

College of Mineral Industries



The
Pennsylvania State University

UNIVERSITY PARK, PA., JANUARY 1958

— FUEL CELLS — Potential Source of Electrical Energy

George J. Young* and Ralph B. Rozelle†

FUEL CELLS — Batteries for converting the chemical energy of common fuels directly into electrical energy — may provide an important source of electric power in the future. Advantages of these cells over conventional generating plants lie in their high conversion efficiencies and long operating life. Suggested applications range from small-scale power sources for military electronic devices to large-scale power plants to supply electrometallurgical industries.

THE MAJOR PORTION of the electric power produced in the world today is generated through some form of heat engine operated by the combustion of fossil fuels — coal, oil, or natural gas. A three-step conversion process is required: transformation of the chemical energy of the fuel into thermal energy by combustion, transformation of the thermal energy into mechanical work in a heat engine, and transformation of the work into electrical energy by means of an electric generator. The fact that fossil fuels are at present our most widely distributed and least expensive primary energy source is an outstanding advantage for this conversion process. However, such an involved procedure will have a low over-all efficiency because of the energy losses in each step. Furthermore, even under ideal conditions the thermodynamics of heat engines places a limitation on the attainable over-all efficiency of converting thermal energy into mechanical work. Even nuclear power plants now being designed are subject to this thermodynamic limitation, which arises because of the restriction on temperatures attainable in practice for heat source and heat sink of the engine.

The thermodynamic limitations and most of the efficiency losses in the other steps in power generation could be avoided if the chemical energy of the fuel were converted directly to electrical energy. The high operating efficiency of electrochemical cells is well known, and, if such cells could be constructed using fossil fuels in some form for the anode (oxidizing) reaction, a practical source of electrical energy would be provided independent of the steam cycle and its inherent limitations. Electrochemical cells employing common fuels or products readily derived from fossil fuels have been studied on a laboratory scale, and their performance suggests that serious attention be given to this source of electrical energy.

A fuel cell operating at room temperature with hydrogen as a fuel is capable of a fuel-use efficiency of 70% to 80% compared with an efficiency of about 35% for a steam power plant operating on coal. Hydrogen, or other fuel gases, for such a cell can be obtained from coal by gasification or by reforming oil or natural gas. On the basis of fuel consumed, the best electrical generating plants require from 0.7 to 0.8 pound of coal per kilowatt-hour of electricity, while a fuel cell would theoretically require only 0.3 pound of coal per kilowatt-hour.

Other advantages of fuel cells would be their high ratio of electrical energy per unit weight, their adaptability for large or small-scale applications, and their long operating life. The components of the cell, other than the fuel, are not consumed in the electrode reactions, and thus the cell could be operated indefinitely if the fuel were continually supplied.

All in all, the fuel cell appears to offer promise of wide future use. Progress is being made in understanding and improving fuel cell operation, the possible applications seem to be numerous and important, and motivation should develop for the immediate employment of this device for more efficient use of our fuel resources.

TYPES OF FUEL CELLS

The fundamental principles of operation of a fuel cell are essentially the same as those common to all galvanic cells. Basically, we are concerned with two half-cell reactions — one involving oxidation and releasing electrons, the other involving reduction and requiring electrons. The two half-cells are separated by an electrolyte barrier so that reaction can occur only by the migration of ions. Such an arrangement of the two half-cells is shown in Figure 1, where the fuel oxidized is hydrogen, and the material reduced is the oxygen of the air. In this case

(Continued on page 4)

Osborn Is Granted Leave of Absence



E. F. Osborn

E. F. OSBORN, Dean of the College of Mineral Industries, has been invited to serve as a visiting scientist with the Department of Mineralogy and Petrology at Cambridge University, England. A leave of absence for this purpose has been granted to Dean Osborn beginning February 1 and ending July 31. He will conduct research at Cambridge as a National Science Foundation Senior Post-doctoral Fellow.

Dean Osborn's special field of interest is high temperature chemistry as applied to the origin of igneous and metamorphic rocks and to problems of steel making. Before the war he was a member of the staff of the Geophysical Laboratory of the Carnegie Institution of Washington where his research dealt with phase equilibria at high temperatures in mineral systems. During the war he was engaged in metallurgical investigations for the National Defense Research Committee on the problem of the erosion of machine gun barrels during rapid fire. The War-Navy Certificate of Appreciation was awarded him for this work. Following the war Dean Osborn worked for a year as research chemist at the Eastman Kodak Laboratories on the devel-

(Continued on page 2)

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PENNSYLVANIA'S COLLEGE OF MINERAL INDUSTRIES

Dedicated to

Instruction and research in all fields of mineral discovery, extraction, and utilization to the end that true conservation — the efficient exploitation of known mineral deposits, the discovery of new deposits, and the development of new techniques for using mineral raw materials not now industrially employed — shall be achieved now and in the future.

DIVISIONS OF SERVICE

EARTH SCIENCES: Geology, Mineralogy, Geography, Geophysics, Geochemistry, and Meteorology.

MINERAL ENGINEERING: Mining Engineering, Mineral Preparation Engineering, Petroleum and Natural Gas Engineering, and Mineral Economics.

MINERAL TECHNOLOGY: Metallurgy, Ceramic Technology, and Fuel Technology.

FIELDS OF WORK

Resident Instruction
Research
Extension Instruction
Correspondence Instruction

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Dean Osborn

(Continued from page 1)

opment of novel optical glasses. Since coming to Penn State in 1946 as professor of geochemistry, he has continued his phase equilibria research, collaborating with graduate students in these studies. He is author or co-author of over 40 scientific papers and several patents. The 1954 Regional Technical Meeting Award of the American Iron and Steel Institute went to Dean Osborn in recognition of his paper, "Phase Equilibria in Steelplant Refractories Systems."

