THERMODYNAMICS AND APPLICATIONS OF BIOELECTROCHEMICAL
ENERGY CONVERSION SYSTEMS

BY

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GPO PRICE $________

CFSTI PRICE(S) $________

Hard copy (HC) 3.00
Microfiche (MF) .50

BIOTECHNOLOGY AND HUMAN RESEARCH
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION,
WASHINGTON, D. C.

Presented at the 6th AGARD Combustion and Propulsion
Colloquium on Energy Sources
and Energy Conversion, Cannes, France,
March 16-20, 1964

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I. Introduction

Bicelectrochemical energy conversion (i.e., converting chemical free energy of biologically catalyzed reactions to electrical energy) is not a newly discovered phenomenon. As long ago as 1786 Galvani observed that a frog muscle twitched when touched with copper-zinc couples in this early insight into the electrical characteristics of biological systems.

Over 50 years ago (1912) Potter demonstrated that a "bacterial culture during the process of energy conversion is in a sense, therefore, a primary electrical half cell and as such should conceivably be able to perform work."

Cohen, in 1930, obtained 1.25 milliamps from six yeast cells biochemically converting glucose in solution. Through this process he later built a battery able to furnish 2 milliamps at about 35 volts.

During the past 10 years interest in biochemical energy has increased fantastically, reaching exponential proportions within the last five. Particular attention in the past two years has been directed to applying the results of research and development to this type of energy.
conversion. This paper will consider these applications in a state-of-the-art review and will present a synopsis of suggested applications ranging from the use of bioelectric currents to identify toxic materials and power human implanted cardiac pace makers to the generation of electric power in remote areas of the world.

Research in biochemical energy conversion -- limited to the laboratory -- is in its infancy. Available data are inadequate to form a sound basis for defining specific engineering and economic criteria that might point the way toward selecting particular technology for development and later applications. Since criteria for bioelectrochemical systems cannot now be defined, it is strongly suggested that present and extrapolated characteristics of such systems should not be compared with those of other energy converters in use or being developed. Such a practice could be discouraged and might result in failure to realize the full potential of bioelectrochemical conversion.
II. **Fundamental Principles**

The fundamental principles of bioelectrochemistry should be considered in order to fully realize the potentialities of this field. Some insight into the electrical potentials associated with bioelectrochemical systems may be derived from the Second Law of Thermodynamics. This law determines the relation between free energy changes and the standard oxidation potential of reactions occurring in biological systems.

A. **Change in Free Energy and Electrical Potentials**

As is well known, the free energy $F$, of the reactants and products in the biochemical system

$$aA + bB \leftrightarrow cC + dD + \text{---}$$

may be expressed in terms of the chemical potentials as

$$F_{\text{react}} = a\mu_A + b\mu_B + \text{---}$$

$$F_{\text{prod}} = c\mu_C + d\mu_D + \text{---}$$

At constant temperature and pressure, the free energy change of the reaction is given by

$$\Delta F_{\text{TP}} = c\mu_C + d\mu_D + \text{---}$$

$$- a\mu_A - b\mu_B - \text{---}$$

The chemical potential $\mu$ is given in the standard state $\mu_0$

$$\mu = \mu_0 + RT \ln \bar{a}$$
where \( \bar{a} \) is the activity of the species in question under defined conditions. Substitution of (4) and (3), and collecting terms,

\[
\Delta F_{TP} = \Delta F^c + RT \ln \frac{C_{\bar{a}}}{D_{\bar{a}}} \frac{C_{\bar{a}}}{D_{\bar{a}}} \frac{a}{b} \frac{A}{B} \tag{5}
\]

When the reactants are incorporated in an electrochemical conversion system.

\[- \Delta F = nFE \tag{6}\]

where \( F \) is the Faraday constant, \( E \) the electrode potential and \( n \) is the number of electrons associated with the reaction. Equation (6) is of great importance since it permits the calculation of standard electrode potentials \( E_0 \) (standard conditions and unit activity) from free energy data. Substituting \(-nFE\) for \( \Delta F \) and \( nFE_0 \) for \( \Delta F^c \) and substituting concentration (\( C \)) for activities (although an approximation).

