

The MIT/Marine Industry Collegium

Opportunity Brief

**POWER SYSTEMS FOR
SMALL UNDERWATER
VEHICLES**

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**October 5-6, 1988
Cambridge, Massachusetts**

A Project of the

MIT Sea Grant Program



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Editor and Production Coordinator: John Moore, Jr.

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Additional copies can be obtained from:

MIT Marine Industry Collegium
Building E38-308
292 Main Street
Cambridge, Massachusetts 02139

For workshop information, call Ms. Joan Corsaro (617)253-7092

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INTRODUCTION

The primary objective of the MIT Sea Grant Marine Industry Collegium (MIC) is to encourage that technology transfer occurs among academia, industry, and government agencies. We at MIC sponsor four to five workshops a year as our primary vehicle to ensure that technology transfer occurs. Historically, these workshops have focused on presenting current research and technological advances that are taking place at MIT and other academic institutions for marine industry to apply. Occasionally, the MIC has also incorporated industry presentations into a workshop to provide a broader perspective on a given topic. When developing the topic for this workshop, "Power Systems for Small Underwater Vehicles", initial thoughts were for a workshop that would have an even distribution of both academic and industry presentations. Further investigation lead to the conclusion that little research is presently being done in the Nation's academic institutions. Thus, the program agenda is comprised primarily of industry speakers who will give presentations on some of their latest developments in power systems and their applications to small underwater vehicles.

The product of this planning is a two-day workshop that will be held at C.S. Draper Laboratories in Cambridge. The speakers are derived from a broad background of power systems development. This broad perspective is in light of the fact that no one power system will solve the needs for all small underwater vehicles i.e. swimmers, autonomous, and remotely operated underwater vehicles (AUV/ROV). Traditionally, electrical storage batteries have been used almost exclusively to meet the energy needs of small underwater vehicles. Although these batteries are easy, relatively safe, and convenient to use, their size and weight severely limit the mission length for an underwater vehicle. New developments in power systems will enhance the designer's options to develop a vehicle to perform its mission be it; antisubmarine warfare, surveillance, pipeline inspection, cable laying or oceanographic data collection.

This workshop is intended to provide a broad perspective on recent developments in high density power systems and their potential applications to marine uses. A discussion session has also been incorporated into the agenda to bring together a panel of experts from marine industry and government agencies to openly discuss with attendees what the long-term future prospects are for high performance power systems.

*John Moore, Jr.
Manager
Marine Industry Collegium*

WORKSHOP AGENDA

POWER SYSTEMS FOR SMALL UNDERWATER VEHICLES

October 5

- 8:30 - 9:00 **REGISTRATION**
- 9:00 - 9:15 **Welcome, Brief Introduction**
John Moore, Jr., MIT Sea Grant
David Burke, C.S. Draper Labs
- 9:15 - 10:00 **Suitability of Silver-Zinc and Silver-Cadmium Batteries
to Underwater Vehicles**
David A. Harma, Whittaker-Yardney Power Systems
- 10:00 - 10:45 **Advanced Batteries for Electrically Powered
Underwater Vehicles**
Nicholas Shuster, Westinghouse Oceanic Systems
- 10:45 - 11:15 **BREAK**
- 11:15 - 12:00 **Pressure Compensated Batteries for Ocean Floor Applications**
Nikola Marincic, Battery Engineering, Inc.
- 12:00 - 1:15 **LUNCH**
- 1:15 - 2:00 **Hydrogen and Oxygen Fuel Cell Development**
Anthony B. LaConti, Giner, Inc.
- 2:00 - 2:45 **Artificial Gill Development for Underwater Power Sources**
Sam Mohanta, Aquanautics, Corp.
- 2:45 - 3:00 **BREAK**
- 3:00 - 3:45 **Aluminum-Air Battery Development for Underwater Use**
Marilyn J. Niksa, ELTECH Research, Corp.
- 7:00 - **DINNER**
- 8:00 - **Superconductivity: Fathoming Fact From Fiction**
Simon Foner, MIT Dept. of Physics

POWER SYSTEMS FOR SMALL UNDERWATER VEHICLES

October 6

- 8:00 - 8:30 **LATE REGISTRATION/REFRESHMENTS**
- 8:30 - 9:15 **Proton Exchange Membrane Fuel Cells**
Donald R. McVay, International Fuel Cells, Corp.
- 9:15 - 10:00 **Current Developments in Rechargeable Lithium Battery Systems**
Gerald L. Griffin, Jr., Altus, Corp.
- 10:00 - 10:30 **BREAK**
- 10:30 - 11:15 **Navy's Current Policies on Lithium Batteries**
James A. Barnes, Naval Surface Warfare Center
- 11:15 - 12:00 **PANEL DISCUSSION**

 Long-Term Future of High Performance Systems
Panel Members:
 Professor A. Douglas Carmichael - Chairman - MIT Dept. of Ocean Engineering
 Dick L. Bloomquist - David Taylor Research Center
 James R. McFarlane - International Submarine Engineering
 David S. Gorham - Lockheed
 Gabriel D. Roy - Office of Naval Research
- 12:00 - 1:15 **LUNCH**
- 1:15 - 2:00 **Thermochemical Heat Engine Power Systems for Underwater Applications**
Allen D. Harper, Allied-Signal, Corp.
- 2:00 - 2:45 **Application of the Stirling Engine for Underwater Vehicles**
William D. Ernst, Mechanical Technology, Inc.
- 2:45 - 3:30 **Experiences with Stirling Engines in Underwater Vehicles**
Mr. Herbert Nilsson, United Stirling AB

SYNOPSIS of PRESENTATIONS

OCTOBER 5

9:15

Suitability of Silver-Zinc & Silver-Cadmium Electrochemistries to Provide Electric Power for Undersea Systems

Mr. David A. Harma, Whittaker-Yardney Power Systems

This presentation presents the results of a study to ascertain the suitability of the silver-zinc and silver-cadmium electrochemistries to serve rechargeable power sources for undersea systems.

The performance characteristics of the silver-zinc and silver-cadmium systems are compared to those of the more widely used lead-acid and nickel-cadmium systems. Included, are such attributes as energy density, specific energy, power density, specific power, operating voltage, charge retention cycle life, and wet life. Such issues as availability of hardware, operating safety, adaptability of existing designs, environmental effects, pressure-compensated design considerations, and charging methods are also investigated. In addition, the general attributes of some of the other candidate high energy secondary systems are also detailed.

This presentation will reveal that both silver-zinc and silver-cadmium systems have special attributes that merit their use for many of these applications. They can provide superior energy and/or power yields, stable voltage performance, a respectable cycle life and wet life, excellent charge retention, a demonstrated record of reliability, and safety. Both systems are fully developed and cells are offered in a wide variety of pressure-compensated or non-compensated designs.

10:00

Advanced Batteries for Electrically Powered Underwater Vehicles

Mr. Nicholas Shuster, Westinghouse Oceanic Division

Electric propulsion systems have numerous benefits for unmanned, untethered submersibles. However, the low energy density and low specific energy of conventional batteries have made electric systems large and heavy.

Four advanced battery technologies, currently under development at Westinghouse, are substantially smaller and lighter than conventional batteries having equivalent power and energy capabilities.

Rechargeable high temperature lithium alloy-iron sulfide cells which demonstrate 2.5 to 3 times the specific energy of advanced lead-acid batteries have been built and tested. More than 500 deep discharge (100% DOD) cycles were obtained before cell failure. Physical and electrical abuse safety tests on this cell design resulted in no venting or other hazardous conditions. Battery systems of 7.2 kWh capacity (200 Ah at 36V) have been built and are being life cycle tested. Cells have achieved specific energies of 110 Wh/kg (220 Wh/liter) and battery systems, based on these cells, are predicted to achieve 85 Wh/kg (100 Wh/liter).

Lithium-oxygen primary batteries are being developed for long endurance (high total energy) applications where electrical recharge is not required. The lithium-oxygen battery consumes lithium metal and stored oxygen (pressurized gas or cryogenic liquid) to produce electrical power. The battery uses a flowing alkaline electrolyte to remove waste heat and reaction products. This battery system is projected to have a specific energy of over 3,000 Wh/kg of reactants.

Aluminum-silver oxide primary batteries (which also use a flowing electrolyte) have been developed for underwater propulsion systems which require high power as well as high specific energy. This seawater activated battery has application as an emergency or auxiliary power source on-board unmanned submersibles.

