Life Support in Small One-Atmosphere Underwater Work Systems

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Abstract:

Manned submersibles and atmospheric diving suits share a number of characteristics - with the most obvious being the rigid hull structure required to maintain a one atmosphere cabin pressure in the presence of high external pressures.

The rigid pressure hull results in a fixed internal volume that allow a simple, mechanical means of precisely controlling the input of make up oxygen to replace that metabolized by the occupant(s). The field proven life support hardware described in this paper is peculiar to monobaric systems but may have applications in other manned cabin situations where a fixed volume is present - regardless of maintenance pressure.

Also briefly described is a state-of-the- art life support monitoring system developed by Nuytco Research Ltd. under contract to the National Energy Board of Canada. The 'Biosensor' is thought to have broad application potential in the manned undersea field.

Background:

In all manned, undersea activities, some form of life-support is required. It may be as simple as an air-hose affixed to an open 'bell', with excess gas allowed to bubble out of the bottom - or as complex and sophisticated as a mixed-gas rig for autonomous operation at great depths, with automatic gas switching for decompression. Generally speaking, there is a considerable overlap in the actual mechanics of life-support systems used in different applications. For example: the autonomous SCUBA regulators used by free-swimming sport and scientific divers are functionally identical to the demand systems in the helmets and masks used by umbilical-supplied commercial divers. Likewise, carbon-dioxide scrubbing systems used in ambient pressure habitats are virtually the same as those used in one-atmosphere submersibles, and so on.

Once in a while, though, a design emerges that is truly a 'niche' situation. That is, it will only be applicable to a narrowly defined type of diving system but does a superb job for that specific application and may well transfer successfully into a totally different field.

Specifically, this is a description of a simple, reliable, mechanical oxygen sensor and controller that is designed to function in a rigid-shelled suit, submersible, habitat, or other fixed volume enclosure.

The controller has the rather pedestrian name of a "bellows-add" system. It has been in use in undersea one-atmosphere diving suits (ADS) and one-atmosphere submersibles for nearly thirty years, in the author's personal experience. The system has proven to be reliable, economical, and simple to design, build, and maintain.

The author has been prompted to re-describe what must be classed as fairly old piece of technology (albeit, now used with a very modern suite of electronic monitoring systems!) by the simple observation that a number of otherwise knowledgeable technical people are agreeably surprised when they first encounter the system in one of our submersibles or atmospheric diving suits. We have built well over a hundred of these 'bellows-add' systems and encountered few if any problems in many thousands of hours of use.

It is thought that there may be cross-applicability to such devices as biosphere systems that are sealed and of fixed volume, rigid-hulled anti-contamination suits, space and near space suits and the like.

A quick review of basics:

The functions of the human body are fueled by the controlled release of chemical-bond energy from the process of oxidation. Oxygen is the gas oxidized or metabolized and, during this process, between 80% and 100% of that oxygen is finally produced as carbon dioxide (CO^2). The variation depends on such factors as previous diet and level of exercise (Denison 1969). CO^2 is a product of this oxidative metabolism and is not a toxin, as many suppose, but one of the governing factors in the regulation of respiration and circulation.

Elevated CO^2 levels are not tolerable, however, and will lead to rapid breathing, cognitive distortions, panic, and ultimately - unconsciousness. It has been recommended (Undersea Vehicle Committee, 1968, U.S. Navy Materials Command, 1973) that CO^2 levels in manned submersibles, for example, should not exceed 0.025 atmospheres absolute .36 psi (2.5%), although much higher concentrations can be tolerated for short periods. (Mekjavic/Savic 1990-91) NASA uses figures giving .15 psi (1%) for indefinite periods, .44 psi (3%) for 1 hour and >3% - terminate EVA (Advanced EVA System (Design, MDTSCO/NASA, 1985).

In the normal course, CO^2 is exhaled into the atmosphere and eliminated, practically, by dilution. In the micro environment of a submersible, ADS, or other closed system, respiratory CO^2 must be removed by 'scrubbing' - usually done with absorbent chemicals, although other means are possible. 'Scrubbing' passes the exhaled gas containing high levels of CO^2 through a chemical bed containing an absorbent material such as a mixture of lime ($Ca(OH)^2$) and caustic soda (NaOH). The reaction that takes place when CO^2 is exposed to porous 'soda-lime' is exothermic and has as its by-products, heat, carbonates, and water.