Equation 5 becomes

\[
E = E_0 - \frac{RT}{nF} \ln \frac{c}{d} \frac{C_a}{C_b} \frac{a}{b} \frac{A}{B} \tag{7}
\]

from the standard oxidation - reduction reaction

\[
X \text{ reduced} \rightarrow X \text{ oxidized} + e^- \tag{8}
\]
B. Generation of Electrical Potentials in Biological Oxidation--Reduction Reactions

Energy transfer reactions in biological systems are of the oxidation-reduction type. Equation (9) permits the calculation of the electrical potential of these systems for various degrees of oxidation.

In general there are two main schemes for the biological oxidation of organic materials. The first (fig. 1) is based on an initial hydrogen removal from the reduced (or fuel) molecule, followed by a successive series of hydrogen atom and electron transfers along a chain of redox couples resulting in electron transfer to oxygen. The entire process is catalyzed by biological catalysts (enzymes).

The second involves the direct activation of molecular oxygen by the oxidase enzymes. Three types of oxidases are those which catalyze: (1) direct oxygen addition to a molecule, (2) reduction of one oxygen atom
BIOLOGICAL ELECTRON TRANSPORT

\[ E^0 \text{ VOLTS} \begin{array}{cccc}
-0.35 & -0.32 & -0.06 & 0.00 \\
\end{array} \]

\[ \Delta E^0 \text{ VOLTS} \begin{array}{cccc}
0.03 & 0.26 & 0.06 & 0.26 \\
\end{array} \]

\[ E^0 \text{ +} 0.26 \quad +0.29 \quad +0.82 \]

\[ \Delta E^0 \text{ +} 0.03 \quad 0.03 \quad 0.53 \]

\[ M^+ \quad DPH^+ \quad FP \quad CYT. b^{+++} \quad Q \quad CYT. c_1^{+++} \quad CYT. c^{+++} \quad CYT. a^{+++} \quad CYT. a_3^{+++} \quad 1/2O_2 \quad H_2O \]

\[ M-H_2 \quad DPN-H^+ \quad FP-H^+ \quad CYT. b^{+H^+} \quad Q-H_2 \quad CYT. c_1^{+H^+} \quad CYT. c^{+H^+} \quad CYT. a^{+H^+} \quad CYT. a_3^{+H^+} \quad 2H^+ \quad 2H_2O \]

\[ \text{ANODE} \quad \text{IONIC CONDUCTOR} \quad 2 \text{OH} \quad \text{CATHODE} \]

M - METABOLITE
DPN - DIPHOSPHO PYRIDINE NUCLEOTIDE
FP - FLAVOPROTEIN
CYT - CYTOCHROME
Q - COENZYME Q
(in O₂) by electron transfer and direct addition of the other to a reacting molecule, and (3) reduction of oxygen to H₂O₂ or H₂O.

In the work reported to date on application of the foregoing principles to bioelectrochemical cells the procedure has been to break the oxidation sequence so that the entire enzyme system is in one or the other of the electrode compartments. Systems such as those shown in figure 1 are divided into an oxygen electrode and an organic fuel-enzyme system separated by a suitable ionic conductor. Of particular significance is the step in the oxidation sequence at which electron transfer to an inert electrode can occur.

1. Bioanodes

Table I lists a number of potential bioelectrochemical oxidation-reduction couples which are anodic to oxygen at the more normal biological pH of 7. The potentials in Table I indicate that with the appropriate enzyme catalysts, substances found in natural sources such as acetaldehyde, xanthine, glucose, and cysteine may be feasible as fuel electrodes with an
TABLE I

