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SIMULATION TESTING OF DIVERS BREATHING APPARATUS

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Navy Experimental Diving Unit
Washington, D.C.

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13. ABSTRACT

The development of human simulation and physiologic testing methods is greatly altering the development cycle for military diver life support equipment. The relationships of both testing methods to each other and to the complete development cycle are discussed. The state of development of the NEDU "human simulator" and the measuring techniques needed to support it are discussed in detail. Areas needing further work are identified.

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INTRODUCTION

The basic development cycle for a piece of diver life support equipment for military use is shown in Figure 1. The development of human simulator and physiological testing methods has been a recent and relatively rapid process. Both may be characterized as being in the adolescent stage: almost all there, but not yet well coordinated.

The human simulator and physiological testing methods are similar in that they are both designed to measure the critical performance characteristics of a piece of equipment over its entire intended operational envelope. The basic difference is the utilization of specially constructed "dummies" vs. human test subjects. This difference produces in turn some significant differences in the measuring approaches and evaluation standards used.

In human simulator testing, the mechanical demands placed on a breathing apparatus are carefully controlled and its responses are carefully measured. The mechanical demands normally consist of depth, breathing mixture, breathing rate, tidal volume, wave form, CO_2 production, and possibly O_2 consumption. The responses normally of interest may include sound levels, inhalation and exhalation pressures, external work of breathing, O_2 and CO_2 levels and at times other quantities. The actual quantities of interest in any one situation are, of course, dependent upon the apparatus being tested.

In physiological testing, the primary controlled variables are depth, breathing media, and diver work rate. The responses of prime interest are the divers general well-being and his arterial partial pressures of O_2 and CO_2. The mechanical quantities controlled or measured in the human simulation testing are intermediate quantities (see Figure 2). Monitoring or measurement of them may be difficult and frequently is not essential for determining whether or not the equipment passes the physiological tests. Measurement or estimation of them is, however, necessary for pinpointing

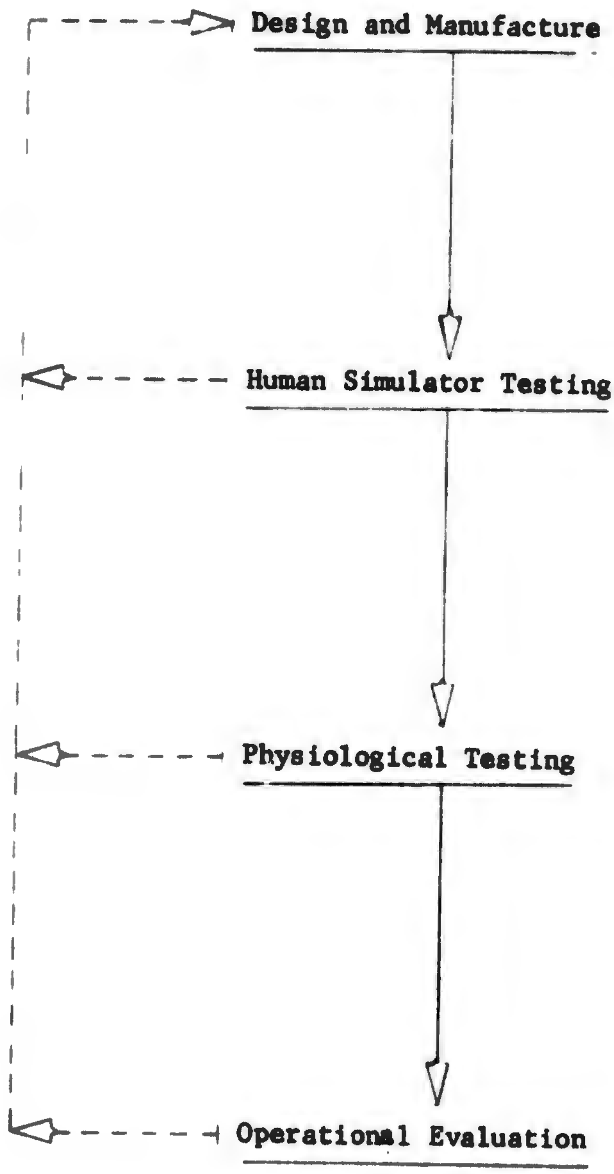
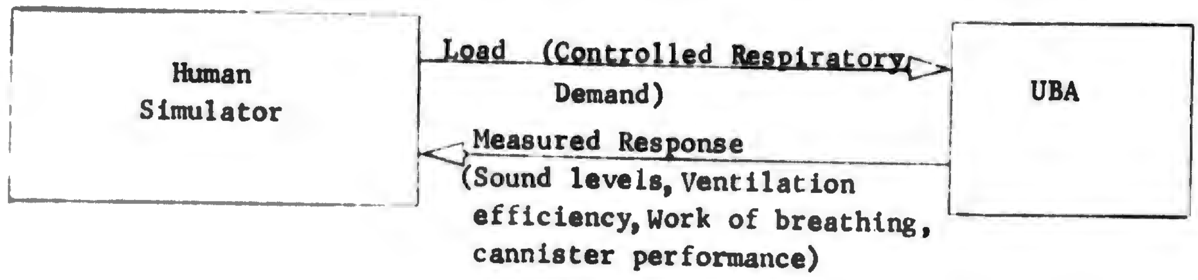
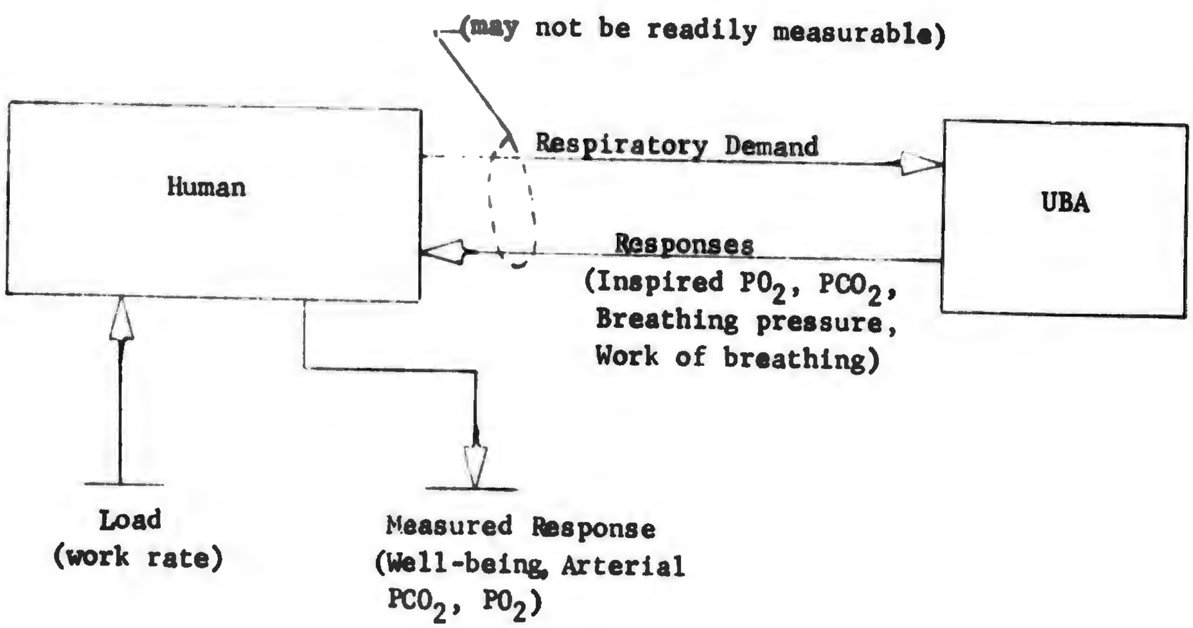