The ability of the scrubber system to 'fix' or 'absorb' CO^2 is dependent on both the temperature and the relative humidity of the gas. Efficiency or performance of the scrubber material decreases markedly at bed temperatures below 20°C and also begins to decrease at high temperatures - over 25°C. Water content must also be present within a working range. If the moisture content is too low, or absent, the desired reaction between the absorbent and the CO^2 will not take place. If the water content is too high, the chemical bed becomes saturated and scrubber efficiency is greatly reduced. For example, the Grace Company manufacturers of High Performance 'Sodasorb'® recommend a moisture level between 6% and 19%.

These temperature and moisture requirements may seem a little daunting, but in practice the moisture content of the supplied chemical plus the chemical condensates, respiratory moisture, metabolic heat and exothermic heat, all combine to keep the cabin gas conditions at fairly optimum levels.

The scrubber material has an enormous absorbent area for its volume, since the manufactured granules of soda-lime comprise a large percentage capillary voids. In a similar material (activated charcoal), it has been estimated that the area of the active surface of the capillaries is of the magnitude of 20 acres to the pound! (Principles of Chemical Engineering - McAdams et al 1937).

When the cabin occupant inhales cabin gas, he/she is, essentially, inhaling normal air at atmospheric pressure - since the cabin was air-filled when sealed and the nitrogen component is inert. When he/she exhales, the expired gas is at the same pressure but is now lower in oxygen content from metabolism and the metabolized O^2 has been replaced with a like volume of CO^2. When the CO^2 rich gas passes through the scrubber the net effect of the scrubbing process is to reduce the cabin pressure by approximately the amount of CO^2 'fixed' and, therefore, the amount of oxygen 'consumed' or metabolized. It should be pointed out that the cabin pressure is lowered only if the cabin is a rigid, sealed shell that is independent of outside pressure. If it were a flexible bag, for example, the cabin pressure would not diminish but, rather, the cabin would reduce in volume.

The drop in cabin pressure is detected or sensed and a controller admits just sufficient oxygen to replace that metabolized and the cycle continues. Uptake of oxygen averages .5-.75 liters per minute with a usually active pilot.

Cabin pressure sensor/gas controller

The system described is that fitted to the current Newtsub DeepWorker 2000 DOV (Directly Operated Vehicle) - a 2000' work-class autonomous underwater work system. The same system has been used in Nuytco's 3000 foot submersible 'Deep Rover' and in atmospheric diving suits such as the 'Newtsuit' and the 'Newtsub-Swimmer' (both developed by the author). The system was also used in Oceaneering Internationals 'WASP' and 'JIM' ADS - in the OSEL 'MANTIS' and in a number of similar systems.

On the DeepWorker, oxygen is delivered to the sealed, cabin enclosure from compressed gas cylinders mounted externally. Storage gas pressure is in the range of 2200-3000 psi. A standard reducer or regulator reduces this pressure to approximately 100 psi and this intermediate pressure or "2nd stage" gas passes into the cabin area through an internal shut-off valve or hull stop. The high pressure regulator may be located immediately inside the cabin or externally depending on certification agency requirements and cabin volume versus supply total volume.

The intermediate pressure oxygen flow splits at this point and a portion of it passes through a calibrated orifice (or hole of a known size) directly into the cabin atmosphere. The flow rate of this 'steady-flow' gas is set at .25 liters per minute - a rate that is considered to be a minimum metabolic requirement with the occupant at rest. The balance is delivered to a 'demand' valve of the type used in SCUBA regulators, fire-fighting, and mine-rescue 'air packs'. Gas will not flow through this 'demand' valve unless a simple or compound lever is depressed - (usually by an inhalation-activated rubber diaphragm) - and the gas is 'demanded'. (Just like a gas station tire-filling valve. No air flows until you press the button or lever. If you put the tire-filling valve into a rubber bag and then sucked hard enough to cause the rubber bag to activate the valve, you would have a conventional 'demand' system - a tough breather, though!)