ELECTRODE POTENTIALS OF BIOCHEMICAL REACTIONS

<table>
<thead>
<tr>
<th>Electrode Couple</th>
<th>Enzyme</th>
<th>$E^*_{m7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetate/Acetaldehyde</td>
<td>Xanthine Oxidase</td>
<td>-0.58</td>
</tr>
<tr>
<td>Latic Acid/Xanthine</td>
<td>Xanthine Oxidase</td>
<td>-0.39</td>
</tr>
<tr>
<td>Gluconolactone/Glucose</td>
<td>Glucose oxidase</td>
<td>-0.36</td>
</tr>
<tr>
<td>Cystine/Cysteine</td>
<td>None</td>
<td>-0.33</td>
</tr>
<tr>
<td>Acetaldehyde/Ethanol</td>
<td>Alcohol dehydrogenase</td>
<td>-0.20</td>
</tr>
<tr>
<td>Pyruvate/Lactate</td>
<td>Lactic dehydrogenase</td>
<td>-0.18</td>
</tr>
<tr>
<td>Oxaloacetate/Malate</td>
<td>Malic dehydrogenase</td>
<td>-0.16</td>
</tr>
<tr>
<td>Fumarate/Succinate</td>
<td>Succinic dehydrogenase</td>
<td>+0.02</td>
</tr>
<tr>
<td>Dehydroascorbate Ascorbate</td>
<td>Ascorbic oxidase</td>
<td>+0.06</td>
</tr>
<tr>
<td>Ferricytochrome c/Ferrocytochrome c</td>
<td></td>
<td>+0.27</td>
</tr>
<tr>
<td>Oxidized cyt. oxidase/Cytochrome oxidase</td>
<td></td>
<td>+0.29</td>
</tr>
<tr>
<td>$O_2 + 4H^+ + 4e \rightarrow 2H_2O$</td>
<td></td>
<td>+0.82</td>
</tr>
</tbody>
</table>

$E^*_{m7}$ is the potential at pH 7 in the presence of equal concentrations of oxidized and reduced forms of reactants.
oxygen (air) cathode. The energy density of these materials is on the order of 5 pounds per kilowatt-hour. Several enzymes catalyzed and whole organism-catalyzed redox couples have been studied under laboratory conditions. The results are discussed below:

(a) Glucose - Glucose Oxidase System

The electrode mechanism has not been critically described for this system. Several mechanisms are suggested. In a direct mechanism glucose and the enzyme glucose oxidase react to form a complex intermediate. The intermediate is oxidized at the anode to gluconolactone and the enzyme is liberated. (Equations 10 and 11).

\[
\begin{align*}
\text{Glucose Oxidase} & \quad \text{C}_6\text{H}_12\text{O}_6 \quad \text{(Glucose . Enzyme)} \\
\text{Anode} & \quad \text{C}_6\text{H}_{10}\text{O}_6 + 2\text{H}^+ + 2\text{e}^- 
\end{align*}
\]  

Anodic polarization data for the glucose-glucose oxidase bio-anodes is shown as figure 2. In these studies, the enzyme glucose oxidase is incorporated in the pt-black electrode surface and glucose (reduced form is added to the cell). As shown in figure 2, the electrochemical
POLARIZATION OF A GLUCOSE BIOANODE

Temperature: 25°C
Medium: Phosphate Buffer
0.1M Glucose
Electrode: Black Pt

Potential, Volts vs SHE

Current Density, Microamps/Sq. cm
oxidation of glucose on platinum is markedly enhanced by the incorporation of the glucose oxidase as a catalyst.

(b) Amino Acid - D - Amino Acid Oxidase System

The normal aerobic reaction products of the amino acid D-amino acid oxidase (DAO) system include the pyruvic acid derivative of the amino acid, hydrogen peroxide and ammonia.

Experiments have been conducted on the bioelectrochemical behavior of the three amino acids Tryptophane, tyrosine and phenylalanine and their respective D-amino acid oxidase reaction products indole-3-pyruvic acid, para-hydroxy phenyl pyruvic acid, and phenyl pyruvic acid. Results to date on platinum electrodes show that observed currents are derived from the electrochemical oxidation of the aromatic pyruvic reaction products. Ammonia not peroxide contributed appreciably to the electrical currents. Currents of the order of 350 μA/cm² at 200 mv have been derived with indole-3-pyruvic acid.

Currents on the order of 45 μA/cm² at 200 mv have been derived from cells in which indole pyruvic acid is generated enzymatically from Tryptophane.
These studies indicate that: (1) the current limitation is enzymatic, (2) the reactive species is the enol form of the keto acid derivative of the naturally occurring amino acids (absorption spectra data), and (3) further studies are needed to determine optimal condition for enzyme and electrochemical activity in order that the potential of utilizing complex natural occurring materials as electrode reactants may be exploited.

