hours.

The Type-D apparatus operated successfully at - 20°C: unit D-1 for 136 min and unit D-2 for 134 min. Both units were still operational when the subjects complained of impending foot blisters and discontinued the test; remaining O₂ pressures were 1200 and 950 psi, respectively. Unit D-2 required high breathing effort from its operator from 29 min on; the operator could not maintain the fast walk for more than 3-5 min without slowing down for 30 sec. However, an adequate air

supply was available when this was done, so the test was considered successful. At - 25°C, unit D-2 experienced a blockage in the inspired air line at 102 min; inspection revealed frost and ice in both the inspired and expired air lines. Unit D-1 operated successfully for 120 min when test was terminated due to prior failure of unit D-2. At - 30°C, unit D-2 did not experience frost or ice buildup, but instead operated for 160 min at which time the CO₂ scrubber permitted the inspired CO₂ level to exceed the safety limits. However, unit D-1 failed when alarm whistle sounded at 650 psi at 93 min and would not shut off. The O₂ tank became exhausted after 6 min.

The Type-M units operated at - 20°C for 68 and 64 min (units M-1 and M-2, respectively), at which time the inspired CO₂ exceeded tolerance limits. This was so close to the 1-hour criterion that the units were also tested at - 15°C.

Units M-1 and M-2 then lasted 68 to 98 min, respectively, before the CO₂ concentration exceed tolerance limits. The more

Table 3. Endurance time and condition of each RBA at end of low temperature operational tests. Phase II: overnight storage at + 20°C.

Test temperature (°C)	RBA unit no.	Endurance time (min)	Pass/Fail test	Condition at end of test
-15	M-1	68	P	CO ₂ to high
	M-2	98	P	operational
-20	D-1	136	P	operational
	D-2	134	P	excessive breathing resistance
-25	M-1	68	P	CO ₂ too high
	M-2	64	P	CO ₂ too high
	D-1	120	P	operational
	D-2	102	F	excessive breathing resistance
	S-1	187	P	out of O ₂
	S-2	211	P	operational
-30	D-1	93	F	out of O ₂
	D-2	160	P	CO ₂ too high
	S-1	120	P	operational
	S-2	71	F	excessive breathing resistance
	S-2	101	F	excessive breathing resistance
		(repeat)		

conservative value of -15°C was accepted as the minimum safe operating temperature for these units after storage at 20°C .

c. Endurance limits. The coldest temperatures in which each type of RBA was observed to operate for at least one half its rate duration during Phases I and II are summarized in Table 4. After overnight cold-soaking and subsequent use at the same temperature, the Type-S apparatus can be expected to operate properly for at least 2 hours down to the temperature of -20°C , as the minimum endurance time observed was 141 min at that temperature. The Type-D apparatus appeared adequate for at least 2 hours down to -10°C , as both units operated for 160 min at that temperature and were still operational when the test was terminated. The Type-M units lasted 1 hour at -10°C , but the minimum endurance of one of these units was 67 min. Sample variations might reduce that margin of safety; heavy workloads should be avoided during last 10-15 min of the hour's operation, if possible.

After overnight storage at 20°C , the Type-S apparatus can be expected to operate properly for at least 2 hours down to a temperature of -25°C . The minimum endurance time observed was 187 min. The remaining O_2 pressure should be monitored carefully, as exhaustion of the O_2 supply was the failure mode at the temperature. The Type-D apparatus appears adequate down to -20°C , as the minimum observed endurance time at the temperature was 134 min with both units remaining operational (the test was terminated due to foot soreness). The Type-M apparatus appears adequate down to -15°C ; the minimum endurance time was 68 min. The endurance time for this apparatus should

be strictly limited to 1 hour, as the failure mode was excessively high levels of CO_2 .

2. Inspired O_2 and CO_2 concentrations.

The concentrations of O_2 and CO_2 inspired air are shown in Appendix A (in Figures 2-10 for Phase-I tests, in Figures 11-17 for Phase-II tests and in Figures 18-19 for control tests). These figures and those that follow for temperatures within the breathing circuit and respiratory pressures are all on the same time scale to facilitate comparison between parameters. The time line began (time = 0) when the first RBA was connected; the time of connection of the other unit of each pair is shown by the start of the plot for that unit. Endurance time was not measured from the time zero of these figures but rather was measured from the beginning of the work-rest cycle which is plotted on each figure as WR. Thus, data generated by the first RBA unit to be connected has been preserved, while still permitting direct comparison of the endurance time of both units as a function of the same work-rest cycle.

a. Phase I: Figures 2, 3, and 4 show the inspired air composition for the Type-S apparatus at -20 , -25 and -30°C , respectively. The successful endurance test was at -20°C . At all temperatures, O_2 rose quickly and remained in the 80-100% range throughout the test, except when the O_2 supply was near exhaustion; then it dropped slightly (Figure 2, unit S-2). Inspired CO_2 never rose above 2% during any operational test, and usually was below 0.5%, except during the fast walk portion of the work cycle. Neither of the Type S units was consistently better at scrubbing CO_2 , that the other, as both exhibited nearly complete scrubbing ability for prolonged periods (Figure 2, unit

RBA type	One-half certified duration (min)	Storage condition	Coldest operating temperature ($^{\circ}\text{C}$)	Measured operating time (min)
D	120	cold	-10	160
		warm	-20	134
M	60	cold	-10	67
		warm	-15	68
S	120	cold	-20	141
		warm	-25	187

Table 4. Coldest temperature for proper operation of RBA's for one-half certified duration. Storage conditions: cold = overnight storage at temperature of subsequent tests, warm = overnight storage $+20^{\circ}\text{C}$.

S-2; Figure 3, unit S-1).

Figures 5, 6 and 7 show the inspired air composition for the Type D apparatus at - 10, - 15 and - 20°C, respectively. The successful test was at - 10°C. O₂ concentrations rose from near 60% initially to above 80% within 30-40 min and then slowly increased throughout the remainder of the test. During the successful test at - 10°C, CO₂ never rose above 0.8%, even during the fast walk. The contrasted with the unsuccessful tests at - 15°C and - 20°C, when CO₂ rose rapidly and reached excessive levels within the first 12 min. This was due to initial failure of the scrubber to function when cold: unit D-1 at - 15°C showed an initially rapid rate of rise to 3.1% CO₂ in 12 min during the slow walk, but then showed a drop in CO₂. Despite the fact that the unit had technically failed, the operator consented to continue to determine if the CO₂ would drop to safe levels. The CO₂ concentration dropped throughout the remainder of the slow walk, then rose to about the 1% level during the fast walk and dropped again during the rest period, at which time the test was terminated. At - 20°C, the CO₂ levels in both Type-D units were already above 3.5% at the start of the first work cycle.

Figures 8, 9 and 10 show the inspired air composition for the Type-M apparatus at - 10, - 15 and - 20°C, respectively. The successful test occurred at - 10°C. O₂ concentrations typically remained in the 60-80% throughout each test, rising in one instance near 100% half-way through the test (Figure 8, unit M-2) in response to repeated operation of the by-pass valve. CO₂ concentrations were always the limiting factor in the performance of Type-M apparatus. CO₂ concentrations were a function of work rate, but showed a trend of progressive increase throughout each experiment. Failure occurred during the fast walk portion of the work cycle. During the successful test at - 10°C it occurred in the second work cycle, while during the unsuccessful attempts at colder temperature failure occurred in the first work cycle.

b. Phase II: The inspired gas concentrations during the tests of Type-S apparatus kept at + 20°C prior to test are shown in Figures 11 and 12 for the successful

test at - 25°C and the unsuccessful test at - 30°C, respectively. O₂ concentrations remained in the 60-90% range during both test, except at the end of the S-1 test at - 25°C, when the O₂ supply became exhausted with 400 psi still indicated on the tank gauge. CO₂ concentrations never exceeded 1% during any test.

Results for the Type-D apparatus during Phase-II tests at - 20, - 25 and - 30°C are shown in Figures 13, 14 and 15. The successful test was at - 20°C. O₂ concentrations in all tests quickly rose to levels above 80% and remained there throughout the duration of test. CO₂ levels at - 20, - 25°C remained below 1%, even during the fast walk periods of the work cycle. During the tests at - 30°C, however, CO₂ levels just exceeded the 1% level during most of the fast walk periods and exceeded 4% during the fourth fast walk for unit D-2 (Figure 15). This indicated a progressive deterioration in the performance of the Type-D scrubbing canister during prolonged exposure to - 30°C.

Results for the Type-M tests at - 15, and - 20°C are shown in Figures 16 and 17, respectively. O₂ concentration remained in the 60-80% range for both tests. The CO₂ concentration in unit M-1 exceeded 4% at the end of the second fast walk in both tests, and early in the second fast walk for unit M-2 at - 20°C. At - 15°C, unit M-2 surpassed the 60 min criterion without exceeding 2.5% CO₂. Because of the rapid increase in CO₂ in the Type-M units during fast walk, heavy workloads should not be attempted with this unit after 30 min of operation, even at - 15°C.

Figures 18 and 19 show the results of control runs at + 10°C for RBA Types S and D, respectively. For both units, O₂ concentrations remained in the range of 70-100% and CO₂ concentrations remained below 0.5% for a minimum duration of 2 hours, using the identical work-rest cycle as in the cold tests. Clearly, the cold tests failures were not due to general malfunctions of the RBA unit but were peculiar to cold temperature operation.

3. Breathing circuit temperatures. The temperatures within the breathing circuit are shown in Appendix B, in Figures 20-28 for Phase-I tests, in Figures 29-35 for Phase-II tests in Figures 36 and 37 for control tests at

+ 10°C. It should be recalled that the time line began at $t = 0$ when the first apparatus was connected; the connection of the other unit of the pair is shown by the start of its plot. Endurance time was measured from the start of the work-rest cycle which is plotted on each figure as WR. The same temperature abbreviations are used on each figure: mask inlet and outlet as M.I. and M.O., respectively; scrubber inlet, surface and outlet as S.I., S.S. and S.O., respectively; and breathing bag outlet as B.B.

a. Phase I. The temperatures for the Type-S units during Phase I are shown in Figures 20-22. The temperature plots show that, in each case, the RBA temperatures had warmed up 1-2°C from the time the units were first turned on until the thermocouple units were connected to the recording system. The M.O. and S.I. temperatures warmed very rapid above 0°C from the respiratory heat, while the B.B. and M.I. temperatures remained below freezing at all times. Despite the expired air temperature being above freezing, post-test inspection revealed frozen condensate adhering to the walls of the expired air hose after every test.

The scrubber functioning is displayed clearly by the progressive rise in S.S. temperature as soon as the units were connected. This was followed by a very dramatic rise in S.O. temperature which was always delayed until the fast walk portion of the first work cycle. Thus the scrubber functioned immediately in the Type-S units,

The Type-D units were more variable than the Type-S units in their response (Figures 23-25). At - 10°C (Figure 23), where they passed the Phase-I tests, S.S. temperatures reached 0°C before the start of the first fast walk period. S.O. temperature was higher than S.S. temperature after the fast walk in unit D-1, but lower than S.S. temperature for 80 min in unit D-2, indicating that successful scrubber operation was not dependent upon heat input from expired air. Figures 24 and 25 show the temperatures during the failed tests at - 15 and - 20°C, respectively. In all 4 runs, CO₂ concentrations exceeded tolerance criteria before the scrubber surface temperatures reached 0°C. At - 15°C, unit D-1 failed at 12 min. The test was continued, however, because the CO₂ concentration had peaked at

the time and subsequently dropped rapidly to acceptable levels (Figure 6). As shown in Figure 24, the S.S. temperature continued to climb, as did the S.O. temperature which lagged the S.S. temperature by 4-5 min. The CO₂ concentration continued at acceptable levels until the test was terminated at the end of the first work cycle. Thus the requirement for proper operation of the Type-D scrubbing system appears to be the surface temperature reaching 0°C before being overwhelmed by the load of CO₂. In every case in Phase I where the S.S. temperature reached 0°C, the CO₂ concentrations remained within acceptable limits.

Temperatures within the Type-M units are shown in Figures 26-28. At - 10°C (Figure 26) they passed the Phase-I test. The S.S. and S.O. temperatures had both reached 0°C before the first fast walk. At - 15 and - 20°C (Figures 27 and 28, respectively), when both units failed during the first fast walk, neither unit S.S. nor S.O. temperature had reached 0°C. This was not the entire story, however, because both units had inadequate scrubbed function at - 10°C during the second fast walk, when both scrubber temperatures were well above 0°C. The progressive rise of CO₂ concentration during the test (Figure 8) suggests a progressive deterioration of scrubber function during the Phase-I tests, rather than a threshold temperature above which proper scrubber function is assured.

b. Phase II. The temperatures within the Type-S units are shown in Figures 29 and 30 for the Phase-II tests at - 25 and 30°C, respectively. S.S. temperature started above 0°C and dropped in response to the cold exposure, reaching a minimum at or just below 0°C within 10-15 min. Thereafter it rose to levels within the range of + 15 to + 30°C and remained there for the duration of the test. S.O. temperatures also rose to or slightly below these levels after a lag time of 15-30 min. The Type-S units failed at - 30°C because of premature exhaustion of the O₂ supply; CO₂ scrubber function was always adequate.

The temperatures within the Type-D units are shown in Figures 31, 32 and 33 for the Phase-II tests at - 20, - 25 and - 30°C, respectively. No difficulties were observed with the CO₂ scrubbing system at - 20 and

-25°C. In both these tests S.S. and S.O. temperatures remained above -2°C. At -30°C, unit D-2, which scrubbed CO₂ properly for 160 min, had S.S. temperatures oscillating between 0 and -10°C (Figure 33). The scrubber on this unit failed at 160 min at the end of the fourth fast walk, after a progressive rise in CO₂ throughout the test (Figure 15). Unit D-1 experienced no difficulty with the CO₂ scrubber, but prematurely exhausted its O₂ supply. The S.S. temperature never dropped below +5°C, which suggests that proper long-term scrubber operation requires an SS temperature above a -5 to -10°C threshold.

The Type-M breathing circuit temperatures at -15 and -20°C are shown in Figures 34 and 35, respectively. Both Type-M units showed a progressive deterioration of CO₂ scrubber function, as in Phase I, despite S.S. and S.O. temperatures remaining above freezing. Ice accumulating on the particles of CO₂ absorbent is not likely therefore, to be the cause of the deterioration in scrubber performance.

4. Inspiratory and expiratory pressures.

The values for maximum inspiratory and expiratory pressures measured within the facemask are shown in Appendix C, Figures 38-54. The inspiratory pressures were recorded and plotted in the negative direction, while the expiratory pressures were recorded and plotted in the positive direction. The points above and below each curve represent the limits of one standard deviation about the mean values calculated over 1 min.

Inspiratory pressures were determined by the effort subjects wished to exert. Expiratory pressures were constrained by the maximum resistance to outward flow that was exerted by the seal of the facemask to the face. This was a function of the tension in the facemask straps which was determined by each subject. On occasions when high expiratory pressures were encountered, air was heard to escape from around the facemask seal. High inspiratory pressures in Figures 38-54 which are not accompanied by symmetrically high expiratory pressures therefore do not mean a restriction to flow only in the inspiratory side of the breathing circuit. When ice or frost was found in one hose of the breathing circuit, it was always found in the other.

The absolute respiratory pressures were generally maintained at or below ± 15 cm-H₂O unless ice deposition occurred. Subjects reported difficulty in breathing when either of the respiratory pressures exceeded 15 cm-H₂O. If the condition persisted, subjects responded by voluntarily lowering their work rate. This was permitted, as it represented a normal response in the real-world situation, but for no more than 30 sec every 2 min. Reductions in workload for longer durations were cause for failure of the test, as was removing the mask because breathing became difficult.

a. Phase I. Results from the pressure measurements in the Type-S apparatus during Phase-I tests at -20, -25 and -30°C are shown in Figures 38, 39 and 40, respectively. Respiratory pressures increased during the slow and fast walk portions of each work cycle, in all 3 tests reaching peak values of 10-15 cm-H₂O during the fast walk. Excessive respiratory pressures were never a cause for RBA failure, despite the high pressures during the fast walk.

The Type-D unit respiratory pressures are shown in Figures 41 and 42 for the tests at -10 and -15°C. The failed test at -20°C was too short to give meaningful 1 min averages so the data have not been plotted. The pressures during these tests generally remained in the range of 3-5 cm-H₂O and were somewhat higher during expiration. This indicated about 50% more expiratory than inspiratory breathing resistance in the system. Pressures increased slightly during the fast walk and decreased during the rest periods, especially during the third and fourth work cycles. There were no reports of excessive respiratory pressures.

Respiratory pressures for the Type-M units at -10, -15 and -20°C are shown in Figures 43, 44 and 45, respectively. Pressures averaged about 3 cm-H₂O at rest and 5-8 cm-H₂O during the slow walk but increased dramatically to levels at or above 15 cm-H₂O during the fast walk. There were occasional reports of excessive respiratory effort during the fast walk.

b. Phase II. Results for the Type-S apparatus during Phase II at -25 and -30°C are shown in Figures 46 and 47, respectively. As in Phase I, pressures increased during the

fast walk portion of the work cycle. At -25°C , the O_2 supply for unit S-1 became exhausted unexpectedly while the bottle gauge indicated 400 psi. This event shows as a dramatically increased inspiratory pressure. In general, the pressure curves for all trails in Phase II are similar in shape and amplitude to those recorded during Phase I.

The Phase-II pressures for the Type-D apparatus at -10 , -25 and -30°C are shown in Figures 48, 49 and 50, respectively. The resting and slow walk pressures were similar to Phase I, but the fast walk pressures were much higher. Excessive respiratory pressure was the cause of failure of unit D-2 at both -20 and -25°C (Figures 48 and 49), with a different subject each time. The high pressures were due to ice and frost blockages in the air hoses. Similarity high pressures were observed in the same unit at -30°C , but did not develop as rapidly.

Figures 51 and 52 show the pressures for the Type-M units at -15 and -20°C , respectively. Both units showed dramatically increased pressures during the fast walk portion of the work cycle, sometimes requiring the subject to reduce his work rate for 30 sec. However, these uncomfortable pressures did not result in failure of the units before the time that the CO_2 levels exceeded the tolerance limits.

Peak respiratory pressures during the fast walk were averaged during both Phase I and Phase II under normal operating conditions in

the absence of ice blocks in order to identify the most and least resistive RBA. These peak pressures averaged 13.5 cm- H_2O for Type-M units, 9.2 cm- H_2O for Type S and 6.4 cm for Type D. On the whole, breathing circuit resistance appears to be least for the Type-D units, intermediate for the Type S and greatest for the Type M, which has the smallest breathing hose diameter (1 inch i.d.).

Breathing circuit pressures at $+10^{\circ}\text{C}$ for the Type-S and -D units are also shown in Figures 53 and 54, respectively. Heated Hans Rudolf pneumotacho graphs were installed in the Type-S units from 0 unit 130 min, thus invalidating any comparisons prior to 130 min. During the last 10 min the units were removed, showing resting pressures to average 2/3 of resting pressures with the devices installed. However, the general pattern and magnitude of the observed pressures was similar to that seen in the Type-S units during the cold temperature tests. A valid control curve for breathing pressures was obtained from the Type-D units and -10°C , however (Figure 54). The pressures are identical to those seen in Phase I for the same units, indicating that cold temperatures *per se* did not raise respiratory pressures.