Magnesium-seawater primary battery chemistry has been developed for low power-long endurance applications where simplicity and low cost are important. The battery consumes magnesium alloy and dissolved oxygen from the seawater. The specific energy of magnesium consumed is expected to be 1500 to 2000 Wh/kg.

Battery characteristics, system features including auxiliary requirements and the current state of development for each of these technologies will be discussed.

11:15

Pressure Compensated Batteries for Ocean Floor Applications

Dr. Nikola Marincic, Battery Engineering, Inc.

Numerous inquiries have been addressed during the last 15 years, related to the application of high energy density lithium batteries under extreme pressure conditions on the ocean floor. The first study conducted by this author was mostly related to the problems of underwater propulsion in general, rather than to the problems of pressure compensation in particular. The work was presented at the Navy Underwater Propulsion Conference, The Presidio, San Francisco, 26-27 August, 1974. This study with small cells demonstrated the feasibility of an advanced light weight torpedo (ALWT), based on the lithium/oxyhalide electrochemical system.

The actual work on the electrode structure for ALWT was conducted through GTE Products Corporation (Subcontract No. CSD-C-79-1103) in 1979/1980. Full size single cells, 12 inches diameter, have been developed and evaluated with the idea of using this basic building block to construct a 200 lb-120 kW ALWT power source. This work was reported in the Navy by the prime contractor, GTE Products Corp. A study related to this work dealing with the design features of the lithium batteries for underwater propulsion, has been presented by this author at the Power Source Symposium, Atlantic City, NJ in 1982.

The design of a totally pressure independent battery has been proposed by this author on behalf of Battery Engineering, Inc. to the Ariadne Office, U.S. Navy, on January 23, 1986. The feasibility tests were conducted under the guidance of Dr. Hatland, Chief Scientist for Ariadne, using DD size cells made by Battery Engineering, Inc. Encouraged by the initial test data from Naval Oceans System Command, San Diego, scaled-up, rectangular, 100 Ah cell prototypes were built for testing by the Navy Crane (Indiana) test facilities. The initial test data, under 8700 psi pressure, were extremely instructive. Due to budgetary delays these tests were never concluded. A proposal for a second set of prototypes to be tested is being reviewed by the Navy as of this writing (July, 1988).

The basic idea behind this design is the elimination of all gaseous battery constituents and products of discharge, using virtually incompressible components and eliminating the need to resist external pressure. The entire battery housing or particularly designated sections became the pressure compensating elements of the complete battery structure.

Significant design difficulties arise in cases of extreme volume changes of active components during discharge. Earlier studies of discharge reaction mechanism for this electrochemical system clearly indicated a substantial volume reduction of active components during the course of discharge. A void is created inside the cell at the rate of 0.504 cc/Ah, causing the cell to collapse gradually, as the discharge proceeds. The challenge of the designer was to anticipate the distortion of cell housing and prevent its interference with the electrode structure.

Indications are that these high density lithium batteries will perform even better under the extreme pressure, than they do under atmospheric conditions. It has been observed that gaseous sulfur dioxide does form towards the end of discharge under ordinary atmospheric conditions. At pressures above 60 psi, at room temperature, sulfur dioxide remains a liquid and thereby would neither interfere with the discharge process nor allow the collapse of the battery system.

1:15

Hydrogen and Oxygen Fuel Cell Development

Dr. Anthony B. LaConti, Giner, Inc.

The hydrated proton exchange membrane (PEM) hydrogen/oxygen fuel cell has been successfully used as a power source for early NASA space missions and has recently received increased consideration for many sea, space and commercial applications.

The PEM fuel cell has many features that make it very attractive for space and sea applications namely; low weight, high energy density, small volume, good efficiency, long operational component life, fast startup/shutdown, insensitivity to CO_2 and the ability to withstand high differential pressures. Alkaline fuel cells are also competitive for many of these applications because of: 1) higher efficiency due to superior cathode performance and lower parasitic losses caused by hydrogen/oxygen permeation; 2) more tolerance to inadvertent combination of reactant gases; and 3) inherently lower materials cost. This paper reviews only the H_2/O_2 fuel cells based on the PEM.

Characteristics unique to the PEM fuel cells are that there is no liquid electrolyte to present problems of leakage, corrosion or electrolyte management. The electrolyte currently used in most high energy density devices is a perfluorocarbon sulfonic acid PEM sold by duPont under the trademark, Nafion. Recently there has also been some promising work conducted with an alternate experimental perfluorocarbon sulfonic acid membrane with Dow Chemical [1,2]. The PEM of about 4 to 8 mil (0.004-0.008 in) thickness (wet) serves as a rugged barrier between the hydrogen and oxygen reactant gases and allows fuel cell operation with up to 500 psi differential pressure when properly supported. As a strong acid (pH $\sim$ 0) It is insensitive to CO_2 and provides for facilitated proton transport when properly hydrated. Typically, thin electrode structures of high surface area noble metals and Teflon are pressed onto the surface of the membrane. For the fuel cell cathode, a wet-proofed structure is required to prevent product water films from obstructing the active sites. The current collector that makes electric contact with the cathode structure is generally designed to enhance collection and wicking of the product water away from the electrode surface for removal from the chamber and phase separation. Multi-cells are generally arranged in a bipolar series configuration with the bipolar element being a thin conductive sheet of an acid resistant material such as Ti, Nb, Zr or C [3]. Current collection occurs only at the two end cells [3].

Some of the other components and technologies common for a PEM fuel cell and stack are current collection, fluid distribution, manifolding, intercell sealing, intercell compression, stack sealing, water management and heat management.

Most of the pioneering work in PEM fuel cells was conducted by General Electric (GE). The technology was transferred with the sale of the business to United Technologies Corp., Hamilton Standards (UTC-HS) division in 1984. Both Engelhard [4] in the United States and Siemens in Germany (originally under GE license) were also actively involved in the development of PEM fuel cell technology and hardware. There were several basic patents [5,6] issued to GE in the late 1960's and 1970's that have recently expired, attracting new entries into the field. Some of these include Ballard Technologies, Ergenics Power System, Inc., Treadwell Corp., UTC International Fuel Cells, (UTC-IFC), Dow Chemical and several automotive companies.

Some of the key technology and hardware developments in the General Electric Programs with PEM's were 1) two 1kW modules for the NASA Gemini spacecraft, 2) a 350W fuel cell for a 40 day Biosatellite spacecraft (first use of Nafion membrane in hardware), 3) a 3kW power plant for a Navy High Altitude Balloon and 4) a packaged 4kW breadboard regenerative fuel cell for NASA evaluation for advanced space applications (Scaleup to 1.1 ft² active area cells). Engelhard was also instrumental in developing a series of low power devices of 5 to approximately 500W for telemetry and remote site applications [4]. Some notable recent hardware developments have been reported by Ergenics [7], Ballard Technologies [8] UTC-IFC [9] and UTC-HS [10]. Significant progress has been made in the water management, packaging and development of passive water separators.

Some of the major achievements that have advanced the technology for PEM H₂/O₂ fuel cells include: 1) demonstration by GE of a multicell fuel cell based on an early Nafion membrane to operate highly invariantly for 60,000 hours with minimal performance decay [11]; 2) development by GE of processes for increasing the state-of-the-art PEM power device performance to 800 W/f² @ 1000 A/ft² with Nafion membrane [11]; and 3) initial demonstration by Ballard of a single-cell laboratory stack that operated at 2000W/f² @4000 A/ft², using a thinner, higher conductivity Dow Chemical membrane [8]. For commercial H₂/air applications recent results by workers at Los Alamos National Laboratories have developed processes that could result in decreasing catalyst loadings from a total noble metal loading of approximately 8g/ft² for state-of-the-art PEM fuel cells to 1 g/ft² [12].

References

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2. Ezzell, W.P., Carl, W.P., and Mod, W.A., AIChE Symposium Series, 248, pp. 45, (1982).
3. LaConti, A.B., Fragala, A.R., and Boyack, J.R., Proceedings of the Symposium on Electrode Materials and Processes for Energy Storage, The Electrochemical Society, pp. 354, (1977).

