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Direct measurement of total dissolved gas pressure

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D'Aoust, B. G., R. White, and H. Seibold. 1975. Direct measurement of total dissolved gas pressure. Undersea Biomed. Res. 2(2):141-149.–The increasing need to monitor the total dissolved gas pressure in natural waters has demanded a more efficient system than is presently available. A compact portable unit for monitoring total dissolved gas pressure is described. The *tensionometer* consists of a length of silastic tube, blind in one end, in a spool configuration through which gases diffuse according to their partial pressure and equilibrate within 6 min. The pressure inside the tube is sensed by an integrated-circuit pressure transducer. The signal is read on a digital voltmeter and can be recorded or telemetered. The cost for the parts of the unit is under $1000; it is suitable for field measurements and is capable of remote sensing of dissolved gas pressure where the need indicates.

tensionometer
supersaturation
dissolved gas monitoring
gas bubble disease
decompression
silastic tubing

Decompression sickness in man and gas bubble disease in fish (Marsh and Gorham 1905) are both the result of supersaturation of dissolved gas. The problem of monitoring gas supersaturation both in natural waters (Rucker 1972; Ebel, Raymond, Moran, Farr, and Tannaka 1975) and in the laboratory (D'Aoust and Smith 1974) has prompted development of a probe with a response time in the order of minutes for measuring and/or monitoring total dissolved gas pressure. In 1971, R. F. Weiss introduced a simple unit that includes a watertight silastic tube across which gases equilibrate according to their partial pressure and a bourden-tube gauge for measuring total gas pressure. The same principle was used by Enns, Scholander, and Bradstreet (1965) to measure the effect of hydrostatic pressure on dissolved gases; however, in that case a Teflon tube was used for its rigidity, along with a manometer.

This paper describes a unit which is portable, accurate, and electrically driven so that it can be operated remotely and be used to provide continuous recordings of time-varying levels. Such a *tensionometer* can be designed for large or small pressure ranges according to the specific needs of the situation. One model has been briefly tested for feasibility in the ocean at a depth of 2000 msw. The main intention of this paper is to draw attention to a particular technique and to supply sufficient information for fabrication and initial operation of a gas equilibrium measuring device.

Theoretical discussion of diffusion of gases through silicone rubber has been published by Buckles (1966) and such information may also be requested from manufacturers of such polymers.

In the present version of the instrument described here we have used one of a new series of solid-state, integrated-circuit pressure transducers (National Semiconductor LX

1600-1700 series) that can provide absolute, differential, or gauge readings in addition to temperature, if needed, and can be obtained fluid-isolated with minimal dead space between the pressure transducer and the gas-exchanging membrane to facilitate rapid equilibration.

The prototype was designed with several specific uses in mind and, consequently, reflects the following requirements: (1) portability for use underwater with scuba; (2) need for a movable probe of convenient size; (3) requirement that the pressure transducer could be used to measure sources of pressure other than dissolved gas; (4) need for optional remote operation at least overnight and the ability to record the pressure signal over that time; and (5) need for minimum design and fabrication time.

GENERAL DESCRIPTION

The above requirements led to the unit described below and pictured in Fig. 1. It consists of three separate packages—power supply, probe assembly, and recorder—interconnected by the necessary wire leads. A single package for recorder, power supply, and amplifiers is desirable if a recorder or telemetry will always be used with it; however, a suitably inexpensive single case was not available at the time the unit was constructed.