6. Subject responses.

a. Breathing difficulty.

1) Phase I. Subjective rating for breathing difficulty for all 3 types of RBA in Phase I are shown in Table 5. These ratings

Work Cycle	Activity	-10°C		-10°C		-20°C	
		D-1	D-2	M-1	M-2	S-1	S-2
1	slow walk	1	0	0	2	0	0
	fast walk	1	2	1	2	0	0
	rest	0	0	0	0	0	0
2	slow walk	0	1	0	2	0	1
	fast walk	2	2	1	3	1	1
	rest	0	1	1	—	0	0
3	slow walk	1	2	—	—	0	0
	fast walk	2	2	—	—	0	1
	rest	1	2	—	—	0	1
4	slow walk	0	2	—	—	0	1
	fast walk	1	2	—	—	0	—
	rest	0	1	—	—	0	—
5	slow walk	—	—	—	—	0	—
	fast walk	—	—	—	—	0	—
	rest	—	—	—	—	0	—

Table 5. Ratings of breathing difficulty throughout operational tests at criterion temperatures (Phase I). Rating scale: 0 = not difficult, 1 = slightly difficult, 2 = moderately difficult, 3 = very difficult, 4 = extremely difficult.

were obtained during the successful tests. During the rest periods, all RBA types received ratings of "not difficult" or "slightly difficult." During their successful test at - 10°C, the Type-D units, received ratings in the range of "not difficult" to "moderately difficult" during the slow walk and "slightly difficult" or "moderately difficult" during the fast walk. The Type-M units, during their successful test at - 10°C, received ratings of only "slightly difficult" from one subject during the fast walks and "very difficult" from another, who rated the breathing during the slow walks as "moderately difficult." The Type-S units during their successful tests at - 20°C received general ratings of "not difficult," occasionally increasing to "slightly difficult" during the slow and fast walks.

The rating of greater difficulty received by the Type-M units are consistent with the higher breathing pressures they induce. The Type-S units were intermediate in their breathing pressures, but were rated lowest in difficulty by their operators. This demonstrates the problems inherent in comparing ratings from individuals who may differ in their tolerance to encountered difficulties or discomfort. The general consensus of the group of experimenters was that the operators of the Type-S units were more tolerant of discomfort, inconvenience

and physical effort that the typical test subject. This should be kept in mind when interpreting the low difficulty and discomfort ratings from the operators of the Type-S apparatus.

2) Phase II (Table 6). Units D-1 and D-2 did not receive similar ratings for breathing difficulty during their successful test at - 20°C. Unit D-2 was rated as "extremely difficult" during the fast walks, eventually failing for the reason due to ice blockage in the air hoses. Unit D-1 received ratings similar to those it received in Phase I, which reached level of only "moderately difficult" during the fast walks. The pressures within each unit reflected these differences (Figure 48). During the fast walks, the pressures in unit D-2 reached 13-19 cm-H₂O,

The Type-M units received ratings in Phase II similar to those in Phase I. The ratings but remained in the 10-13 cm range for unit D-1. never exceeded "moderately difficult," even during the fast walk.

The Type-S units were rated as "not difficult" during all portions of the work-rest cycle throughout their successful test at - 25°C. This was true despite breathing pressures which reached 10-13 cm-H₂O in unit S-1 and 8-12 cm-H₂O in unit S-2 during the fast walks (Figure 46). This demonstrates

Table 6. Ratings of breathing difficulty throughout operational tests at criterion temperatures (Phase II). Rating scale: same as Table 5.

Work Cycle	Activity	- 20°C		- 15°C		- 25°C	
		D-1	D-2	M-1	M-2	S-1	S-2
1	slow walk	0	1	1	1	0	0
	fast walk	0	4	2	2	0	0
	rest	0	1	1	0	0	0
2	slow walk	0	1	2	0	0	0
	fast walk	1	4	2	0	0	0
	rest	0	1	1	0	0	0
3	slow walk	0	2	2	0	0	0
	fast walk	2	4	—	—	0	0
	rest	1	1	—	—	0	0
4	slow walk	2	—	—	—	0	0
	fast walk	—	—	—	—	0	0
	rest	—	—	—	—	0	0
5	slow walk	—	—	—	—	0	0
	fast walk	—	—	—	—	0	0
	rest	—	—	—	—	0	0
6	slow walk	—	—	—	—	0	0
	fast walk	—	—	—	—	—	0
	rest	—	—	—	—	—	0

the relative insensitivity of the operators of these units to breathing difficulty.

b. RBA comfort. Overall comfort ratings were obtained for each RBA in order to determine in the 3 types differed. From Tables 7 (Phase I) and 8 (Phase II) it is clear that they do not differ markedly. All units were rated "slightly" to "moderately" uncomfortable, principally due to their weight, restriction to motion and cutting action of the attachment harness straps, particularly when worn over bulky cold-weather clothing.

c. Facemask comfort. Tables 9 and 10

show the ratings for facemask comfort during the successful tests in Phases I and II, respectively. Type-D facemasks were generally rated "moderately comfortable" to "slightly uncomfortable" in both phases. Type-S facemasks were rated the same, except for unit S-2 in Phase I at -20°C. During that test, the inside of the S-2 facemask became wet with condensate from a combination of expired water vapor and facial sweat, which was rated by the operator as "moderately uncomfortable." The Type-M facemasks were rated as "slightly" to "moderately" uncomfortable, rating less favorable by one

Work Cycle	Activity	- 10°C		- 10°C		- 20°C	
		D-1	D-2	M-1	M-2	S-1	S-2
1	slow walk	2	1	1	3	1	0
	fast walk	2	2	2	3	1	2
	rest	1	1	2	2	1	3
2	slow walk	2	3	2	3	1	1
	fast walk	2	2	2	3	1	3
	rest	2	3	3	—	1	2
3	slow walk	2	3	—	—	1	2
	fast walk	2	4	—	—	1	2
	rest	2	4	—	—	1	2
4	slow walk	2	3	—	—	1	1
	fast walk	3	4	—	—	1	—
	rest	2	3	—	—	1	—
5	slow walk	—	—	—	—	1	—
	fast walk	—	—	—	—	1	—
	rest	—	—	—	—	1	—

Table 7. Ratings of RBA comfort throughout operational tests at criterion temperatures (Phase I).
Rating scale: 0 = quite comfortable, 1 = moderately comfortable, 2 = slightly uncomfortable, 3 = moderately uncomfortable, 4 = quite uncomfortable.

Work Cycle	Activity	- 20°C		- 15°C		- 25°C	
		D-1	D-2	M-1	M-2	S-1	S-2
1	slow walk	2	1	2	2	1	1
	fast walk	2	2	2	2	2	1
	rest	1	2	2	2	1	1
2	slow walk	2	2	3	2	2	1
	fast walk	2	2	3	2	1	1
	rest	2	2	3	2	1	1
3	slow walk	2	2	3	2	1	1
	fast walk	3	3	—	—	2	1
	rest	2	2	—	—	2	1
4	slow walk	3	—	—	—	1	1
	fast walk	—	—	—	—	2	1
	rest	—	—	—	—	1	1
5	slow walk	—	—	—	—	2	1
	fast walk	—	—	—	—	2	1
	rest	—	—	—	—	—	1
6	slow walk	—	—	—	—	—	1

Table 8. Ratings of RBA comfort throughout operational tests at criterion temperatures (Phase II).
Rating scale: same as Table 7.

category than were received by the Type-D or -S facemasks. No mask was consistently rated either as "quite uncomfortable," or as "quite comfortable."

Discussion

The Type-S devices performed best of the three types. This was true not only when cold-soaked but also after storage at room temperature. Unlike those of the Type-D and

-M apparatus, the Type-S CO₂ scrubbers gave no indication of being affected by sub-freezing temperatures. The Type-S scrubbers functioned right away, even at temperatures below those of the successful criterion tests. This is presumably due to the LiOH scrubbing material in the Type-S units, which were the only units to use this material as a scrubber. The major deficiency in the design of the Type-S units which renders them poorly equipped to function at cold temperatures is the mechanism for arming the lower O₂ pressure alarm system. This system is armed and the unit made operational by O₂ bottle

Table 9. Ratings of facemask comfort throughout operational tests at criterion temperatures (Phase I). Rating scale: same as Table 7.

Work Cycle	Activity	-10°C		-10°C		-20°C	
		D-1	D-2	M-1	M-2	S-1	S-2
1	slow walk	1	0	1	3	1	2
	fast walk	1	2	2	3	1	3
	rest	0	1	2	3	1	3
2	slow walk	1	1	2	2	1	3
	fast walk	1	1	2	2	1	3
	rest	1	1	1	—	1	3
3	slow walk	1	1	—	—	1	3
	fast walk	1	1	—	—	2	3
	rest	2	1	—	—	2	3
4	slow walk	1	1	—	—	2	3
	fast walk	1	1	—	—	2	3
	rest	1	0	—	—	2	—
5	slow walk	—	—	—	—	2	—
	fast walk	—	—	—	—	2	—
	rest	—	—	—	—	2	—

Table 10. Ratings of facemask comfort throughout operational tests at criterion temperatures (Phase II). Rating scale: same as Table 7.

Work Cycle	Activity	-20°C		-15°C		-25°C	
		D-1	D-2	M-1	M-2	S-1	S-2
1	slow walk	1	0	2	2	2	1
	fast walk	2	0	2	2	2	1
	rest	1	0	2	2	2	1
2	slow walk	2	0	2	2	2	1
	fast walk	2	1	3	2	2	1
	rest	2	1	3	2	2	1
3	slow walk	2	1	3	2	2	1
	fast walk	3	1	—	—	2	1
	rest	2	1	—	—	2	1
4	slow walk	2	—	—	—	2	1
	fast walk	—	—	—	—	2	1
	rest	—	—	—	—	3	1
5	slow walk	—	—	—	—	3	1
	fast walk	—	—	—	—	3	1
	rest	—	—	—	—	—	1
6	slow walk	—	—	—	—	—	1

pressures in excess of 1600 psi, presumably to prevent a user from inadvertently starting out with an incompletely filled O₂ supply. At sufficiently cold temperatures, however, even a properly filled bottle will be reduced in pressure to the extent that the bottle will either vent during the arming process or will not arm the RBA at all, despite having an adequate quantity of O₂ to last 4 hours. A fairly simple redesign of the alarm system to permit its arming at pressures down to 800–1000 psi when used in cold temperatures should eliminate this problem.

The other problem with the Type-S devices appears to be intermittent or sluggish operation of the O₂ demand valve which should be "automatically" operated when the operator's tidal volume exceeds the volume of the breathing bag. Redesign of the mechanism or use of materials with appropriate coefficients of thermal expansion for cold weather use might readily solve this problem. If these problems can be overcome, the Type-S apparatus would appear to have potential for proper operation in cold temperatures down to -25 or -30°C throughout the duration of their 4 hour O₂ supply. The potential problem of hoses becoming obstructed with frost and ice at these temperatures can be circumvented by using special cold-weather hoses of slightly larger diameter and of slightly softer composition, to permit the operator to dislodge these types of obstruction and keep them dispersed in the corrugations of the hoses.

The Type-D apparatus is not going to be able to properly cope with cold temperatures until either its CO₂ scrubber is modified to start up at cold temperatures or the unit's operating procedures are changed to require 15 min use in above-freezing temperatures prior to going into cold temperatures down to -20°C. Once in operation, the Type-D units appeared to function properly at least down to -20°C. The effect of a slightly longer warm-up period, perhaps 30 min, in above-freezing temperatures should be investigated on scrubber performance at temperatures below -20°C, if use below this temperature can reasonably be expected. Prolonged use in temperatures below -20°C for more than a few minutes appears unlikely, however, as

mine rescue personnel will pass through the sub-freezing regions in the mine rather quickly, no matter what temperature of air is being forced in from the outside. The Type-D apparatus is a very high O₂ pressure system and appears not to be susceptible to problems resulting from the air temperatures reducing the tank pressures below some threshold value. These units are also amenable to being equipped with compliant, large-diameter cold-weather hoses to defeat frost and ice blockage.

The Type-M units are another matter entirely. They are of marginal utility, barely lasting one hour at -15°C when not pre-chilled. The designs of the CO₂ scrubber and hose appear to be fundamentally incompatible with cold weather use. Mention has already been made of the progressive deterioration in scrubber performance over time at all testing temperatures. The cause is not known. The size or shape of the CO₂ absorber granules used in their rechargeable scrubbers may become altered with time, due to the interaction of temperature and expired water vapor, or the chemical reaction which absorbs CO₂ may proceed at an inadequate rate in the cold as the outer regions of each granule react with CO₂. In addition, the stiff portion of the Type-M hoses will not permit squeezing the hoses to dislodge accumulated frost and ice; the diameter of these hoses is also smaller than that of the Type-D or -S hoses as well. Because of the progressive deterioration of CO₂ scrubber performance at all temperatures tested, use of this instrument in below-freezing temperatures is strongly discouraged. Redesign or modification of these out-of-production RBA is not recommended.

As presently constituted, none of the RBA types tested is specifically designed for use in below-freezing temperatures. The Type-S units appear useable down to -20°C when cold-soaked and to -25°C if not, provided that the units do not lose excessive amounts of oxygen during the arming cycle of the alarm and breathing circuit when they are first turned on. In addition, the operator's O₂ pressure gauge must be redesigned, as it readily becomes inoperative or leaky even in normal use.

The Type-D units appear useable down to

- 10°C when cold-soaked and to - 20°C when not. However, since the unit's principal deficiency is failure to start scrubbing CO₂, it should be used in sub-freezing temperatures only as a last resort and then with the recommendation that cold units be turned on and used for 15-30 min in an above-freezing, non-toxic environment. CO₂ overdose is not readily detectable, so the operator should be warned to report any of its symptoms: headache, blurred vision (as distinguished from fogging of the eyepiece) and sensations of not being able to breath deeply or rapidly enough. In addition, the operator should be watched for indications of hyperventilation, as this is perhaps the most reliable symptom of CO₂ buildup.

The Type-M units do not appear useable in sub-freezing temperatures for more than a few minutes and probably should not be used at all in such temperatures. Without temperature measurement, the actual temperature of the scrubber material cannot be determined with any certainty after storage in unheated buildings, due to daily variations in ambient temperatures. If the overnight temperatures fell below freezing, the units may remain frozen for several hours.

Every unit used in the cold must be absolutely "bone-dry" when reassembled after cleaning. In the experience of the experimenters, this requires use of a drying agent (in our case, 95% ethanol) followed by forcing heated air through all passages until 100% inspection using flashlights guarantees dryness. Prolonged storage (24-48 hours) in a warm environment at least 40°C and of less than 30% humidity prior to reassembly may be an equally effective alternative, if the air motion through the hoses equals or exceeds 1 m • sec⁻¹. However, this alternative should be tested before use.

Conclusions

1. None of the tested RBA units was well-designed for use in sub-freezing temperatures.
2. The Type-S units operated best, both when at room temperature and after cold-

soaking. They were useable for at least 2 hours down to - 20°C when cold-soaked overnight and down to - 25°C when not so treated. Their CO₂ scrubbers started properly in the cold and continued to function properly throughout all criterion tests.

3. The Type-S units appear to offer the potential for being redesigned to permit safer use in sub-freezing temperatures. A more durable operator O₂ pressure gauge, a more reliable O₂ demand value and hoses of large diameter and sufficient compliance to permit disruption of accumulated frost and ice blockages would overcome the observed failures.
4. The Type-D units are useable for at least 2 hours down to - 10°C when cold-soaked and down to - 20°C when not so treated. Their major defect was an inability of the CO₂ scrubber to start functioning properly in the cold. For this reason, their use in sub-freezing temperatures is discouraged, particularly after cold-soaking.
5. The Type-D units require CO₂ scrubbers of different design that will operate properly in sub-freezing temperatures in order to be considered safe for use under those conditions.
6. The Type-M units, although useable for just over 60 min down to - 10°C when cold-soaked and down to - 15°C when not so treated, are not recommended for use in sub-freezing temperatures. Their CO₂ scrubbers showed progressive deterioration in function with time at all temperatures tested.

Acknowledgments

This report was prepared by the U.S. Army Research Institute of Environmental Medicine under USBM Contract No. JO188026. The contract was initiated under the Minerals Health and Safety Technology Program. It was administrated under the technical direction of the Pittsburgh Mining Safety and Research Center with Dr. Richard L. Stein and Mr. George M. Bockosh acting as Technical Project Officers. Mr. Frank M. Naughton was the contract administrator for the Bureau of

Mines. This report is a final report summarizing all contract work during the period September 1978 to December 1980. This report was submitted by the authors on 31 March 1981.

The authors would like to express their appreciation to the following individuals for their technical assistance in the conduct of the study and analysis of data: Dr. Yair Shapiro, Mr. Fredrick R. Winsmann, Mr. Leander A. Stroschein, Ms. Ella H. Munro, Mr. James E. Bogart, Mr. Gerald W. Newcomb, Ms. Nancy A. Pimental, Mr. Thomas L. Endrusick and SP5 Basavapathruni Onkaram, all of USARIEM. Special thanks to Mr. Anthony

Sparks, U.S. BuMines, and Mr. Daniel A. Berkowitz, USARIEM, for the daily inspection, maintenance and preparation of the Rescue Breathing Apparatus. Special thanks also to the test subjects: SP5 Arturo de los Santos, SP4 Quincy R. Grant, SP4 Richard R. Kristol, SP4 Roy Padgett, SP4 John H. Rice, SP4 Robert J. Trainor, Jr., SP4 Thomas D. Young, and SP4 Richard C. Williamson.