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5. Niedrach, L.W., US Patents Nos. 3,297,485, (1967), and 3,432,355, (1969).
6. Maget, H.J.R., US Patent No. 3,489,670 (1970).
7. Rosso, M., "Fuel Cell Systems Suitable for Low Ambient Temperature Operations, Presented at The 33rd International Power Sources Symposium, Monmouth, N.J. (June 13, 1988).
8. Watkins, D.; "Canadian Solid Polymer Fuel Cell Development", Presented at The 33rd International Power Sources Symposium, Fort Monmouth, NJ, (June 13, 1988).
9. Meyers, A., "Proton Exchange Membrane Fuel Cells", Presented at The 33rd International Power Sources Symposium, Fort Monmouth, NJ June 13, 1988.
10. Leonida, A., "Hydrogen/Oxygen Fuel Cells with *In Situ* Product Water Removal", Presented at The 33rd International Power Sources Symposium, Fort Monmouth, NJ, June 13, 1988.
11. LaConti, A.B., Proceedings of Oronzio DeNora Symposium, Venice, Italy, pp. 94, (1979).
12. Sprinivasan, S., Ticianelli, E.A., Derouin, C.R., and Redondo, A., Proceedings of Space Electrochemical Research and Technology, NASA-Lewis Research Center, Cleveland, OH, pp. 197, (1987).

2:00

Artificial Gill Development for Underwater Power Sources

Dr. Sam Mohanta, Aquanautics, Corp.

Aquanautics Corporation has completed its fourth year under contract to the Defense Advanced Research Projects Agency (DARPA) to develop an artificial gill that extracts dissolved oxygen from seawater. This system may be useful for autonomous underwater vehicles (AUV) in conjunction with fuel cells. Aquanautics has developed a parametric computer model which designs AUVs with different power systems and oxygen sources. Each design may be compared to determine the most advantageous combination for a given vehicle mission. This presentation will detail some of the results of our research work to date.

Aquanautics has made substantial technical progress toward making this technology a reality. Three major technical issues, energy consumption, size/cost, and longevity, have prevented a system from working in a practical vehicle. The company has demonstrated retirement of the first two issues and is now focusing on the third issue. Concurrently, engineering issues are being addressed such as an optimum membrane gill design and antifouling considerations. Several gill-fuel cell hardware integrations have been completed in the laboratory. These will continue until the technology is fully developed.

Aquanaautics completed a survey of many of the companies in North America that are currently developing energy converters (fuel cells) in order to choose one for integration with the artificial gill. Upon completion of this survey, Aquanaautics chose to work with ELTECH Corporation of Cleveland who is developing an aluminum-air fuel cell for commercialization. This fuel cell was selected for its high energy output, and relative ease of operation, and safety.

An aluminum fuel cell can produce about 400 watts per minute with one liter of oxygen which compares with only 200 watts per minute for hydrogen. Lithium can produce up to 600 watts per minute but it is plagued with a Navy reputation for safety problems. Gould (now Westinghouse) is developing a lithium system that may address some of these present safety concerns.

The system diagram of the artificial gill - aluminum fuel cell integration is illustrated in figure 1.

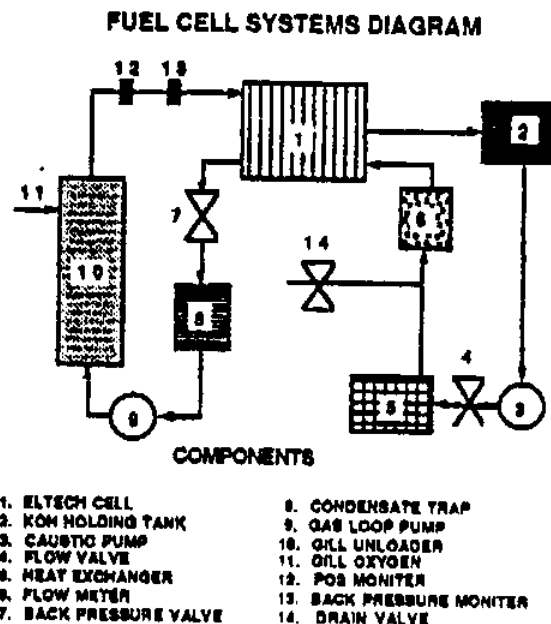


Figure 1: Artificial gill fuel system

The artificial gill oxygen extractor is connected to the aluminum-air fuel cell in a closed loop circuit. The exhaust gas from the fuel cell which contains about 0.1 atmospheres of oxygen is recirculated back to the gill unloader. The gill extracted oxygen is unloaded at about 0.32 atmospheres and is mixed with the exhaust gas to enrich it. The mixture is then fed back into the fuel cell for further combustion. This arrangement ensures maximum use of all available oxygen. Since the next presentation deals specifically with the details of the ELTECH aluminum-air system, this presentation will not repeat that description.

The important aspect of this system from an AUV viewpoint is the net power produced from such an arrangement. The gill operated at 0.5 cell volts and 9 amps to consume 4.5 watts of power. The fuel cell operated at 1.5 cell volts and 12 amps to produce 18 watts of power. Therefore, the net power produced from this integration was 13.5 watts or about 75% net output. The theoretical power ratio of the fuel cell to the gill is $410/102 = 4$. The actual performance of this small scale system was 4.0 to 4.2. The system operated in this configuration over a period of 3 days without deviating more than 10% from the original performance.

3:00

Aluminum-Air as a Fuel Cell

Ms. Marilyn J. Niksa, ELTECH Research Corp.

This presentation will discuss the development of the aluminum-air fuel cell at ELTECH Research Corporation. This development effort includes component research, cell design and systems research of electrolyte management and process controls. A comparison of several of the most common fuel cells with the aluminum fuel cell will also be given.

The aluminum-air system is in reality not a battery but a fuel cell. Metal-air (or oxygen) fuel cell electrochemically couple a reactive anode to an air cathode. The theoretical capacity of these systems is very high and is usually dictated by the choice of anode materials. Several primary and secondary metal/air systems have been explored notably iron/air, zinc/air, aluminum/air, and lithium/air. The latter two are deemed "mechanically rechargeable" in that the anodes cannot be electrochemically regenerated. The cell is returned to a full charge by replacement of metal anodes, removal of the discharge product, and addition of water. A major advantage of the "mechanical recharge" is that the cell can be replenished in a short period of time. In addition, with the aluminum/air fuel cell, the fuels aluminum and water are easily and safely stored.

The metal/air system has several major advantages over a hydrogen/oxygen fuel cell: oxygen efficiency is greater and the metal fuel is a compact source of power that is easily and in most cases (with exception of lithium) safely stored.

A comparison of the systems is shown below:

Metal	Ah/g	Theoretical Cell Voltage	Theoretical Specific Energy (Wh/g)	Typical Operating Voltage
Li	3.86	3.4	13	2.4
<u>Al</u>	<u>2.98</u>	<u>2.7</u>	<u>8.2</u>	<u>1.5</u>
Zn	0.82	1.6	1.3	1.0
Fe	0.96	1.3	1.2	0.7

The oxygen efficiency is generally improved over the H_2/O_2 system as well due to the more energetic nature of the metal:

System	Watts/ LPM O_2
H_2/O_2	180
Li/ O_2	568
<u>Al/O_2</u>	<u>375</u>
Zn/ O_2	232
Fe/ O_2	162

The actual operating current density of each of these systems varies depending on the polarization characteristics of the metal anode.

Metal refuel plates can be stored in a smaller space than an equivalent number of Wh of hydrogen:

Fuel	Wh/g (actual)	Wh/cm ³
Lithium	9.26	4.94
<u>Aluminum</u>	<u>4.2</u>	<u>12.96</u>
Zinc	0.82	5.8
Iron	0.96	5.25
Hydrogen:		
As FeTi	0.217	0.844 (1)
2000 psi	0.168	0.233 (1)

As it can be seen, the aluminum-air system is second only to lithium in power and energy yields. Aluminum metal has, by far, the highest volumetric energy yield and is also a safe, compact, fuel source that is easy to store and employ. These characteristics of the aluminum-air system demonstrate the strong potential for their deployment in underwater vehicles.

Reference

1. Sandrock, G., and Huston, E.L., "How Metals Store Hydrogen", Chemtech, 1981 pp. 754-762.

OCTOBER 6

8:30

Proton Exchange Membrane Fuel Cells, *Mr. Don McVay, International Fuel Cells*

The proton exchange membrane (PEM) fuel cell has intrinsic characteristics which give it a unique potential for simplified power plant designs relative to those of other fuel cell technologies. Simplified power plant designs can provide reduced power plant capital and operating costs as well as improved reliability, weight, and volume. International Fuel Cells is combining this unique potential with the graphitic materials it has developed and manufactured under its commercial fuel cell programs to produce a simple, no moving parts, passive heat and water removal subsystem powerplant for aerospace, undersea, and other applications.

For undersea applications, International Fuel Cells is studying integration of this PEM power plant concept with a variety of different stored fuel cells and oxidants. The future development and employment of these power system concepts will permit tailoring the complete system to specific mission requirements. A discussion of various fuel options and their affect on range and operability will be presented. In addition, a description of International Fuel Cell's power plant concept and testing program will be given.