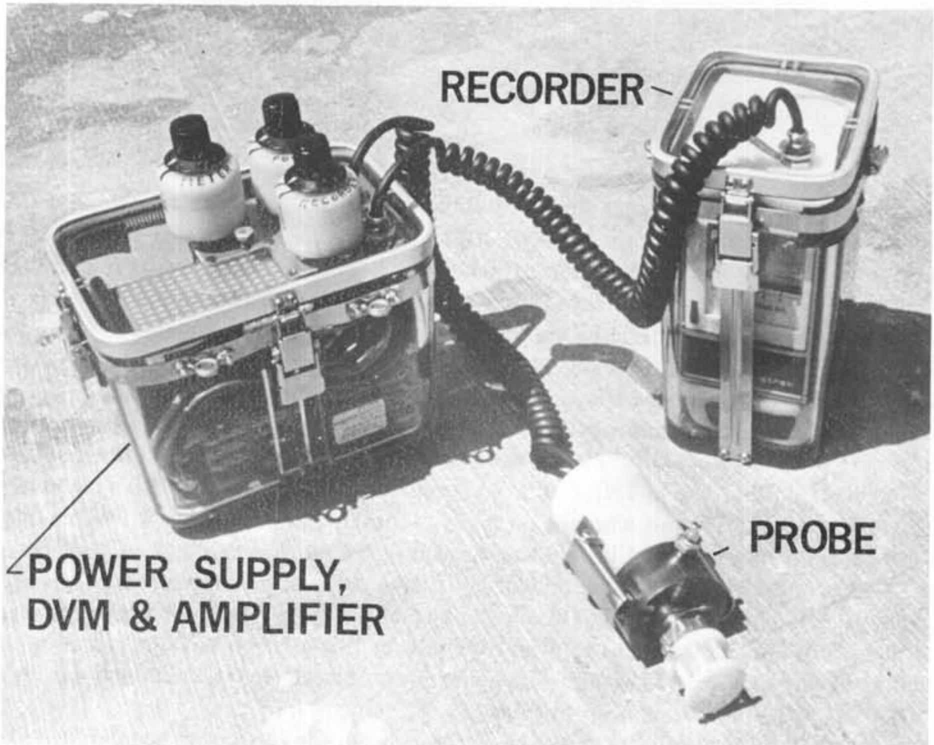

Fig. 1. Complete tensionometer unit with recorder. Power supply, amplifier, and digital display are contained in large Ikelite case (left) equipped with three wafer switch controls for digital display (top left); power and light switch (top right); and recorder-range switch (bottom right). Russtrack recorder is shown in smaller Ikelite case on right and tensionometer probe is shown in middle. The nylon body (B in Fig. 2) and Lexan front end of the probe (C in Fig. 2) are shown latched together ready for use with the nylon spool holding the silastic tubing.

PROBE

The probe, diagrammed in Fig. 2, is built around a nylon cylinder, 3½ inches long. It has a 2½-inch outer diameter (O.D.) and an internal diameter (I.D.) of 1 and 7/16 inches at one end, ½ inch at the other. A five-conductor flexible waterproof lead passes through a standard Ikelite (cat. #4006) bulkhead connector at the ½-inch end. The end face of the nylon cylinder is equipped with an 0-ring groove for a 2-225 0-ring and fitted with a cover of cylindrical Lexan® polycarbonate. A 1-inch extension on the polycarbonate cover also has an 0-ring groove which fits into the large bore of the nylon cylinder. The faced shoulder of the Lexan cover compresses the 2-225 0-ring on the faced end of the nylon housing when it is compressed against it by two stainless steel snap fasteners. The other 0-ring provides a sliding internal seal.

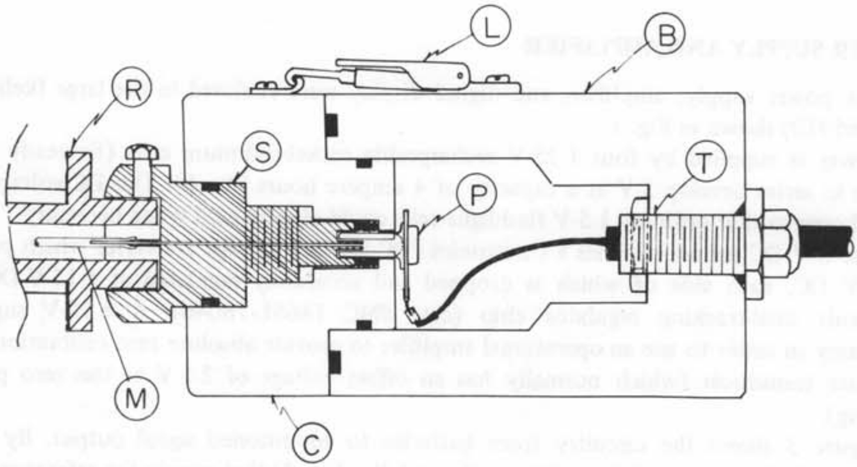

Fig. 2. Tensionometer probe. Ⓑ Nylon cylinder 2½-inch O.D. x 3½ inches long, Ⓒ Lexan polycarbonate cover which holds pressure transducer Ⓟ which is connected to 5-lead bulkhead connector Ⓣ. Ⓒ is held to Ⓑ by means of two latches Ⓛ, only one of which is shown. Pressure transducer is held by stainless steel screw Ⓢ compressing O-rings around nipple of Ⓟ. Capillary communicates from pressure transducer to the silastic tube Ⓜ, only one end of which is shown. The remaining silastic tube is wound around the nylon reel Ⓡ, which fits into the recess in the stainless steel screw Ⓢ and is held by the 8-32 machine screw.