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

Appendix A. Inspired O₂ and CO₂ Concentrations (Figures 2-19)

Legend: WR = work-rest cycle

S = slow walk, VO₂ = 1 liter · min⁻¹

F = fast walk, VO₂ = 2 liters · min⁻¹
R = rest, VO₂ = 0.3 liter · min⁻¹

Figure 2

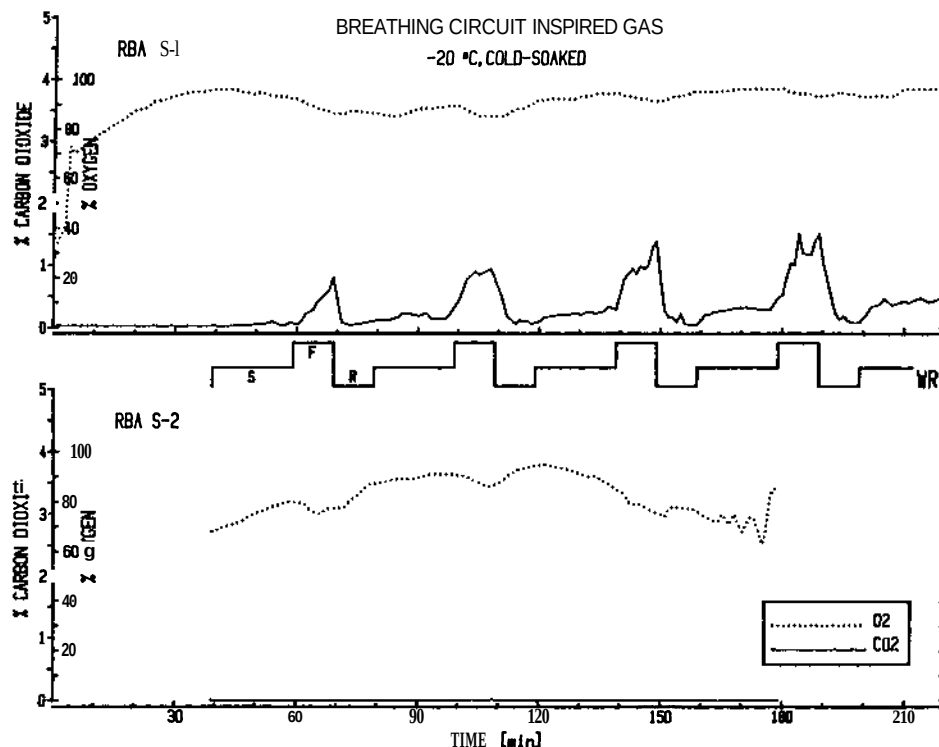


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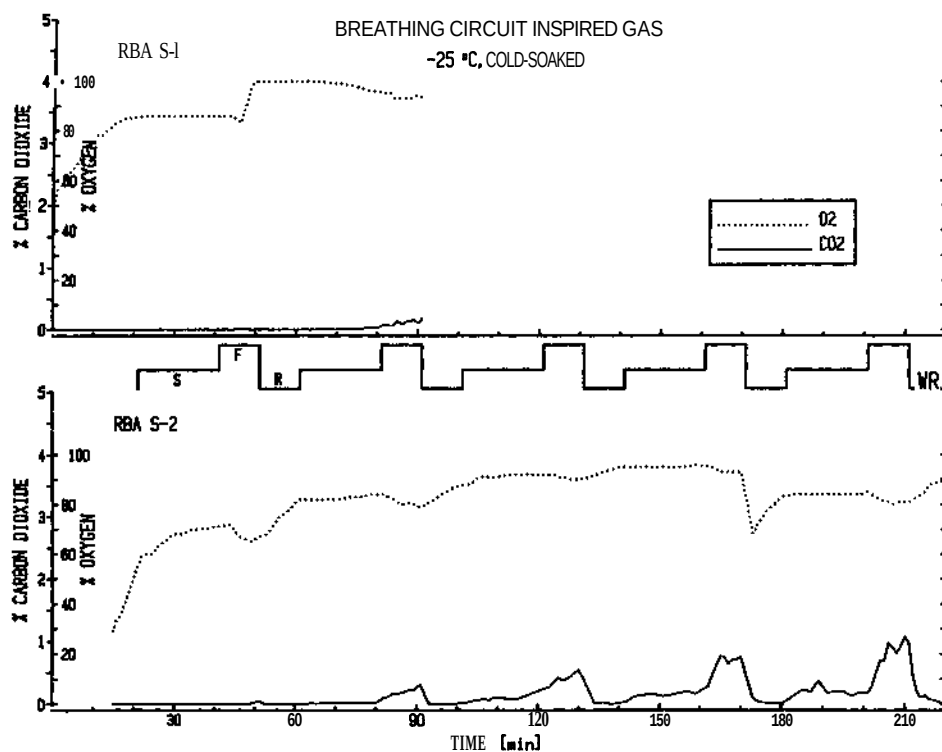


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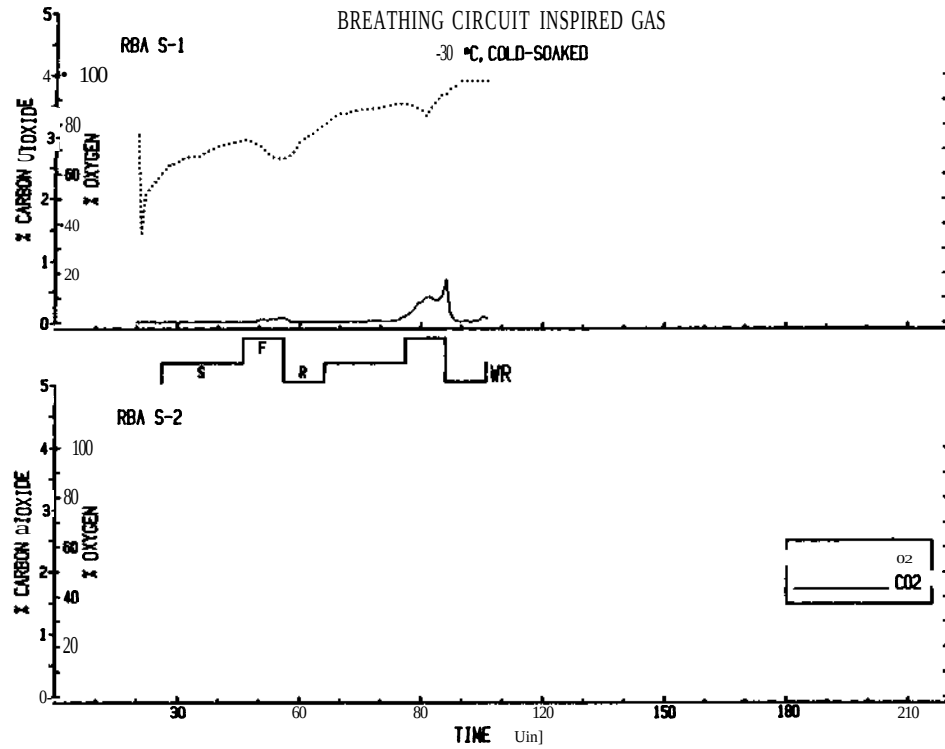


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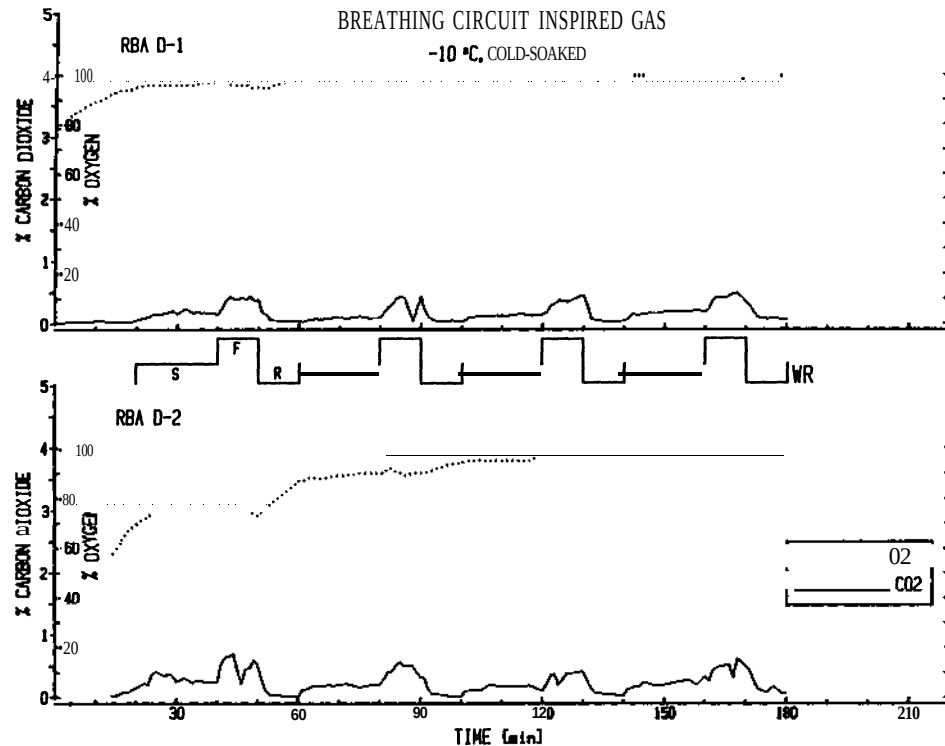


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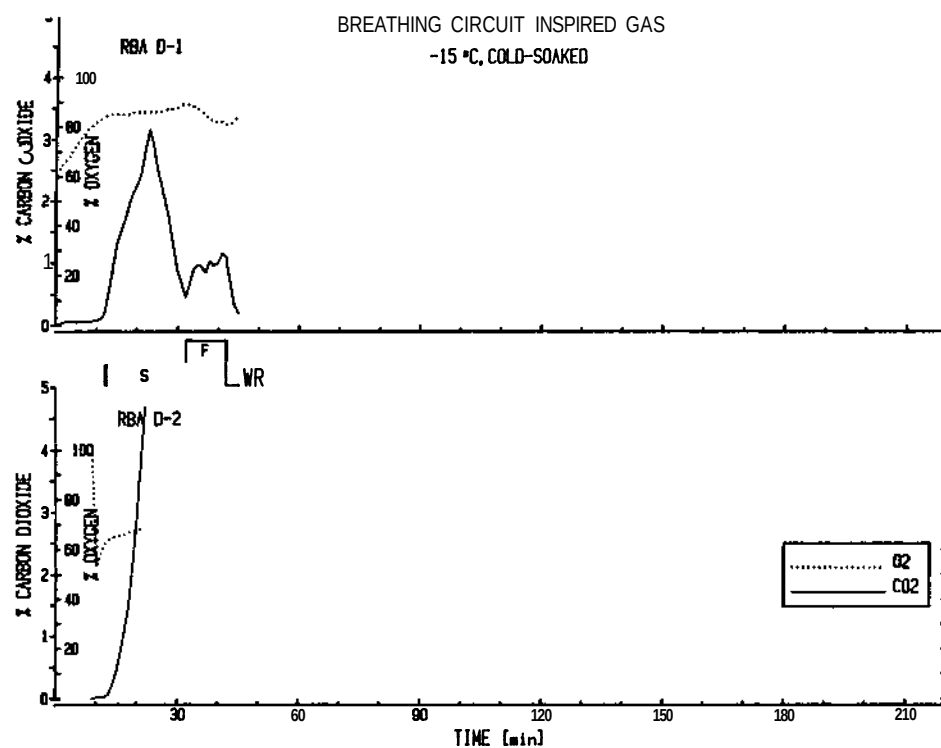


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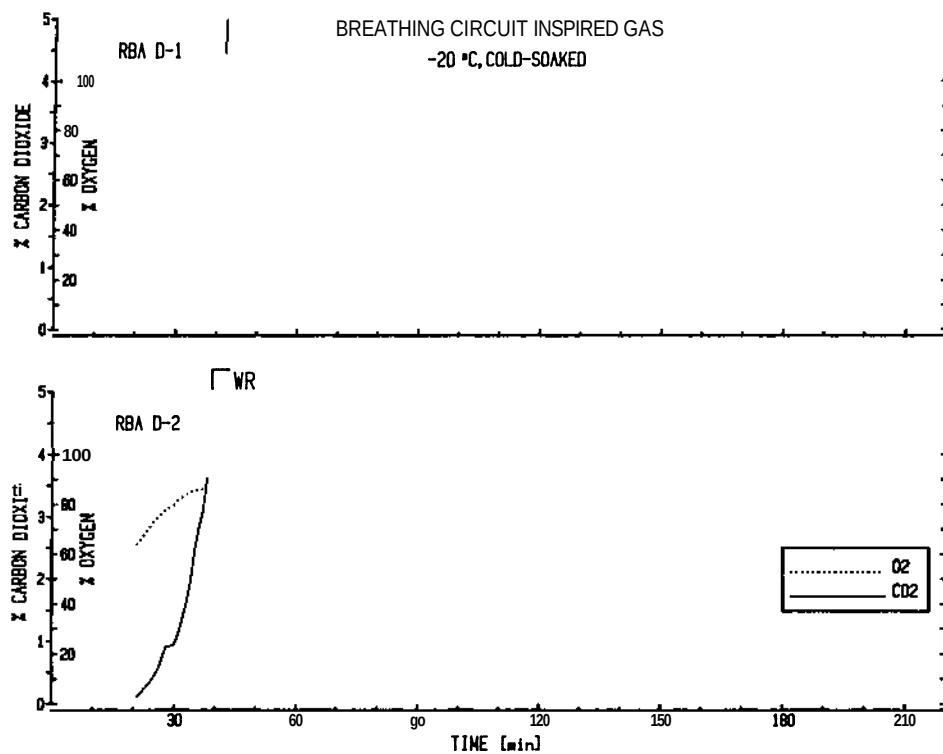


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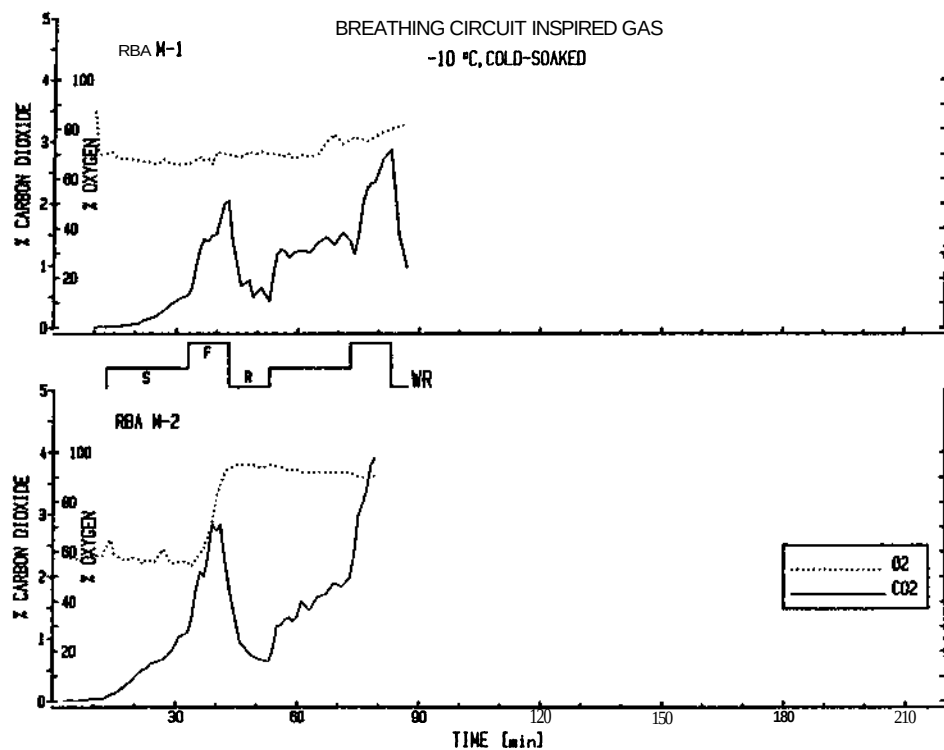


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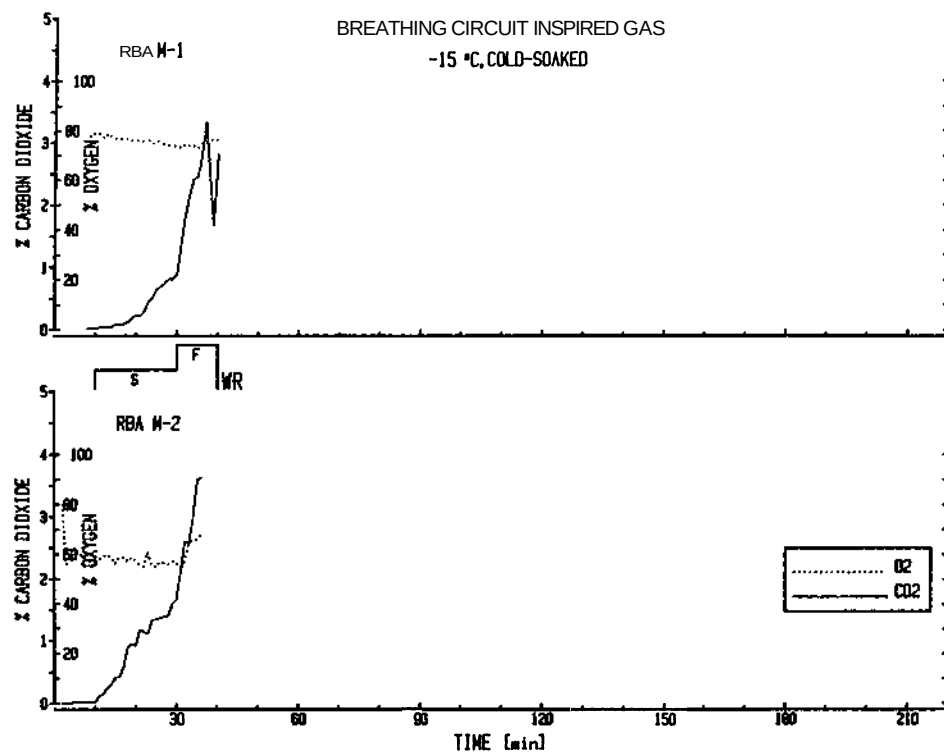


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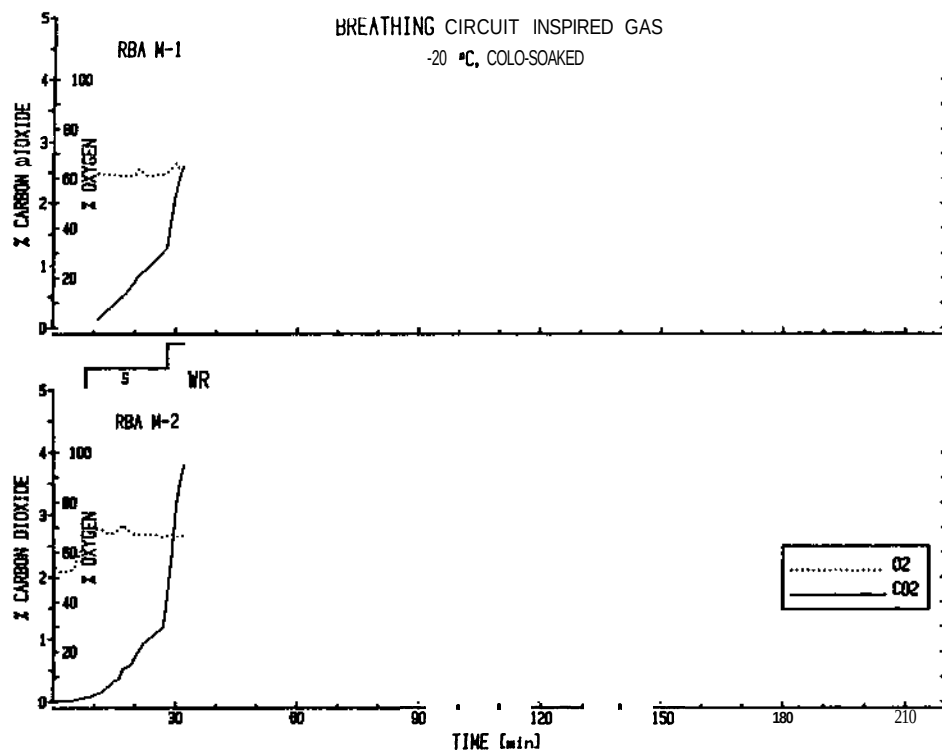