9:15

Current Developments in Rechargeable Lithium Battery Systems *Mr. Gerald L. Griffin, Jr., Altus, Corp.*

This presentation will first describe presently available primary lithium thionyl chloride large size cells and their suitability in power systems for small underwater vehicles.

Under demonstration and test programs both 2,000 Ah, 17 inch diameter cylindrical cells and 10,000 Ah prismatic cells have been qualified for missile silo ground power batteries by the U.S. Air Force. The 10,000 AH lithium battery, the Minuteman Extended Survival Power (MESP) source, is currently being delivered by Altus under a multi-year production contract. These battery cells have demonstrated sustained and pulse power surge capability, altitude and pressure insensitivity, and safety under abuse conditions. They provide energy densities of 200 watt-power per pound and 16 watt-hours per cubic inch in a rugged, hermetically sealed case.

Following this, current performance of rechargeable hermetically sealed lithium-copper (II) chloride AA, D size, and larger (12" X 12") demountable cells will be presented. This system, recently developed by Altus as a high voltage (3.4 volts per cell) high energy replacement for commercial nickel-cadmium cells, has achieved a 200 cycle life with full safety in multi-cell battery configurations. The cells maintain 3.3 volts at 0°C temperature at a C/10 rate of discharge.

Finally, scale-up to 1,000 Ah size rechargeable cells offers a near-term, affordable, and safe high energy rechargeable battery building block. Power requirements, mission length, and packaging form factor can be then used to design the appropriate rechargeable battery for a particular untethered underwater vehicle application.

10:30

The Navy's Current Policies on Lithium Batteries

Dr. James A. Barnes, Naval Systems Warfare Center

Mr. Patrick B. Davis, Naval Systems Warfare Center

Lithium batteries offer many advantages for Navy Systems, but they may also exhibit undesirable hazardous behavior. Safety problems with lithium batteries have been traced to a variety of chemical and physical causes. The Navy has established a central point of contact with responsibility for the safety review of all proposed lithium battery use. Before an item is approved for use by the Navy, it must pass both a design review and a set of end-item tests. These reviews focus on the complete systems composed of a battery inside the end-item. After system approval, specific regulations that govern the transportation, storage, and disposal of the unit containing the lithium batteries are developed. This presentation will discuss each of these areas with particular emphasis placed on those changes in policies and procedures that have occurred since 1982.

Reference

Bis, R.F. and Barnes, J.A., "Policies Governing the Use of Lithium Batteries in the Navy", The 1982 Goddard Space Flight Center Battery Workshop: NASA Conference Publication 2263, 23, 1983.

1:15

Thermochemical Heat Engine Power Systems for Underwater Applications
Mr. Allen D. Harper, Allied-Signal

In the evaluation of non-nuclear power sources for underwater applications, objectives that directly affect the selection of candidate approaches include:

- o Minimizing power system volume and weight to allow maximization of mission duration and/or payload within given envelope dimensions. Options with high volumetric and gravimetric energy densities are required.
- o Assuring compatibility with launch/recovery platforms.
- o Certifying the system and vehicle safe for underwater operations.
- o Minimizing vehicle radiated noise signatures.
- o Ensuring growth potential for future increased requirements.
- o Adopting a flexible approach that will readily integrate with other advanced subsystems, such as AI command/control systems.
- o Achieving all of the above at affordable development and production costs and schedule lead-times.

Significant advancements in the state-of-the-art are required to meet these objectives. Typically, mission planners specify ambitious scenarios, but reduce their objectives drastically when faced with the ramifications of the above considerations.

Initially, this presentation will define all viable options for non-nuclear underwater power. General categories are systems that produce electricity directly and systems that produce heat, then convert thermal to electrical energy in various types of heat engines. A large number of heat source variations are included as well. A reduced list of attractive candidates is given below:

Direct Electrical Systems

- o Secondary Batteries
 - Silver-Zinc
 - Silver-Iron
 - Lithium-MoS₂
- o Fuel Cells
 - Al-O₂
 - H₂O₂ SPE
 - DF-O₂ Carbonate
 - DF-O₂ Solid Oxide

Thermochemical/Heat Engines

- | | |
|---|---|
| <ul style="list-style-type: none">o Heat Sources<ul style="list-style-type: none">Carbon StorageLi-SF₆Advanced Li-SF₆H₂-O₂DEPSDF-O₂DF-H₂O₂ | <ul style="list-style-type: none">o Heat Engines<ul style="list-style-type: none">RankineClosed BraytonStirling |
|---|---|

Advantages of direct electrical systems include similarity to current systems, usually lead-acid batteries; flexibility in control to accommodate varying duty cycles; and, for some systems, convenient re-charge. Advantages of thermochemical/heat engines include production of direct shaft power (lower parasitic losses); availability of waste thermal energy for heating; and, usually, higher power density (power per unit weight or volume). As indicated above, the key issue is specific energy production, and for AUV/UUV's, this is indicated in weights/volumes related to storage of the energy (e.g., reactants or cell dimensions).

Next, a simplified model (methodology) for conceptual system layout/sizing/performance estimation is summarized. This model is currently suitable for primary battery/fuel cells or thermochemical/heat engine systems, although it could easily be extended to include secondary batteries. A model of this type is satisfactory because for most advanced approaches the layout is essentially driven by the propellant/reactant volumes. The model includes first-order corrections due to component performance characteristics and the effect of mission duty cycle. The model has been mechanized in BASIC for MSDOS PC's and operates in a highly user-interactive mode.

This evaluation methodology is applied to a variety of postulated mission scenarios with varying degrees of "reality" and results are given in term of energy density specific performances as well as vehicle geometric layouts (cartoons).

The conclusion of this presentation will summarize the results and present initial generalizations on preferred approaches for future missions. In general, these numbers indicate that advanced thermochemical heat sources driving closed-cycle gas turbines are superior for underwater systems which tend to be more volume than weight-restrained.

Clearly, this approach addresses only the first of the several selection criteria listed above in any depth. However, the energy production issue must be resolved before any of the remaining considerations become germane. Also, energy delivery can be quantified with significantly more objectivity, therefore, there is some hope that generalized treatment of this type can yield results with at least a degree of "universal" validity. These results can then serve as a "point-of-departure" for evaluating the remaining issues, that by their nature must be more qualitative.

2:00

Application of the Stirling Engine for Underwater Vehicles

Dr. William D. Ernst, Mechanical Technology, Inc.

Stirling Engines with their inherent features of continuous external combustion, high efficiency, low noise, and high reliability are excellent candidates for air dependent underwater applications. The Mod II kinematic Stirling engine was developed over 10 years under an Automotive Stirling Engine Program for vehicular use. Presently, this engine design, which is the result

of over 18,000 hours of laboratory and field testing, is being evaluated for underwater applications. The engine has completed its preliminary development phase and two engines are in operation; one in a test cell and one in an United States Postal Service vehicle. This vehicle is expected to enter field service in FY 1989.

The development status, design configuration and performance projections of the Mod II are presented and reviewed. Projections are made for package size and fuel consumption of the Mod II in a configuration for a typical underwater system.

2:45

Experiences with Stirling Engines in Underwater Vehicles

Mr. Herbert Nilsson, United Stirling AB

Underwater operations, offshore as well as military, depend on the supply of large amounts of energy. The ability of the Stirling engine to utilize any heat source of sufficiently high temperature allows it to be combined with high density storage, resulting in considerably increased endurance under water as compared with conventional systems. Silent, vibration-less operation is another attractive feature, not least in military applications. Heat is generated in an air-dependent combustion system using hydrocarbon fuels and pure oxygen. Within a development program for the Royal Swedish Navy, where Kockums is the main contractor responsible for system integration, a number of air-independent Stirling power modules are being manufactured and tested for installation in an operational Swedish submarine. A prototype system has already been successfully run in a submarine test section at Kockums. United Stirling AB is currently involved with Comex of Marseilles to provide two Stirling underwater engines for installation in Saga I, a manned diver lock-out submarine. Another program with the Royal Swedish Navy is aimed at the development of an air-independent propulsion system for an untethered autonomous remotely operated vehicle. The energy system will be based on a well proven Stirling engine concept adapted for underwater operation.

PUBLISHED PAPERS on POWER SYSTEMS

Batteries

Harma, D.A., **Suitability of Silver-Zinc and Silver-Cadmium Electrochemistries to Provide Electrical Power for Undersea Systems**, Proceedings, AUVS 15th Annual Symposium and Exhibition, San Diego, CA, 1988.