In this case the usual rubber diaphragm is replaced by a flexible metal bellows that is sealed at 14.7 psi -one atmosphere. The metal bellows is positioned just touching the demand valve lever. When the occupant metabolizes the oxygen in the cabin atmosphere and replaces it with a nearly equal amount of carbon dioxide - the pressure in the cabin remains constant - but as the CO^2 is passed through the soda lime scrubber and is chemically bound to the scrubber chemical ('absorbed' by the chemical) the cabin pressure falls by an amount equal to the CO^2 scrubbed and therefore, equal to the oxygen consumed. When the pressure in the cabin falls, the sealed gas in the metal bellows expands. The bellows then contacts and depresses the demand valve lever and oxygen flows into the cabin atmosphere until the cabin pressure equalises with that in the sealed bellows - 14.7 psi - upon which, the bellows contracts to its former size and the demand valve closes - a simple mechanical sensing and control system.

The metal bellows is fitted into a threaded cylinder with the demand valve located at one end of the cylinder. In practice, the sub pilot opens the hull stop valve to pressure the system and then screws the bellows up to the lever until oxygen just begins to hiss - the bellows is then backed-off, fractionally, until the hissing stops. That's it. The 'bellows-add' system is set.

Other components are a high pressure gauge to monitor the oxygen supply pressure, a low pressure gauge to indicate intermediate - ' 2^{nd} stage' pressure - and a push-button by pass valve to manually operate the demand lever if required.

The actual O^2 flow into the cabin is a combination of the small volume of 'steady flow' gas (which is at least sufficient to support life in the event of a failure of the 'bellows-add' system) and the (usually) larger volume of the 'bellow-add' gas. Cabin pressure is monitored by a sensitive analog gauge (barometer or altimeter) and/or by an electronic pressure sensing and read-out system. Cabin O^2 percentage is sensed and displayed by an electronic oxygen analyzer and CO^2 percentage is handled in a similar manner. The oxygen sensing and display system may be fitted with high and low audio/visual alarms and the CO^2 system may be also be fitted with a high alarm.

Electronic Monitoring

The combination of mechanical control and full electronic monitoring of the life support system used in the DeepWorker is unusual.

Physiological monitoring is carried out by a proprietary system called the "Biosensor", originally developed by Nuytco Research Ltd. under contract to the National Energy Board of Canada. The Biosensor reads out physiological data such as pilot respiratory rate, life support duration at current usage rate, cabin temperature, cabin pressure, cabin O^2 percentage, cabin CO^2 percentage - and a previous five minute electronic graph of O^2, CO^2, and cabin pressure, and depth, to look at 'trending' information. Systems status data are also monitored by the Biosensor and these indicate Port and Starboard O^2 supply pressures, ballast gas supply pressure, battery draw and duration at current usage rate, etc. Future development on the Biosensor program includes the obtaining of actual blood gas measurement by a miniature laser spectrometer mounted on an ear-lobe clip.

Data from the Biosensor system is read out in the DeepWorker on a flat screen notebook computer and faxed to the surface communications station by a wireless communication link. The term 'faxed' is used purposely since the protocol will require a 'read-back' to ensure that the data has been accurately received on the surface. The Biosensor system also makes surface intervention quite possible in the unlikely event of pilot incapacitation. Digital control can be used to operate the life support functions, blow ballast tanks, release drop weight, etc.

Scrubber system

The scrubber system used in DeepWorker is unremarkable. It consists of the following components:

- a scrubber cannister with sealing lid, removable for refilling
- CO^2 absorbent chemical (Soda-lime)
- Scrubber fan or blower (at 160 Lpm)
- Oral-nasal mask for passive breathing (in case of power failure)

Each individual cannister holds 5 liters (3.35 kg - 7lbs) of soda lime. (the DeepWorker has two totally separate and redundant oxygen supply/CO^2 renewal systems. The combined scrubber absorbent material is 14 lbs).

As previously discussed, the CO^2 scrubber material is a mixture of calcium hydroxide with a small percentage of both sodium hydroxide and potassium hydroxide. The blower-induced air flow through the scrubber causes a chemical reaction which removes the CO^2 from the cabin micro-environment while producing some heat. Air flow through the cannister may also be created by the pilots lungs in the passive, oral-nasal mode. High Performance Sodasorb® and Sofnalime® are commercially available scrubber absorbents that are used interchangeably in the DeepWorker life-support system.

Duration of the scrubber system under harsh conditions is a subject to which we have devoted considerable attention. In 1990-91, the author commissioned the School of Kinesiology at Simon Fraser University in Wester Canada, to conduct a comprehensive series of tests on the life support system previously described. The work was carried in a climate chamber located in the hyperbaric laboratory of the University. Tests were conducted both at 20°C and 10°C in a cold-water tank. Continuous measurements were made of CO^2 concentration, ambient temperature, cabin temperature and humidity. In this series of experiments, the efficiency of the CO^2 scrubber was evaluated through a range of temperatures between 10°C and

20°C and for different relative humidities of the cabin air (0% through 100%).