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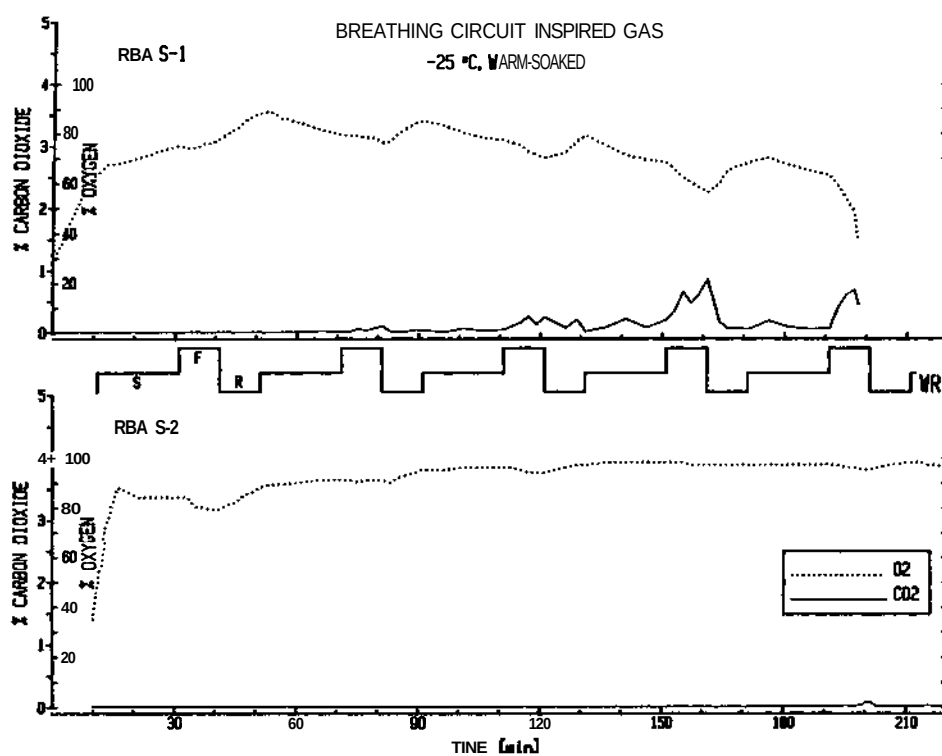


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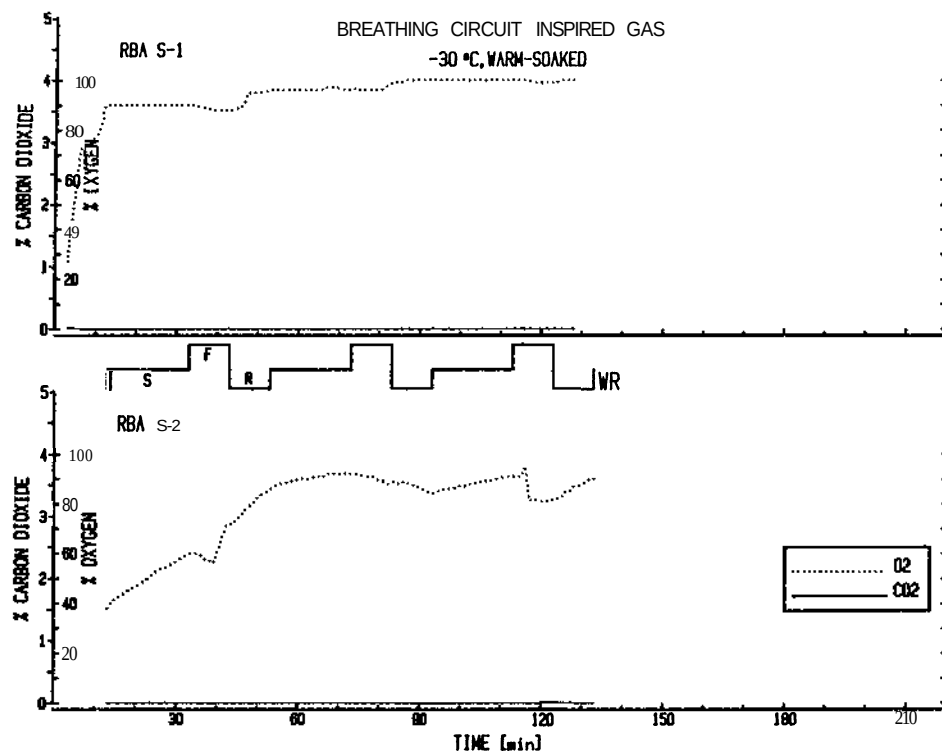


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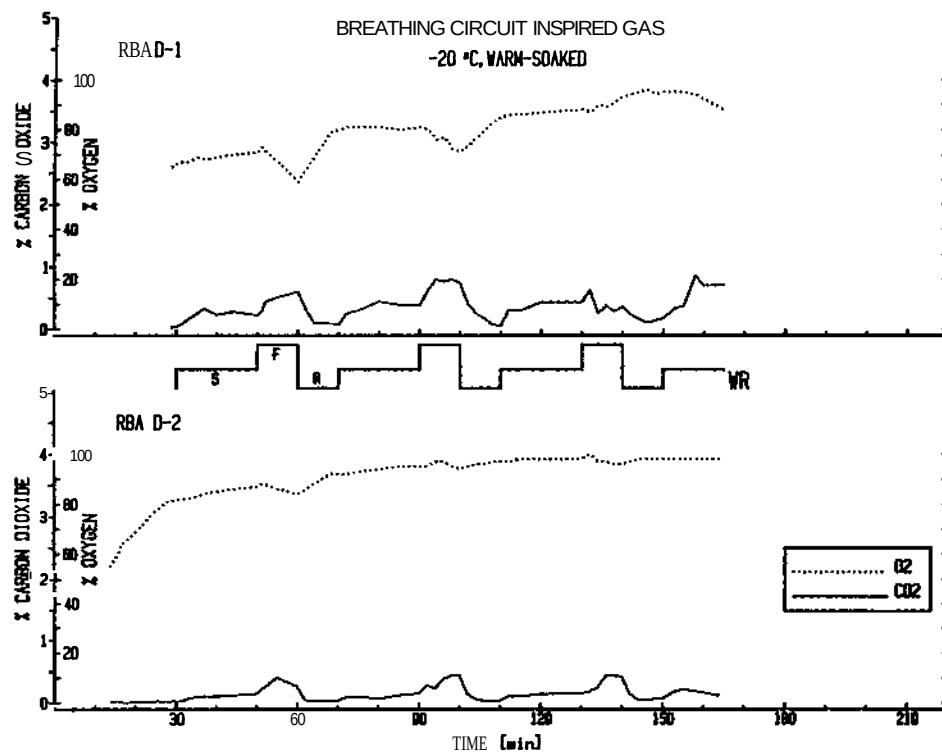


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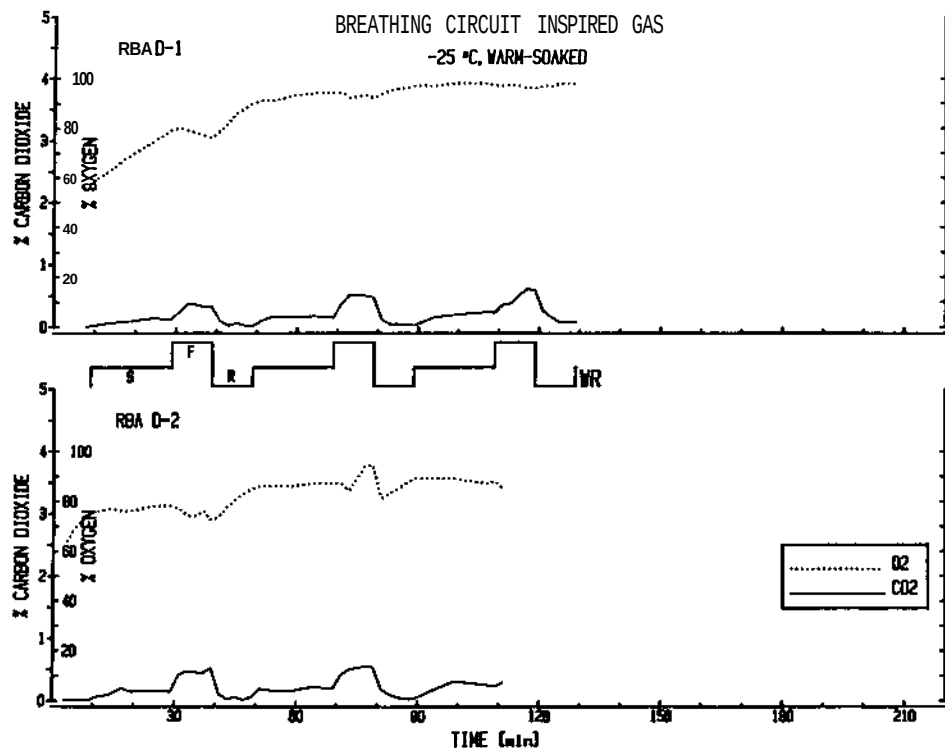


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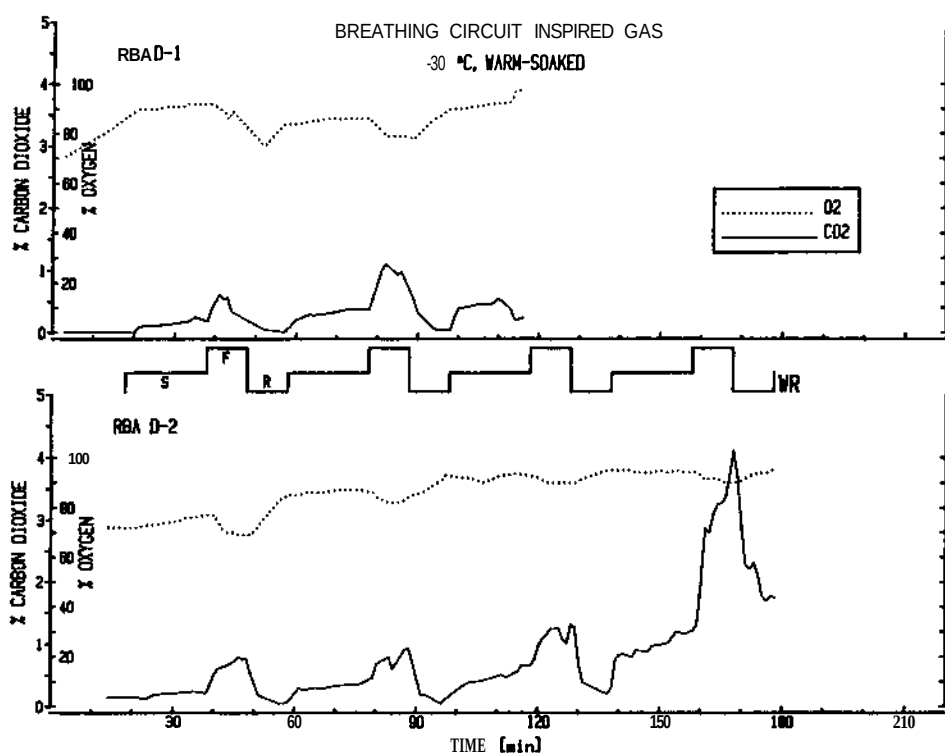


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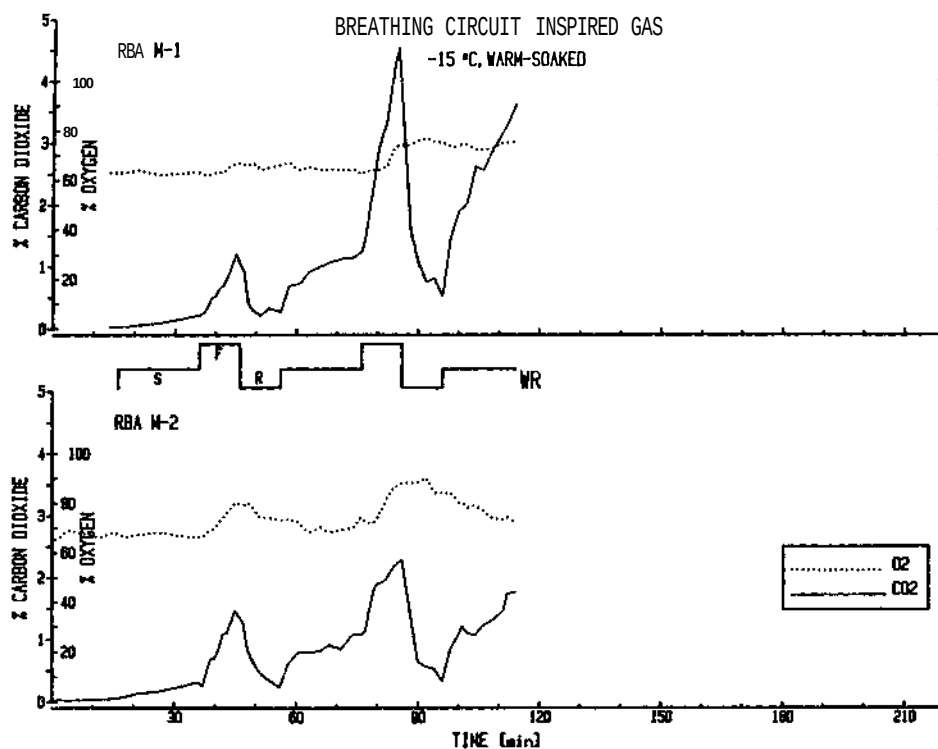


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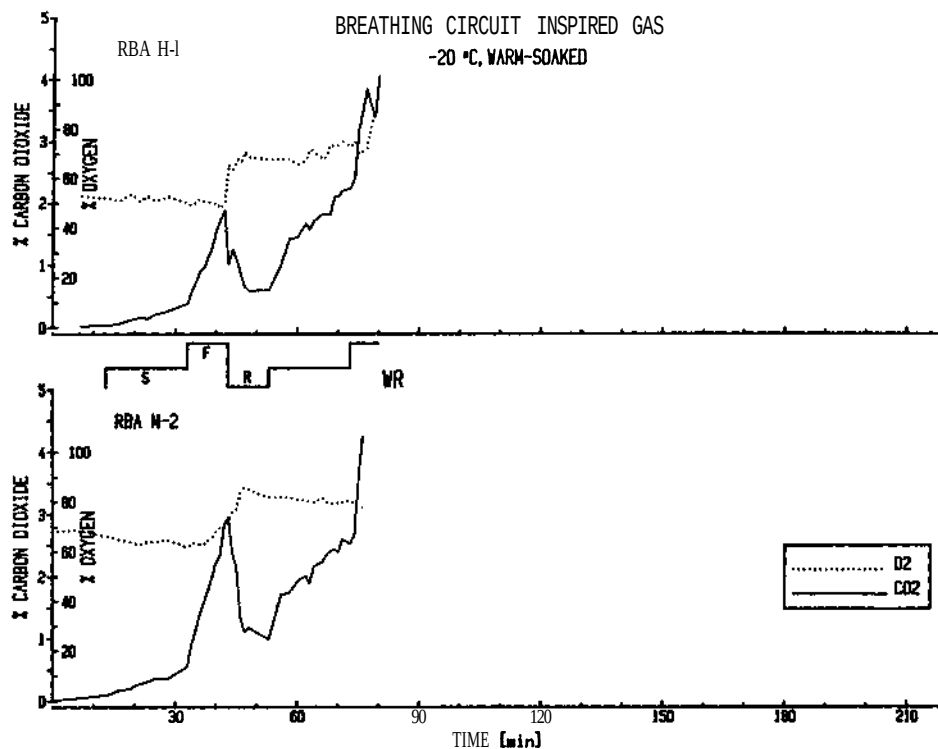


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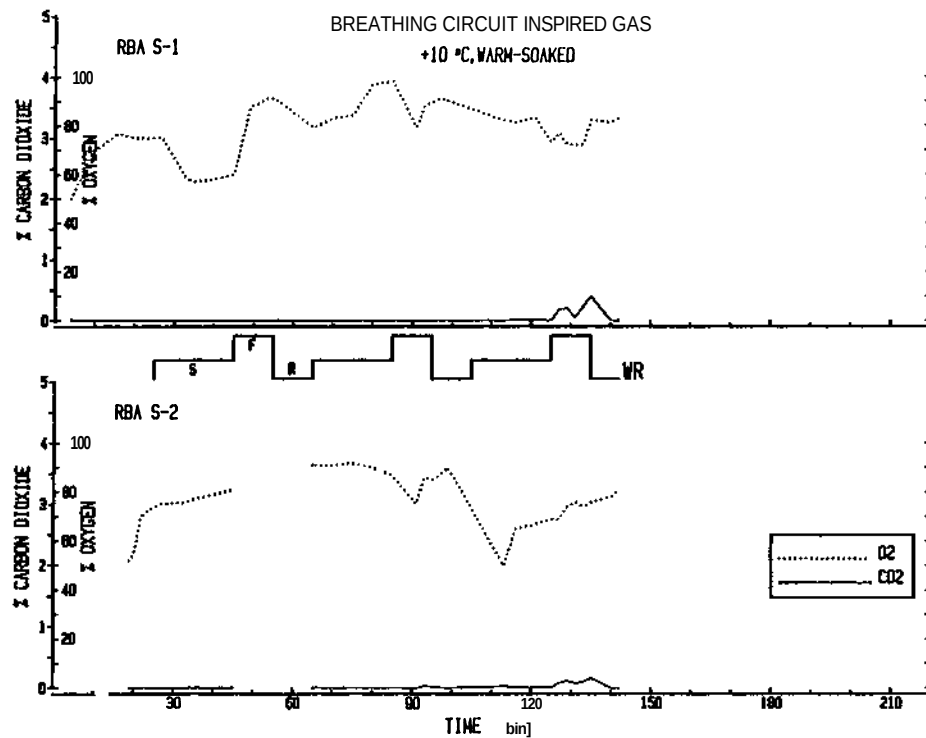
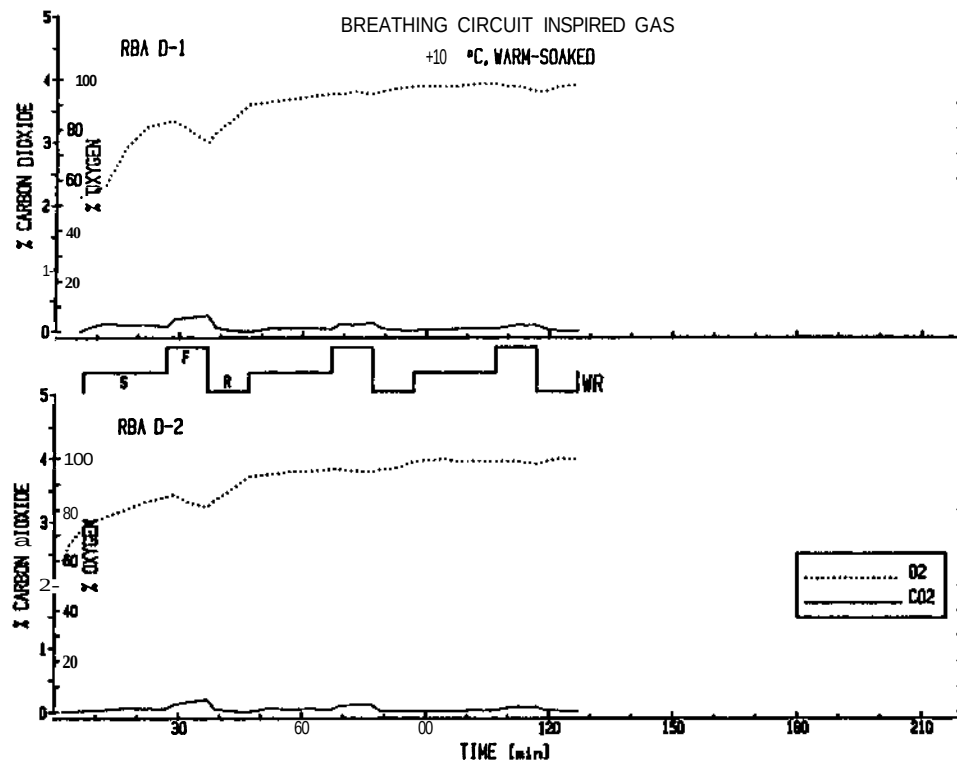