This paper describes the performance characteristics of silver-zinc and silver-cadmium systems and compares them with lead-acid and nickel-cadmium systems. Such design attributes as energy and power density, specific energy and power, operating voltage, charge retention cycle, and wet life are addressed. Important issues of availability, safety, charging methods, pressure-compensated design, and adaptability are also investigated. Lastly, general attributes of other candidate high-energy secondary systems are also detailed.

Griffin, G.L., Zolla, A.E., Waterhouse, R.R., and DeBiccari, D.J., **Primary Lithium Thionyl Chloride Cell Evaluation**, AFWAL-TR-80-2076, Wright-Patterson AFB, Ohio, 1980.

Performance and safety testing was conducted to evaluate the Altus 1350 Amp-hour cell against the Minuteman Survival Ground Power requirements. Twelve large cells, each with a 17 inch diameter, and 13/8 inch thick were fabricated and tested. Energy density exceeded 150 watt-hours per pound and 15 watt-hours per cubic inch. Discharge rates varied from C/100 to C/400.

Abuse testing demonstrated safety under conditions of external short circuit, short circuit by penetration with conducting object, forced discharge, and forced charging.

Griffin, G.L., Zolla, A.E., Waterhouse, R.R., and DeBiccari, D.J., **Lithium Thionyl Chloride Battery**, LA4-1799001, Ballistic Missile Office, Norton AFB, CA, 1980.

A large, 2,000 Amp-hour cell was developed and tested to the MX ground survival power load profile. Cell dimensions are 17 inch diameter, 2 inch thick, and weight is 39 pounds. Average energy density was 189 watt-hours per pound and 16.4 watt-hours per cubic inch, at the C/250 discharge rate. Fifty-three cells were built and tested at rates from C/80 to C/500 and under abuse conditions including a 20 foot drop to a steel surface, crush, forced charge, forced discharge into reverse voltage, puncture, and short circuit. The results of these tests demonstrated a rugged, altitude insensitive design and the required safety.

Marincic, N., **Design Features of Large High Rate Lithium Batteries for Torpedo-Like Applications**, Proceedings of the 30th Power Sources Symposium, Atlantic City, NJ, 1982, pp. 208-210.

The experience in the design of various sizes of reserve type batteries, based on lithium/oxyhalide systems, tells us that, in this case, slightly over 50% of the total battery volume is available for the electrode structures (cells, submodules) while the rest of the volume is occupied by the electrolyte storage tank and the delivery and circulation equipment. With the average density of close to 2 g/cm^3 for an activated battery, one arrives at the energy density of 5.8 W-hr/cu in. or only one third of the maximum volumetric energy density routinely obtained from oxyhalide batteries with low rate electrode configuration. The power density, however, changes from 39 average to about 78 W/cu in. based on the volume of the battery structure alone. This appears to be the most critical figure to be guided by in all attempts to develop a torpedo-like battery.

Schlaikjer, C.R., Goebel F., and Marincic, N., **Discharge Reaction Mechanisms in Li/SOCl₂ Cells**, Journal of Electrochemistry Society 126, 1979, pp. 513-522.

The processes taking place during the discharge of Li/SOCl₂/C cells were studied. Test vehicles included wound D, bobbin configuration 2D cells, and 2000 A-hr prismatic cells. Dried cathodes taken from 2D cells, discharged at 150 mA were analyzed quantitatively for lithium-sulfur oxyacid salts. Little or no such salt was found for cells discharged at ambient temperature. Appearance of a nonvolatile reducing species occurred in the cathodes of cells discharged at -20°C, that were not present in cathodes from cells discharged at higher temperature. The 2000 A-hr cells were used to measure dissolved SO₂ and SO₂ escaping at atmospheric pressure and ambient temperature from anode-limited and cathode-limited cells.

Fuel Cells

Niksa, M.J., and Wheeler, D.J., **Aluminum-Air Batteries for Remote Applications**, Proceedings, MTS, ROV'87, Brighton, England, 1987, pp. 334-337.

The Aluminum-Air battery is a new electrochemical system that is being actively developed by ELTECH Systems Corporation. Although similar to an energy storage battery, such as lead acid, it operates more like a fuel cell. In this case, the fuel is metallic aluminum and air. The battery is "mechanically rechargeable" in that it is returned to a fully charged state by addition of fresh aluminum in the form of plates. The coupling of a reactive anode to an air electrode provides the battery with virtually inexhaustible cathode reactant and results in a very high theoretical system specific energy. The capacity of the system is then

limited primarily by the ampere capacity of the aluminum anode. Mechanical recharging permits short recharge times and allows mass production of the battery "fuel", or aluminum plates, at facilities optimized for their production. The aluminum is also easily and safely stored and the cell design need not be highly complex (as in the case of a methanol fuel cell). Power capabilities are virtually independent of the state of charge and little voltage decline is noted.

Niksa, M.J., **Use of the Aluminum-Oxygen Fuel Cell as a Power Source for Long-Range AUV'S**, Proceedings, 15th Annual Technical Symposium and Exhibition, San Diego, CA, 1988.

A comparison of the various types of metal/air fuel cells and the hydrogen/oxygen fuel cell. Particular emphasis is placed on the unique advantages of the aluminum-oxygen fuel cell. Includes a brief discussion on the coupling of an aluminum-oxygen fuel cell with an artificial gill.

Niksa, M.J., and Wheeler, D.J., **Aluminum-Oxygen Batteries for Space Applications**, Journal of Power Sources, Vol. 22, 1988, pp. 261-267.

An aluminum-oxygen fuel cell is under development at ELTECH Systems Corporation. Several highly efficient cell designs have been constructed and tested. Air cathodes catalyzed with cobalt tetramethoxyporphyrin have demonstrated more than 2000 cycles in intermittent use conditions. Aluminum alloys have operated at 4.2 kWh kg^{-1} at 200 mA cm^{-2} . A novel separator device, an impeller fluidizer, has been coupled with the battery to remove the solid hydrargillite discharge product. A 60 kW, 720 kWh battery system is projected to weigh about 2200 lb for an energy density of 327 Wh lb^{-1} .

McVay, D.R., **Status of PEM Fuel Cell Development at International Fuel Cell Corporation**, , IECEC, August, 1988.

Although proton exchange membrane (PEM) fuel cells offer the potential of simple low cost power systems none have been realized. A PEM fuel cell power system test is described which virtually eliminated ancillary components. All stacked parts except for the electrochemical cells are fabricated of low cost graphitic materials drawn directly from a commercial fuel cell production run.

McVay, D.R., **Proton Exchange Membrane Fuel Cells**, Presentation at 33rd International Conference, Sponsored by U.S. Army Laboratory Command, Fort Monmouth, NJ, 1988.

This paper describes the development and testing of a 15 cell proton exchange membrane fuel cell stack. Passive heat and product water management techniques are used which provide the basis for a simple reliable power system. The fuel cell stack is fabricated using low cost materials and assembly approach.

LaConti, A.B., Fragala, A.R., and Boyack, J.R., **Solid Polymer Electrolyte Electrochemical Cells: Electrode and Other Materials Considerations**, Proceedings of the Symposium on Electrode Materials and Processes for Energy Conversion and Storage, 1977, pp. 354-374.

The voltage efficiency and high current density capability of hydrated solid polymer electrolyte (SPE) electrolyzers has largely resulted from understanding/solving material compatibility problems and the development of improved electrode, current collector and sulfonic acid ion exchange membrane systems. Materials research studies have been conducted to define stability and transport properties of select ion exchange membranes and relationship to controllable manufacturing parameters including water content, degree of sulfonation and contaminant species. The composition/structure of electrode catalyst and current collectors and the interaction with the hydrated SPE has been shown to be an important factor in achieving highly efficient and invariant performance.

Kosek, J.A., and LaConti, A.B., **Novel Electrode Systems for A Regenerative Hydrogen-Bromine Battery**, Presentation at 33rd International Power Sources Symposium, sponsored by U.S. Army Laboratory Command, Fort Monmouth, NJ, 1988.

The hydrogen-bromide fuel cell system has been investigated in recent years as an attractive technology for large-scale terrestrial energy storage and for deep base defensive military applications. The system can be independently sized for various energy and power requirements, and reactants and products stored external to the electrochemical cell.