He is a fellow of the Geological Society of America, the Mineralogical Society of America and the American Association for the Advancement of Science and a member of the American Ceramic Society, the American Chemical Society, the Mineralogical Society (London), the Mineralogical Association of Canada, the Society of Economic Geologists, the American Institute of Mining, Metallurgical and Petroleum Engineers, the Geochemical Society, the Geological Society of Washington, Phi Beta Kappa, Phi Lambda Upsilon, Sigma Xi and Kerosmos. He serves as chairman of the National Science Foundation's Divisional Committee for the Mathematical, Physical and Engineering Sciences, as a member of the Executive Committee of

SCHOLARSHIPS AVAILABLE IN MINERAL INDUSTRIES CURRICULUMS

Scholarships Listed by Company,
Organization, or Individual Donor,
or by Name of Scholarship

American Brake Shoe Co.
American Ceramic Society
(Philadelphia Section)
American Coal Sales Association
American Encaustic Tiling Co.
American Society for Metals
Anonymous
Bituminous Coal Research, Inc.
Chevron Oil Company

Cooperative Program in Metallurgy
Edwin L. Drake Memorial

B. F. Drakenfeld & Co.
Wilbur B. Driver Co.
Eastern Gas and Fuel Associates
Garfield Refractories Co.
General Refractories Co.
Harbison-Walker Refractories Co.
Haws Refractories Co.
O. Hommel Co.
International Nickel Co.

Koppers Company
E. J. Lavino Co.
E. J. Lavino Co.
John G. Miller Memorial
National Coal Association
National Refractories Co.
North American Refractories Co.
Pennsylvania Ceramics Association
Pennsylvania Glass Sand Corp.
Pfaudler Company
Pittsburgh Consolidation Coal Co.
Pittsburgh Plate Glass Co.
Precision Grinding Wheel Co.
Socony Mobil Oil Company, Inc.

Stackpole Carbon Co.
Hiram Swank's Sons Refractories Co.
Swindell-Dressler Foundation
John and Elizabeth Holmes Teas

Texas Company

Texas Company
Universal-Rundle Corporation
Vesuvius Crucible Company
Matthew J. Wilson

Field	No. of Scholarships	Annual Stipend
Mineral Industries	1	\$ 600.00
Ceramic Tech.	1	350.00
Fuel Tech.	1	1000.00
Ceramic Tech.	1	500.00
Metallurgy	1	400.00
Fuel Tech.	1	500.00
Fuel Tech.	2	500.00
Geophysics & Geochemistry	1	500.00
Metallurgy	10-12	370.00
Geology-Mineralogy or Petroleum	7	350.00
Ceramic Tech.	1	500.00
Metallurgy	1	650.00
Fuel Tech.	2	500.00
Ceramic Tech.	2	500.00
Ceramic Tech.	1	500.00
Ceramic Tech.	3	500.00
Ceramic Tech.	1	500.00
Ceramic Tech.	1	450.00
Metallurgy, Mining, Geology	1	650.00
Fuel Tech.	1	500.00
Ceramic Tech.	1	500.00
Min. Economics	1	500.00
Mineral Ind.	1	100.00
Fuel Tech.	2	500.00
Ceramic Tech.	1	500.00
Ceramic Tech.	1	500.00
Ceramic Tech.	1	250.00
Ceramic Tech.	1	350.00
Ceramic Tech.	2	500.00
Fuel Tech.	2	500.00
Ceramic Tech.	4	500.00
Ceramic Tech.	1	250.00
Petroleum & Earth Sciences	2	750.00
Ceramic Tech.	1	500.00
Ceramic Tech.	1	500.00
Ceramic Tech.	1	500.00
Geology, Geophysics & Geochem.	6	1000.00
Petroleum & Natural Gas	1	425.00
Fuel Tech.	1	425.00
Ceramic Tech.	1	500.00
Ceramic Tech.	2	500.00
Mineral Ind.	1	600.00

AWARDS

Name of Award	Departments Eligible	Amount
Jerome N. Behrmann	Meteorology	\$100.0
William Grundy Haven Memorial	Mineral Industries	250.0
Ellen Steidle Memorial	Mineral Industries	Senior 250.0
	Mineral Industries	Junior 75.0
Lewis E. Young	Mining, Metallurgy Geology & Petroleum	200.0

the Board of Directors of the American Ceramics Society, as a member of the Board of Directors of the American Geological Institute, and he serves on numerous other committees of national scientific societies and scientific organizations of the federal government.

At Cambridge Dean Osborn will focus on geology, the field in which he did his M.S. and Ph.D. research. He plans to apply experimental data which have been obtained in the laboratory to certain problems of crystallization of natural magmas. He will be

associated with Professor C. E. Tilley, head of the Department of Mineralogy and Petrology, and one of the world's leading petrologists.

While abroad, Dean Osborn plans also to visit research laboratories and universities in England, Scotland, the Netherlands, Belgium, Sweden, Norway, Denmark, France, Germany and Italy. He plans to go on a geological field trip in July through Norway and Sweden arranged as a feature of the Nordiska Geologiska Motet celebrating the 100th Jubilee of the Swedish Geological Survey.

M. I. Faculty Active in Many Fields

Papers presented by members of the Department of Metallurgy at the 1957 Metal Congress in Chicago, November 3-7, included one on "Dispersion Hardening by Spherical Particles" by H. R. PEIFFER, H. J. READ and A. J. SHALER; and another by A. PAL and H. M. DAVIS on "The Release of Hydrogen from Molten Aluminum."

ALFRED K. BLACKADAR, associate professor of meteorology, is editor of a group of monographs which has recently been published by the American Meteorological Society. Entitled "Meteorological Research Reviews," the 283-page volume summarizes research progress from 1951 to 1955 in several fields of meteorology, including Climatology, Meteorological Instruments and Observations, Radar Meteorology, Forecasting, Physics of the Upper Atmosphere, Atmospheric Electricity, and Physics of Clouds and Precipitation. The work includes contributions by nine authorities selected by a special committee appointed in 1954 by the American Meteorological Society.

P. L. WALKER, professor and head, Department of Fuel Technology, has been appointed

a member of the newly reactivated Committee on Chemical Utilization of Coal in the Division of Chemistry and Chemical Technology of the National Research Council, National Academy of Sciences.

R. F. NIELSEN, professor of petroleum and natural gas engineering, led a discussion on "Temperature and Fluid Distributions in a Thermal Recovery Process," at the Secondary Recovery Study Group Meeting, of the Eastern District, API, Bradford, Pa. on December 9.

MALCOLM MCQUARRIE, associate professor of ceramic technology, presented a paper entitled, "Effect of Microstructure on the Dielectric Properties of Ceramics," at a meeting on ceramics held at the Massachusetts Institute of Technology, Cambridge, Massachusetts, December 2.

PAUL D. KRYNINE, professor of petrology and sedimentation, gave two lectures by invitation at the University of Texas, Austin, Texas: "Re-evaluation of Petroleum Geology" on November 25 and "The Structure of Science" on November 26.