Figure 19



Appendix B. Breathing Circuit Temperatures (Figures 20-37)

Legends: WR = work - rest cycle

S = slow walk, $\text{VO}_2 = 1 \text{ liter} \cdot \text{min}^{-1}$

F = fast walk, $\text{VO}_2 = 0.3 \text{ liter} \cdot \text{min}^{-1}$

R = seated rest, $\text{VO}_2 = 0.3 \text{ liter} \cdot \text{min}^{-1}$

M.I. = mask inlet temperature

M.O. = mask outlet temperature

S.I. = scrubber inlet temperature

S.S. = scrubber surface temperature

S.O. = scrubber outlet temperature

B.B. = breathing bag outlet temperature

Figure 20

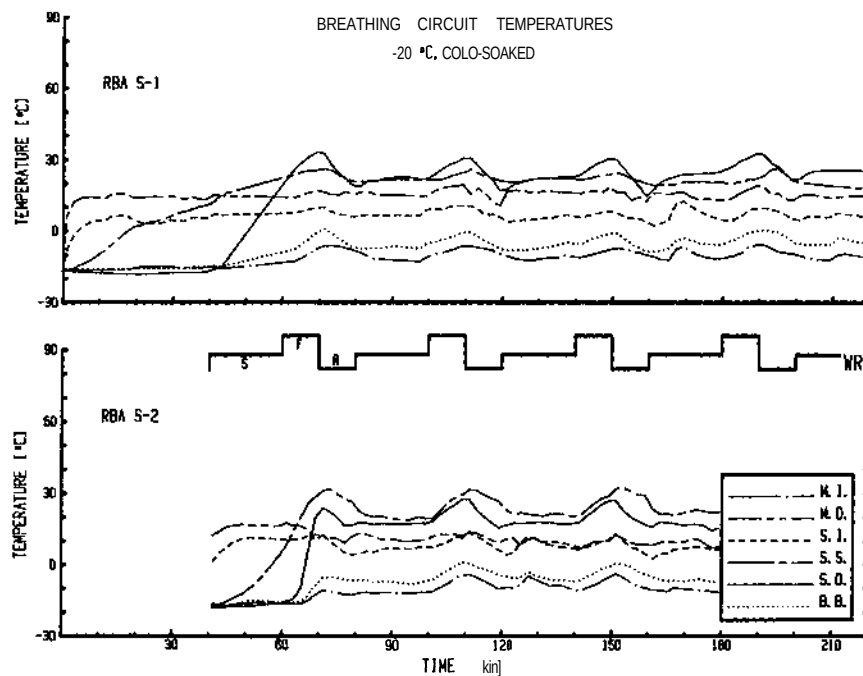


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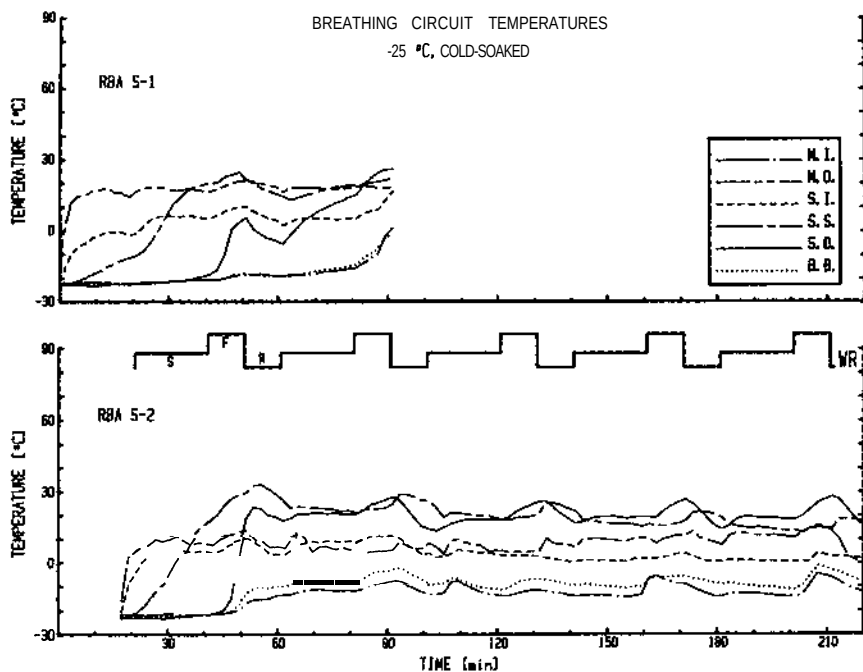


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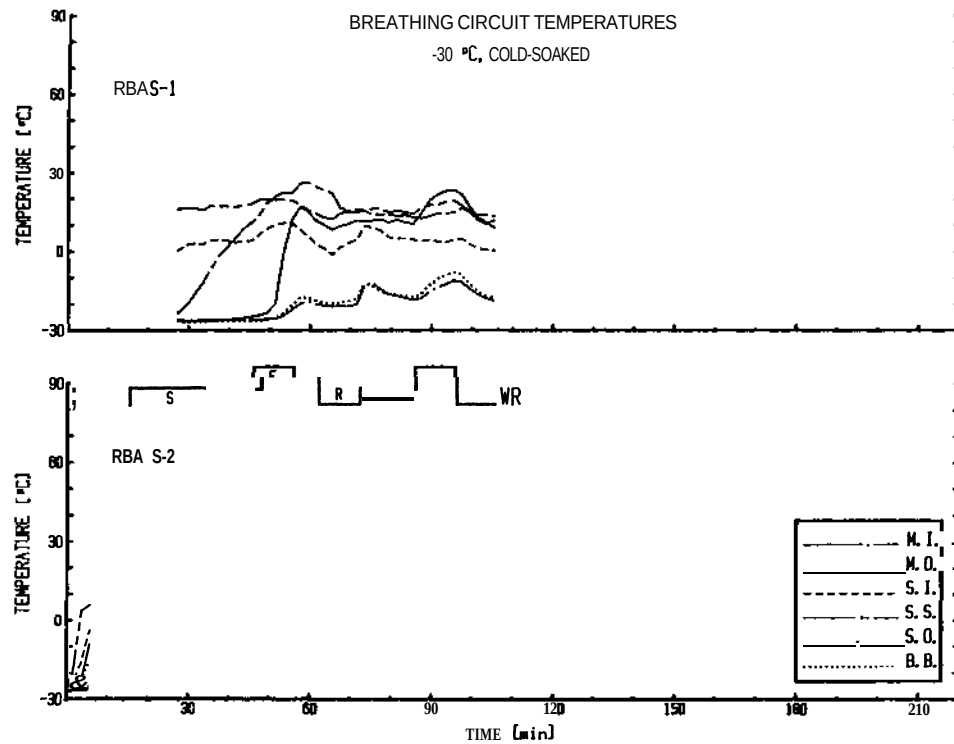


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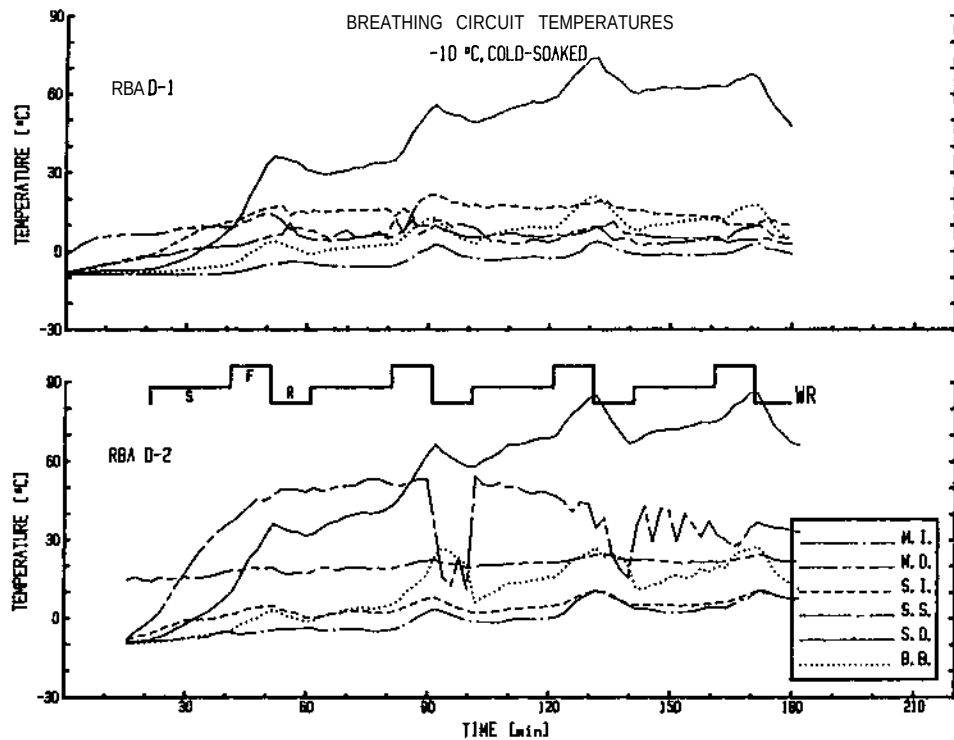


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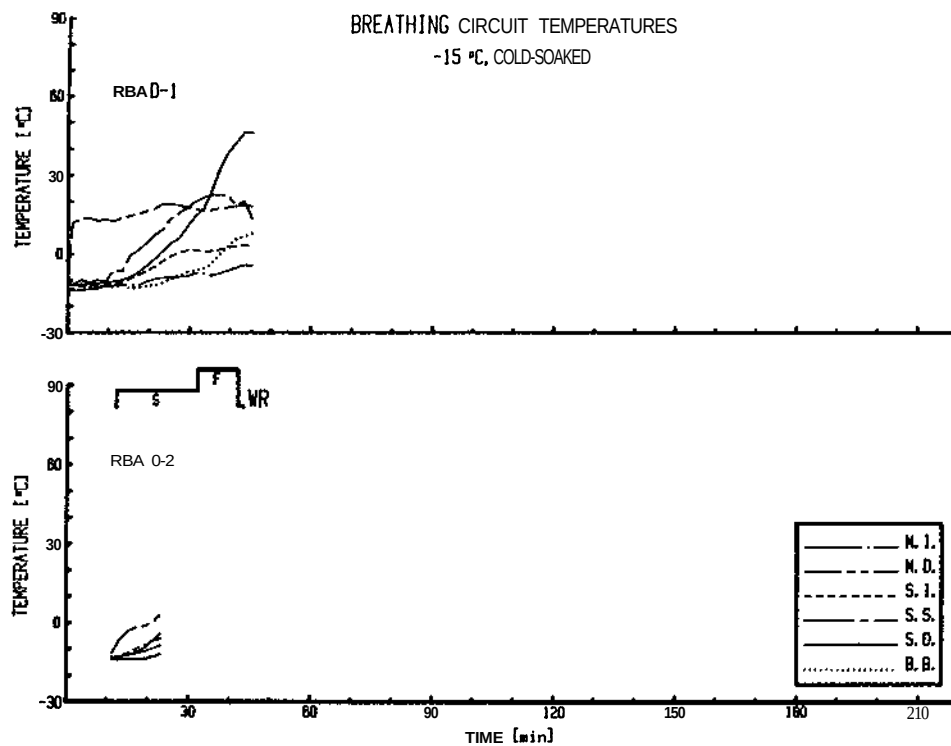


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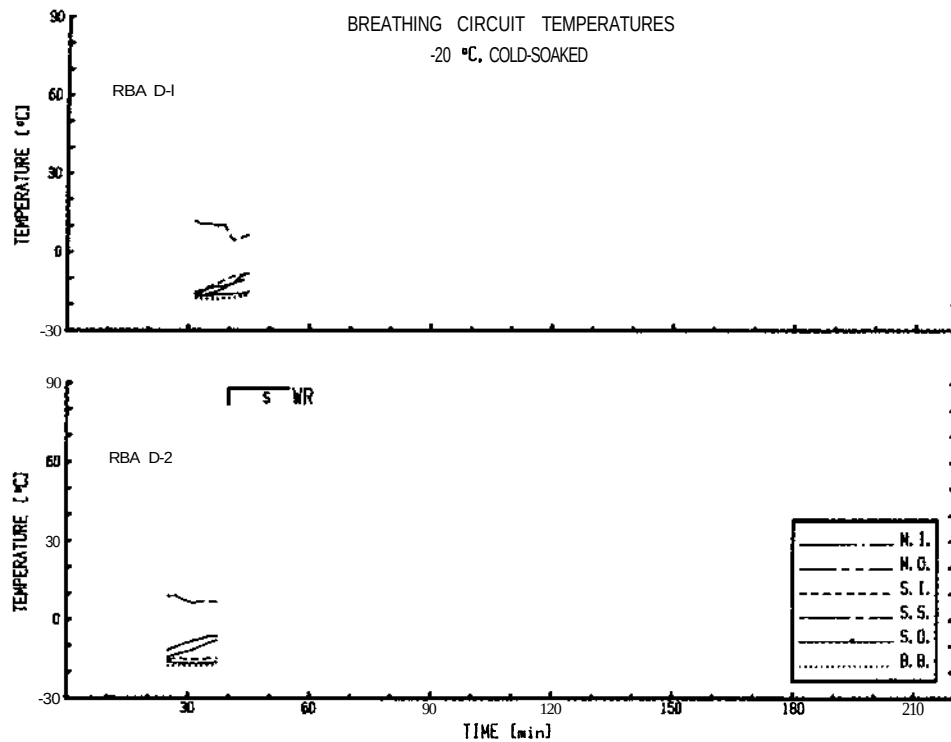


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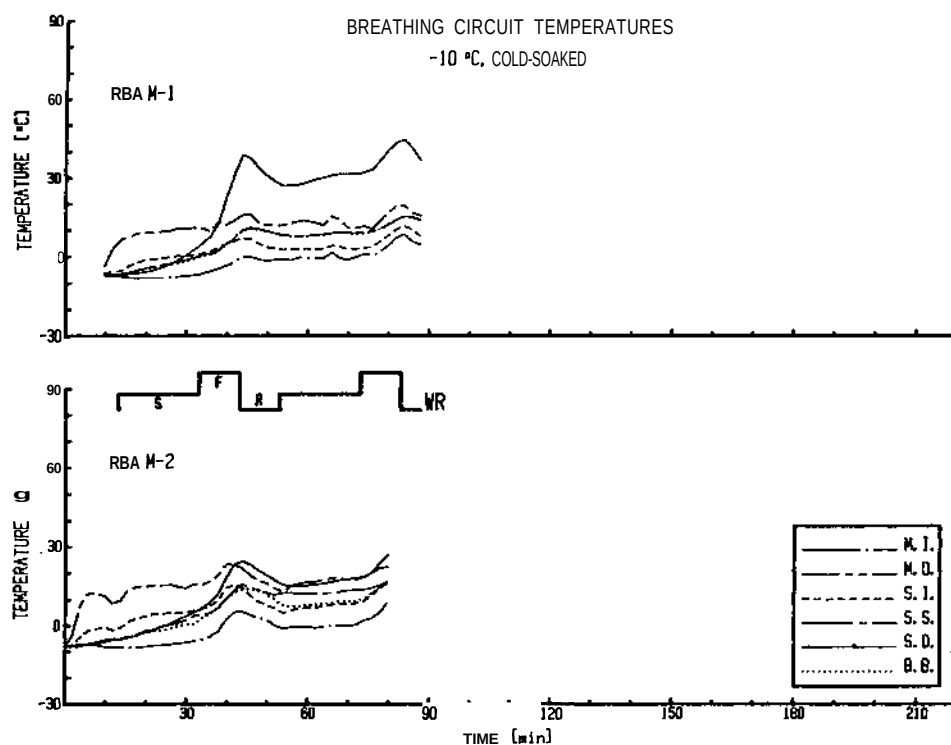


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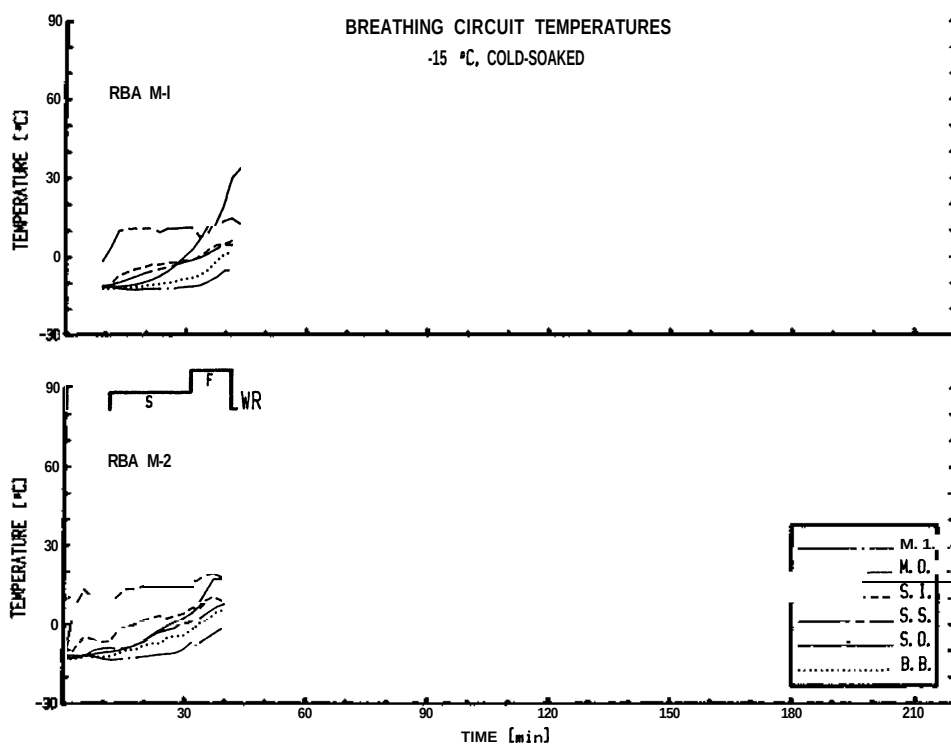