FIGURE 1 BASIC DEVELOPMENT CYCLE FOR DIVER LIFE SUPPORT EQUIPMENT



Human Simulator Testing



Physiological Testing

FIGURE 2 RELATIONSHIP OF PRIMARY LOAD AND RESPONSE VARIABLES IN HUMAN SIMULATION AND PHYSIOLOGICAL EQUIPMENT TESTING trouble spots and for correlating the results of the physiologic tests with those of the human simulator testing. Indeed, it is the value of these intermediate quantities, measured or estimated, plus operational evaluation experience, that ultimately establish the test conditions chosen for the human simulator. They also establish the envelope of satisfactory responses for any particular apparatus undergoing simulator testing. Figure 3 shows basically how this iteration process works.

This paper is concerned with the state of the art of human simulator testing and with the measuring techniques necessary to support it. This includes all the measuring techniques used with the simulator, and the techniques used in physiological testing to measure the mechanical performance of the diver and his breathing apparatus. Also treated are the standards by which the performance of an apparatus is judged.

NEDU TESTING

Table 1 lists the mechanical quantities that may be required to be known or measured during a simulation or physiologic test. Normally all these quantities can be measured or controlied when using the human simulator at NEDU. During physiological testing, monitoring just what is happening between the diver and his breathing apparatus may not always be possible. Table 2 lists the quantities that can normally be controlled or measured with present equipment as a function of breathing apparatus and testing methods.

The "human simulator" used at NEDU is not one large complicated machine. It is rather a collection of specialized and general purpose equipment that can be organized, as required, to test particular pieces of diving equipment. The major equipment items are the breathing machine, EDU dummy, CBS acoustical manikin, precision sound level meter, a wet testing box, and, of course, a hyperbaric chamber. Table 3 lists the characteristics of these items. Figures 4 thru 7 show some of the equipment set ups that have been used within the last year. They show the basic patterns in which the test equipments are usually organized.