D. R. Mitchell Is Named Acting Dean



D. R. Mitchell

D. R. MITCHELL, chairman of the Division of Mineral Engineering and senior member of the executive committee of the College of Mineral Industries, has been named Acting Dean during Dean Osborn's leave of absence. He has been on the faculty at Penn State since 1938.

Professor Mitchell was graduated with the bachelor of science degree in mining engineering in 1924 and the master of science degree in the same field in 1926, both from Penn State. He received the professional degree, engineer of mines, from the University of Illinois in 1930 where he was on the faculty until coming to Penn State. He has served in numerous capacities in the National Coal Association and the Coal Division of the A.I.M.E. and is a member of Sigma Xi.

THE PENNSYLVANIA STATE UNIVERSITY ENROLLMENT — FALL 1957

College of Mineral Industries

	Freshmen	Sophomores	Juniors	Seniors	Graduate	Total
Geology and Mineralogy	43	20	13	11	63	150
Geophysics						
and Geochemistry	14	7	11	9	38	79
Meteorology	11	10	12	39	19	91
Geography	1	3	10	8	17	39
Mineral Economics	6	0	4	5	9	24
Mining	17	6	6	4	6	39
Mineral Preparation	2	3	3	2	10	20
Petroleum and						
Natural Gas	32	11	16	18	16	93
Fuel Technology	23	16	1	1	36	77
Metallurgy	85	38	22	28	15	188
Ceramic Technology	17	14	9	9	14	63
Special	8
Total	251	128	107	134	243	871

Note: These figures represent the count by departments made in December by the Dean's Office and include 25 students enrolled at Penn State Centers. They differ slightly from the official figures compiled by the Registrar's Office early in the fall.

State Coal Research Board Visits the College of Mineral Industries

The State Coal Research Board met on the campus November 25 at the invitation of Dean E. F. Osborn, to consider the progress of state-financed coal research in the Commonwealth. The group picture shows members of

the Board, which administers \$525,000 recently appropriated by the State Legislature for coal research, and their guests.



Left to right: First row, August Lippi, District No. 1 President; Martin Brennen, District No. 7 President; and Joseph Kershetsky, District No. 9 President — all of the United Mine Workers of America; Mrs. Mazie Gutschall, Secretary to Mr. Kennedy and Administrative Officer with Coal Research Board; Joseph T. Kennedy, Secretary of the State Department of Mines and Mineral Industries; Francis O. Case, President of Glen-Alden Corp.; R. G. Pfahler, Consultant for Berwind-White Coal Co.

Second row, William Gillespie, Pierce Management, Inc.; George J. Clark, President, Reading Anthracite Co.; Frank W. Earnest, Jr., President of Anthracite Institute; John Connell, President, Connell Coal Co.; D. B. Millward, Mine Inspector, State Department of Mines and Mineral Industries; D. R. Mitchell, Chairman, Division of Mineral Engineering; E. F. Osborn, Dean, College of Mineral Industries.

Third row, J. D. Ridge, Assistant Dean, College of Mineral Industries, and Head, Department of Mineral Economics; H. L. Hartman, Head, Department of Mining; Ralph Lambert, Mining Engineer for Department of Mines and Mineral Industries; Gerald L. Barthauer, Pittsburgh Consolidation Coal Co.; John Seddon, Secretary-Treasurer of District No. 3, United Mine Workers of America.

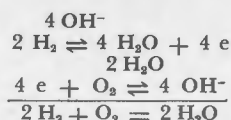
Fourth Row, O. F. Tuttle, Chairman, Division of Earth Sciences; P. L. Walker, Head, Department of Fuel Technology; and William Spackman, Director of Coal Research Section.

cells. This illustrates that one of the major problems in research on fuel cells is to obtain suitable rates of reaction at the electrodes at as low a temperature as possible.

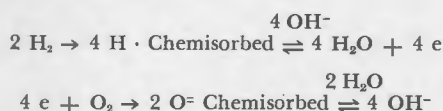
CURRENT RESEARCH

Of the three general types of fuel cells described (direct cells, fuel gas cells, and redox cells), the fuel gas cell appears to be most suited for present commercial development. For this reason, much of the current research has been conducted on cells of this type. Basic problems in developing a practical fuel gas cell are: (1) to achieve potentials approaching the theoretical potential for the cell reactions, (2) to obtain high rates of reaction to give suitable current densities at low temperatures, and (3) to design electrodes to give a high ratio of current density per unit cell volume. The main approach to these problems is through improvements in electrode catalysts and surface characteristics and in proper design of the electrodes themselves.

Research conducted in the Department of Fuel Technology has contributed to the development of a practical fuel cell through fundamental studies of the catalysts of electrode reactions⁶ and of electrode construction. The cell potentials calculated from thermodynamic data apply only to reversible reactions. For the oxidation of hydrogen in a reversible fuel cell the standard state potential would be 1.23 volts at 25°C for the half-cell reactions:



However, the reactions given above are not reversible in the thermodynamic sense for practical fuel cells. In a fuel cell the gases (hydrogen and oxygen in the above illustration) are chemisorbed on the surface of the catalysts at their respective electrodes. The equations for the electrode reactions therefore should be written as follows:



These equations imply that the equilibrium reaction which is associated with the potential of the cell is actually the equilibrium between the chemisorbed gases and the electrolyte and not between the free gases and the electrolyte. The above consideration leads to two important conclusions. First, the potential of a given cell will depend on the manner in which the gases are chemisorbed (i. e., on their energy state when chemisorbed), the theoretical potential being approached when the energy of the chemisorbed gas is nearly that of the free gas. Second, the capacity of the cell to supply electrons under current drain will also depend on the nature of the chemisorbed gases and how rapidly they can be desorbed and react with the electrolyte. Thus, for both open circuit potentials and for high reaction rates, the electrode catalysts play an important role.

An example of the use of catalysts shows their enormous influence on fuel cell characteristics: If the fuel cell illustrated in Figure 1 is operated with only the porous

graphite electrodes, an open circuit potential of about 0.1 volt is developed, and the potential rapidly falls to an immeasurably low value under current drain. When the porous graphite electrode on the hydrogen side of the cell is impregnated with palladium (extremely small amounts are adequate), the open circuit potential increases to about 0.8 volt. The potential at a current density of 30 amperes per square meter of actual electrode area is about 0.6 volt (the true surface area of an electrode may be several times the apparent or geometric area.) Now if in addition the electrode on the oxygen side of the cell is impregnated with silver-silver oxide, the open circuit potential increases further to 1.15 volts, a value very close to the theoretical value of 1.23 volts, and the potential under current drain is again greatly enhanced.