(c) The Urea-Urease System

Theoretically it would be expected that in this cell the enzyme urease would generate ammonia from urea and the ammonia electrochemically oxidized:

\[
\begin{align*}
\text{CO (NH}_2\text{)}_2 + \text{H}_2\text{O} & \xrightarrow{\text{Urease}} 2 \text{NH}_3 + \text{CO}_2 \quad (12) \\
2 \text{NH}_3 + 6 \text{OH}^- & \rightarrow \text{N}_2 + 6 \text{H}_2\text{O} + 6\overline{e} \quad (13)
\end{align*}
\]

In studies to date the Urea-Urease System has presented a rather consistent dilemma. In cells with bright platinum electrodes in 0.25 M ammonium nitrate in tris buffer (tris-hydroxymethyl amino methand) at pH of 6.5 - 9.0 ammonia was reportedly not oxidized. In the same cell, nevertheless, the action of urease resulted in the augmentation of the cell current and the enzymatic hydrolysis of urea parallels the cell current, (fig. 3). Other studies have shown that
RELATION OF CELL CURRENT TO EXTENT OF UREA HYDROLYSIS

- CURRENT
- HYDROLYSIS (μG NH₃/ML)

COMMERCIAL UREASE. 200 GMS. (56 SU)
0.45 GMS UREA
30 ML pH 6.5, 0.25 M PHOSPHATE BUFFER
ANODE POTENTIAL 0.60 VS SCE
at pH 6 in a KCl - citrate buffer using platinum impregnated carbon electrodes incorporating the urease enzyme, short circuit currents of 1-3 ma/cm² were derived on addition of urea. Further studies on this system are being conducted.

2. Sulfate Biocathode

Potentials associated with biologically catalyzed reductions have also been investigated. The reduction of sulfate to hydrogen sulfide by the organism Desulfovibrio desulfuricans, attached to porous iron electrodes, has been extensively studied. However, the mechanism for this electrode has not been completely established. It is thought that the reactions for the bioelectrochemical reduction of sulfate may be as follows:

\[
\begin{align*}
2H_2O + 2e^- & \rightarrow \text{Cathode} \rightarrow H_2 + 2OH^- \quad (14) \\
SO_4^{2-} + 4H_2O & \text{D. Desulfuricans} \rightarrow S^{2-} + 4H_2O \quad (15) \\
SO_4^{2-} + 4H_2O + 8e^- & \text{D. Desulfuricans} \rightarrow S^{2-} + 8OH^- \quad (16)
\end{align*}
\]

C. Biological Generation of Fuels for Electrical Energy

Biological energy sources may also indirectly generate electricity. Biochemical agents may generate chemical species specifically tailored to a biological energy
conversion system optimized to the requirements and consistent with available fuel. Examples include the generation of hydrogen, ammonia, or methanol from higher molecular weight materials (such as sugars, proteins, fats, starches, urea) by means of whole living cells or cell free extracts or crystalized enzymes.

Samples of biochemical systems for the generation of primary fuels from complex materials are presented as Table II. The literature has been reviewed and over 200 references are included in the bibliography under "Generation of Bioelectrochemical Fuels."

Applications of bioelectrochemical conversion are discussed in the following paragraphs.
<table>
<thead>
<tr>
<th>NATURAL FUEL</th>
<th>NATURAL SOURCE</th>
<th>CATALYST</th>
<th>PRIMARY FUEL</th>
<th>LB/KWH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMMIONIA GENERATORS</td>
<td></td>
<td>UREASE (CRYSTALLINE ENZYME)</td>
<td>NH₃</td>
<td>0.83</td>
</tr>
<tr>
<td>UREA</td>
<td>URINE</td>
<td>AMINO ACID OXIDASE (ENZYME)</td>
<td>NH₃</td>
<td>1.2-3</td>
</tr>
<tr>
<td>AMINO ACIDS</td>
<td>PROTEIN DIGESTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HYDROGEN GENERATORS</td>
<td></td>
<td></td>
<td>H₂</td>
<td>1.8</td>
</tr>
<tr>
<td>FORMIC ACID</td>
<td></td>
<td>FORMIC DEHYDROGENASE (ENZYME)</td>
<td>H₂</td>
<td>1.8</td>
</tr>
<tr>
<td>METHANE GENERATORS</td>
<td></td>
<td></td>
<td>H₂</td>
<td>1.8</td>
</tr>
<tr>
<td>PROPRIONIC ACID</td>
<td>FATS, OILS</td>
<td>METHANOBACTERIUM PROPRIRICUM (LIVING BACTERIA)</td>
<td>CH₄</td>
<td>1.0</td>
</tr>
</tbody>
</table>
III. Applications of Bioelectrochemical Conversion

A. General

Research and development looking toward the applications of bioelectrochemical conversion is in its early phases. However, at present four general areas for potential future applications appear to be emerging.