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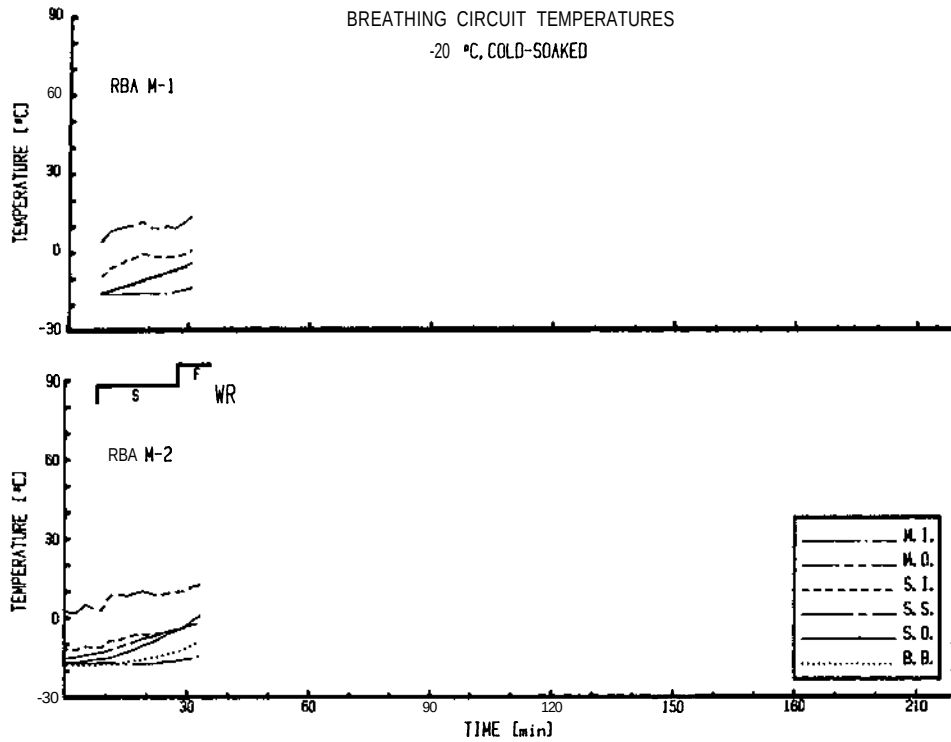


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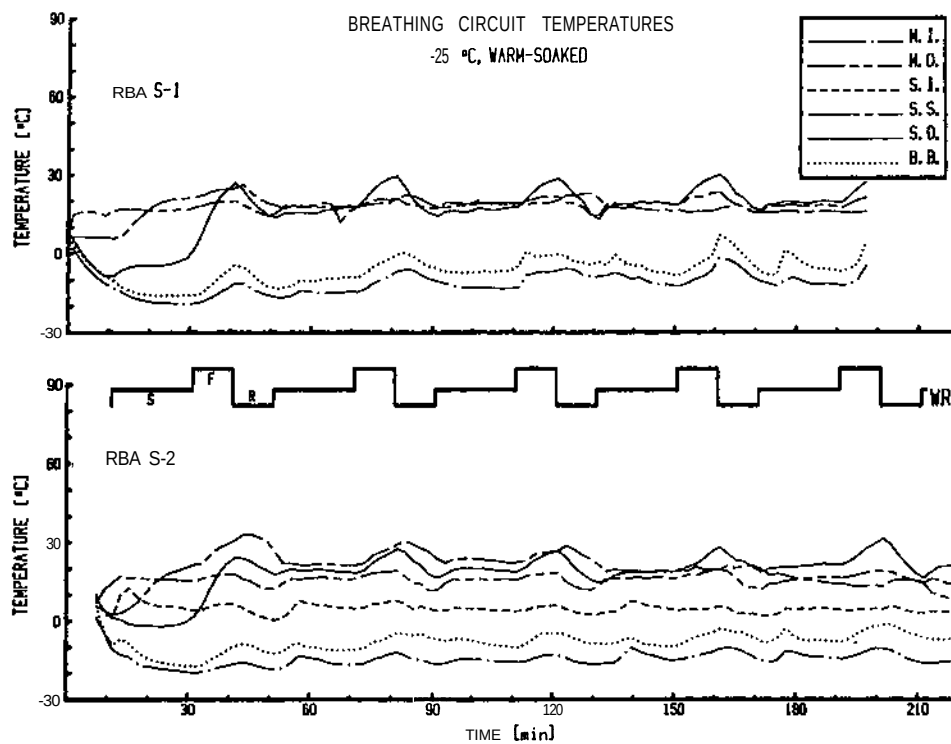


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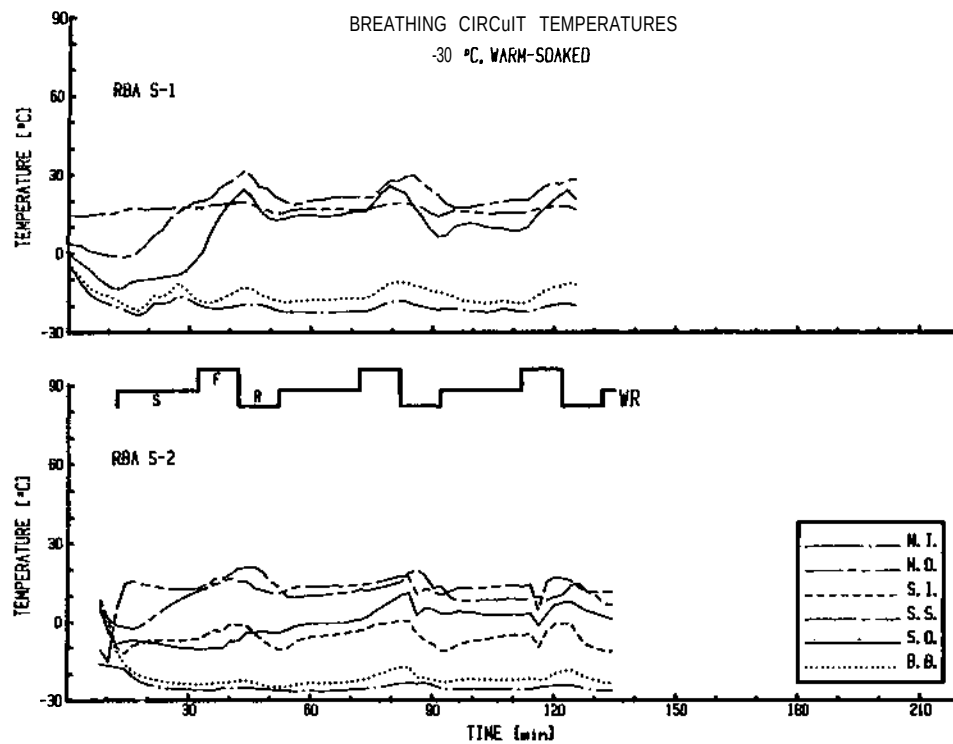


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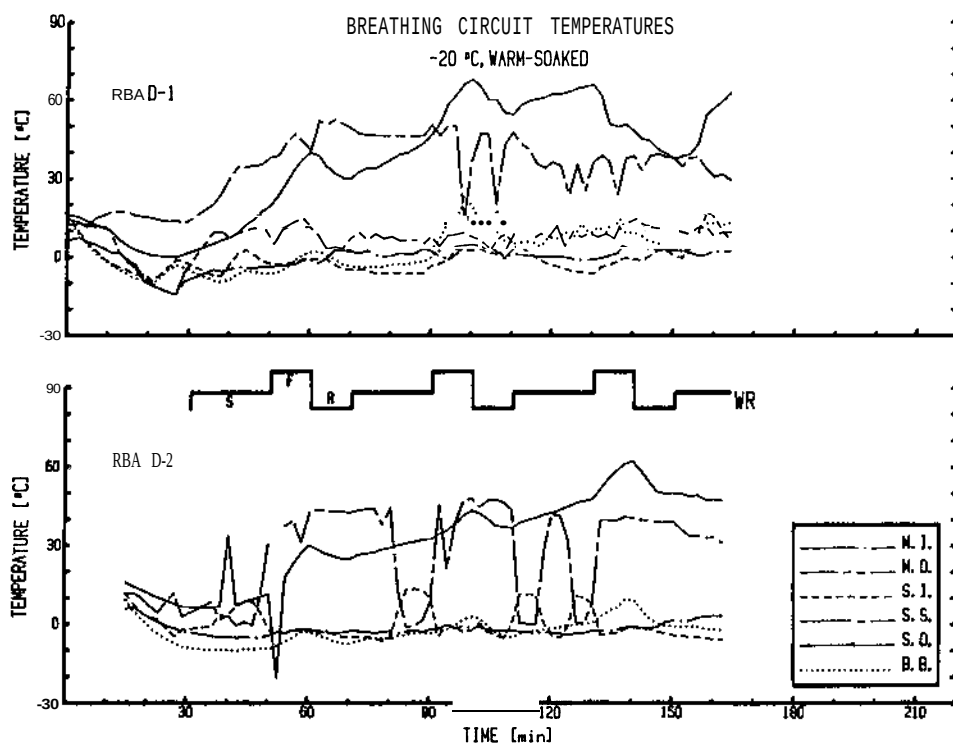


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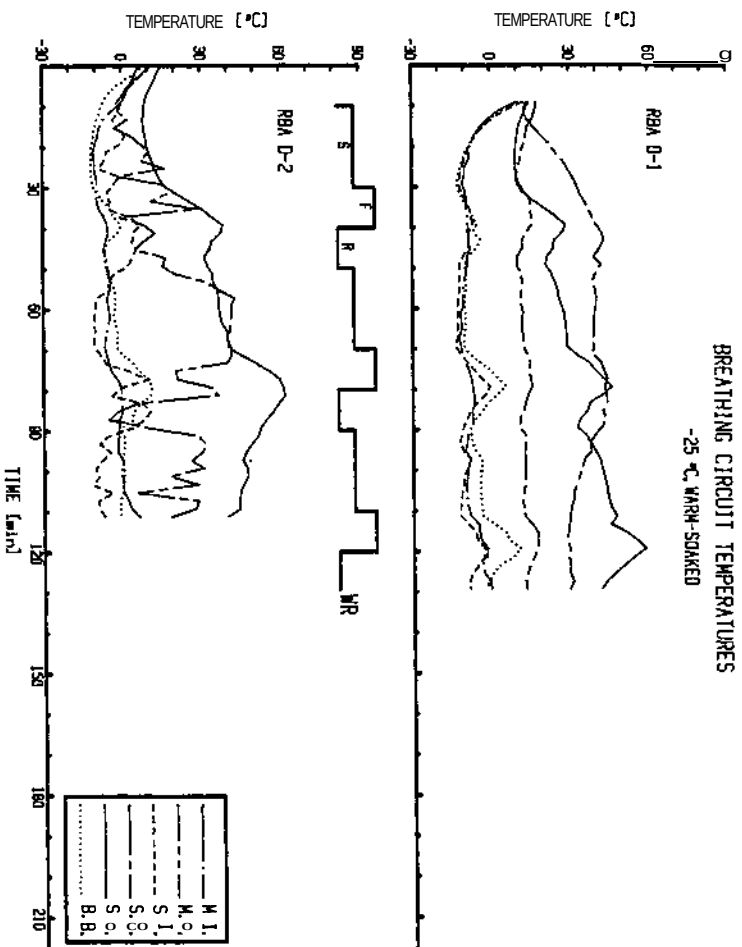


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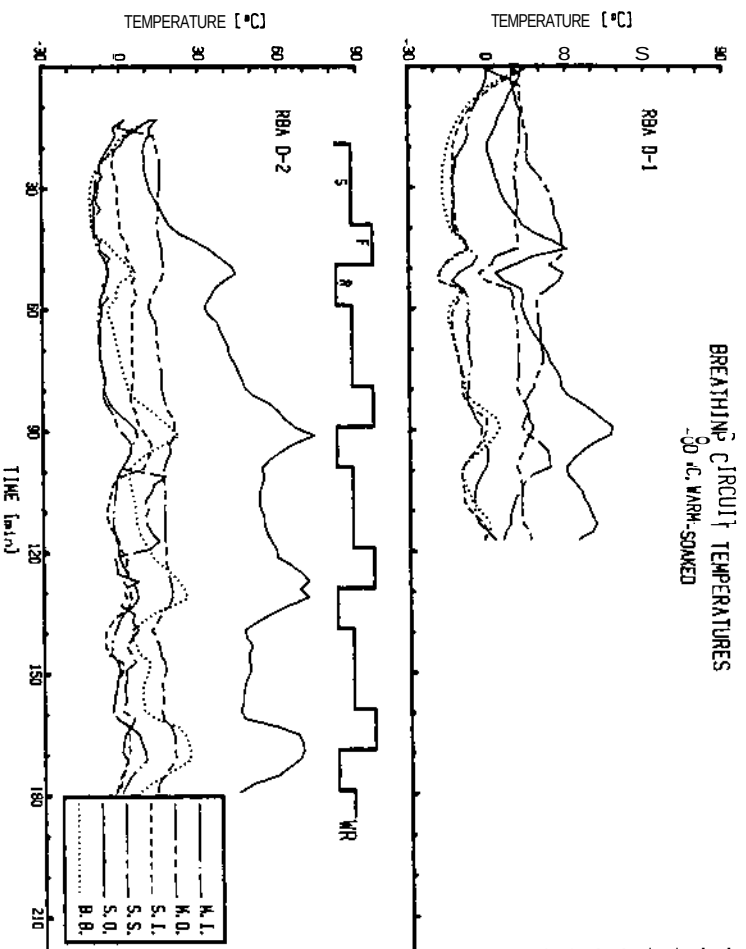


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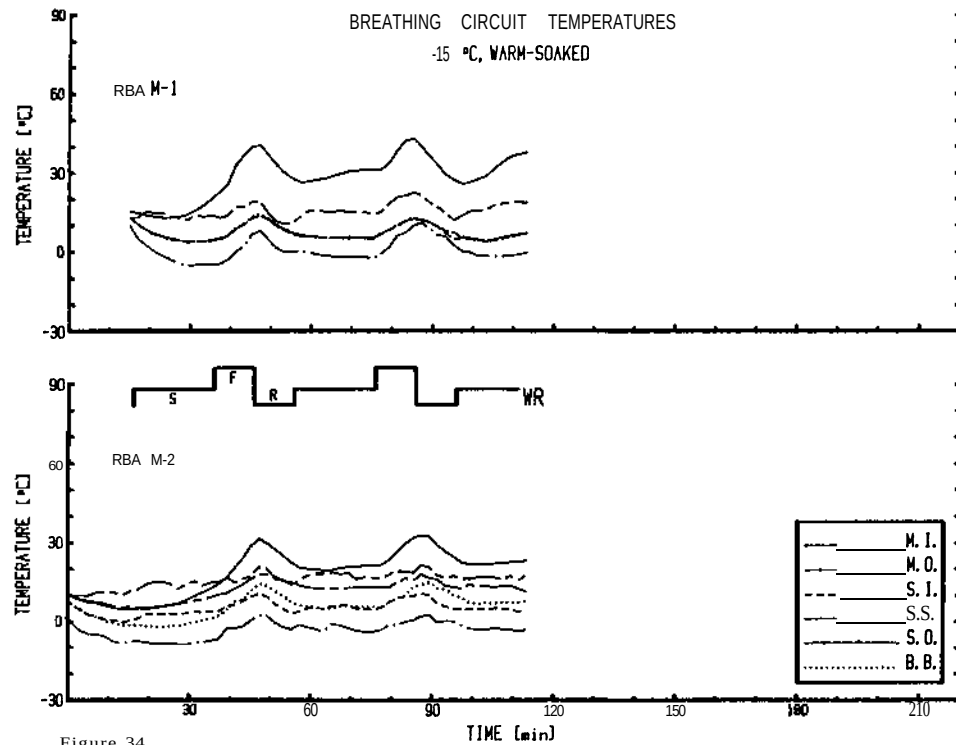