The net result of these trials were to demonstrate that the system operated reliably, and maintained the cabin CO^2 concentration at 0.25%, rising to 0.55% during mild exercise and rapidly returning to the previous level after cessation of exercise. Further the system met all the requirements of duration - both for routine use and emergency provision. (Savic/Isbister, 1990-91).

The durations recorded were consistent at 4 hours per pound of soda lime. Thus the 14 pounds of soda lime carried on DeepWorker for both routine and emergency use indicate a total duration available of 56 hours. Spacing provisions have been made for up to 72 hours of life support as an option on DeepWorker.

Conclusion

The described life support system has proven to be reliable and accurate over a long period of field use. The bellows-add oxygen sensor/controller is a refreshingly simple piece of mechanical hardware. Such controller systems may be easily fabricated by any qualified technician or purchased at low cost.

The sensor/controller may well have application in other than the undersea field for which it was developed.

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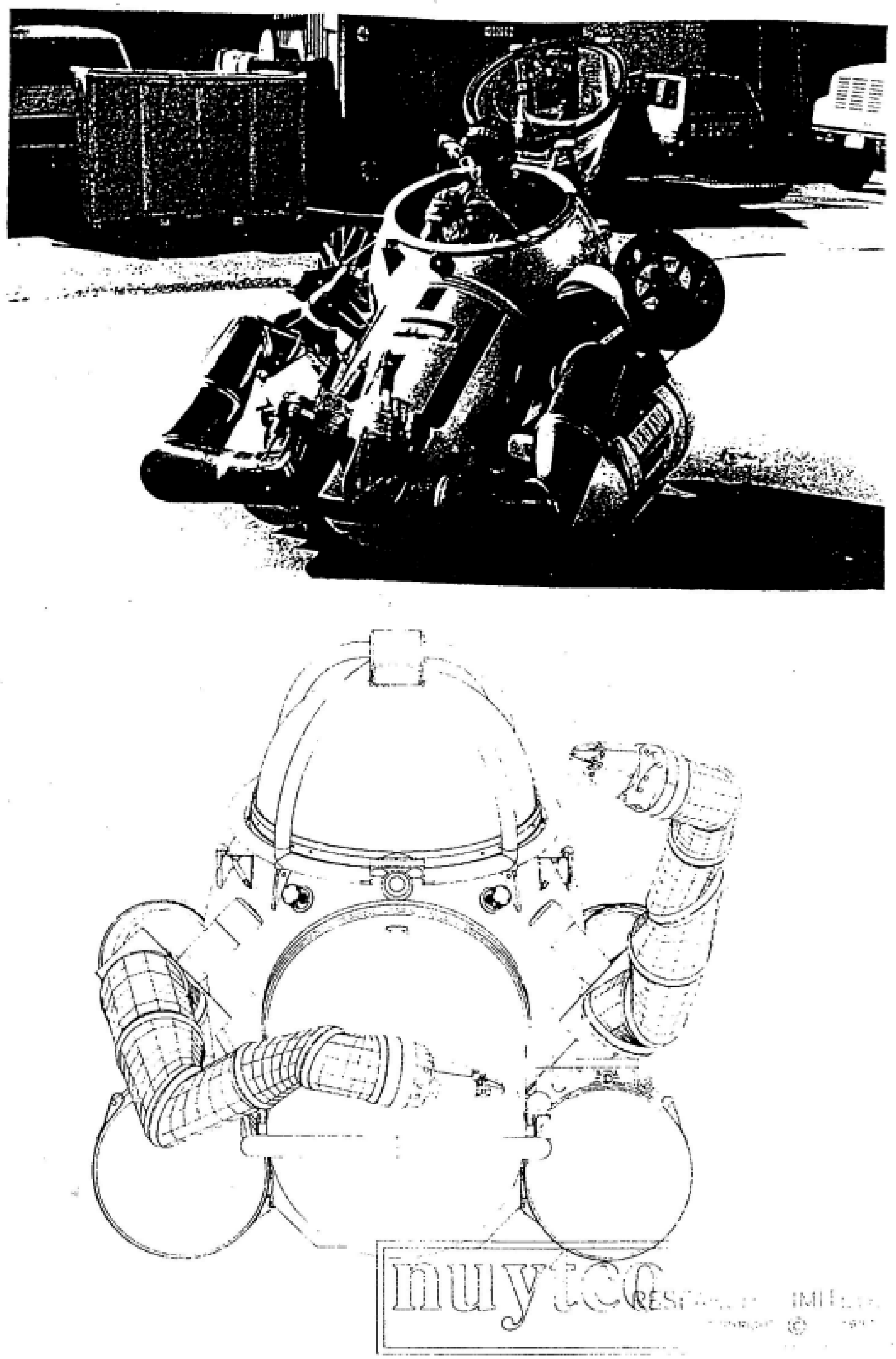