One configuration of this system, undergoing evaluation at Giner, Inc., utilizes a solid polymer electrolyte membrane, such as Nafion, as the cell separator/electrolyte. Hydrogen and bromine electrocatalysts are prepared, characterized separately, and the most promising candidates then evaluated under full cell conditions. Since the hydrogen-bromine battery currently undergoing development at Giner, Inc. is a regenerative system in which the same electrochemical cell is used for both charge and discharge, the electrodes and overall performance are evaluated in both modes of operation.

Kosek, J.A., and LaConti, A.B., **Advanced-Hydrogen Electrode for a Hydrogen-Bromine Battery**, Journal of Power Sources, Vol. 22, 1988, pp. 293-300.

Binary platinum alloys are being developed as hydrogen electrocatalysts for use in a hydrogen-bromine battery system. These alloys have been varied in terms of alloy component mole ratio and heat-treatment temperature. Electrocatalyst evaluation, performed in the

absence and presence of bromide ion, includes floating half-cell polarization studies, electrochemical surface area measurements, X-ray diffraction analysis, SEM analysis, and corrosion measurements. Results obtained to date indicate a platinum-rich alloy has the best tolerance to bromide ion poisoning.

Smarz, G.A., LaConti, A.B., and Nuttall, L.J., SPE Fuel Cells, Extended Abstracts: Seventh Battery and Electrochemical Contractor's Conference, Crystal City, VA, 1985, pp. 337-344.

This paper focuses on work at Hamilton Standard to develop new membranes for solid polymer electrolyte (SPE) electrochemical systems that will reduce the cost of the membrane and electrode catalysts while maintaining performance levels. A low cost membrane was identified and successfully tested for over 1200 hours. Performance was similar to the baseline Nafion 117 membrane. Catalytic electrode cost was reduced to less than one half of that in the baseline fuel cell.

Heat Engines

Ernst, W.D., Automotive Stirling Engine Development Program: Mod II Technology Applications, 25th Automotive Technology Development Contractors' Coordination Meeting, 1987.

Since its inception in 1978, the Automotive Stirling Engine (ASE) program has focused on the development of the MOD II engine. This experimental engine is now completing its development for demonstration of the program goals in June, 1982. This paper identifies and examines the unique characteristics of the engine relative to the requirements for potential near-term commercial applications. Both specialty vehicles and stationary applications are surveyed and the status of demonstration efforts summarized. Further, a plan is presented for commercialization of the MOD II engine through a field test in FY90 and pilot production in FY94.

Grandin, A.W., and Ernst, W.D., Alternative Fuel Capabilities of the MOD II Stirling Vehicle, SAE, 1988.

The Stirling Engine is an inherently multifuel engine that has been demonstrated to operate on a wide range of alternate fuels. Among the attractive fuel alternatives for the Stirling engine in a variety of applications are methanol/ethanol, natural gas, jet fuels and synthetic fuels.

Based on the development activities accomplished by MTI over the past nine years, it has become obvious that the Stirling engine's

characteristics make it a prime candidate for both multi-and alternate-fuel* uses. The use of Stirling-powered vehicles could make the transition from conventional to alternate fuels, such as CNG and methanol, easier. For other applications, the Stirling could take advantage of indigenous or low quality fuels such as coal and landfill gas. In addition, Stirling engines offer high fuel efficiency, low emissions, and quiet operation.

* In this context, alternate fuel refers to an engine whose combustion system has been designed to operate on a single fuel other than gasoline or diesel. A multifuel engine is one that can operate on more than one fuel without substantial operator intervention.

Ernst, W.D., **Mod II Engine and Technology Development**, 19th Intersociety Energy Conversion Conference, 1984.

The second-generation automotive Stirling engine, known as the MOD II, will be used to accomplish the Automotive Stirling Engine (ASE) Program objectives. Preliminary design has advanced to the point of procuring long-lead components to evaluate manufacturability. The master head castings of the Hot Engine System (working gas cycle) are being procured, while the V-block casting of the Cold engine/Drive System is being sectioned for evaluation. The technology required for these designs, and their impact on MOD II performances, have progressed to the design substantiation stage, and successful accomplishment of the program objectives is expected.

Harper, A.D. and Spragins, W.W. **Development of a Thermal Storage Heater for a Closed Brayton Cycle Engine**, IECEC Paper 779036.

A heat source was developed for a 40 hp CBC engine. This system's applicability to larger systems was also defined where energy productions 4 to 10 times that of lead-acid batteries were projected.

Mason, J.L., Pietsch, A., Wilson, T.R., and Harper, A.D., **5 MW Closed Cycle Gas Turbine**, ASME Paper 84-GT-268.

An un-recuperated CBC engine bottomed with a steam cycle was developed for an enhanced oil recovery cogeneration power system. The system burned low-cost solid fuels.

Pietsch, A., Trimble, S.W., and Harper, A.D., **Brayton Cycle Space Power System**, IECEC Paper 859443.

Considerations of the economics of isotope electrical power in space and an up-date on the NASA/DOE BIPS power system development were presented.

Norman, L.W., and Harper, A.D., **Application of Thermochemical Power Systems to Swimmer Delivery Vehicles**, Presentation at Oceans '86 Engineering Conference, Washington, D.C., Sept. 22, 1986.

Presentation briefly reviewed the results of a preliminary study of 5 and 7 ft diameter SDV power systems using near and far-term energy delivery technologies.

BIOGRAPHIES of PRESENTERS and PANELISTS

Dr. James A. Barnes

*Naval Surface Warfare Center, Group Leader, Battery Applications
Engineering and Safety Group*

Dr. Barnes is currently Group Leader of the Battery Applications Engineering and Safety Group within the Electrochemistry Branch of the Naval Surface Warfare Center, Silver Spring, Maryland. This group provides support to Navy programs in the design and evaluation of electrochemical power systems. NSWC is designated as the lead laboratory for the Navy's program in Lithium Battery Safety.

Dr. Barnes joined NSWC as a research chemist in 1983. Prior to that he taught chemistry at Austin College in Sherman, Texas for 10 years. He has also worked at the Naval Research Laboratory, Southwest Research Institute, Texas Instruments, and Shell Development Co.

Mr. Dick L. Bloomquist

David Taylor Research Center, Senior Project Engineer

Mr. Bloomquist is responsible for project management, advanced program studies, and consultation on various special projects for the U.S. Navy. Currently, he serves as the Center's principal investigator for the development of advanced energy and power systems for underwater vehicles. He has served as Navy representative to the Marine Board, National Research Council, and the National Academy of Sciences for long range deep ocean technology planning and advanced submersible power and propulsion systems.

Dr. A. Douglas Carmichael

MIT, Department of Ocean Engineering, Professor

In 1970, Dr. Carmichael came to the U.S. to be Professor of Power Engineering in the Department of Naval Architecture and Marine Engineering (now Department of Ocean Engineering) at MIT. His research interests have been focused on the fields of fluid mechanics and thermodynamics as they relate to the production of power and propulsion for ships. He has served as advisor for several Navy investigations which include power and energy systems for small underwater vehicles and the recent intercooled regenerative gas turbine program. His research in the field of energy conversion has also resulted in the study of various advanced thermal power plant systems and alternative ocean sources of energy such as wave energy and Ocean Thermal Energy Conversion.

Dr. William D. Ernst
Mechanical Technology, Inc., Manager, Kinematics Programs, Stirling Engine
Systems Division

Dr. Ernst is presently Manager of the kinematics Program of the Stirling Engine Systems Division of MTI. In this position he is responsible for the direction of all kinematic Stirling engine development and subsequent commercialization programs. Previous positions at MTI, have been associated with the development of Stirling engine systems for automotive applications. Prior to MTI, Dr. Ernst was President of Rensselaer Associates, an Instructor at Rensselaer Polytechnic Institute, and a Research Associate with the MIT Hydrodynamics Laboratory.

Mr. David H. Gorham
Lockheed Missles and Space Company, Inc., Director, Undersea Systems
Advanced Marine Systems

As Director of Undersea Systems at LMSC, Mr. Gorham is responsible for the management of several technical teams that are involved in the development of underwater vehicle prototypes and advanced underwater vehicle programs. In this position, he also oversees developing support technologies and the management of new and existing business programs.

Mr. Gorham is a retired U.S. Navy Captain having served 29 years in the armed forces. His active duties in the Navy have included: commanding a nuclear powered strategic missile submarine; Director and Senior Manager of the Navy Nuclear Propulsion Examining Board; Construction Supervisor of the U.S. Navy's newest submarine repair ship; and Squadron Commander in charge of all U.S. Navy Deep Submergence vessels, systems, and support ships.

Mr. Gorham received both his B.S. in engineering and business administration from the University of Colorado. He has also served as Assistant Professor at the University of Kansas.

