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Artificial Gill

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The methods of extracting oxygen from sea water for use as an oxidizer in an underwater vehicle are considered. The Aquanautics artificial gill is the baseline system: its feasibility requires further improvements in the oxygen carrier, electrode surfaces, or both. Current performance of the baseline is half of what is required for the proposed test vehicle. JASON considers the proposed test vehicle premature: much more work on electrochemical research is in order.

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ABSTRACT

Two methods of extracting oxygen from sea water for use as an oxidizer in an underwater vehicle are considered. The Aquanautics artificial gill is the baseline system: its feasibility requires further improvements in the oxygen carrier, electrode surfaces, or both. Current performance of the baseline is half of what is required for the proposed test vehicle. JASON considers the proposed test vehicle premature: much more work on electrochemical research is in order.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 ARTIFICIAL GILL

A system which would permit an undersea vehicle to extract oxygen from the seawater is intriguing, and may permit the development of very long endurance low velocity undersea vehicles. The work by Aquanatics on the development of an artificial gill is a step in this direction, and raises a number of interesting questions.

1. Such a system competes directly with lithium batteries and lithium-seawater fuel cells. We cannot compare their merits, because the gill is in early development, and its ultimate performance is not known.

2. The success of the artificial gill requires further improvement in the oxygen carrier, electrode surfaces, or both. The best achieved electrochemical power requirement of $\geq$ 120 watt-minutes/liter is 20 times short of the theoretical minimum of 6 watt-minutes/liter quoted by Aquanautics. It is impossible to say how much further development of carriers and electrode surfaces will reduce the electrochemical power. A factor of two improvement would appear to be sufficient to allow operation of the proposed self-propelled test vehicle. Essential to the success of this

project will be a continuing program of electrochemical research.

3. The design of a test vehicle was necessary to define the required performance parameters. Its actual construction and demonstration is not now necessary, and would divert resources from more important work on the electrochemistry. A premature demonstration would not only waste money and human resources, but would also unnecessarily pose extra risks--those of failure for some reason unrelated to the gill itself (for example, unexpected inefficiencies in pumps and other auxiliary equipment).

4. A very long range goal might be the development of a vehicle which could truly be self-sustaining, like a fish, obtaining both fuel and oxidant from the sea. The fuel would presumably be suspended organic matter. Many means of using it are conceivable including drying and burning, and fermentation to produce combustible gases. The development of such a system would clearly be a very long range basic research project, but may be worth consideration. It should not supplant the development of an artificial gill, which is very much closer to fruition.

2.0 COMPARISON OF THE GILL WITH PHYSICAL EXTRACTION OF O_2 GAS FROM SEAWATER

The Aquanautics artificial gill requires the development of several challenging subsystems, notably an electrochemical unloader and a gill module with a large surface area to transfer oxygen from seawater to the carrier flow loop. If the goal of the DARPA program is to extract dissolved oxygen from seawater rather than to foster the development of synthetic carrier molecules for oxygen, it is worth examining other extraction methods with less technological risk. We have not made an exhaustive study of alternate methods but we will discuss physical extraction of dissolved oxygen from seawater as one example.

The removal of a dissolved gas from a liquid is a fairly common operation in chemical engineering. It may be accomplished by low pressure distillation, heating, or flushing the liquid with an inert carrier gas, a process sometimes called sparging. A simple device to extract oxygen for a submerged vehicle is sketched in Figure 2-1. Seawater is admitted at its ambient pressure p_1 to a large batch extraction tank of Volume V. The tank is isolated from the sea by closing valves 1 and 4. The pressure control piston is withdrawn to decompress the water in the tank to a pressure p_1 which is less than one atmosphere. The mechanical work required for this decompression is