Figure 1

Newtsub 'DeepWorker 2000'. Autonomous submersible work system - 2000 foot rated.

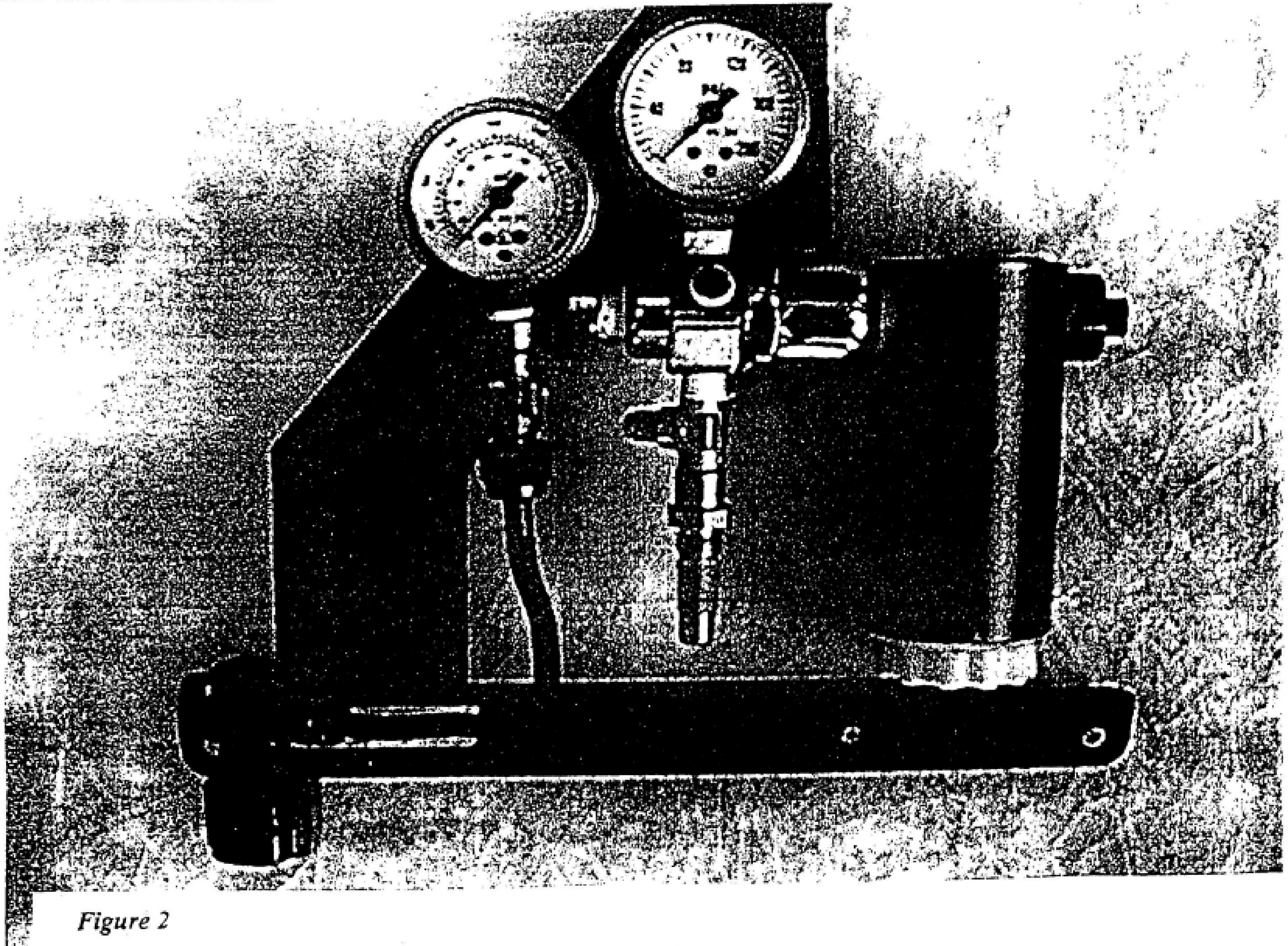


Figure 2

DeepWorker Oxygen controller assembly. Adjustable position, metal bellows in threaded cylinder on right. Hull stop valve on far left of mounting frame. Supply and intermediate pressure gauges mounted to pressure reducing regulator