FIGURE 3 BLOCK DIAGRAM
DEVELOPMENT OF HUMAN SIMULATOR FOR UBA'S
WITH APPROPRIATE PERFORMANCE STANDARDS

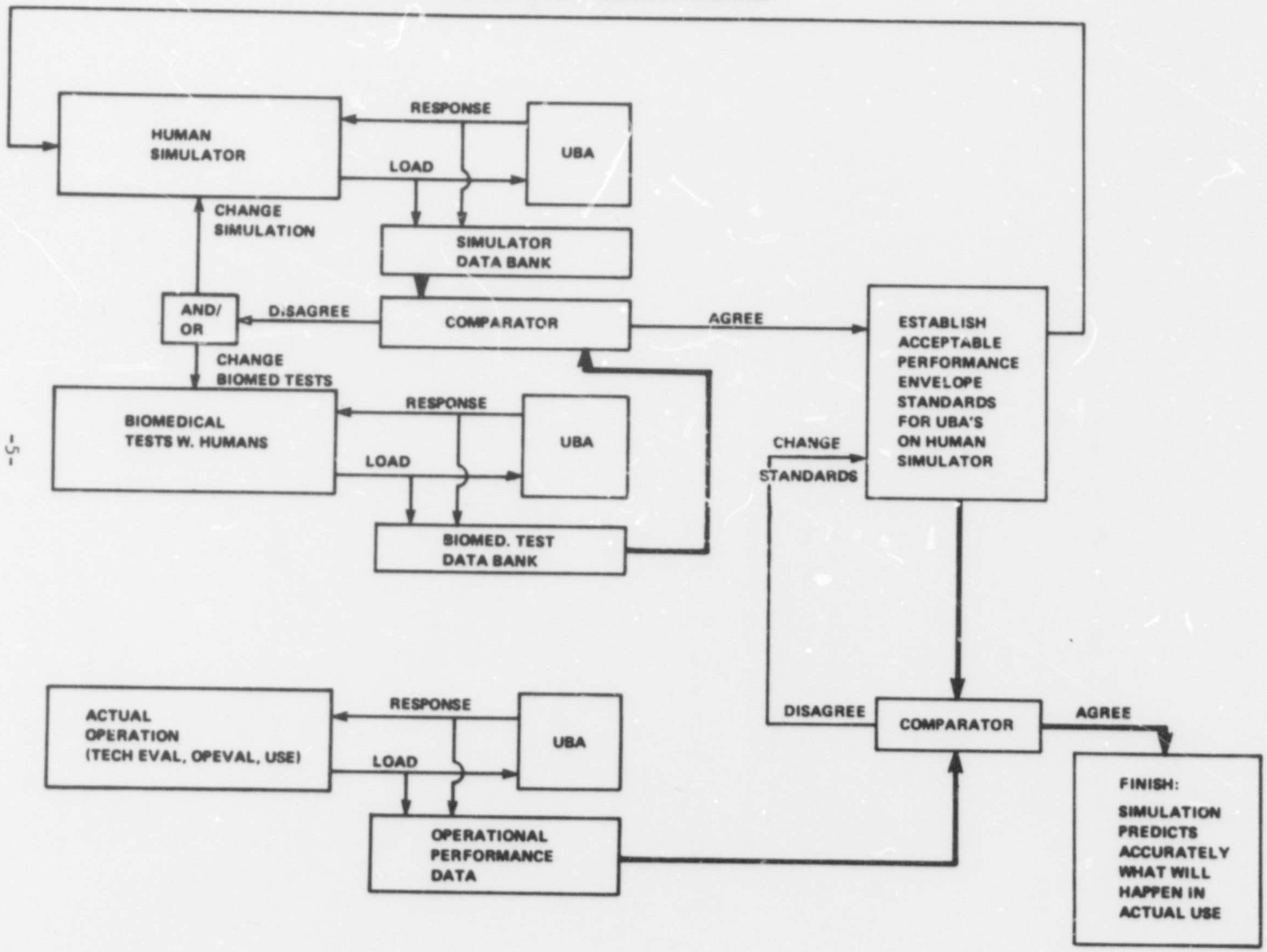


TABLE 1

CONDITIONS THAT MAY REQUIRE MEASUREMENT OR KNOWLEDGE DURING SIMULATION OR PHYSIOLOGICAL TESTING

Acoustic Characteristics

- Sound levels
- Microphone and speaker effectiveness

Ventilation Characteristics

- PCO_2
- PO_2
- Flow rates

Pressures

- Oral-Nasal pressure (breathing pressure)
- Apparatus pressures as appropriate
- Supply pressure
- Line losses in flowing state

External Work of Breathing

- Source
- Quantity

Cannister Performance

- Efficiency
- Duration as a function of temperature

Dummy or Diver Mechanical Performance

- Breathing rate
- Tidal volume
- Wave form
- CO_2 production
- Exhaled temperature and humidity
- O_2 consumption

Other Conditions

- Depth
- Breathing media
- Ambient temperature
- Orientation
- Wet or dry

TABLE 2 MEASURING CAPABILITIES AS A FUNCTION OF APPARATUS AND TEST CONDITIONS

Breathing Apparatus	Quantity to be Measured	Operating Condition: Human Simulator Test: Dry	Human Simulator Test: Wet	Human Simulator Test: Dry U.P.	Human Simulator Test: Wet U.P.	Physiologic Test: Dry	Physiologic Test: Wet	Physiologic Test: Dry U.P.	Physiologic Test: Wet U.P.
SCUBA Single-hose	Diff. Pressures	✓	✓	✓	✓	✓	*	✓	*
	Resp. Flow Rate	C.V	C.V	C.V.	C.V.				
	Ext. Work of Breathing	✓	✓	✓	✓				
SCUBA Double Hose	Diff. Pressures	✓	✓	✓	✓	✓	*	✓	*
	Resp. Flow Rate	C.V.	C.V.	C.V.	C.V.	✓	✓		
	Ext. Work of Breathing	✓	✓	✓	✓	✓	✓		
Bandmask Open Circuit and Demand	Diff. Pressures	✓	✓	✓	✓	✓	*	✓	*
	Resp. Flow Rate	C.V.	C.V.	C.V.	C.V.				
	Ext. Work of Breathing	✓	✓	✓	✓				
	Inspired PCO_2	✓	✓	✓	✓				
	CO_2 Production	C.V.	C.V.	C.V.	C.V.				
Helmet Open Circuit	Diff. Pressures	✓	✓	✓	✓	✓	*	✓	*
	Resp. Flow Rate	C.V.	C.V.	C.V.	C.V.				
	Ext. Work of Breathing	✓	✓	✓	✓				
	Inspired PCO_2	✓	✓	✓	✓				
	Helmet CO_2 levels	✓	✓	✓	✓	✓	**	**	**
	CO_2 Production	C.V.	C.V.	C.V.	C.V.		**		**
	Gas Consumption	✓	✓	✓	✓	✓	✓	✓	✓
	Sound Level	✓	✓	✓	✓				
Helmet Recirculating	Diff. Pressures	✓	✓	✓	✓	✓	✓	✓	*
	Resp. Flow Rate	C.V.	C.V.	C.V.	C.V.				
	Ext. Work of Breathing	✓	✓	✓	✓				
	Inspired FO_2, PCO_2	✓	✓	✓	✓				