These include:

- Power sources for supplying relatively small amounts of electrical energy in specialized applications and locations.
- Detectors for specific contaminants in low concentrations.
- Sensors for generation of control signals.
- Catalysts for the generation of electrochemical reactants from complex naturally occurring materials and from waste materials.

Available information indicates that bioelectrochemical power generation will most likely be limited to specialized applications. Competition with major power generation methods is unlikely. Bioelectrochemical power
generation will probably supply limited emergency power, serve remote and unattended power supplies, and supplement existing natural fuels (such as vegetation) when transportation costs for additional fuels are excessive.

B. **Sources of Energy or Power**

As power sources bioelectrochemical converters may be arbitrarily classified in terms of power levels for suggested applications.

1. Requirement for 1-10 milliwatts

Low power level implantable transducers, stimulators, and other electronic devices are needed to regulate physiological and biological functions. For example, the present day pacemaker used in the regulation of the electrical profile of the human heart requires electrical energy at about 2.4 volts with current pulses 2 milliseconds in duration at a frequency of one to two/second. The average current and power are about 25 μ amperes and 100 μ watts, respectively. This energy is normally supplied by five primary cells, calculated to last for two to three years, which are made part of the implantable package. Surgery is required to replace the
dead batteries. The operating life of batteries for other implantable devices may be much less.

The development of implantable energy converters which derive their energy on a continuous or periodic basis from physiological fluids may be quite advantageous. Consequently, the development of an implantable fuel cell with output of 200 \( \mu \) watts at a voltage level in the vicinity of 1 volt may be a very worthwhile objective.

The literature available on the measurement of oxidation-reduction potentials of mammalian blood is extensive. Electrode potentials ranging from 0.5 to 4.3 are relatively common in mammalian body fluids. With a fuel cell of 0.5 volt at a current density of 10 \( \mu \) amperes per square centimeter, the power output would be 5 \( \mu \) watts per \( \text{cm}^2 \) of electrode surface area. Even at such low current densities the pacemaker power requirements could easily be satisfied with electrode surface areas of the order of 100 \( \text{cm}^2 \).

In an experimental analog of the conditions found in the blood stream the open circuit voltage was
approximately 0.1 volt when platinum black electrodes were used. Current densities ranging from 10 to 50 $\mu$amps per square centimeter were found to be linear with the polarization voltages having a slope of nearly 2 1/2 millivolts per $\mu$ampere per square centimeter.

2. Requirements for 2-5 watts

Attention has been given to the application of direct bioelectrochemical converters for long duration unattended power generation. Use of these converter systems to supply 2-5 watts of power in the ocean has been broadly explored. Sulfate, available in the ocean, has been studied extensively as the cathodic reactant of such a power source device. In this device bacteria (*Desulfovibrio desulfuricans*) are applied to the cathode where they consume hydrogen and reduce sulfate ion to sulfide ion. The anodic process is the oxidation of magnesium. Limiting current densities as high as 3 $\text{ma/cm}^2$ at -0.8V vs SCE have been reported under optimum conditions. Cell design has not been optimized but power densities in the range of 5-20 $\text{W/ft}^3$ and energy densities of approximately 30 $\text{KWH/ft}^3$ may be estimated for a cell to operate two years without attention. A laboratory fuel cell is shown in figure 4.
3. Requirements for 20 watts

The availability of used oxygen and the enzyme urease has suggested their use in an open-cycle power generator. Several investigations have been conducted of the electrochemical performance of a urease urea oxygen (air) battery. In the future this type of battery might be used to produce relatively low power (below 20 watts) for short periods of time (2 weeks, for example).

