AN ENCAPSULATED, IMPLANTABLE METAL-OXYGEN CELL
AS A LONG-TERM POWER SOURCE FOR MEDICAL AND
BIOLOGICAL APPLICATIONS*

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Abstract—This study describes the structure and performance of an encapsulated, implantable aluminium/platinum black electrochemical cell. It is covered with a silicone rubber membrane, and the anode and cathode compartments are separated by an anionic ion exchange membrane. In vitro studies and intermittent in vivo tests with rats demonstrate that a cell of 5.5 cm² area gave a continuous power output of more than 70–100 µW at 0.9 V over 12 months. Although the results of long term implantation experiments now in progress remain to be assessed, preliminary data show that there was no leakage of waste products, and that tissue-cell reactions should not be serious enough to affect cell performance. It is considered that this cell can overcome the disadvantages of unencapsulated biogalvanic cells, and that it offers great promise as a long-term in vivo power source.

1. INTRODUCTION

DURING the past ten years, the increasing application of implantable devices such as cardiac pacemakers, and telemeters for clinical and investigative purposes have prompted the development of in vivo biological power sources which could give a much longer life than the existing mercury cells. The main aspects of this work include: (i) the use of piezoelectric crystals which generate electricity during muscle movements (Enger and Kennedy, 1964); (ii) the generation of electricity by a galvanic cell consisting of two dissimilar electrodes implanted in the body, with the body fluids as the electrolyte medium (Strohl et al., 1966); (iii) electricity generated from a fuel cell which has its continuous supply of fuel and oxidant from the body fluids (Wolfson et al., 1968); (iv) power obtained from a hybrid cell in which the anode is consumed while oxygen from the body fluids is reduced at the cathode (Massie et al., 1968).

The feasibility of substantial power production from a hybrid cell consisting of a platinum black/aluminium electrode pair has been studied by Strohl et al. (1966), Massie et al. (1968) and many others. The work of Massie et al. (1968) showed that 50–75 µW of electrical power could be obtained from a 16 cm² platinum black/aluminium electrochemical cell implanted subcutaneously in a rabbit for a period of 200 days. The electrodes used were not protected, and there was a gradual decay in power output over the test period. It was concluded that this was due to extensive tissue-electrode reaction and the accumulation of insoluble aluminium oxidation products on the cathode surface. Another disadvantage of this system is the spreading of these products throughout the body, which is a potential health hazard, since it has been shown (Kortus, 1967) that chronic accumulation of aluminium exerts a harmful effect on phosphorus metabolism.

* Received 23 November 1970.
If these disadvantages can be overcome, a hybrid cell with aluminium/platinum black electrodes offers the most promising approach to the development of a long term in vivo power source (Myers and Parsonnett, 1969). The purpose of this study is to develop such a cell which can give the required power output to drive cardiac pacemakers, etc. for at least 5 yr and be compatible with the body environment. The theoretical background of this study is outlined and the possible applications of this cell for medical and biological purposes are discussed in the light of the results obtained.

A preliminary account of this work has been disclosed in U.K. Patent application No. 51401/69 (Tseung et al., 1969). Long term implantation experiments in connection with the present study will be published elsewhere.

2. THEORETICAL CONSIDERATION AND DESIGN STUDIES

A hybrid cell consists basically of a cathode at which the reduction of oxygen takes place, and a metal anode which can undergo dissolution. The merits and disadvantages of the currently studied hybrid cells as in vivo power sources will be discussed with the example of an Al/O2 cell, in which the electrode reactions are as follows:

Anodic reaction: \[ 2\text{Al} + 60\text{H}^- = 2\text{Al(OH)}_3 + 6e^- = \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O} + 6e^- \]

Cathodic reaction: \[ 6e^- + 3\text{H}_2\text{O} + 1\frac{1}{2}\text{O}_2 = 6\text{OH}^- \]

Overall reaction: \[ 2\text{Al} + 1\frac{1}{2}\text{O}_2 = \text{Al}_2\text{O}_3 \]

Since the oxygen required for the cathodic process is obtained from the dissolved oxygen in the body fluids, the total weight of the hybrid cell can be reduced to a very much lower level than that of the mercury cells. Moreover, the oxygen supply is continuously available and this enables the hybrid cells to offer a much longer life, provided the other requirements are satisfied. There are, however, certain disadvantages to be eliminated. The possible toxic effects of corrosion products and the phenomenon of an electrode-tissue reaction leading to the coating of the electrode surface by necrotic debris with a resultant decrease in performance have been mentioned in the previous section. In addition, the metal anode placed in the body fluids would tend to undergo self-discharge in the presence of dissolved oxygen, leading to lower cell performance and shorter life. Also, since the body fluids are used as the common electrolyte medium, it is not possible to build up a stack of cells in order to obtain higher cell voltages.

These shortcomings may all be overcome by covering the cathode and anode surfaces with suitable membranes. A schematic design for such an encapsulated Al/O2 cell which can give a long life and be compatible with the host body is described in Fig. 1. The actual size and structure of an Al/O2 cell are shown in Figs. 2a and 2b. The entire structure is encapsulated in a layer of oxygen permeable membrane for which silicone rubber is preferred because it is inert to the host body. Inside the cell, the cathode and anode compartments are separated by a barrier such as anionic ion exchange membrane which is relatively impermeable to oxygen and not permeable to large molecules or corrosion products of aluminium while allowing the \( \text{OH}^- \) ions to diffuse through. As a result, the proposed cells do not use the body fluids as the conducting medium but carry their own electrolyte solution, 0.9% sodium chloride solution being preferred since it rules out the possibility of osmotic effects. The circular anode is made of corrotable metal. Aluminium is preferred although other metals such as magnesium alloy, zinc, lead or...