TABLE 2 (CONT.) MEASURING CAPABILITIES AS A FUNCTION OF [illegible] TEST CONDITIONS

Breathing Apparatus	Quantity to be Measured	Operating Condition: Human Simulator Test: Dry	Wet	Dry U.P.	Wet U.P.	Physiologic Test: Dry	Wet	Dry U.P.	Wet U.P.
	Helmet and Recirc PO_2, PCO_2	✓	✓	✓	✓	✓	**	**	**
	CO_2 Production	C.V.	C.V.	C.V.	C.V.	✓	✓	✓	✓
	Gas Consumption	✓	✓	✓	✓	✓	✓	✓	✓
	Recirculator Flow	✓	✓	✓	✓	✓	✓	✓	✓
	Sound Level	✓	✓	✓	✓				
UBA Semi-closed Circuit	Diff. Pressures	✓	✓	✓	✓	✓	*	✓	*
	Resp. Flow Rate	C.V.	C.V.	C.V.	C.V.	✓	✓		
	Ext. Work of Breathing	✓	✓	✓	✓	✓	✓		
	Inspired PO_2, PCO_2	✓	✓	✓	✓	✓	**	**	**
	CO_2 Production	C.V.	C.V.	C.V.	C.V.				
	O_2 Consumption	Not possible				✓	**	**	**
UBA Closed Circuit	Diff. Pressures	✓	✓	✓	✓	✓	*	✓	*
	Resp. Flow Rate	C.V.	C.V.	C.V.	C.V.	✓	✓		
	Ext. Work of Breathing	✓	✓	✓	✓	✓	✓		
	Inspired PO_2, PCO_2	✓	✓	✓	✓	✓	**	**	**
	CO_2 Production	C.V.	C.V.	C.V.	C.V.				
	O_2 Consumption	Not possible							

NOTES:
C.V. - Controlled Variable
U.P. - Under Pressure
*Instruments to be used under pressure but must remain dry.
**Instruments must remain dry and at 1 atmosphere.

TABLE 3
CHARACTERISTICS OF MAJOR TEST EQUIPMENT

Item	
Breathing Machine	Type - Positive displacement piston
	Piston Drive - Cam follower
	Depth capability - 0-1500 fsw
	Breathing rate - 0-37 bpm
	Tidal volumes - 0.5, 1, 1.5, 2, 3.0, liters
	Waveform - sinusoidal with exhale/inhale time ratios of 1.0, 1.1, 1.2, 1.3 available
	CO_2 - add 0-4 slpm
	Humidity - add only up to saturation
	Heat - add only
EDU Dummy	Separate tubes 5/8" I.D. for inhalation and exhalation
	Separate ¼" I.D. tube for chin level pressure reference
	4 CO2 sample connections on head
	Ears rigged to allow addition of a B&K 4131 1" condenser microphone and cathode follower (dry mode only)
	All penetrations come out of torso at hip level
CBS Acoustical Manikin (with special jig can be used underwater)	Ears, B&K 4131 1" condenser microphones
	Mouth, calibrated speaker
	Head shape - 95 percentile American Head, acoustically identical to human head.
Hyperbaric Chamber	Depth - 0-1000 fsw Ports - 6 Ample piping and electrical penetrations
Precision Sound-Level Meter	Bruel & Kaejar Type 2301 with octave band filter set
X-Y Plotter	Brush - 1000