As anode materials platinum black electrodeposited platinum, platinum impregnated carbon, active impregnated carbon, activated carbon, Raney silver, and electrodeposited nickel have been investigated. Crystalline enzyme catalysts would be incorporated in the electrodes; monel screens and porous carbon blocks used as current collectors. A 3 M KCl, citrate buffer at pH6, resulted in maximum limiting current densities. The air cathode is a porous platinized carbon electrode. These fuel cells have achieved an open circuit voltage of about 0.8V and a short circuit density of 3.6 amp/ft² for short periods of time.
4. Power Requirements Greater than 20 watts

Several factors need to be analyzed when considering bioelectrochemical convertors for power applications in excess of 20 watts. Worldwide energy demand and fuel logistics are two of these important considerations. A distribution of the world's yearly electrical energy consumption is shown as table III, distribution by country as figure 5, and distribution on the basis of world population as figure 6. These data show that about 24 percent of the world's countries, with 37 percent of its population, have an average yearly electrical energy consumption of only 20 kilowatt hours per capita. It is evident from this fact that special remote locations throughout the world may well be provided with a minimal power source at minimal costs by using biological sources of energy.

Biological sources of energy could be used for the generation of electrical power directly by bioelectrochemical energy conversion or indirectly by biocatalytic generation of simple fuels from complex
<table>
<thead>
<tr>
<th>Group</th>
<th>Range KWH per capita</th>
<th>Average KWH per capita</th>
<th>Percent Countries</th>
<th>Percent Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1,000-10,346</td>
<td>2,964</td>
<td>24.2</td>
<td>28.9</td>
</tr>
<tr>
<td>B</td>
<td>500-1,000</td>
<td>681</td>
<td>11.3</td>
<td>4.3</td>
</tr>
<tr>
<td>C</td>
<td>200-500</td>
<td>331</td>
<td>16.1</td>
<td>6.9</td>
</tr>
<tr>
<td>D</td>
<td>100-200</td>
<td>129</td>
<td>10.5</td>
<td>4.4</td>
</tr>
<tr>
<td>E</td>
<td>50-100</td>
<td>70</td>
<td>13.7</td>
<td>18.3</td>
</tr>
<tr>
<td>F</td>
<td>0-50</td>
<td>20</td>
<td>24.2</td>
<td>37.2</td>
</tr>
</tbody>
</table>
YEARLY WORLD ENERGY-COUNTRY DISTRIBUTION

- GROUP-F AVERAGE 20 KWH/C
- GROUP-E AVERAGE 70 KWH/C
- GROUP-D AVERAGE 129 KWH/C
- GROUP-C AVERAGE 331 KWH/C
- GROUP-B AVERAGE 681 KWH/C

- GROUP-A AVERAGE 2964 KWH/C

HUMAN WASTE AT 50% ENERGY CONVERSION EFF.

- URINE 18.3 KWH/C
- FECES 22.1 KWH/C

ENERGY KILOWATT HOURS/CAPITA

PERCENT OF COUNTRIES IN WORLD
naturally occurring materials. Of particular significance is the utilization of biological energy sources in their natural form.

(a) Urinary Waste as a Source of Energy

Theoretically, bioelectrochemical conversion of urea in human urinary wastes could supply on the order of 18 KWH per capita yearly based on a conversion efficiency of 50 percent.

Work has already been conducted on the electrochemical behavior of systems fueled by raw urine and catalyzed by growing bacteria. The bacteria *Bacillus pasteurii* has been studied in a system because of its established ureolytic activity. Preliminary data (fig. 7) indicate that a preliminary 18-hour incubation of raw uring with this bacteria provides increased current. At 170 mV, for example, the current carrying capacity of the electrode fueled by preincubated material was greater by a factor of 15 than the unincubated material.

(b) Vegetative Sources of Energy

Several other systems using natural materials as fuels have been studied. Laboratory studies have shown
ANODIC POLARIZATION OF PLATINUM IN URINE,
EFFECT OF B. PASTEURII GROWTH

TEMPERATURE 25°C
pH 9
ANODE AREA 10 CM²

UNABLE TO OBTAIN STEADY POTENTIAL

URINE WITH B. PASTEURII
BEFORE GROWTH

URINE WITH B. PASTEURII
AFTER GROWTH (18 HOURS)
(CORRECTED FOR OBSERVATION TIME)

ANODE POTENTIAL, VOLTS /S SCE

CURRENT, MILLI AMPS
that some power gains may be realized by the biological catalyzation of electrochemical systems using natural materials such as fresh mushrooms, toadstools, sucrose, and algae as fuels and oxygen (air) cathodes.