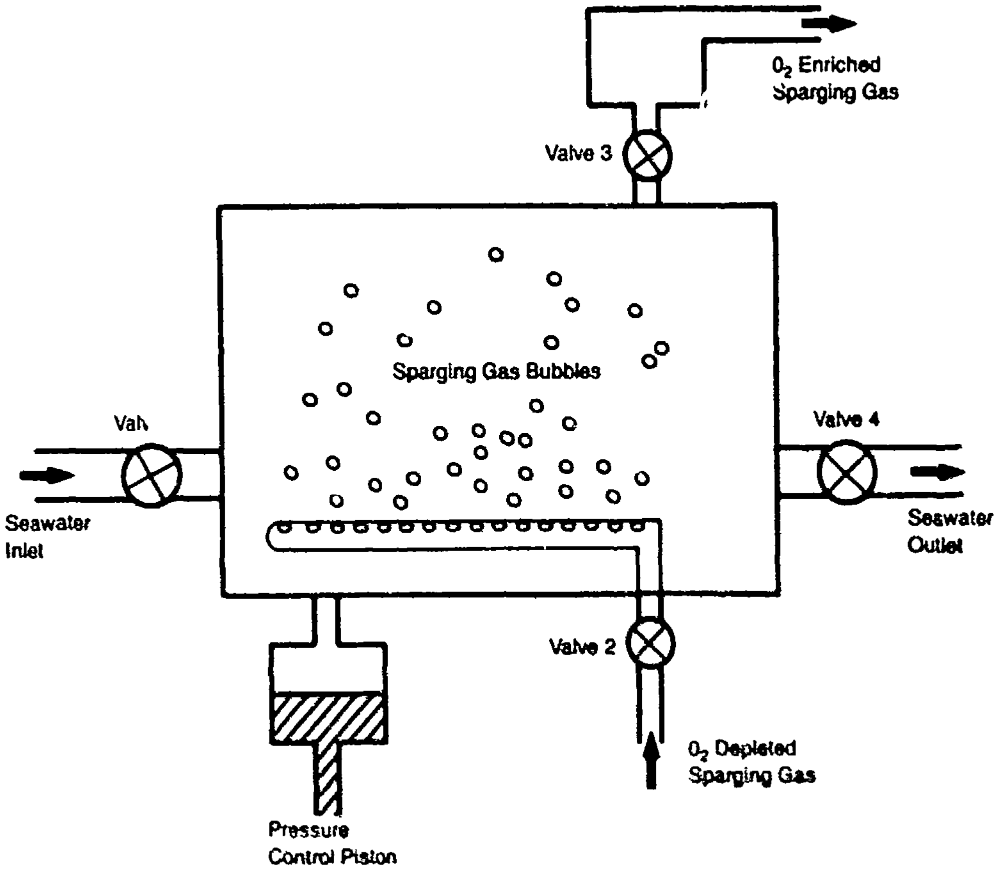

Figure 2-1 A simple system to strip 0_2 from seawater for a submerged vehicle

$$W_1 = \frac{1}{2}\frac{p_o^2}{k}\left[\left(\frac{p_1}{p_o}\right)^2 - \left(\frac{p_2}{p_o}\right)^2\right]V = 22\,\frac{\text{ergs}}{\text{cm}^3}\left[\left(\frac{p_1}{p_o}\right)^2 - \left(\frac{p_2}{p_o}\right)^2\right]V$$

where $p_0 = 1.01 \times 10^6$ dyne/cm^2 = 1 atm is atmospheric pressure and $k = 2.22 \times 10^{10}$ dyne/cm^2 is the bulk modulus of elasticity for sea water. At a depth of 100 meters $p_1 = 11$ atm and the work needed to decompress the seawater is 2662 erg/cm^3, assuming p_2 is negligibly small.

The O_2 content of the seawater is removed by bubbling N_2 gas at a pressure of 0.8 atm through the decompressed seawater. Since the seawater is saturated with N_2 gas at a pressure of 0.8 atm, no nitrogen will be transferred from the water to the sparging gas. A certain amount of work must be done to bubble the gas through the liquid, at the very least, enough work to overcome the surface tension during inflation of the bubbles. This work will be on the order of

$$W_2 = N \cdot 4\pi r^2 \gamma$$

where $\gamma = 77$ erg/cm^2 is the surface tension of water, r is the bubble radius and N is the number of bubbles needed to extract the oxygen. Suppose that some 100 bubbles of radius 0.1 cm are needed to strip each cm^3 of seawater of its oxygen. The work involved is then 968 erg/cm^3, somewhat smaller than the decompression work.