A commercial cell with components similar to those of the cell illustrated in Figure 1 has been developed by the National Carbon Company.⁴ This cell apparently was designed to supply electrical energy for electronic circuits and is finding application in such military devices as small radar units.

A high pressure fuel cell which also uses hydrogen as a fuel and which gives excellent current drain characteristics is being investigated by Bacon⁷ at Cambridge University. This cell employs an aqueous electrolyte and operates at a temperature of about 250°C with pressures up to 800 psi. The high pressures are necessary because the vapor pressure of the electrolyte solution rises markedly at the higher temperatures. The open circuit potential of the cell is 1.05 volts, and current densities of 151 amperes per square foot of apparent electrode area at a potential of 0.9 volt can be developed. Although the Bacon cell represents one of the more promising cells being studied, there are still some obstacles to be overcome. As far as has been reported, no attempt has been made to use impure hydrogen as a fuel (for example hydrogen obtained from the gasification of coal), nor have there been any results on the long-term performance of such cells.

A high temperature cell being investigated by the Pittsburgh Consolidation Coal Company represents another approach to the development of fuel gas cells. This cell operates at temperatures of the order of 400°C to 800°C, using molten salts as electrolytes and such fuel gases as carbon monoxide and methane. Very good current drain characteristics are obtained in these cells since high reaction rates are obtained at the higher temperatures. However, they suffer from a loss in efficiency due to heat losses and the lower potentials found at higher temperatures. Cells of this type offer one method for the direct use of light hydrocarbons. The hydrocarbons can be cracked directly in the cell to hydrogen and carbon, and the carbon removed by including a small amount of carbon dioxide in the fuel gas stream.

FUEL SOURCES

The fuel source for fuel gas cells should logically depend on the type of cell used, the availability and cost of various fuel gases, and the electrical power requirements of the application. For example, in low power output cells providing electrical energy for such applications as portable electronic equipment, hydrogen would probably be the ideal fuel gas. Hydrogen for this purpose could be ob-

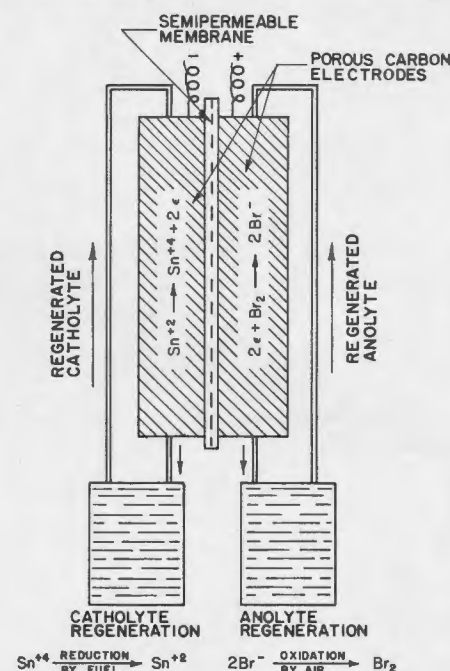


Figure 3. Redox Fuel Cell.

tained from metal hydrides; lithium hydride would be a good choice. A little over eight grams of lithium hydride will produce one cubic foot of hydrogen—enough fuel to supply 54 watt-hours of electrical energy. Of course, the use of lithium hydride as a fuel supply would not be practical for large power requirements.

In order to realize the advantages of fuel cells for large-scale applications in a given area, the fuel costs should not greatly exceed those of fuels that would be used in heat engines. At present the fuel gases that can be used most effectively in fuel gas cells are hydrogen and carbon monoxide. Thus, the cost and availability of these fuel gases will determine the feasibility of large-scale application of the fuel cell for electric power generation in a given area.

Underground gasification of coal is a potential means for recovering coal reserves that

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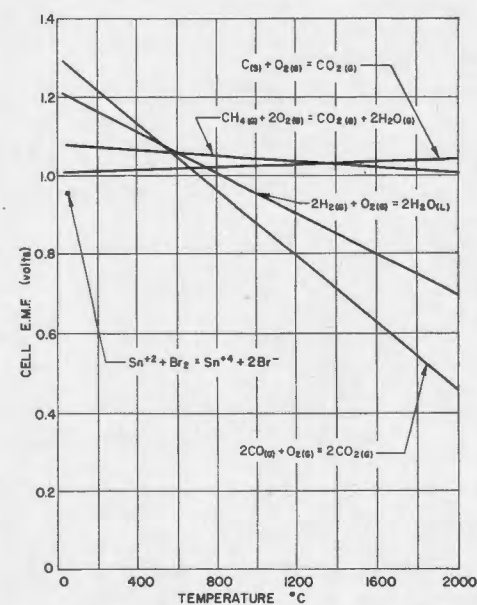


Figure 4. Fuel Cell Voltages as a Function of Temperature for Various Fuel Gas Reactions.

⁶ Young, G. J. and Knapp, E. C. "Heterogeneous Catalysis at Fuel Cell Electrodes," Symposium on the Defect Solid State, Alfred University Publication, 1957.

⁷ Bacon, F. T., British Patent 667, 298 (1952).

FUEL CELLS - Potential Source of Electrical Energy —

(Continued from page 1)

the electrolyte is aqueous sodium hydroxide, and the hydroxyl ions are the mobile species which serve to transport the oxidizing agent to the fuel electrode.

Since our fossil fuels are predominantly carbonaceous in nature, a cell in which carbon is used directly as the fuel electrode would appear advantageous. For example, in such a cell coal could be used as the anode where it would be oxidized to carbon dioxide in the half-cell reaction. Cells of this type have been constructed¹, and a schematic representation of such a cell is shown in Figure 2. In this cell the half-cell reactions ideally are:

$$C + 2 O^- \text{ electrolyte} = CO_2 + \text{electrolyte} + 4 e^-$$

$$4 e^- + O_2 + \text{electrolyte} = 2 O^- \text{ electrolyte}$$

$$C + O_2 = CO_2$$

Unfortunately fuel cells utilizing carbon directly as the anode have several disadvantages. The oxidation of the carbon by the electrolyte species proceeds only at a negligible rate at room temperature. Thus, to obtain a reaction rate sufficient to permit reasonable current drain, the cell must be operated at high temperatures (around 1000°C). Operation of a fuel cell at temperatures greater than the temperature of its surroundings results in heat losses, which represent a loss in efficiency. In addition, at temperatures where a high reaction rate is obtained, much of the fuel electrode would be consumed by carbon dioxide (the product of the electrode reaction) through the reaction:



This represents an additional loss in efficiency of fuel utilization since the latter reaction does not contribute to the electrical energy of the cell. These limitations on the efficiency of cells directly employing solid carbonaceous fuels added to the difficulties encountered in high temperature operations make the direct



George J. Young

type of cell unattractive for commercial development.