Figure 34

Figure 35

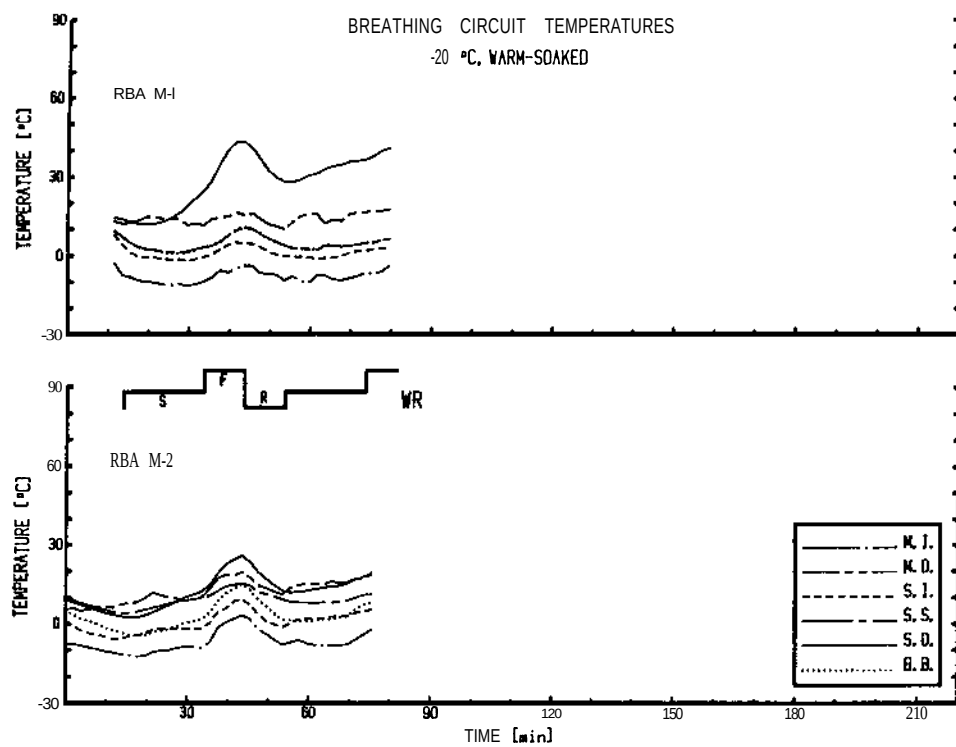


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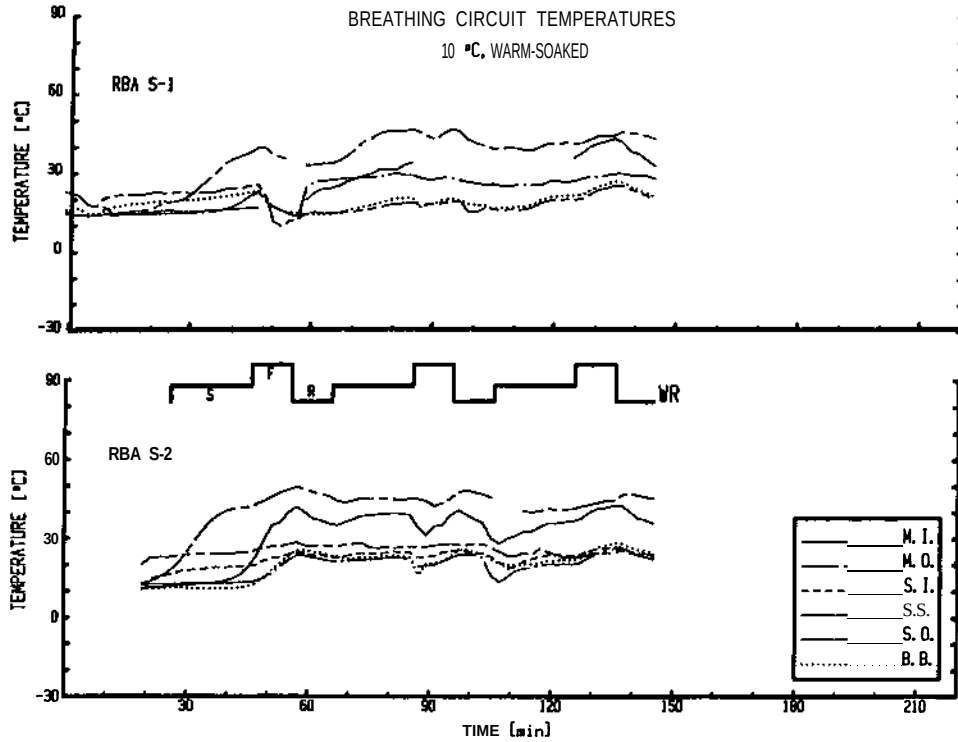
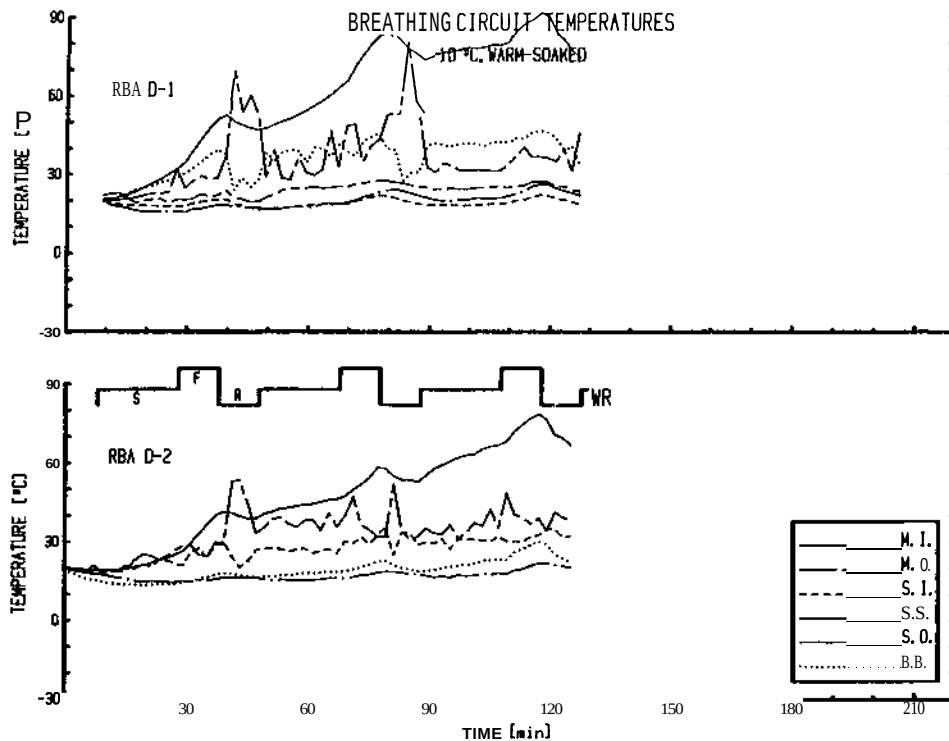


Figure 37



Appendix C. Inspiratory and Expiratory Respiratory Pressures (Figures 38-54)

Legends: WR = work - rest cycle

S = slow walk, $\text{VO}_2 = 1 \text{ liter} \cdot \text{min}^{-1}$

F = fast walk, $\text{VO}_2 = 2 \text{ liters} \cdot \text{min}^{-1}$

R = rest, $\text{VO}_2 = 0.3 \text{ liter} \cdot \text{min}^{-1}$

Figure 38

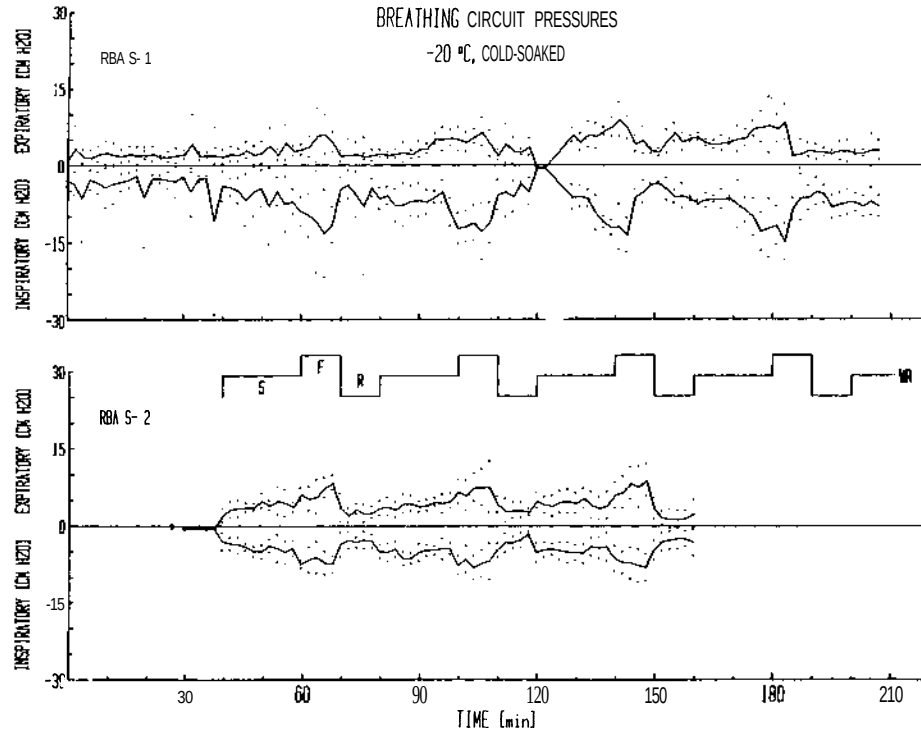


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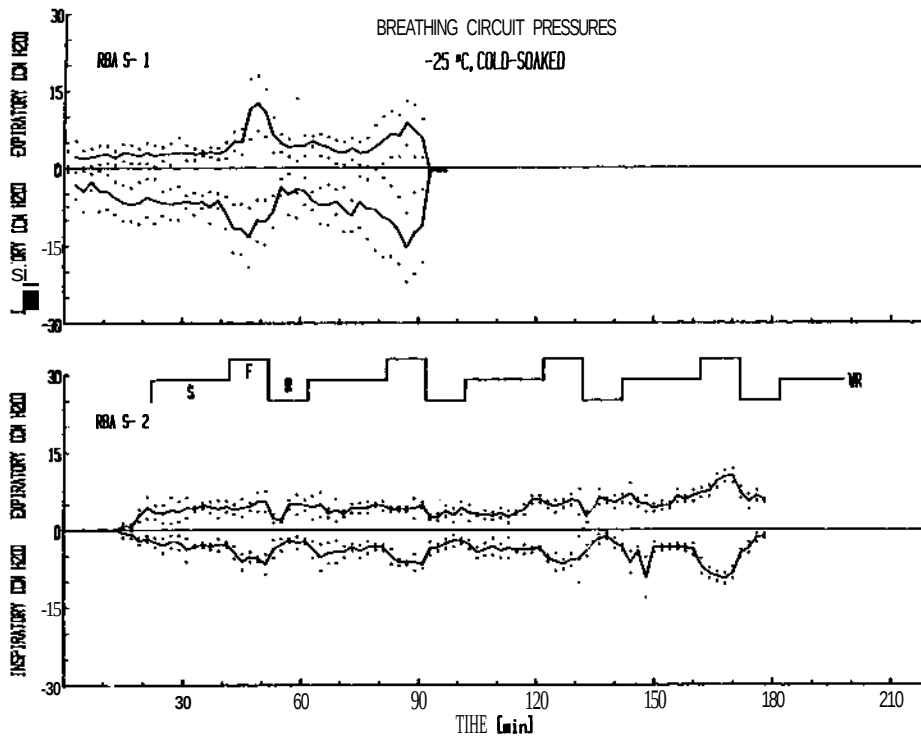


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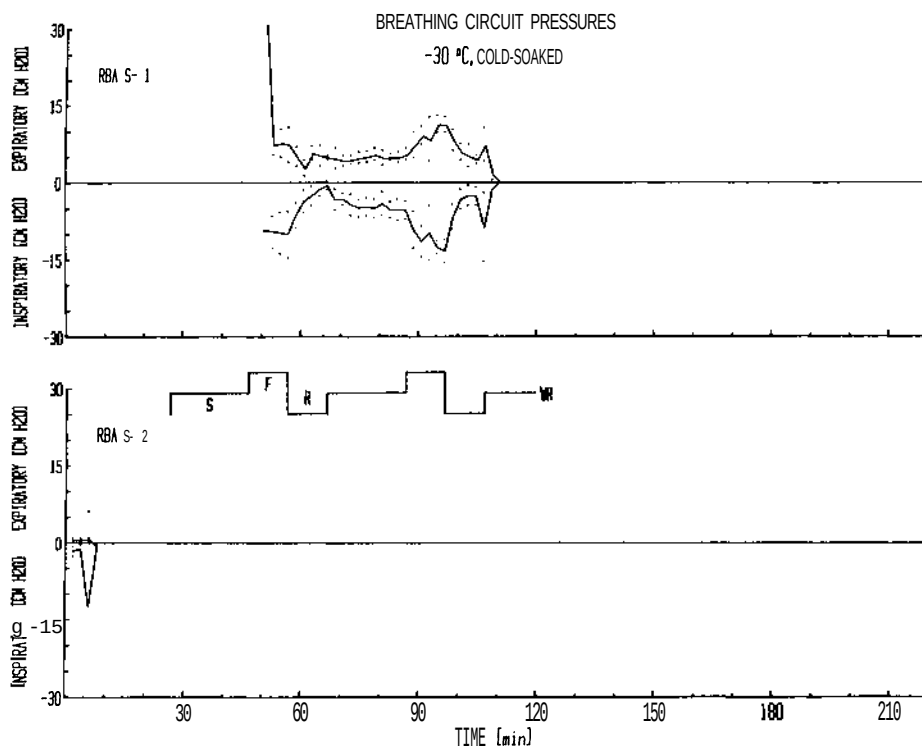


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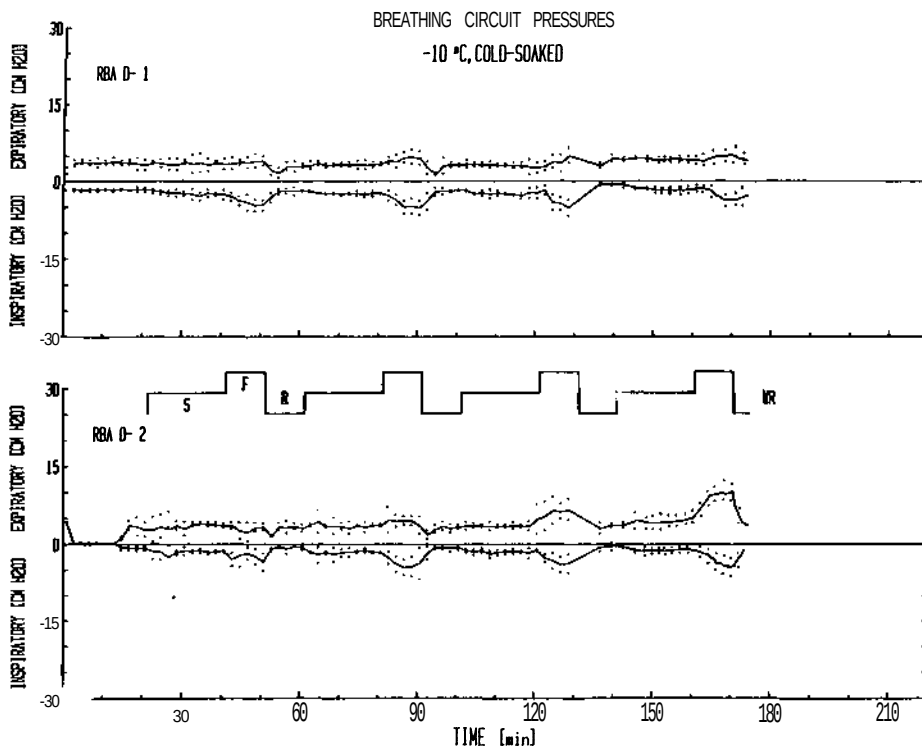


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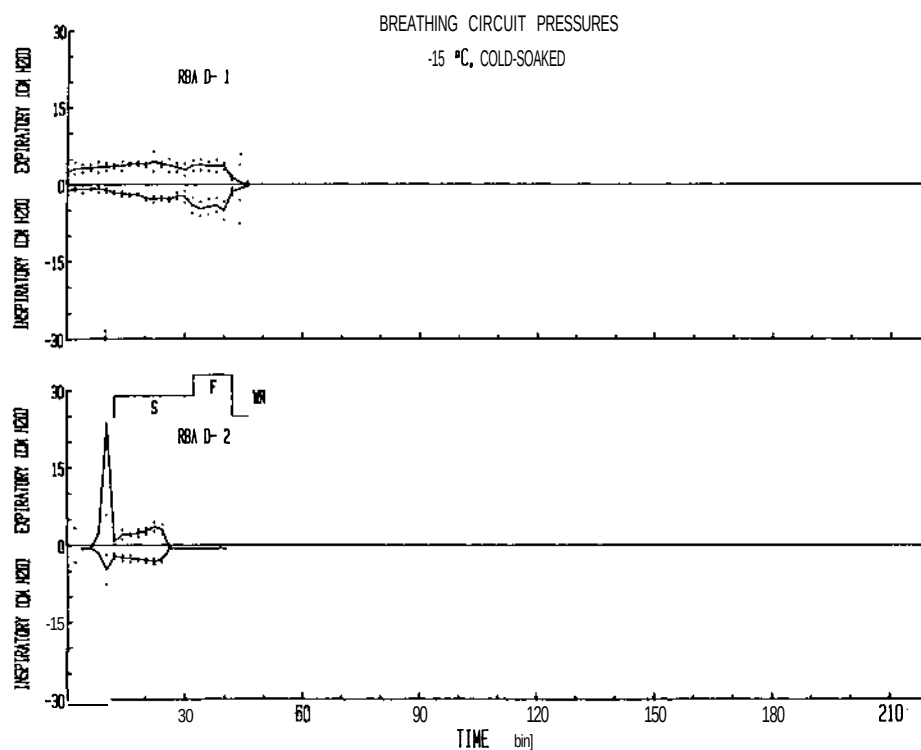


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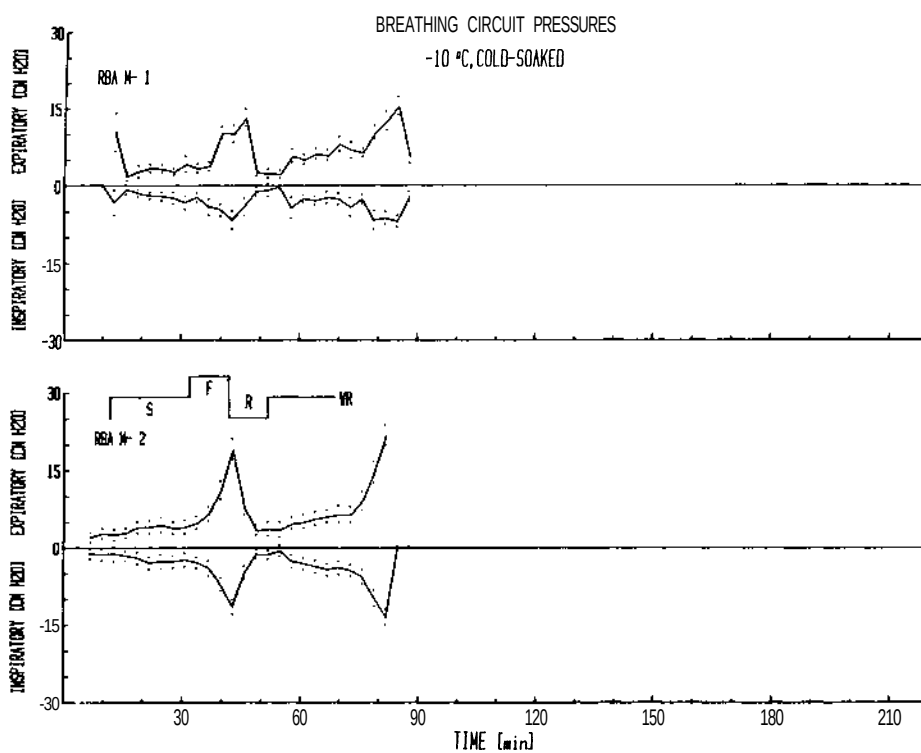


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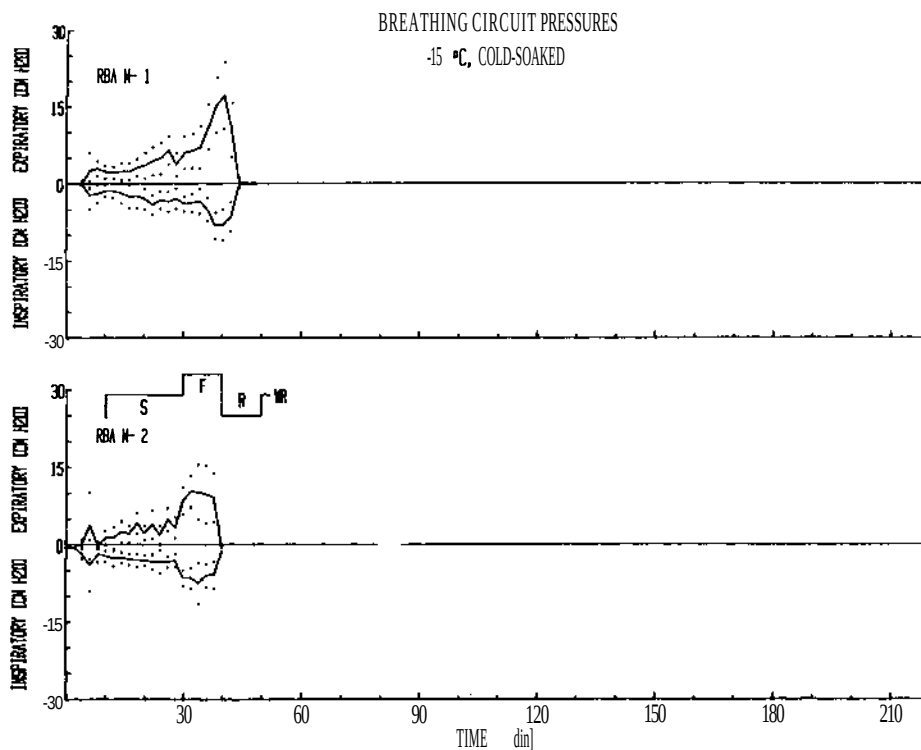