Mr. Gerald L. Griffin, Jr.
Altus Corp., Director for Government Marketing

Since 1984, Mr. Griffin has been Director of Government Marketing for Altus and is responsible for developing new business with the government and related customers. Prior to his present position, he was Program Manager for various power battery systems development at Altus. Mr. Griffin has also worked within the microwave industry primarily as a Contract Administrator. He has also served six years active duty with the U.S. Navy as Engineering Duty Officer and presently is a Lieutenant Commander with the U.S. Navy Reserve.

Mr. David A. Harma

Whittaker-Yardney Power Systems, Applications/Proposal Manager

Mr. Harma is responsible for Applications Engineering at Whittaker-Yardney. In this position, he has been responsible for the design and proposal development of both primary and secondary silver-zinc, silver-cadmium, silver-chloride-magnesium, and nickel-hydrogen systems. Prior to joining Whittaker-Yardney, Mr. Harma worked with battery systems as a Production Engineer for Johnson Controls, Inc. and as Design Engineer for Eagle Picher Industries, Inc.

Mr. Allen D. Harper

Allied-Signal Aerospace Company, Project Engineer

Mr. Harper is presently leader of Advanced Undersea Systems within the Fluid Systems Division of Allied-Signal. Prior positions during his 15 year association with Garrett have involved applications of closed Brayton cycle (CBCs) gas turbines and other power cycles to underwater, industrial, and space applications. He was responsible for the design and development of a sensible heat storage device that was later tested by the David Taylor Naval Research Center with a Garrett-furnished 40-horsepower CBC gas turbine. In prior positions at Lockheed, JPL, TRW, and Dynamic Science, he was involved in propulsion system analysis, propellant feed/expulsion systems, monopropellant rocket thruster development, aircraft fuel systems safety, automotive vehicle handling/safety characterization, and vehicular crash safety.

Dr. Anthony B. LaConti

Giner, Inc., Vice President

Dr. LaConti joined Giner, Inc. as Vice President in September, 1986, and has the overall responsibility for all technical programs. He has over 20 years of experience in directing applied research and development programs for electrochemical applications. His prior work experience included 2 years as Engineering Manager for United Technologies, Hamilton Standard Electro-Chem Products and 20 years as Manager of Materials and Technology Development for General Electric Electrochemical Energy Conversion Programs.

Dr. LaConti has developed novel catalyst and electrode systems for rechargeable fuel cells and gas generating systems. His work has led to the development and commercialization of: 1) advanced hydrogen/oxygen generators for life support, gas chromatograph flame ionization detectors, electrical generator cooling and corrosion control; 2) electrochemical sensors for carbon monoxide and other volatile gases/vapors; and 3) advanced chlorine generator and power devices.

Dr. Nikola Marincic
Battery Engineering, Inc., Founder and President

Dr. Marincic has been President of Battery Engineering, Inc. since he founded the company in 1978. Prior to that, from 1973-1978, he was manager of GTE Laboratories Inc., Power Sources Center, in charge of all aspects of GTE's battery activity. From 1966-1973, Dr. Marincic was Project Manager for P.R. Mallory & Co., Inc.'s development of lithium sulfur dioxide batteries. He has authored numerous publications and currently holds 21 patents in the field of electrochemistry.

Mr. James R. McFarlane
International Submarine Engineering, Founder and President

Mr. McFarlane has been President of ISE since he founded it in 1975. At ISE, he has been involved with the design, construction and operation of remotely and autonomously operated vehicles. Prior to founding ISE, he was the Vice President of Engineering and Operations at International Hydrodynamics. He has also held numerous positions both afloat and ashore during his 18 years of service in the Canadian Navy.

Mr. McFarlane received his B.S. in Mechanical Engineering from the University of New Brunswick and his M.S. in Naval Architecture and Marine Engineering from MIT. In 1988, he received an Honorary Doctor of Engineering from the Royal Military College and the University of Victoria.

Mr. Donald R. McVay
International Fuel Cells, Corp., Manager of Business Development, Military Programs

Mr. McVay is currently responsible for International Fuel Cells marketing activity to the Navy, Air Force, and SDI. In his Navy capacity, Mr. McVay is currently focused on fuel cells for the emerging high energy requirements of future Navy missions.

He holds a B.S. in Chemical Engineering, an M.S. in Mechanical Engineering, and an MBA. Mr. McVay has three patents and has one publication.

Dr. Sam Mohanta
Aquanaautics Corporation, Director of Engineering

Dr. Sam Mohanta is an electrochemical engineer and has been Director of Engineering for Aquanaautics Corp. since 1987. He received his Ph.D. in 1974 from the University of Waterloo in Canada and has twelve years of industrial electrochemical experience. He was a technical manager at Duracell and HSA Reactors, Ltd. with responsibility for developing many electrochemical products and processes. He is currently Aquanaautics Team Leader on the multi-disciplinary DARPA artificial gill program.

Ms. Marilyn J. Niksa
ELTECH Research Corporation, Project Leader

Ms. Niksa has been with ELTECH Research Corp. since 1981. She first served as a Research Supervisor and is now a Project Leader for their development of the Aluminum-Air fuel cell. Prior to ELTECH, she worked as Senior Research Chemist for Corporate Research at Diamond Shamrock Corp. and previous to that as Power Sources Engineer at Atlantic Richfield, Medical Products Division. Ms. Niksa has worked with a variety of high density power sources and has co-authored numerous papers. She presently holds 10 patents in the electrochemistry field.

Mr. Herbert Nillson
United Stirling AB, President

Mr. Nillson joined United Stirling AB in 1979 and was appointed President of the company in 1987, with overall responsibility for the development and commercialization of Stirling-based underwater power systems. His background includes wide experience in submarine engineering gained through many years spent at Kockums, Malmö, Sweden. Since 1982, he has been Professor in the Department of Underwater Technology at Chalmers University in Gothenburg. He is the author of several papers on the structural strength of submarines and underwater Stirling systems.

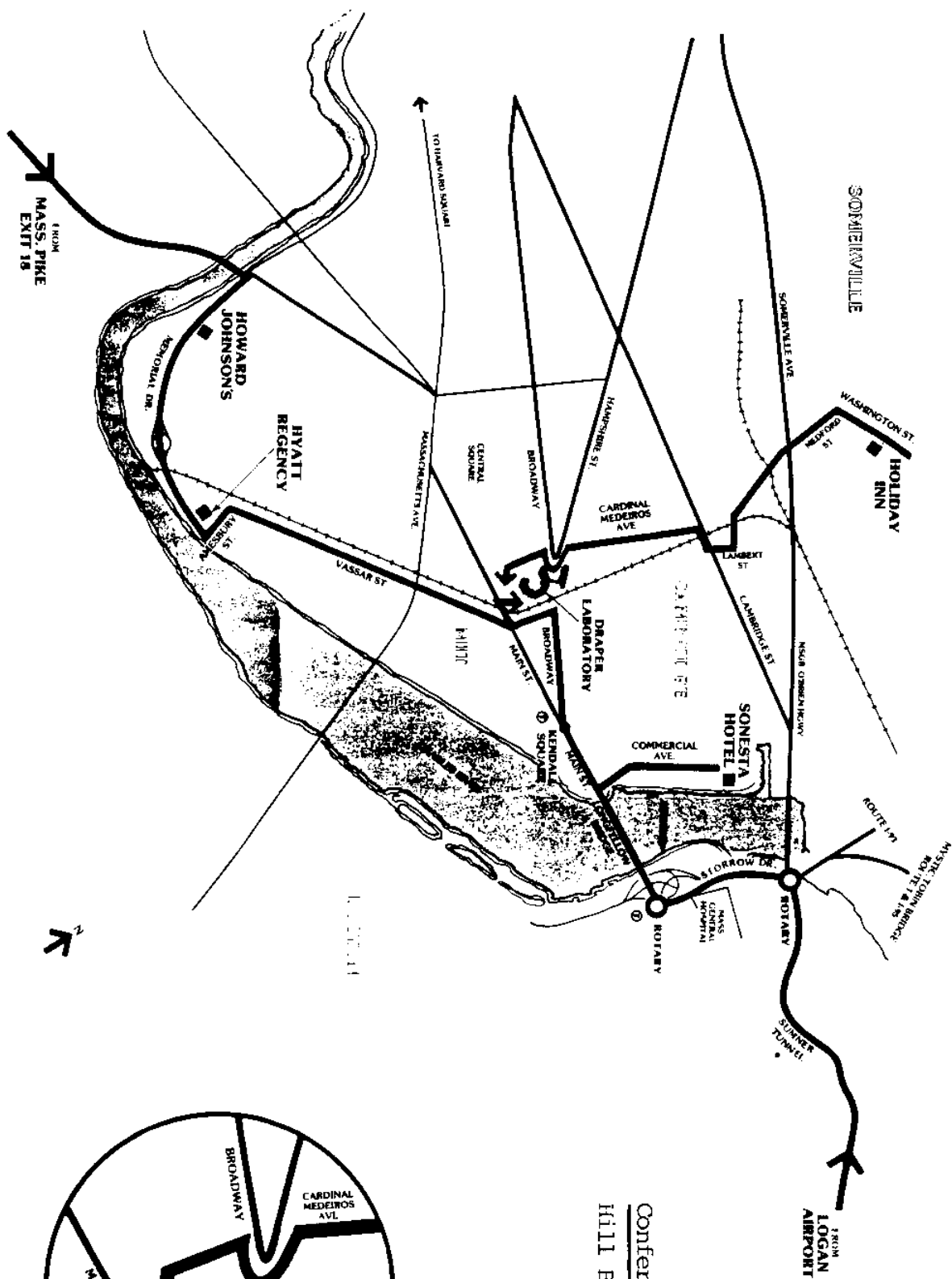
Dr. Gabriel D. Roy
Office of Naval Research, Propulsions and Energy Programs