An alternative to the direct use of solid fuels is to use fuel gases—such as hydrogen, carbon monoxide, or hydrocarbons—obtained either from the gasification of coal with steam or by reforming oil or natural gas. In a cell using a gas as fuel, oxidation of the gas must take place on the surface of a conductor since the gas itself cannot form a conducting electrode. Oxidation of fuel gases by the electrolyte species can usually be achieved at moderate temperatures by the use of proper catalysts, and in most cases no side reactions occur. Thus by employing fuel gases in a galvanic cell, the limitations imposed when using solid carbonaceous fuels directly are avoided. In the fuel gas cell shown in Figure 1, the gases, hydrogen and air, diffuse into the porous graphite electrodes which are impregnated with catalysts. The gases react on the surface of the catalysts with the electrolyte species according to the half-cell reactions shown. The graphite electrodes serve as conductors of the electrons flowing in the circuit. A slight positive gas pressure prevents the electrolyte from flooding the electrodes. Several variations of hydrogen fuel cells have been developed^{2,3,4} employing aqueous electrolytes and temperatures from 25°C to 250°C with pressures up to 800 psi.

Another approach to design of cells using gaseous fuels has been to employ molten salts as electrolytes and cell temperatures of 500°C to 800°C. The loss in efficiency and operational difficulties encountered at higher temperatures are partially offset by faster reaction rates and more favorable current characteristics. Also, gaseous hydrocarbons can be cracked directly in the cell and then electrochemically oxidized.

A third type of fuel cell has been proposed⁵ which makes indirect use of the fuel as a reducing agent. This type of cell, usually referred to as a redox cell, is illustrated in Figure 3. The electrolyte solutions, which are separated by a membrane impermeable to the

active ions, contain ions that undergo oxidation and reduction in the cell. The electrolyte solutions are regenerated by using carbonaceous fuel for reduction and air for oxidation. While there are no thermodynamic restrictions on the efficiency of this type of cell, in practice the regeneration of the electrolyte solutions offer many difficulties. Various metal ions in addition to the stannic ion (used for illustration in Figure 3) can be reduced by coal in acid solution by autoclaving at moderate temperatures (circa 200°C). However, complete reduction is not obtained in reasonable periods of time, and the activity of the coal in effecting reduction is varied and unpredictable. The autoxidation of the bromide ion in acid solution by air proceeds satisfactorily when catalyzed by nitrogen peroxide.

THERMODYNAMICS

Under thermodynamically reversible conditions the theoretical potential developed by a galvanic cell, \mathcal{E} is given by the equation,

$$\Delta F = -n \mathcal{E}$$

where ΔF is the difference in free energy between the products and reactants in their standard states, n is the number of electrons involved on a molecular basis, and \mathcal{F} is the Faraday Constant. The change in free energy, and hence the potential of the cell, can be determined at any other temperature if the enthalpy of the reaction and heat capacities of the products and reactants are known. Since these data are commonly available, the theoretical potential of a cell can be calculated as a function of temperature for various fuels. In Figure 4 the results of such calculations are shown in a graph where the cell potential in volts is plotted against temperature. Typical reactions for the three types of cells described have been selected.

The potential expected from a single fuel cell is shown in Figure 4 to be of the order of 1 volt depending on the fuel oxidized and the temperature. Of course, higher voltages can be obtained by putting a number of cells in series. Figure 4 also indicates that to obtain maximum possible voltage a cell should be operated at as low a temperature as possible. Thus, if the electrode reactions were adequately fast at low temperatures, there would be no reason to use high temperature

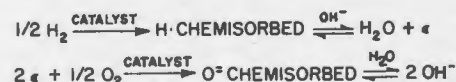
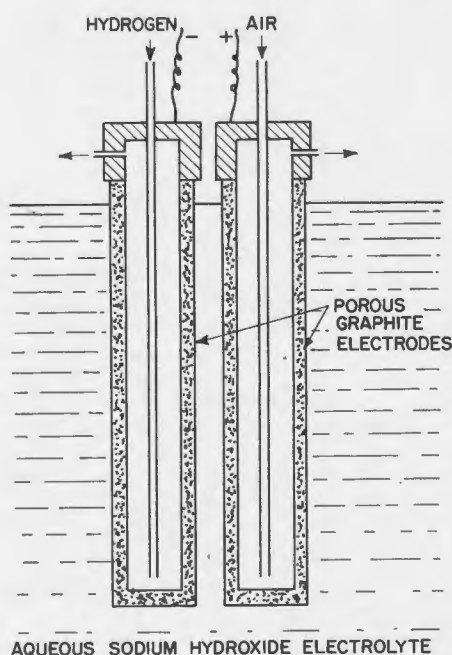


Figure 1. Schematic Drawing of a Fuel Gas Cell.

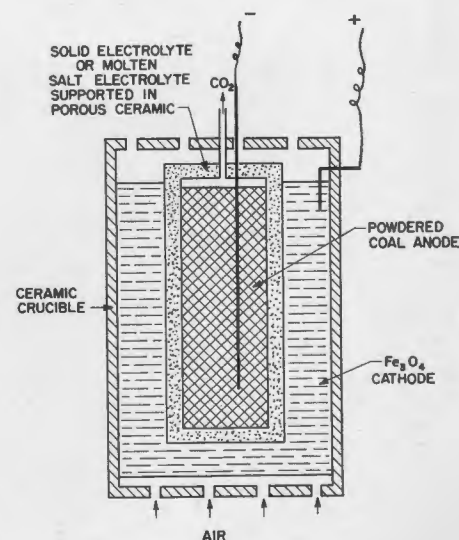


Figure 2. Direct Fuel Cell.

² Davtyan, O. K., Moscow Academy of Sciences. 48 (1947).

³ Bacon, F. T., Beama J. 61, 6 (1954).