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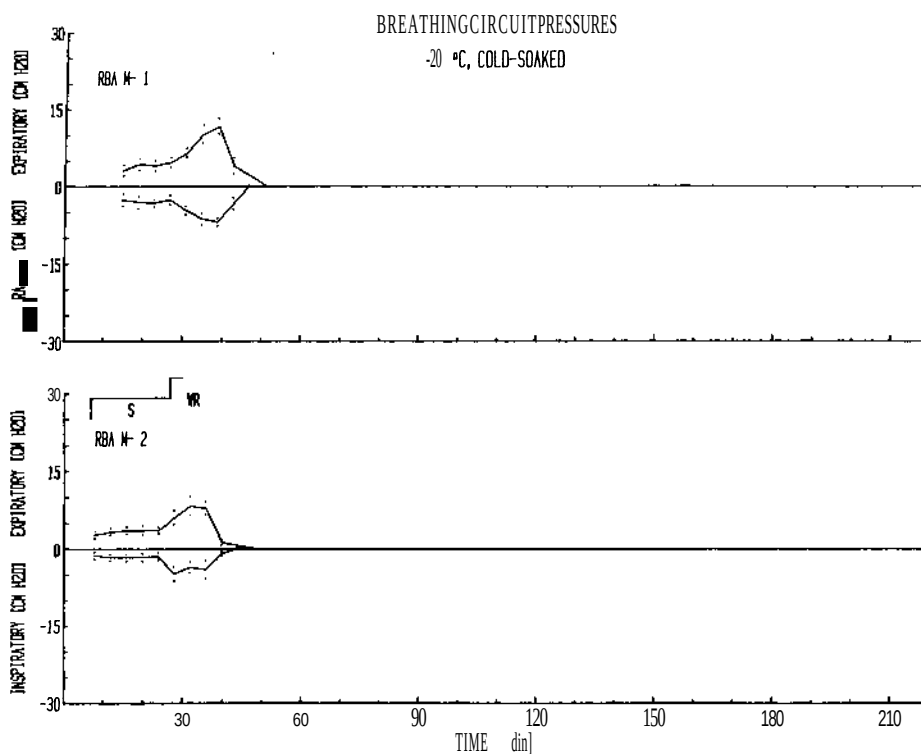


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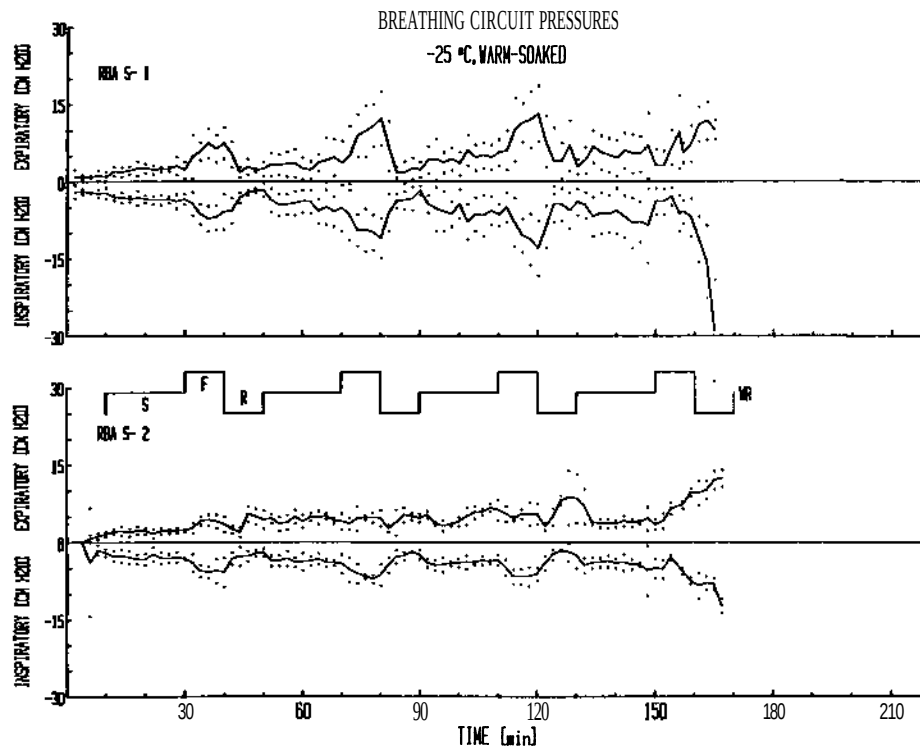


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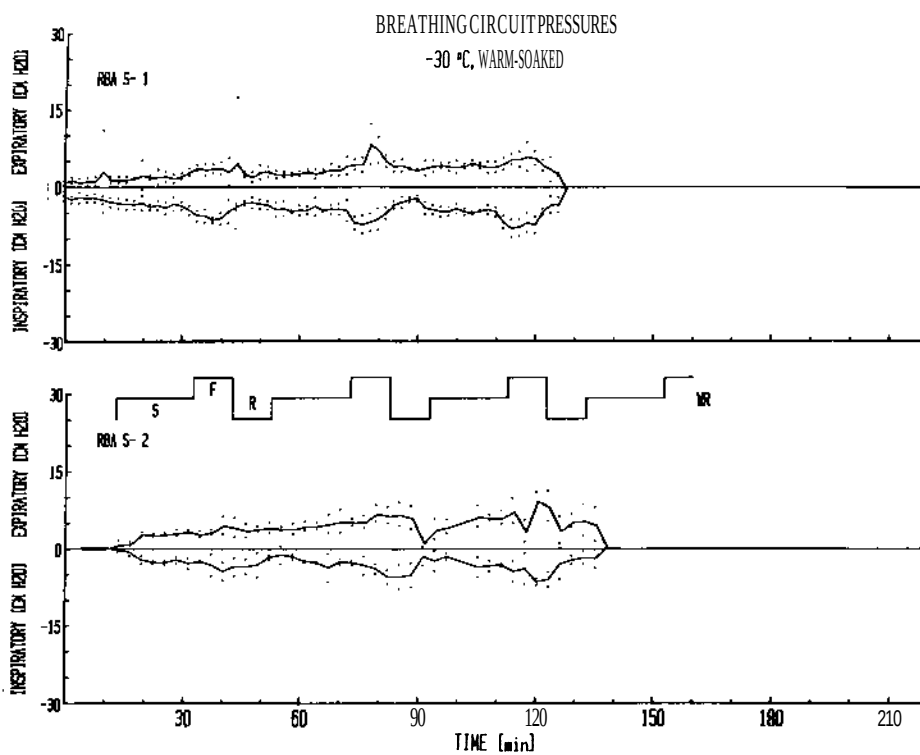


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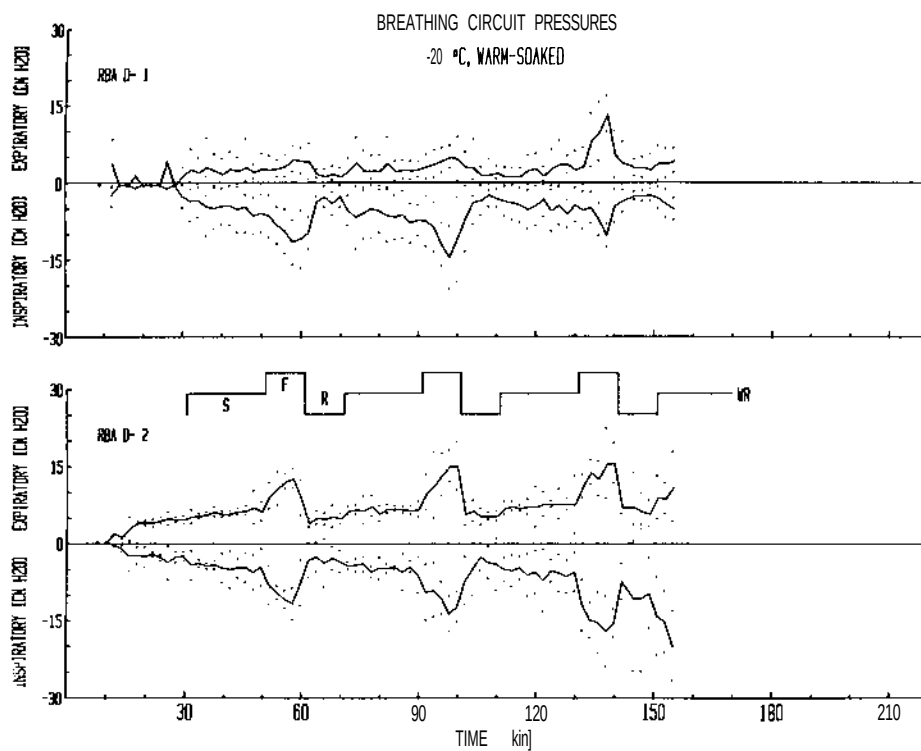


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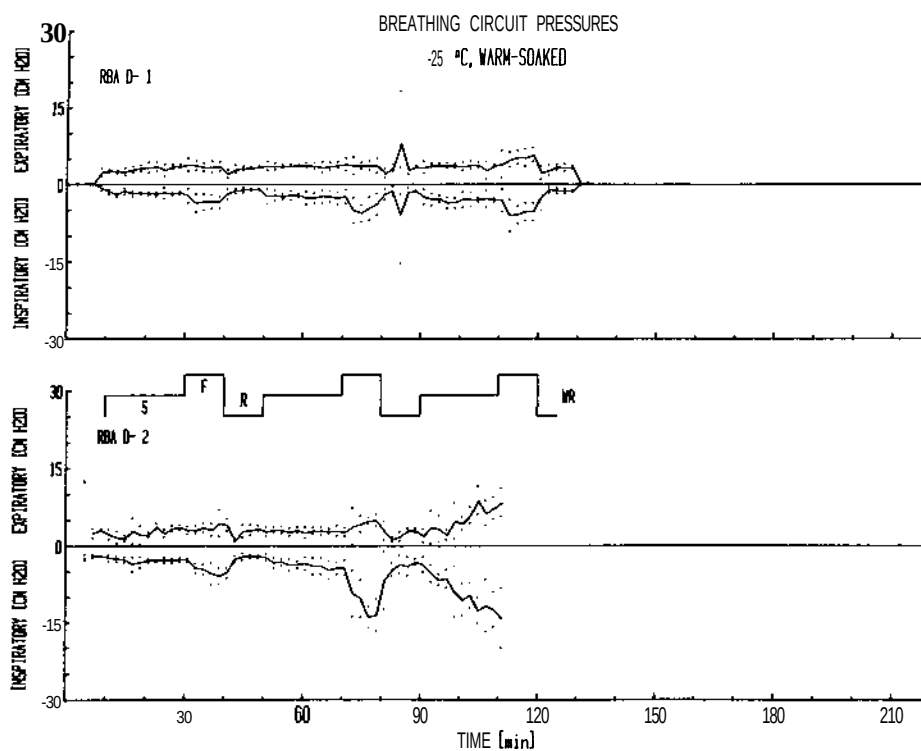


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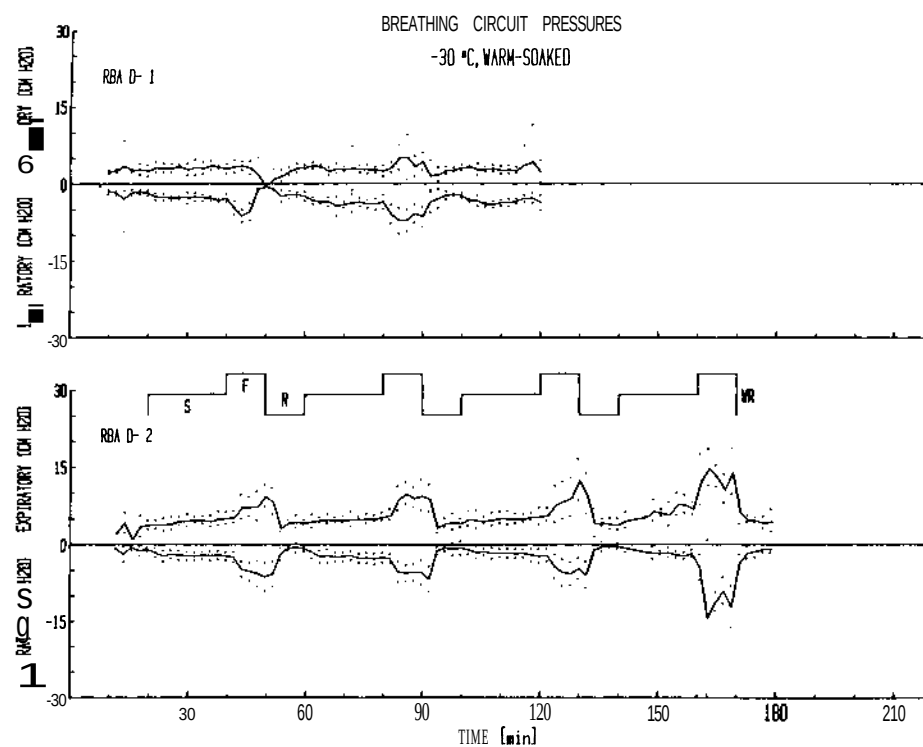


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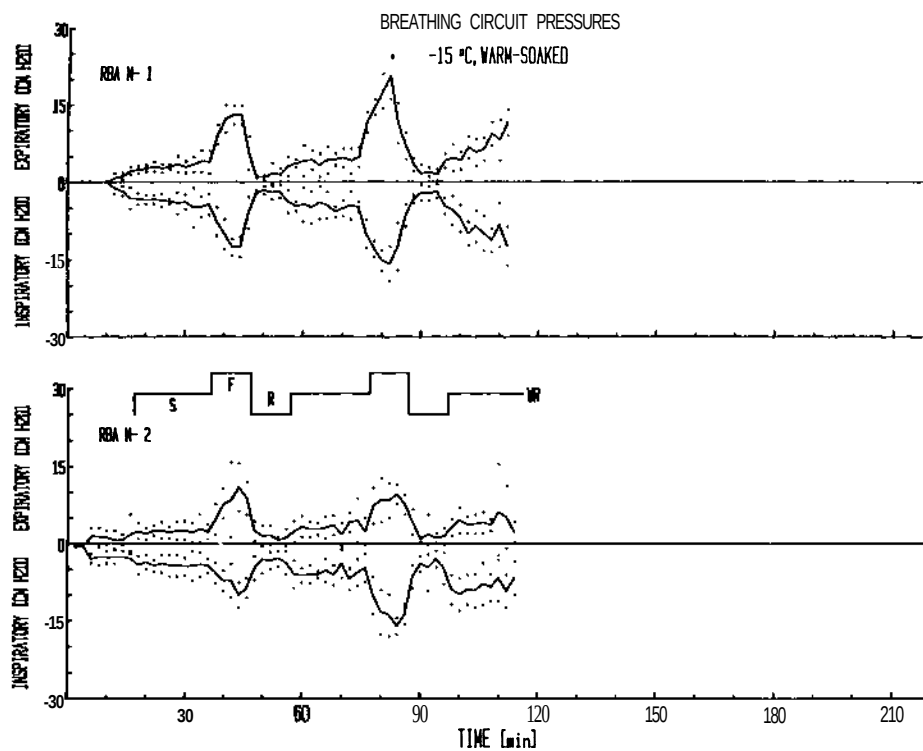


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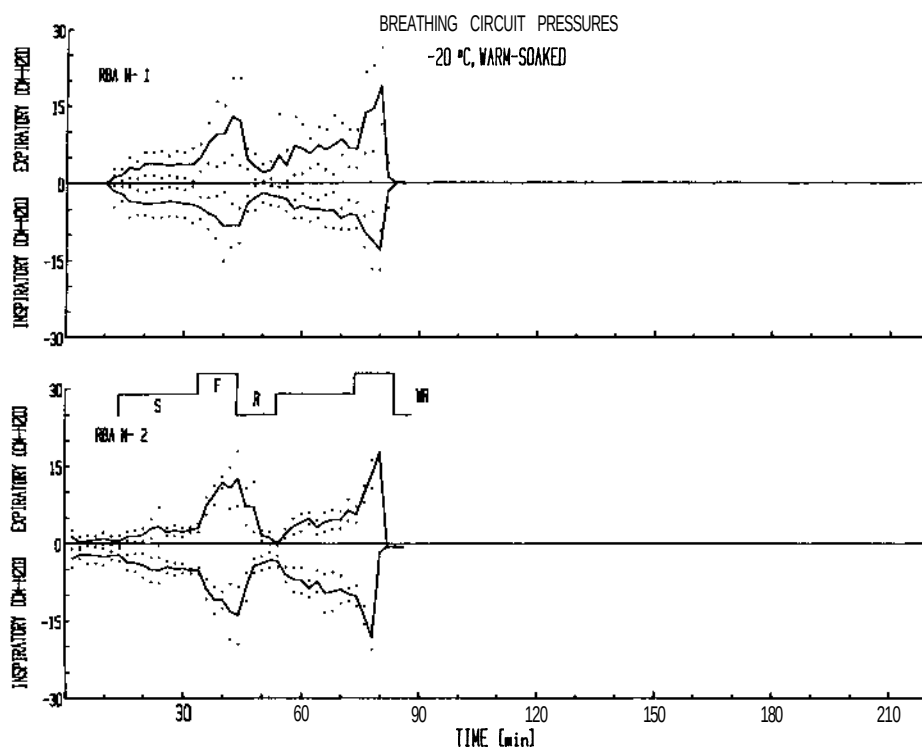


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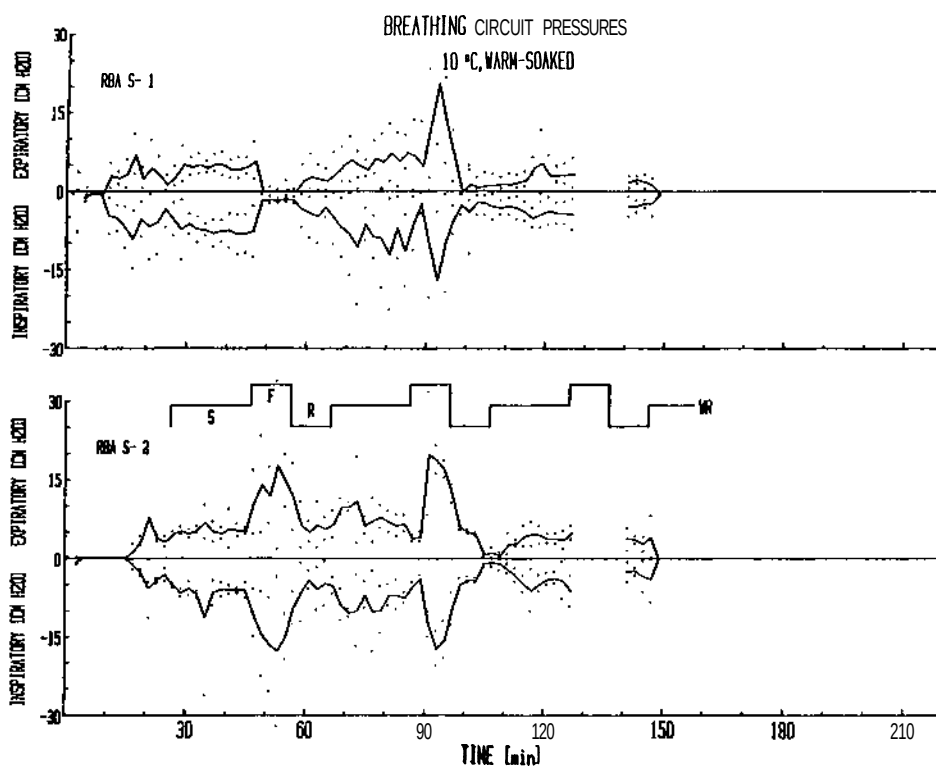


Figure 54