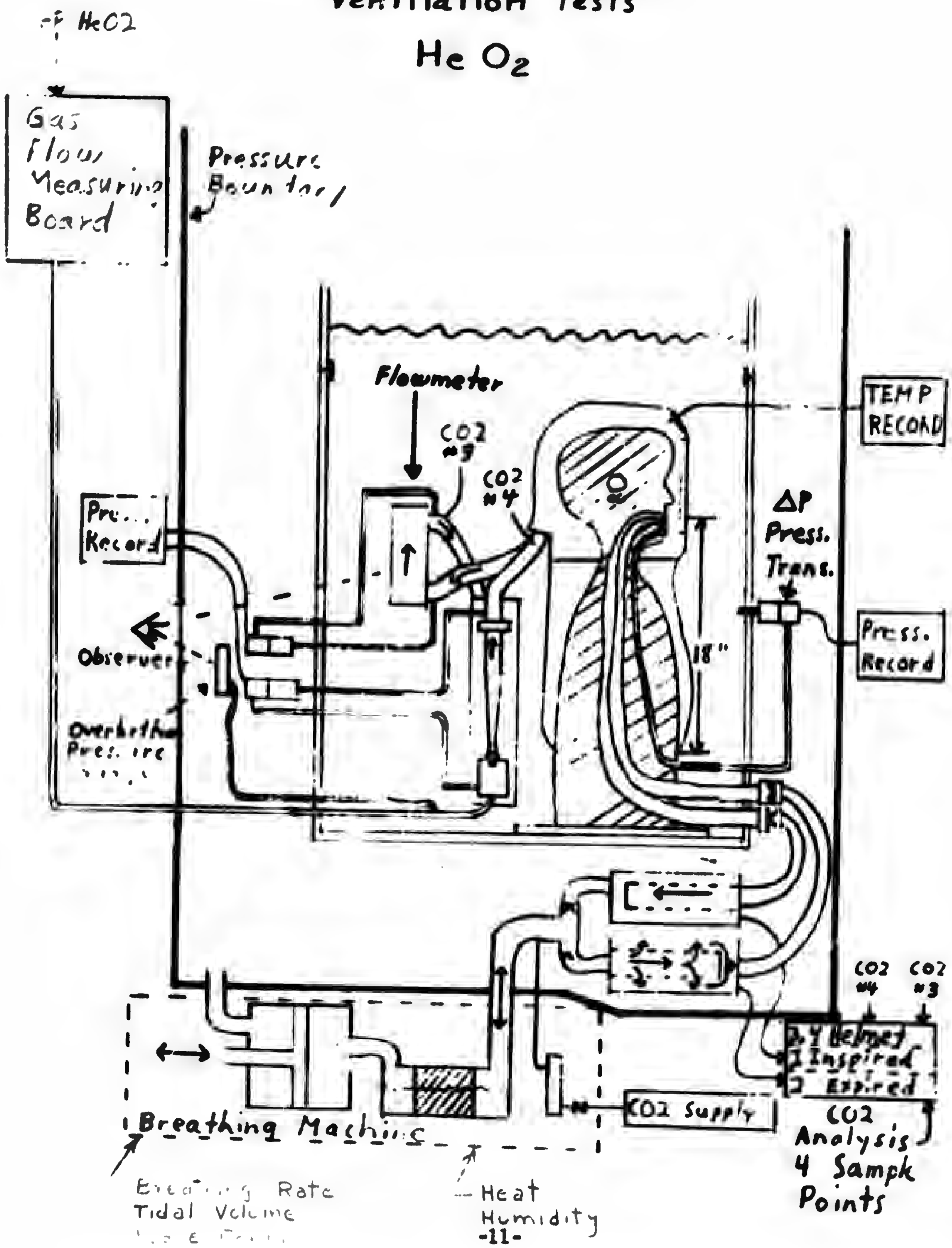
TABLE 3 (CONT.)
CHARACTERISTICS OF MAJOR TEST EQUIPMENT

Item	
Strip Chart Recorder	Sanborn 964 - 4 channel
Pressure Transducers	Pace Eng. - PD 15's Validyne Eng. - DP 15's
Flowmeters	Fischer & Porter Rotameters
Wet Testing Box	30" I.D. Hexagon (acrylic plastic) by 4' high. Allows any water temperature desired.