The pressure transducer used in the unit described here was a National Semiconductor LX 1610 AF (absolute fluid-isolated) unit which was connected to the five-lead wire by means of a small clip, fashioned from one side of a linear integrated-circuit socket.

The 3/16-inch O.D. by ½-inch long stainless steel nipple of the pressure transducer is held firmly in the Lexan cover and sealed gas-tight by a stainless steel screw compressing an accurately machined nipple against two O-rings separated by a close-fitting stainless steel washer.

A fine capillary tube soldered in the center of the stainless steel compression screw can extend some distance into the nipple of the pressure transducer to minimize dead space. The other end of the steel capillary is connected to the silastic tubing by simple expansion of the latter. The other end of the tubing (not shown in Fig. 2) can be closed with a simple overhand knot or a close-fitting wire.

The connection of the silastic tube to the capillary tubing is protected from impact by its location in the recess machined in the stainless steel nut as shown in Fig. 2. This arrangement was adopted to allow a variety of gas-exchange membrane configurations to be evaluated on the same unit. The system shown used approximately 10 ft of Dow Corning silastic tube 0.025 O.D. by 0.012 I.D. (cat. #602-105), wound around a hexagonal array of 12-24 N.F. stainless steel machine screws held in a nylon block. The nylon block fits into the inside of the stainless steel compression screw and is locked by a small 8-32 machine screw. The length of tubing wound around this block had an internal volume of approximately 260 microliters. This volume, in combination with a dead space of approximately 100 microliters, provided equilibration within 6 min (showing a half-time [$t_{½}$] of 45 sec). Silastic tubing is the simplest way to achieve a high surface-area/volume ratio, but other configurations can be used if equilibrium time is unimportant.

POWER SUPPLY AND AMPLIFIER

The power supply, amplifier, and digital display were enclosed in the large Ikelite case (cat. #5910) shown in Fig. 1.

Power is supplied by four 1.25-V rechargeable nickel-cadmium cells (Eveready #CF4) which in series develop 5 V at a capacity of 4 ampere hours (A · h). This DC voltage range was chosen so that ordinary 1.5-V flashlight cells could also be used when necessary.

The 5-V DC source supplies a Caritronics (DC-D-5-22) voltage converter which provides ± 22 V DC, each side of which is dropped and accurately regulated at ± 15 V DC by a Motorola dual-tracking regulator chip (cat. #MC 1468L-78040). A ± 15-V supply is necessary in order to use an operational amplifier to provide absolute zero calibration of the pressure transducer (which normally has an offset voltage of 2.5 V at the zero pressure reading).

Figure 3 shows the circuitry from batteries to conditioned signal output. By proper choice and adjustment of the resistors (R_3 and R_9, Fig. 3) that supply the reference side of the operational amplifier, the offset voltage of the pressure transducer is eliminated. The signal output is conditioned by adjustment of the gain across resistors R_{10} and R_{11} to read in the pressure units desired. The conditioned signal, E_0, goes directly to the digital display or through appropriate resistors, not shown, to the Russtrack current recorder.

READOUT AND RECORDER

Since the unit was designed for use in the field, a digital multimeter (Danameter Model 2000) was chosen to provide a low power, liquid-crystal digital display as well as complete V.O.M. functions. Alternatives that are more compact and less expensive are possible, however, and should be considered for particular applications. In the unit described here, the absolute pressure transducer's range was 0 to 60 psia or 135 fsw. Resistances R_3 and R_{11} (Fig. 3) were chosen to make the digital voltmeter read 13.50 V for 135 fsw. In use, the meter was turned on and set at the 20-V range prior to closing and sealing the lid of the Ikelite case. Three Ikelite camera controls (cat. #5010) were used to actuate three wafer switches: (1) a meter-range switch which allowed checks on the battery, regulated voltage and transducer-output voltage, and calibrated reading in pressure units; (2) a recorder range-selection switch; and (3) a power and light switch for use of the unit at night. Calibration of the probe was carried out in a hyperbaric chamber and revealed deviations from linearity of less than ± 0.4% of the full scale.