Chemical digestion of natural materials with sulfuric acid and potassium hydroxide results in the generation of electrochemically active organic and inorganic material and an over-all net reaction may be written:

$$\frac{1}{2} \text{CH}_2\text{O} + \frac{1}{2} \text{O}_2 \rightarrow \frac{1}{2} \text{CO}_2 + \frac{1}{2} \text{H}_2\text{O} \quad (17)$$

(Biological fuel)

Some laboratory results for the non-biologically catalyzed systems are presented as figure 8.

The biological catalyzed oxidation of natural fuels with sulfuric acid using the bacteria Desulfovibrio may be used as anodic reactants in a system with an oxygen (air) cathode. The over-all net reaction may be given as follows:

$$2 \text{CH}_2\text{O} + \text{H}_2\text{SO}_4 + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2 + 3\text{H}_2\text{O} + \text{S} \quad (18)$$

Laboratory results for several systems studied are presented as figure 9. A comparison of
CURRENT-VOLTAGE OF VEGETATIVE BIO-FUELS

40% POTASSIUM HYDROXIDE OR 1.8 MOLAR SULFURIC ACID
CURRENT-VOLTAGE
OF BIOLOGICALLY CATALYZED VEGETATIVE BIO-FUELS

E, Volt

CURRENT DENSITY, MICRO AMP/CM²
figures 8 and 9 indicates a greater than 4 fuel increase in current densities may be realized by biological catalysts in systems using complex natural fuels. These studies have been conducted under laboratory conditions in order to elucidate the parameters effecting bio-electrochemical activity. Much work remains to be done before the feasibility is established of utilizing such phenomena as practical applicants where complex natural materials are readily available.

C. Detection and Generation of Control Signals

Another area of applications for bioelectrochemical conversion is in (1) the detection of simple and complex chemical species in extremely low concentrations, and (2) in the use of electric signals associated with biochemical systems for control. Illustrative work to date includes the toxic gas detector and myoelectric serve boost system.

The influence of various chemicals on the activity of naturally occurring microorganisms has been utilized in the detection of toxic agents.

The activity of the microorganism has been found to be proportional to the concentration of various agent.
Specific biological agents have been preselected which will provide detection of trace materials at concentrations of parts per billion.

The feasibility has been demonstrated of using electrical signals associated with contraction of muscles to control a servo boost system which would enable an individual to remotely handle adverse tasks. In this application silver foil electrodes are attached externally to a subject and a potential of 1-3 millivolts peak to peak at 3-1000 cycles/second are picked off and used to direct an external control logic.

Finally, in the broadest sense, bioelectrochemical energy conversion may show numerous and varied applications. Such applications are arbitrarily organized according to the level of associated power as figure 10. The applications illustrated do not represent a complete survey, since the entire area is relatively new and a complete picture has not been developed.

However, it is hoped that the above discussion will serve to stimulate thinking in this area.
APPLICABLE POWER LEVELS FOR BIOELECTROCHEMICAL CONVERSION

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POWER LEVEL - WATTS

FUEL ENZYME FUEL CELLS

INDIRECT POWER GENERATION BIOLOGICAL FUEL GENERATION AND CONVENTIONAL POWER CONVERSION

DIRECT UTILIZATION OF NATURAL FUELS

BIologically CATALYZED FUEL CELLS

BIOMEDICAL TRANSDUCERS DETECTORS SENSORS FOR GENERATION OF CONTROL SIGNALS

DURATION YEARS
REFERENCES


BIBLIOGRAPHY

The following bibliography on bioelectrochemical energy conversion and related subjects has been compiled from referenced works in the area of bioelectrochemistry. The listing is not complete. It is intended to establish a representative compilation of references needed by an investigator to embark upon research in this area. The following abbreviations were used in the bibliography to assist in the location of reports and documents.

N numbers refer to Scientific and Technical Aerospace Reports (STAR)

A numbers refer to International Aerospace Abstracts

AD numbers refer to Armed Services Technical Information Agency (ASTIA) now called Defense Documentation Center (DDC)
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