FIGURE 4

Venturi Recirculator Helmet Ventilation Tests

HeO_2



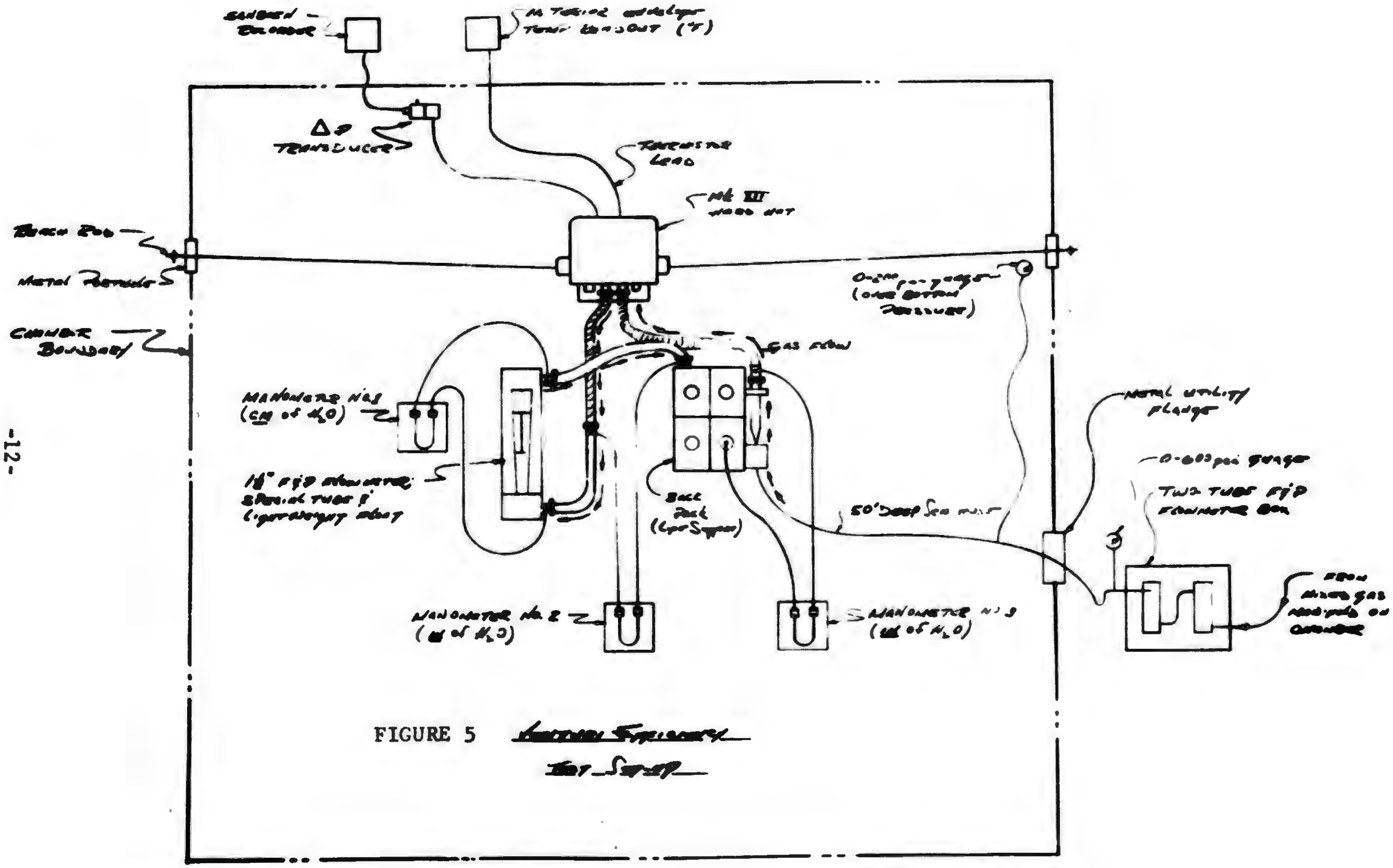
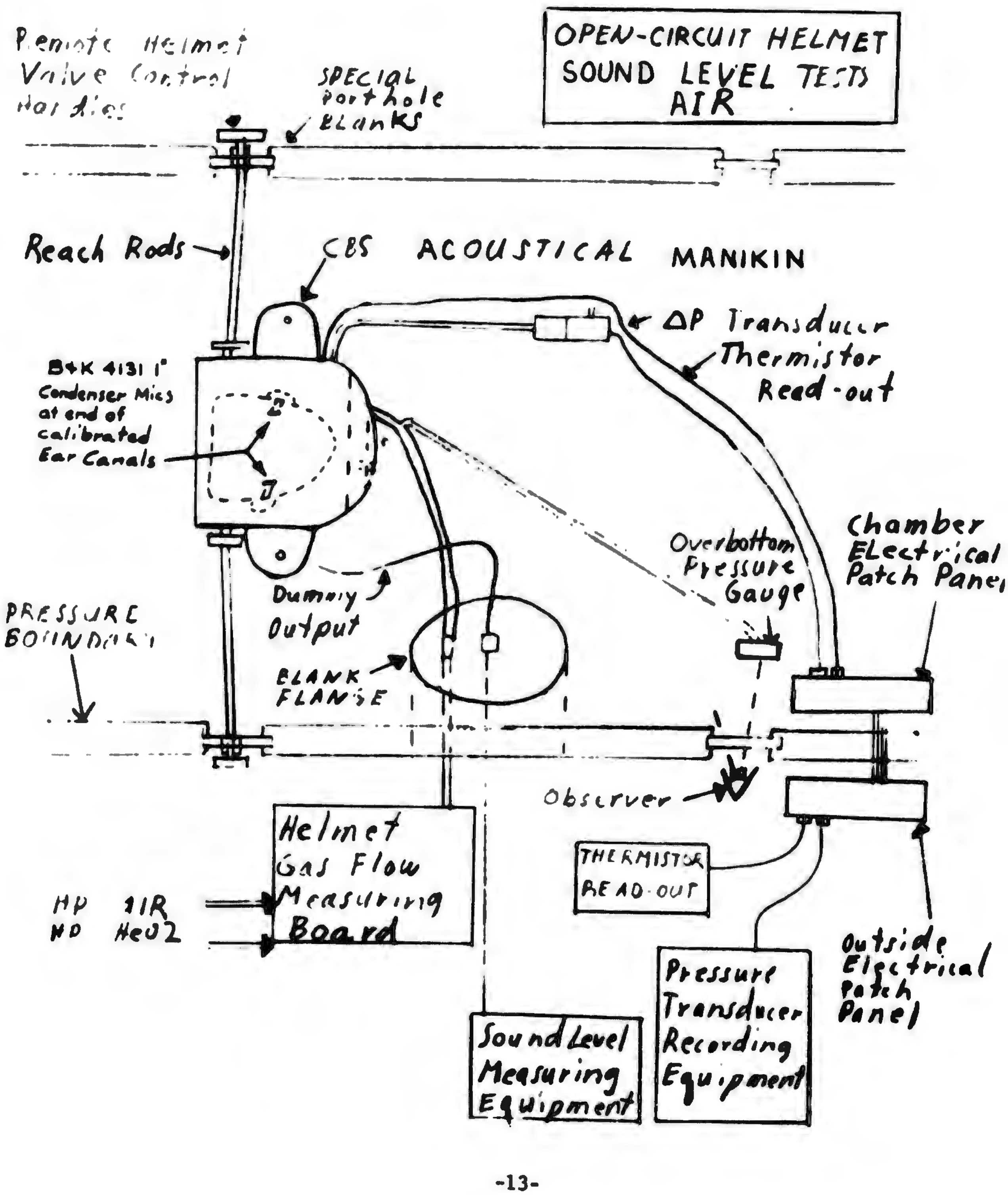