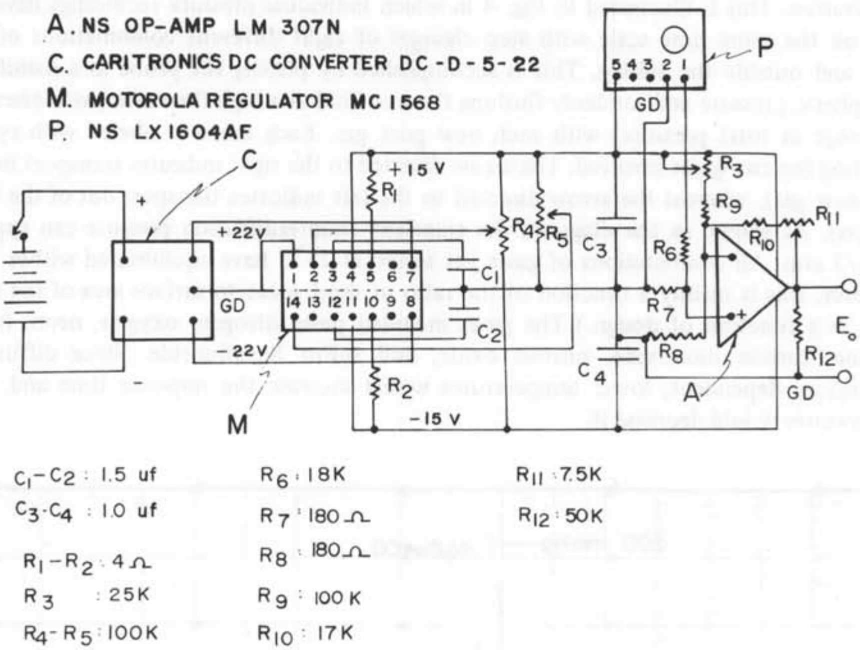

Fig. 3. Circuitry used for assembling components. Ⓐ operational amplifier (National Semiconductor LM 307N), Ⓒ Caritronics DC-D-5-22 voltage converter, Ⓜ Motorola dual-tracking regulator chip (MC 1468L-780-40), Ⓟ pressure transducer (National Semiconductor LX 1604AF). Any LX 1600 series pressure transducer can be used in the circuit. Resistances and capacitances are shown on figure. The components in the schematic can be easily integrated by following manufacturer's recommendations.

Because of the need for power conservation a Russtrack recorder (Model 288, 0 to 10μA) was chosen for use with the unit. Any high-impedance millivolt recorder would be suitable if power is not a constraint. The terminals on the back of the recorder were relocated on the top of the recorder so that it would fit into an Ikelite case (Model 5710). Use of standard Ikelite cases, bulkhead connectors, and camera controls made design and fabrication relatively simple and rapid.

UNIT RELIABILITY: MEASUREMENT AND MONITORING TECHNIQUES

It must be emphasized that such a device is reliable only at equilibrium–that is, when all partial pressure gradients have been eliminated. It is essential, therefore, to determine the response time of the instrument at different temperatures by subjecting the probe to given increases and decreases in pressure and measuring the time necessary for full pressure difference to be indicated.

Any transient measured by this technique must therefore be considerably slower than the rate of equilibration of the probe. This equilibration rate, with any particular change in gas pressure, depends on mass transport which is dependent on the diffusivity of each gas, its solubility in the silastic tube, and composition of the gases on either side of the tube during equilibration. Since gases vary widely in their solubility and diffusivity in all plastics, counterdiffusion (Idicula, Graves, Quinn, and Lambertsen, *in press;* Graves, Idicula, Lambertsen, and Quinn, 1973) can produce positive and negative pressure transients during equilibration. This is illustrated in Fig. 4 in which individual pressure recordings have been made on the same time scale with step changes of eight different combinations of gases inside and outside the tubing. This is accomplished by placing the probe in a manifold at atmospheric pressure and suddenly flushing the manifold at a high flow rate (with essentially no change in total pressure) with each new pure gas. Each curve is labeled with symbols indicating the two gases involved. The arrow directed to the right indicates transport into the tube (new gas), whereas the arrow directed to the left indicates transport out of the tubing (old gas). As shown in the diagram, the transient counterdiffusion pressure can approach over 1/3 atm. All combinations of gases yet tested at 25°C have equilibrated within 7 min. (However, this is mainly a function of the ratio of dead space to surface area of the silastic which is a function of design.) The gases included pure nitrogen, oxygen, neon, helium, methane, carbon monoxide, nitrous oxide, and sulfur hexafluoride. Since diffusion is temperature dependent, lower temperatures would increase the response time and higher temperatures would decrease it.