For efficient extraction one would probably want to have a counterflow stripping column rather than the simplistic scheme of Figure 2-1. The basic idea is sketched in Figure 2-2. Once the batch of seawater has been stripped of its oxygen the valves 2 and 3 are closed, the pressure control piston is advanced to repressurize the batch tank to the ambient pressure of seawater, and valves 1 and 4 are opened. The spent water is ejected and replaced by fresh seawater and the cycle described above is repeated.

The works of compression and decompression are nearly equal and opposite so the net work could nearly cancel for a well engineered system. However, we shall assume no recovery of the compressional work at all and take this as representative of the energy needed to extract O_2 from seawater. We assume that the countercurrent stripping system extracts the full 0.006 liter/liter of O_2 at STP dissolved is saturated seawater. Then 167 liters or something over 40 gallons of seawater must be stripped to extract one liter of oxygen at STP. At a depth of 100 m some 45 joules of compressional work are needed to extract one liter of O_2, i.e., 0.74 watt-minutes/liter. Comparing this to the best achieved value quoted by Aquanautics of 120 watt-minutes/liter for operation of the electrochemical part of their artificial gill, and the theoretical optimum

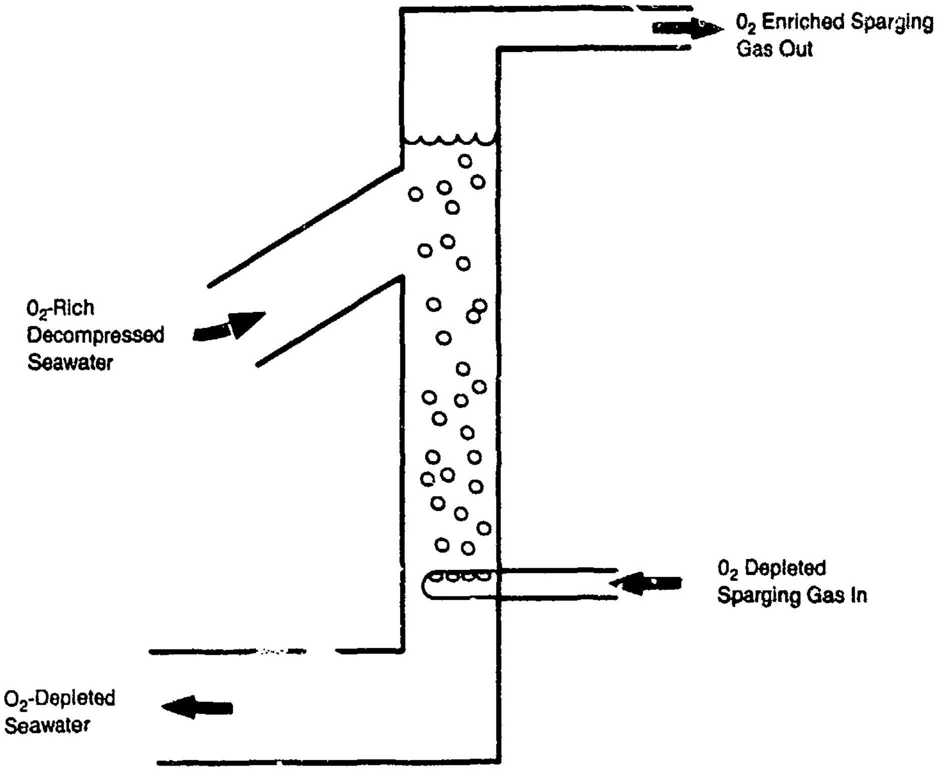

Figure 2-2 For most efficient stripping of O_2 a counter current sparging system should be used.

value of 6 watts-minutes/liter we see that further study of the alternative oxygen extraction system discussed above and other schemes would be worthwhile since much smaller operating powers seem attainable. The physical stripping scheme will have to process about the same amount of water as the Aquanautics gill but the exchange membrane, the carrier molecules and the electrochemical cycle can be dispensed with.

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