Δp
Transducer
Thermistor
Lead
Gas Flow
Chamber
Boundary
Manometer No. 2
Metal utility
flange
0-600 psi gauge
Two tube F&P
Flowmeter Box
Back
Pack
(Life Support)

FIGURE 5

FIGURE 6


OPEN-CIRCUIT HELMET
SOUND LEVEL TESTS
AIR
Remote Helmet Valve Control Handles
SPECIAL port hole BLANKS
Reach Rods
CBS ACOUSTICAL MANIKIN
ΔP Transducer
Thermistor Read-out
B+K 4131 1" Condenser Mics at end of calibrated Ear Canals
Dummy Output
PRESSURE BOUNDARY
BLANK FLANGE
Overbottom Pressure Gauge
Chamber Electrical Patch Panel
Observer
Helmet Gas Flow Measuring Board
HP AIR
HP HeO2
THERMISTOR READ-OUT
Outside Electrical Patch Panel
Pressure Transducer Recording Equipment
Sound Level Measuring Equipment

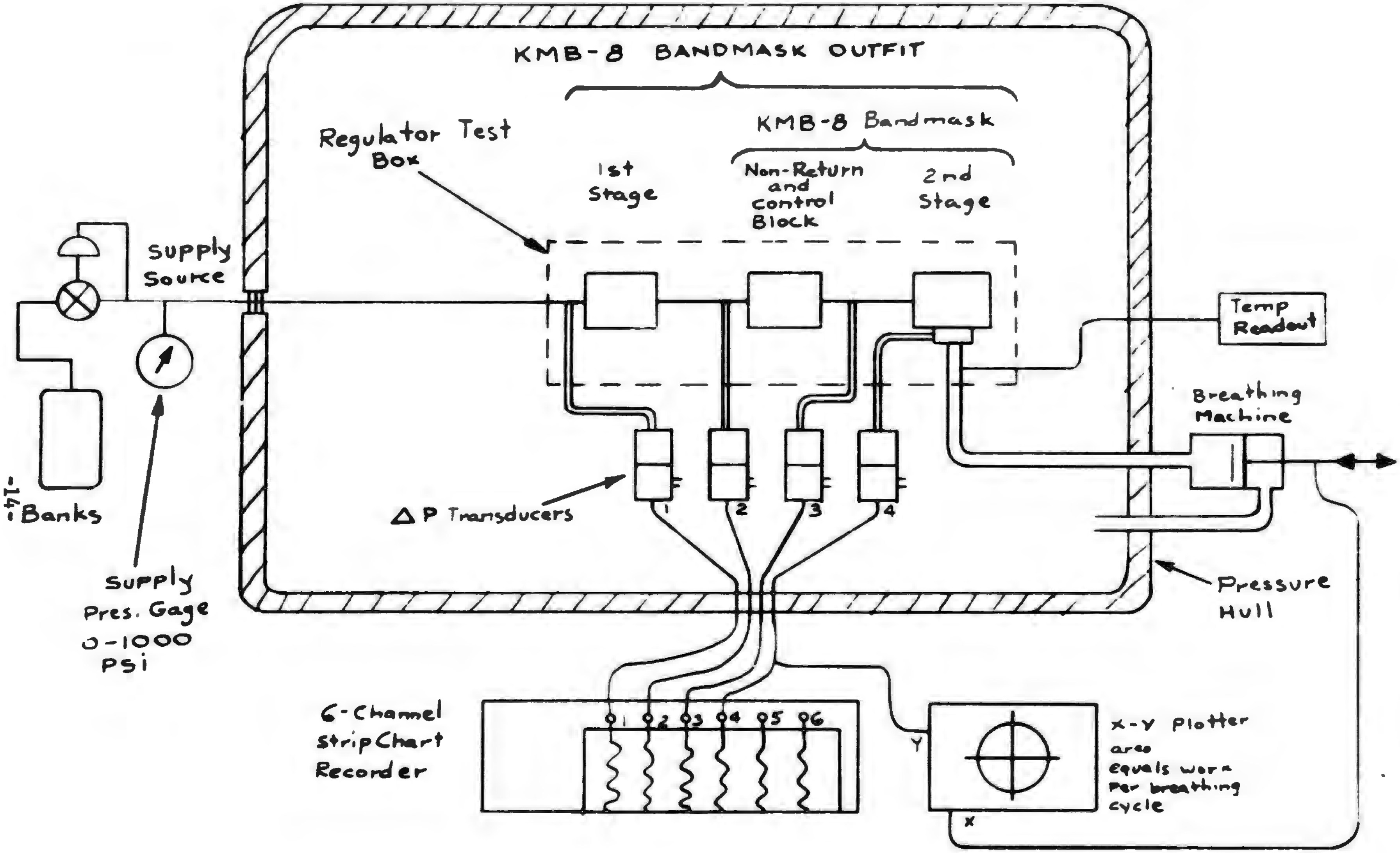


FIGURE 7 Bandmask Schematic
Breathing Resistance Tests

TESTING PROBLEMS

Although all the quantities listed in Table 1 can be measured using NEDU's present simulation equipment, there are some difficulties. Accurate measurement of inspired and expired PCO_2 is a particular problem due to the need to carry the gas to a 1 atmosphere analyzer exterior to the pressure chamber. The mixing boxes, evident in Figure 4, were created to reduce this problem by eliminating the need for rapid-response CO_2 analysis. Their volume, 3.5 liters each, is nearly twice the most commonly used tidal volume of 2 liters. The resultant dwell time of the gas in the boxes permits the CO_2 analyzers to see nearly steady state CO_2 levels that represent a time average of the inhalation and exhalation CO_2 levels. The exhalation box, also enables stabilization of the dummy's exhaled CO_2 level at a constant value over his inhaled level. Without it, the CO_2 add systems commonly in use produce an end-tidal CO_2 spike of 10-15% S.E. The pneumatic capacitance added by the mixing boxes is insignificant under most simulation conditions.

Other difficulties come from a lack of flowmeters and differential pressure transducers that can be used underwater.

From Table 2, it is clear that the problems involved in measuring the mechanical performance of a diver and his breathing apparatus during physiological testing are more severe. Since the diver is not pre-programmed to breathe in a certain fashion, his breathing performance must be measured. This, of course, is not always necessary, but there are many times when it is highly desirable, particularly for engineering purposes.

A case in point is the recent physiological testing of the MK 10 UBA. Heavy breathing resistance problems were encountered during physiological tests at 1000 feet. Breathing rate and breathing pressure were the only engineering parameters available. Human simulator testing at the same depth and breathing rates produced comparable breathing pressures and indicated External Work of Breathing rates that were clearly intolerable. A fix on the problem has been carried out and simulator testing indicates that it is effective. However, without more detailed information on how the divers were breathing during the physiologic tests,in particular their tidal volume, simulator testing alone is not sufficient to verify the adaquacy of the fix.

The ability to monitor how a diver is breathing in an apparatus is also desirable from the standpoint of evaluating divers subjective comments. Divers are very adaptable, and within limits they readily adapt their breathing patterns to the limitations of their apparatus. Consequently, during subjective evaluations one often gets an accurate subjective evaluation of breathing resistance only on the first dive.

Needed in particular is a good compact pneumotachograph for use underwater at high ambient pressure. EDU has on order a pitot tube pneumotachograph and a special differential pressure transducer for use with it. If it works, it will allow the measurement of respiratory flow, wave form and external work of breathing in double-hose open circuit, semi-closed, and closed circuit UBAs. Measurement of respiratory flow in single hose open circuit SCUBA and bandmasks appears to be feasible using the same technique. Measurement of respiratory flow in a helmet does not appear to be possible with present equipment.