⁴ Chemical and Engineering News, 35, No. 38 Pg. 25 (1957).

⁵ Posner, A. M., Fuel. 34, 330 (1955).



Mineral Economics

The United States Pays for Its Lack of Mineral Policy

John D. Ridge*

The Current Situation

In the United States, at the present time, no one is satisfied with the position of mineral raw materials in the country's economy. The mining company, large or small, lives in a widely fluctuating series of cycles which run the gamut from boom to bust over a few years. The worker in the industry lives in the same economic climate; he experiences enough prosperity to become accustomed to it and then finds himself out of a job in a one-industry community, usually at some distance from any other source of employment. The buyer of mineral raw materials is no better off. He passes from a period of high prices and short supply into one of huge surpluses and falling prices so quickly as to be unable to order his raw materials or price his product with any confidence. The foreign mining company which sells its product in this country can be reasonably sure of a warm welcome during days of short supply when it is encouraged to expand its productive capacity (generally aided by U.S.-furnished loans) to meet American demand. No sooner has the foreign company done this than it finds demand for its product has dropped and U.S. mining firms pleading with the Federal government to raise tariffs to keep competitors from selling in this country. The incentive to a sound exploration program provided by the depletion allowance given mining companies is attacked as unequal tax relief by those who do not realize that, if it were not given, the price of mineral raw materials would have to rise or exploration would have to be curtailed. Inefficiency and waste are charged against the mining industry by those who do not give sufficient weight to the short-range problems which often prevent mining companies from taking the broad view of their operations which true conservation requires. Thus far, the Federal government has done very little to provide a sound and effective mineral policy for the country and its short term attempts to build up domestic production through exploration, assistance, loans, bonus payments, and fast write-offs of expansion costs have resulted in the present over-supply (domestic production plus imports) of many mineral materials. The Federal government's initial solution to this problem (stockpiling excess domestic production) temporarily alleviated the situation, but in the long run compounded the severity of the present crisis. The current proposal of raising tariffs against foreign imports does not, as will be shown, offer any sounder basis of dealing with the problem.

U. S. Mineral Program in World War II

In the mineral raw materials field during World War II the government did as much as could have been expected from an organization with essentially no experience in the

problem of stimulating and controlling the finding, producing, and allocating of minerals. Despite the hodge-podge of controlling agencies with their often vague and overlapping authorities, this country met practically all its World War II mineral needs. The government, when faced with a crisis in mineral administration, usually created a new agency or transferred control of some phase of mineral activity from one agency to another. For example, in February 1943, the Board of Economic Warfare took over from the Reconstruction Finance Corporation "the authority and functions of the four subsidiary companies of the RFC . . . as they pertained to imported materials, with exception of their responsibilities relating to the corporate execution of imported materials contracts, the disbursement of funds thereunder, the necessary accounting with respect to such disbursements, and the acceptance of delivery of commodities and materials." In July of 1943, however, the Office of Economic Warfare was established, and to it were transferred all of the functions of the former Board of Economic Warfare and those of the United States Commercial Company, the Rubber Development Corporation, Petroleum Reserves Corporation, and the Export-Import Bank, with the functions and responsibilities of the RFC that were directed toward foreign production and procurement activities. Only a little over two months later, the Foreign Economic Administration was organized as a consolidation of the former office of Lend-Lease Administration, Office of Foreign Relief and Rehabilitation Operations, Office of Economic Warfare (including all of its previously acquired agencies), and that part of the office of Foreign Economic Coordination (of the State Department) which had been responsible in part for government-to-government negotiations. The Foreign Economic Administration, however, had no control over domestic mineral activities; these were in the hands of the War Production Board, the Petroleum Administration for War, Coal Mines Administration, and Office of Price Administration. In addition to these agencies, the Geological Survey and the Bureau of Mines had definite mineral procurement responsibilities, mainly in the areas of mineral exploration.

This group of agencies was able to continue without change in organization until the end of the war, with the exception that the Metals Reserve Company, the Defense Plant Corporation, and the Defense Supplies Corporation (which had in large part been transferred to the Board of Economic Warfare in February 1943) were returned to the RFC on July 1, 1945. There were, however, numerous changes in personnel brought about mainly by disgust with the difficulty of determining who had the right to do what about which.

All this confusion of organization, notwithstanding, enough mineral raw materials of

the right kinds were assembled in pretty much the right places at the right times. This was done, however, only at a much greater cost in dollars to the country and at much greater damage to our mining industry than would have been necessary had a sound and well-thought-out plan been ready for implementation at the beginning of the war. The damage to the industry was mainly in mining without carrying out concomitant exploration, both within operating mines and in new territory. Known ore was mined without attempts made to replace it, and, in certain instances, mines were abandoned as mined out without sufficient study having been made of the situation to rule out the possibility of the existence of further mineable extensions. Through the premium price plan, the government, on the other hand, penalized the efficient and conscientious mining company and put a premium on mining marginal ore which yielded a smaller tonnage of usable material than would have been attained by equal effort concentrated on ore of normally profitable grade. Of course, extracting this marginal ore well may have raised the total mineral recovery in some districts. At prices that prevailed after the war (once ceilings were lifted), however, most of the marginal ore mined at such expense during the war would have been much more legitimately mineable after November 1946.

U. S. Mineral Program in the Korean War

Experience in World War II should have alerted the Federal government to the dangers of facing the future without a mineral policy; but, except for the beginning of the stockpiling of certain strategic mineral raw materials, the country entered the Korean War with no more of a mineral policy than it had before World War II. The setting of the Korean conflict, however, was appreciably different from that which obtained nine or ten years previously. Instead of being cut off from, or seriously limited in our access to, foreign sources of mineral raw materials, this nation was able to import almost all the mineral commodities needed to make up the difference between domestic production and consumption. The authorities, nevertheless, proceeded on the theory that the country must reach as near domestic self-sufficiency as the utmost stretching of our mineral resources would permit. No one could quarrel with the encouragement of exploration in this country. But, in addition, many methods of promoting the opening of new mines were enacted into law which later contributed heavily to the present over-supply. It should again be emphasized that this over-supply exists only on a world-wide basis (we still are far from being able to meet all our mineral needs from domestic production) and only in this present time (in not too many decades consumption will solve the over-supply problem permanently).