and micro-valve for steady-flow gas in center of assembly

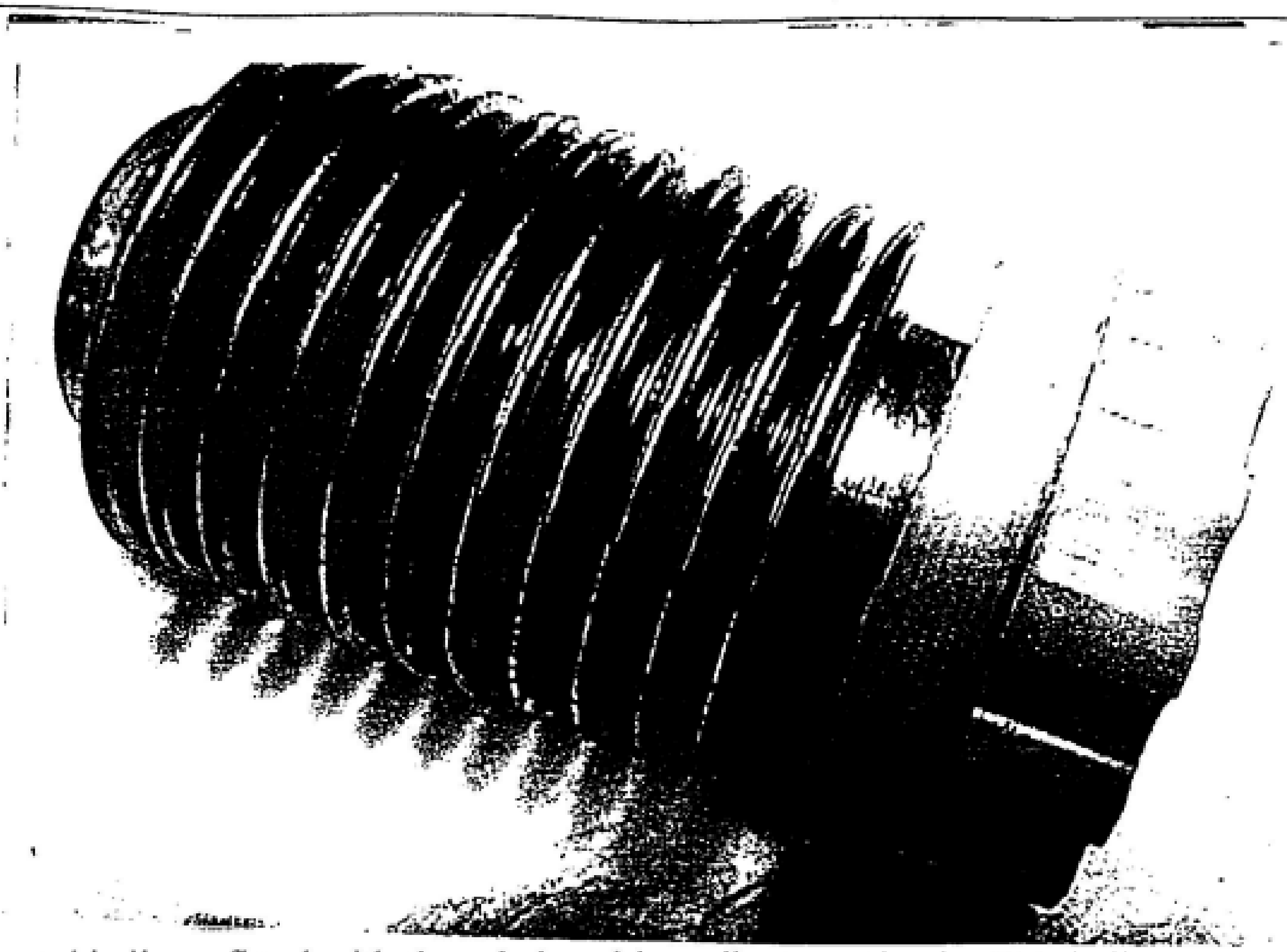


Figure 3

Sensitive metal bellows fitted with threaded position adjustment knob. This bellows is sealed at atmospheric pressure but may be fitted with a removable plug to adjust sealed volume for use in environments with an ambient pressure that differs from sea level.