Monitoring of divers CO_2 production and O_2 consumption during a physiologic test are other frequent problems. However, a lack of detailed information on these quantities has not yet been a serious difficulty. These quantities are usually of more interest to the engineers than to the doctors, and good estimates are often sufficient.

FUTURE WORK

In addition to the equipment items described above, several other areas need attention.

The effect of orientation on the validity of human simulator and physiologic test data has not yet been determined. Currently, the physiological tests are conducted with the diver at approximately 45° to the vertical. The simulation tests have all been run with the dummy in a vertical position.

Standards are an item that need particular attention (see Figure 3). The only breathing resistance standards in existence are the peak inhalation and exhalation pressure limits published for open circuit SCUBA by MIL-R-24169A and MIL-R-19555A. Cooper's work[1] and experience at EDU indicate that these need revision downward. Also, consideration should be given to replacing the old standards of maximum allowable peak inhalation and exhalation pressures with external work of breathing. Peak inhalation pressures have reliable meaning only with respect to open circuit SCUBA regulators. In neck seal helmets they are of apparently little importance. Peak inhalation pressures in neck seal helmets of 40 cm H_2O and more have almost no noticeable effect, since they are usually of very short duration.[2] Rebreathing UBA's can also exhibit breathing pressure spikes, particularily at end of expiration or end of inspiration as the breathing bags become overfilled or empty. For these apparatuses, external work of breathing would be a much more appropriate standard, and much less subject to misinterpretation.

Maximum allowable inspired PCO_2 levels also need to be clarified. There seems to be a wide variety of opinions as to what is allowable.

Noise in helmets and chambers is a serious but largely unrecognized problem. The diving community at this time uses for a standard the maximum allowable noise levels in the occupational safety regulations.[3] Are these applicable to the hyperbaric environment? How much noise is permissable in a hyperbaric chamber?

One possible use of equipment in hand, that has not yet been tried at all, is to use the CBS acoustical manikin for communications studies. It would be a beautiful, accurate and inexpensive way to test earphone effectiveness in helmets. It must, however, be kept dry. If its speaker were calibrated for depth, it could also be used to test microphones.

The breathing machine at NEDU is generally satisfactory, although it needs many minor redesigns. Its major deficiency is that it cannot remove O_2. A simple oxygen removal system would be of great benefit.

Computer data analysis is a must. The human simulation and physiological testing work currently underway at NEDU are producing great quantities of data. Sometimes the cost of the data reduction is the largest part of an experiment's cost, and the problem can only get worse unless some computer data analysis is used.

CONCLUSION

With only a few exceptions, the technology required to accomplish complete and accurate human simulation testing exists and is available. The greatest need, at this time, is to refine, organize, and make use of the testing capabilities now in existence. The test procedures and equipment to be utilized also need to be standardized and this information distributed throughout the diving community.

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