The Defense Production Act of September 1950 was designed, among other things, to provide for assistance in mineral exploration through subsidies, advances, accelerated tax amortization, government loans, loan guarantees, firm or conditional contracts to procure mineral raw materials from the additional production generated, and access roads. As long as the company involved was American, DPA assistance could be granted for work on properties either at home or abroad. To implement this portion of the act, authority was delegated from the Defense Production Administration in the Commerce Department

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to the Defense Minerals Administration in the Interior Department to develop programs for exploration and production of minerals other than fuels and to make recommendations to the DPA for amortization acceleration for tax purposes. In addition to the DMA, the Petroleum Administration for Defense and the Defense Solid Fuels Administration were also organized with similar functions in their fields of responsibility.

In August 1951, DMA was succeeded by the Defense Materials Procurement Agency which, under the administration of the General Service Administrator, took over the authority of the Secretary of the Interior for emergency mineral assistance. Some two weeks later, however, the Administrator delegated back to Interior the exploration assistance responsibilities and budgets which were of a long-run rather than an emergency nature. The Secretary of the Interior then organized the Defense Minerals Exploration Administration which obtained its personnel mainly by transfer from the DMA's Production Expansion Division. The GSA, under orders from the Budget Bureau, took in most of the DMA personnel shortly thereafter, as well as minerals people from the Economic Cooperation Administration which itself had committed some \$110 million over-all for prospecting, developing, and expanding production of strategic minerals in areas considered under ECA supervision.

The DMPA then carried out, with aid from the GSA, work formerly done by the DMA with the exception of exploration responsibilities assigned to the DMEA. This meant DMPA's final purpose was to recommend domestic and foreign mineral expansion programs to the DPA where the right of final approval lay. With this concentration of government thought and action on increasing current mineral production, it is not surprising, that no long-range mineral policy came out of the Korean War nor that the country was over committed in the support of new production soon to come on the market.

The net result of the government's Korean War activities was to put into production nearly every deposit of mineral raw materials in this country that could be brought to that state by any type or types of inducement authorized by law. Huge sums of money were invested by public and private capital in properties which could operate profitably only at tremendous production. As soon as peace permitted supply to catch up with demand this situation would add heavily to the pressure on the price structure. At the time these operations were being put into production, however, there was no sign that the government (or private industry for that matter) expected that prices of mineral raw materials would drop by any appreciable extent in the foreseeable (or better unforeseeable) future.

At the same time that the Federal government was attempting to increase mineral production in this country, other branches (or in some instances even the same branches) of the government were striving, through the several agencies mentioned and others and by a variety of methods, to make certain that this country would receive ever-growing mineral imports. Little effort was expended to make certain that these increases would come from areas which would be least likely to be cut off in time of war, and less effort was used to insure that such increased production had a sound economic base.

The Paley Report

The chaos engendered by the country's lack of a mineral policy before the Korean War was apparent to the administration in Washington. In January 1951, therefore, the President set up the President's Materials Policy Committee and instructed it to study the materials problem in the U. S. and its relation to the free and friendly nations of the world. The committee's five-volume, final report in June of 1952, presented much information basic to the formulating of a mineral policy on the history of mineral raw material use, the resources available here and abroad, future demand in the U. S. and in other countries, the technological tasks to be carried out in the minerals field, and a considerable number of special reports on subjects which did not fit directly into the main topics. The Paley report (so-called after the committee chairman) had a mixed reaction from interested groups here and abroad, with many mining companies in the United States believing that it put too much emphasis on foreign sources of supply. The Paley report did not, in any sense, establish a mineral policy for the United States, and little use has been made of the material which it presented.

U. S. Mineral Program Since the Korean War

In the fall of 1953, after the active fighting in Korea had stopped, the new administration met the problem of our lack of a mineral policy by the President's naming a cabinet committee to inquire into national policies affecting the production and utilization of metals and minerals. This certainly was a step in the direction of a mineral policy, but the report of the committee, published some 13 months later (November 30, 1954), contributed little to the solution of the problem and provided much less material basic to future planning than did the Paley report. The main recommendations were: (1) that the strategic stockpile objectives be critically reviewed and that additional purchases be made beyond the long-term stockpile goals to bolster the market for certain metals, (2) that sufficient domestic production be maintained to provide a base for a future mobilization effort, (3) that the supply situation for each metal and mineral be evaluated periodically to establish the proper level of domestic production, (4) that full mobilization planning be assured through inter-agency cooperation, and (5) that optimum economic development of domestic mineral resources be encouraged. The only recommendation actually implemented was the first one, and the net result of stockpiling done because of it was to put off for a few years the crisis in zinc and lead mining. The crisis is now with us and is even worse than it would have been had it not been so delayed.

Because we have had no real mineral policy and have none now, we have reached the stage at which we must admit that we can neither provide for our mineral needs from within our own borders nor correctly balance our mineral deficit with imports. This country's production, plus what is being offered for sale here from abroad, is far more than we can consume except in years of war or industrial boom. Much of the foreign material must be sold here if the countries concerned are to avoid economic disturbance or disaster. Worse still, the countries that would be most affected by a tariff-generated reduction in U. S. imports are countries which would most like to be friends to us and to

which we have given the most reason to suppose we would be friends in bad times as well as good. Despite our dependence on, and obligations to, these countries, the only solution that the Federal government has proposed for raising the domestic prices of those mineral commodities which are in greatest oversupply is to increase tariffs on them.

A Current, Specific Mineral Problem

As an example of a specific difficulty into which our lack of a mineral policy has pushed this country, the present agitation for protection for domestic lead and zinc mining will serve. In November, the U. S. Tariff Commission began hearings on changing (i. e., increasing) the tariff rates on imported lead and zinc. As President Eisenhower last summer promised to request the Commission to "expedite its consideration of the matter," that body is likely to produce some scheme of raising tariffs on these and perhaps on other metals such as copper. These increases are likely to approximate those requested by the executive branch from the last session of Congress. No bill to put these administration recommendations into effect was sent to the floor of either house, and nothing was, therefore, accomplished legislatively. This forced the President's appeal to the authority of the Tariff Commission to do the job.

It is not surprising that those nations which have been exporting these metals to the United States should be concerned at the course of events. All will suffer reduced income no matter how small the tariff increases may be; worse still, the increases will affect all countries supplying the U. S. to the same extent. Those least able to bear them well may be the ones we would most like to remain prosperous and from which we would be best able to continue to receive supplies no matter what political events might occur as a result of Soviet penetration of countries contiguous to the U.S.S.R. and its satellites. In short, such a tariff increase will go a long way toward reducing our ability to obtain from abroad what minerals we still need even in these times of reduced demand. In addition, through forcing us to obtain more of our needs at home, it will shorten the time until we must depend to a far greater extent than now on imports from abroad.