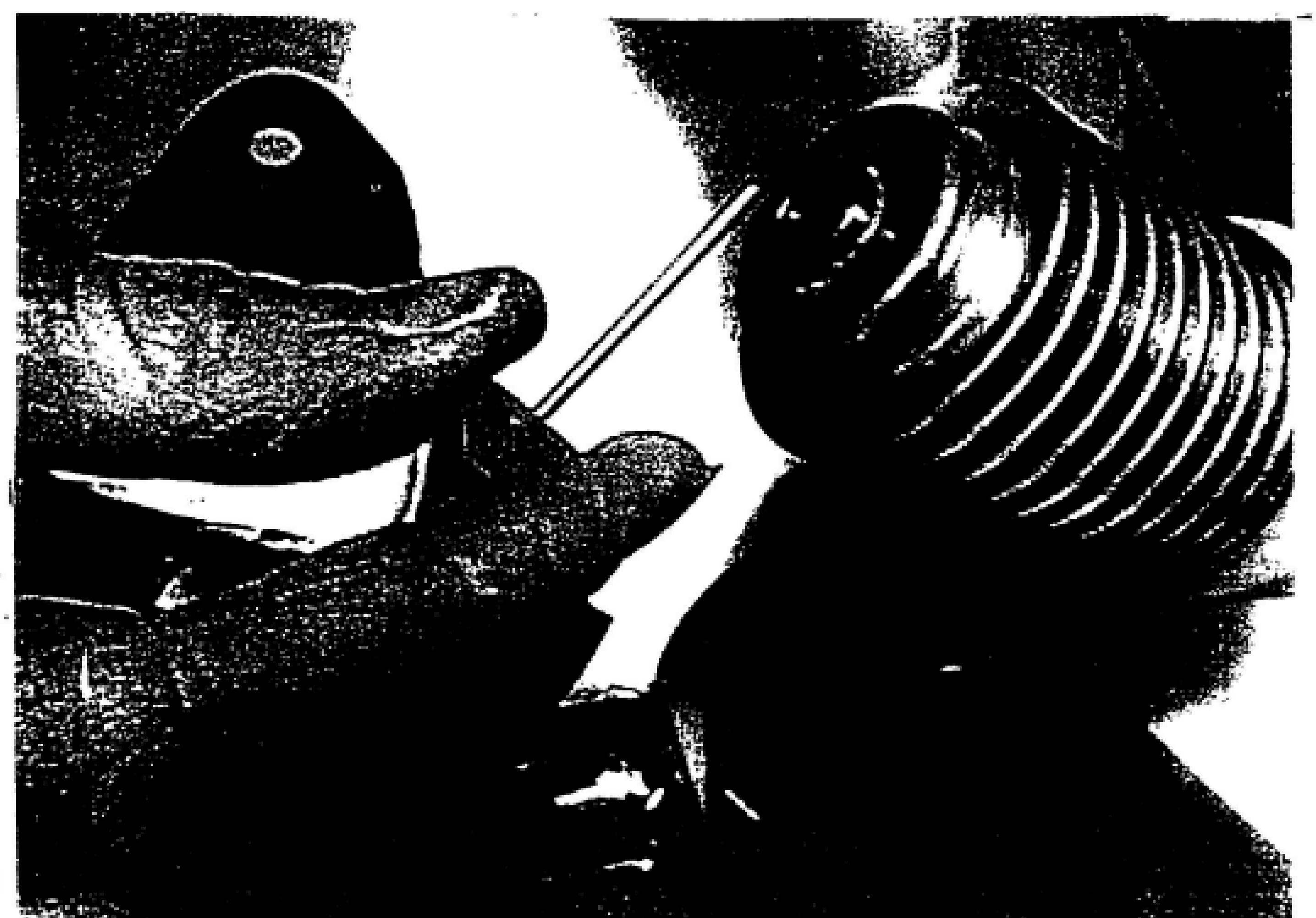
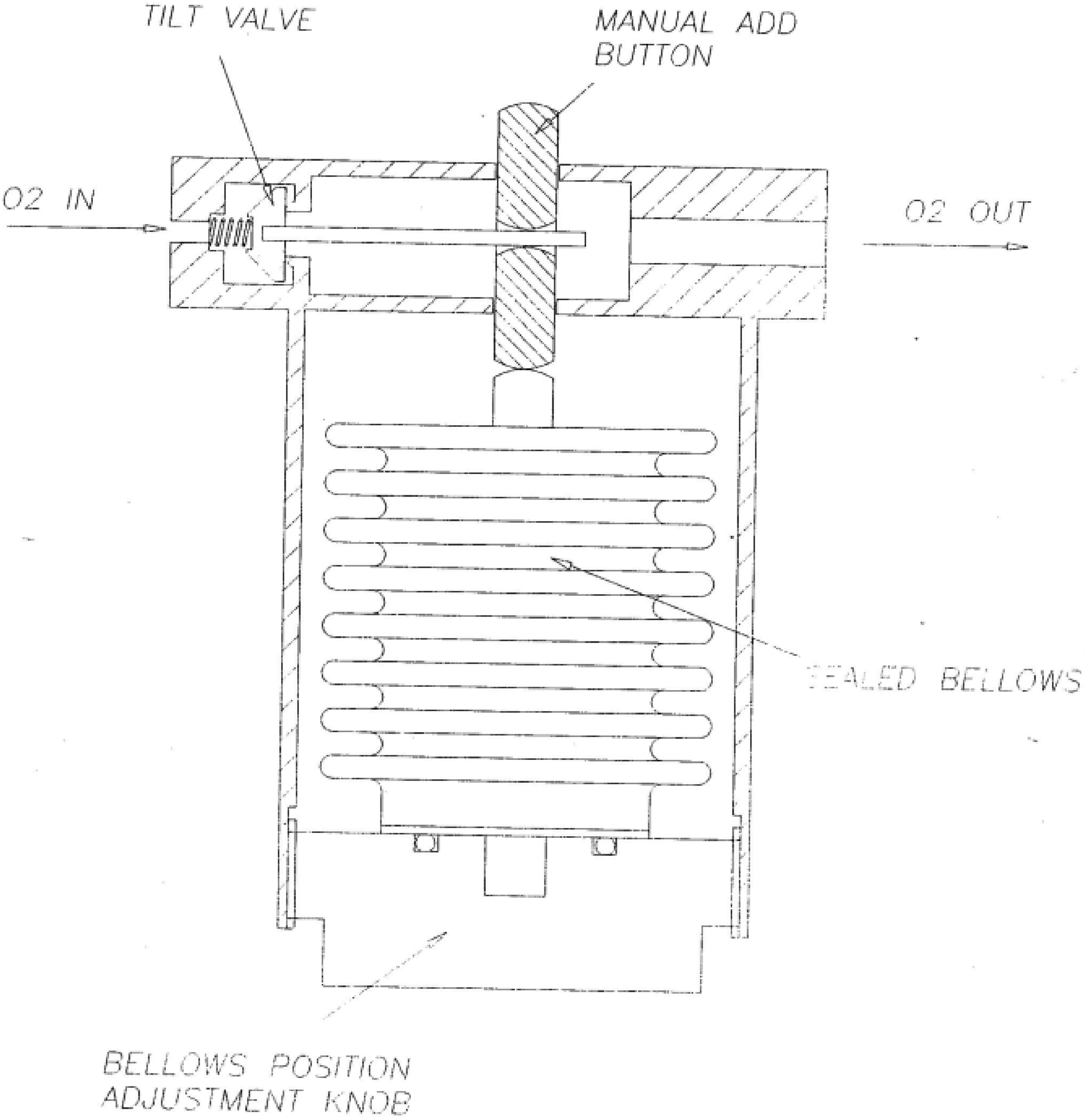


Figure 4

Bellows and 'add-valve'. The add-valve is a conical upstream pressure sealing valve of a type commonly called a 'tilt-valve'. These are found in virtually all types of demand breathing systems - fire fighters' 'air packs', mine safety rescue systems, etc. When the bellows expands due to lowering of sub cabin pressure, it contacts the lever rod of the add-valve and tilts it off its sealing seat, allowing gas to flow around it.



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