Dr. Roy's areas of expertise are Fluid/Plasma dynamics, Heat Transfer, Combustion, and Propulsion. He has been actively involved in research in Magnetohydrodynamic Power Generation, and has a number of publications to his credit. Prior to joining the ONR, he served as Project Manager at TRW, California. At ONR, Dr. Roy is responsible for the management of the Navy's basic research programs in combustion and propulsion for underwater and air-borne systems. In addition, he also manages Strategic Defense Initiative Organization's Pulse and Power Conditioning Programs (SDIO/IST) and Non-nuclear Space Power and Power Conditioning Programs (SDIO/SBIR).

Dr. Roy has held several faculty positions in India and in the U.S. He is a member of the ASME, AIAA and Sigma XI Honor Society, and a member of the AIAA Technical Committee on Propellants and Combustion.

Mr. Nicholas Shuster
Westinghouse Oceanic Division

Mr. Shuster has held various positions within Westinghouse Oceanic since 1983, all of them directly related to the development of various lithium based battery power systems. Recently, he has demonstrated the feasibility of a lightweight, long duration, low power, lithium-water power source for undersea applications. He is presently managing the engineering scale-up to a full size prototype unit for a lithium-water battery that will undergo in-ocean testing by the end of 1988.

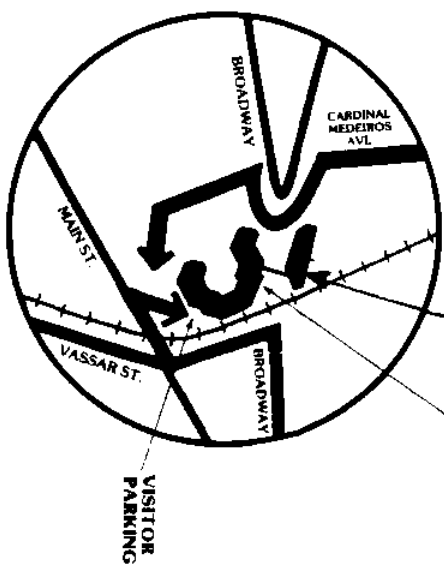


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Conference Location:

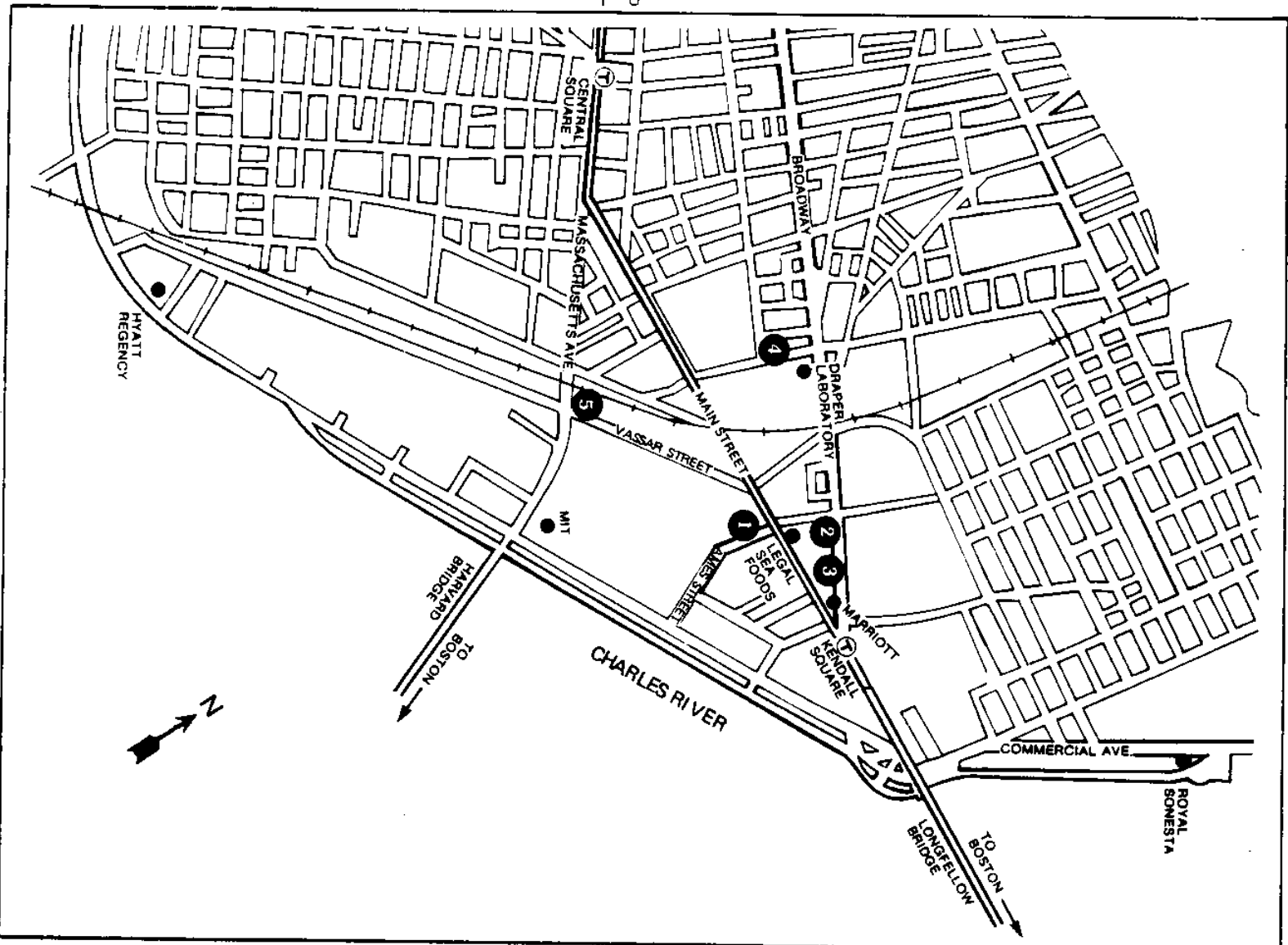
Hill Building, First Floor



Kendall Square Vicinity Parking

- 1 Ames Street Lot
Ames and Main Street
225-0847
- 2 Cambridge Center Garage
5 Cambridge Center
Broadway and Ames Street
(off of Main St., next to Legal Sea Foods)
492-1956
- 3 Cambridge Center Marriott Hotel
2 Cambridge Center (Valet parking)
494-6600
- 4 Polaroid Parking Garage
Adjacent to Draper Employee Parking
Garage
Technology Square
- 5 Vassar Street Lot
Vassar St. and Massachusetts Ave.
(next to BayBank Automated Teller
machine)

NOTE:
There is limited Draper Lab visitor parking available.
Many area hotels provide shuttle service to Draper Lab.



ACCOMMODATIONS*

**Cambridge Marriott
2 Cambridge Center
Cambridge, MA
(617) 494-6600**

**Royal Sonesta Hotel
5 Cambridge Parkway
Cambridge, MA
(617) 491-3600**

**Hyatt Regency
Memorial Drive
Cambridge, MA
(617) 492-1234**

**Howard Johnson
777 Memorial Drive
Cambridge, MA
(617) 492-7777**

***Listed in descending order to proximity of Workshop location.**

NOTES