Has the U. S. Established a Mineral Policy by Default?

The implication is that the United States has established a mineral policy—a policy calling for an attempt to be as self-sufficient as possible for as long as possible followed by being forced to depend almost entirely on foreign sources of supply which well may, by then, have been alienated from us or put out of business by this country's tariff policy.

Both the administration in Washington and the Tariff Commission probably do not consider that they have adopted such a policy, and, consciously, neither has done so or intends to do so. Yet the result of raising tariffs is at least the first step in establishing the mineral policy which has just been summarized. And the most deadly aspect of this first step is that, once taken, it is almost impossible not to take more in the same direction. On the other hand, it is much more difficult later to undo what is now being done. Even repealing these new tariffs after a few years will not automatically remove the damage to our trade relations which has occurred.

(Continued on page 8)

Three Workshops for Management Groups of Coal Industry Held

A series of three workshops for management groups of the coal mining industry have recently been completed by The Pennsylvania State University. The Mineral Industries Extension Services and the Management Training Staff of General Extension collaborated in presenting one workshop for executive management last April; another in November for superintendents and general foremen; and a third, also in November, for first line supervision.

R. B. Hewes, professor of mineral industries extension, served as coordinator for the workshops which were held at the White Sulphur Springs Hotel, at Mann's Choice, Bedford County, Pa.

Lecturers for the program came from the Penn State Staff and from the coal industry in about equal numbers.

In the accompanying picture David H. Davis, vice-president and general manager of operations, Mathies Coal Co., leads a group discussion at the workshop. Seated around the table are: left to right: Louis C. Fyock (with back to camera), Johnstown Coal & Coke; Robert D. Lauder, Mathies Coal Company; W. P. Watson, Harmar Coal Company; Mr. Davis; David Page, Vest-Shannopin Coal — J. & L.; Edward Onuscheck, Emerald Coal and Coke Company; and George C. Price, Rochester & Pittsburgh Coal Co. Mr. Hewes is at the far right.



Fuel Cells

(Continued from page 5)

are economically marginal or submarginal for normal production. Underground gasification experiments have been conducted with some success in this country, in Russia, and in England. Unfortunately, the fuel gases obtained are of very low heating value, making their direct industrial use questionable. However, such gases could be used effectively in fuel cells. Thus, underground gasification of coal may provide one future source of fuel for fuel gas cells. Of course, gasification of coal can also be carried out in conventional gasifying units to provide fuel gases.⁸

Fuel cells can most easily provide low voltage direct current and thus would be ideal as a power supply for such electrometallurgical industries as an aluminum refining plant. An aluminum plant located in the southwest might find fuel cells operating on reformed natural gas an economical electric power source. Natural gas is relatively inexpensive in this area, costing approximately \$0.15 per thousand cubic feet. The natural gas could

operations, and efficient use of this excess hydrogen may at times constitute a problem. If the hydrogen were used as a fuel in fuel cells, sufficient electrical energy for the entire refinery could be produced.

Nuclear power plants may also provide an inexpensive source of fuel for fuel cells. A water-cooled nuclear reactor produces hydrogen and oxygen by the radiolysis of water. These gases can be separated by diffusion processes, taking advantage of the low molecular weight of the hydrogen. Operating fuel cells from the gases produced by radiolysis would provide a source of supplementary power to be used during peak loads.

PRESENT AND FUTURE APPLICATIONS

In many small-scale electric power applications, such as mobile electronic equipment or signal devices, the cost of the fuel for the power source is usually of secondary importance in comparison to reliability and long operating life. Batteries generally have been used for the power source in such applications. Fuel gas cells may offer some distinct advantages over conventional batteries for

markets that the National Carbon Company will attempt to develop for its commercial hydrogen fuel cell. The fuel source for these cells probably will be either a chemical which readily liberates hydrogen (perhaps lithium hydride as suggested) or small tanks of compressed hydrogen.

The use of fuel gas cells as large-scale electric power sources will depend primarily on the economics of the fuel gas supply. Several sources of fuel gas have been suggested that would enable a fuel cell installation to compete effectively with other large-scale electric power sources. In addition to being used for primary electrical energy requirements, fuel cells also may find application in power storage devices. For example, steam power plants (or nuclear power plants) must operate at overload during "peak hours" and at less than full capacity during "off hours." It would be more economical if the power plant could operate continuously at its optimum capacity. It has been suggested that power plants could use the excess electrical energy available during "off hours" to electrolyze water into hydrogen and oxygen. These gases could be stored and used in fuel cells for supplementary power during "peak hours." Thus, the power plant could operate at its optimum capacity at all times. Such energy storage devices should be particularly attractive for water-cooled nuclear power plants where hydrogen is produced by radiolysis.

Mineral Industries
January 1958

Mineral Policy

(Continued from page 7)

Either the mining industries of our favorite suppliers will have been put out of business or they will have found other markets which they will not be likely to desert for so uncertain a customer as the United States is proving to be.

Surely, rather than take so important a step as the setting up of a mineral policy by default, the administration should pause long enough to consider seriously whether it really wants to be bound almost irrevocably in the future by the results of tariff increases ostensibly made to tide the zinc and lead industries over a short period of lowered prices and constricted markets. The answer almost certainly is that the administration does not want to be so bound, but bound it will be unless drastic action is taken to change the course of the current on which it has been drifting for so long.

be reformed with steam to yield about 2000 cubic feet of hydrogen per thousand cubic feet of methane. A fuel cell power plant operating on natural gas in this manner could produce electrical energy (5 volts D.C. at 1000 amperes) for a fuel cost of approximately two to three mills per kilowatt-hour.

Another potential fuel source is to be found in the oil industry's refining plants. Considerable hydrogen is produced in the cracking

these uses. Storage batteries deteriorate when stored over long periods of time and, of course, have a limited operating life. Fuel cells, on the other hand, can be stored indefinitely, and their operating life is limited only by the fuel supply. These factors suggest that fuel cells could be used advantageously as power sources for such applications as military electronic devices⁹, railroad signal equipment, telephone relay stations, and stand-by power sources in hospitals and other service centers. These are probably the

⁸ Gorin, E., U.S. Pat. 2,570,543 and U. S. Pat. 2,581,650.