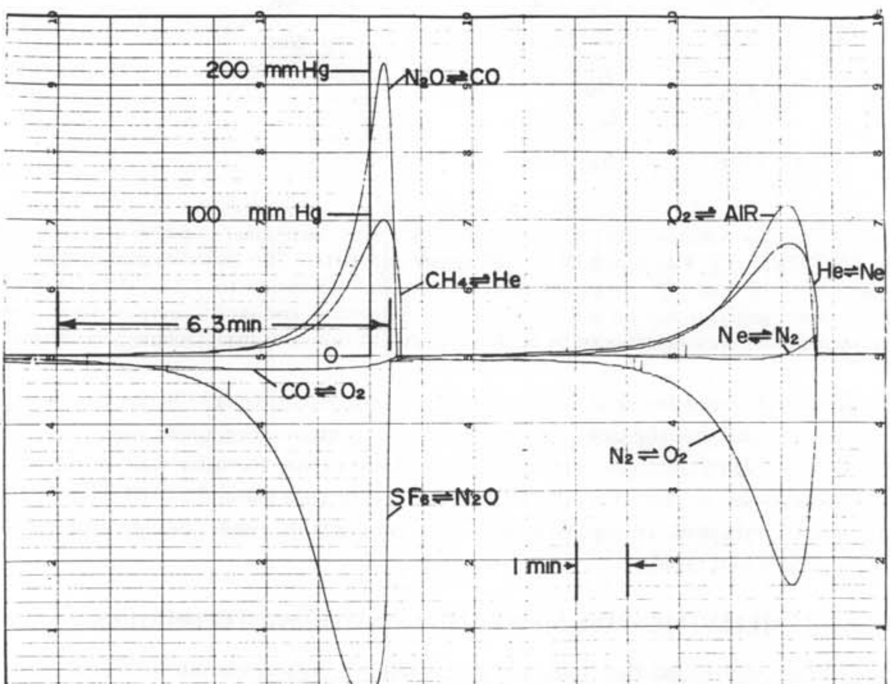

Fig. 4. Pressure transients produced by counterdiffusion with the probe in the gas phase. Ambient pressure is at 5.0 on the vertical scale. Such transients are also possible but less apparent (except with helium) when the probe is in water. These records were superimposed by winding back the strip chart to allow comparisons of pressures and times.

The probe was placed in a manifold (vented to the atmosphere) which could be rapidly flushed with pure gases. Each curve represents the positive or negative transient which reflects the algebraic sum of the flux of entering and exiting gas, and is labeled with the convention that gases entering (new gas) are on the left and the gas which is leaving is on the right. Note that each combination of gases provides a unique curve but *that in all cases equilibrium is virtually complete in 7 min.* With respect to N_2, O_2, He, Ne, and N_2O, this has been repeatedly verified by experiment.

The same counterdiffusion effects can be shown by the probe in water; however, since counterdiffusion pressure transients depend on total flux which in turn depends on solubility of the gases in the water as well as agitation of the probe or stirring of the water past it, these transients are much reduced and are only appreciable when helium is involved. Experience with the probe in natural waters indicates minimal agitation is necessary for reliable readings unless supersaturation is present.

The unit has been used successfully to measure supersaturation. Figure 5 is a record of the probe readout of gas pressure in supersaturated solution. Equilibrium is achieved at approximately the same rate in water as compared to gas provided there is adequate mixing.

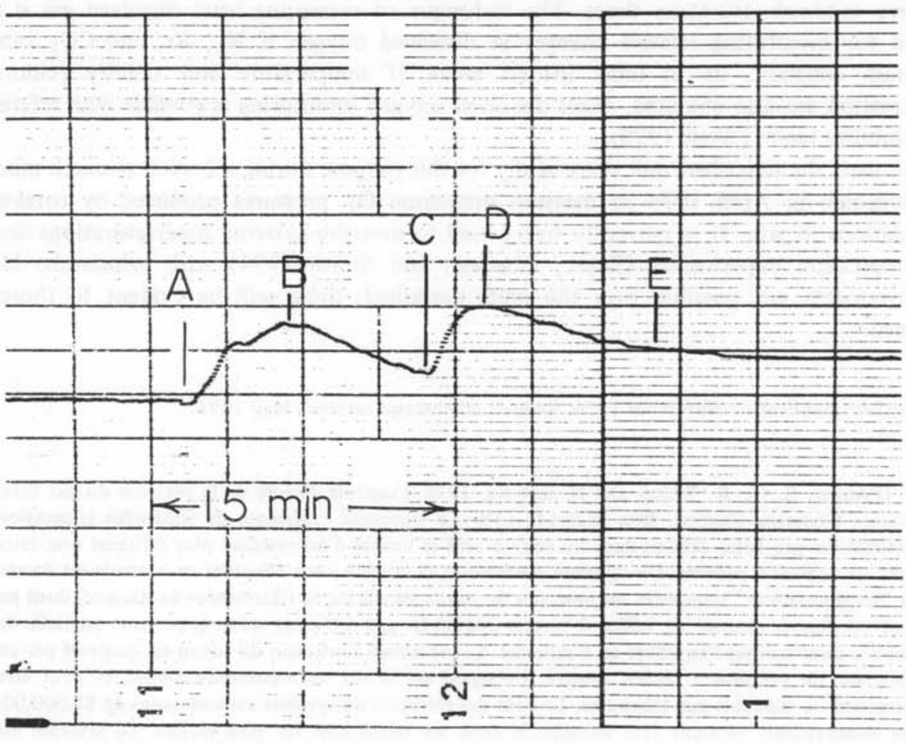

Fig. 5. Russtrack recordings of probe response to supersaturated water (3 gallons of water equilibrated at 60 fsw and decompressed to surface). (A) Insertion of probe following reading of atmospheric pressure; (B) maximum reading before effect of bubble growth begins to decrease pressure; (C) stirring of water past the probe by manual agitation with consequent restoration of an even greater dissolved gas pressure reading (D) in the water, which is now equilibrating with the atmosphere more rapidly due to agitation of the probe; this is shown by the secondary pressure decrease after (D) and continuing on past (E) . Re-equilibration of the water is extremely slow, and is not shown on the recording. One division equals 3.75 min. Maximum supersaturation pressure recorded is 100 mm Hg.

In cases where water is constantly supersaturated, only approximate readings are possible unless sufficient agitation of the probe is used. This is illustrated in Fig. 4 and is due to the continual growth of small bubbles on the surface of the silastic tube resulting in its reflecting an average steady-state pressure which is less than that actually in the water. This problem has also been encountered by others using this method and indicates the need for constant agitation for reliable readings. Performance of the unit has been compared with analysis by

Van Slyke/gas chromatography and has agreed within 3% of the total when manual agitation was used. This relatively large error, however, applies only to situations where supersaturation occurs.

In comparing results of measurements made in supersaturated water with other analytical techniques, it must be emphasized that under conditions of supersaturation, tensionometry can underestimate the actual dissolved gas content, and quantitative techniques (such as Van Slyke extraction combined with gas chromatography) can overestimate the dissolved gas tension. In both cases this is because microscopic bubbles may be present. Such errors are small but must be acknowledged.

Experience with these units to date indicates the importance of minimizing dead space to achieve minimal saturation times. The technique of measuring total dissolved gas is also useful for monitoring relative changes in dissolved oxygen if N_2, Ar, and CO_2 can be assumed constant, as in most littoral areas. If temperature and salinity (chloride) information are also obtained, exact dissolved oxygen monitoring is possible with reference to solubility tables (Weiss 1970).

We used the described unit successfully for this purpose during a 2-week research mission in Hydrolab in April 1974 to measure maximum O_2 pressures produced by coral-algal associations in situ. It is currently being used to measure extreme supersaturations during decompression experiments (Beyer, D'Aoust, and Smith 1974) with salmonids. Many improvements are possible over the units described; these will be evident to those so inclined.

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D'Aoust, B. G., R. White, and H. Seibold. 1975. Controle directe de la pression du gaz total dissous. Undersea Biomed. Res. 2(2):141-149.–La nécessité croissante de controller la pression partielle du gaz total dissous dans les eaux a créé le besoin d'un système plus éfficient que ceux dont on dispose à présent. Un système portable et compacte pour éffectuer ce controle est decrit. Le "tensionomètre" comporte un morceau de tuyau en silastique (élastomère de silicone) dont un bout est fermé, arrangé en hélice à travers duquel les gaz diffusent selon la pression partielle de chacun, pour trouver l'équilibre en 6 minutes. La pression à l'interieur du tuyau est controlé par un détecteur de pression à circuit integré. Le signal est lu sur un voltomètre digital, et peut être enregistré ou transmis par telemètre. Le coût des éléments du système est audessous de $1.000,00. Les mesurements peuvent être enregistrés dans les conditions les plus variées. Le système est capable aussi de controller la pression des gaz dissous à distance, si ceci devient nécessaire.

tensionomètre — maladie des bulles de gaz
sursaturation — décompression
controle des gaz dissous — tuyau en silastique

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