PROCEEDINGS OF THE 18th

IECEC '83

INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

VOLUME
4
OF 5 VOLUMES

ENERGY STORAGE & CONVERSION

18th
INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

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VOLUME 4
ENERGY STORAGE & CONVERSION

"Energy for the Marketplace"

SHERATON-TWIN TOWERS
ORLANDO, FLORIDA
AUGUST 21-26, 1983

Participating Societies

SAE The Engineering Resource For Advancing Mobility

Intersociety Energy Conversion Engineering Conference

PURPOSE:

To reduce the overlapping and duplicative effort of the sponsoring societies in the field of advanced or non-conventional energy conversion. This conference is concerned with the engineering and application aspects of non-conventional energy conversion systems and devices as opposed to the details that are presented at various specialist conferences. Papers are screened for technical competence, clarity and brevity.

ORGANIZATION:

A standing IECEC Steering Committee consisting of two members from each society coordinates all conference activities. Each year a society (this year AIChE) sponsors the conference. Session Organizers are appointed by the General Chairman and the Program Chairman. Session Organizers invite abstracts and receive abstracts from a general solicitation through the Program Chairman. Within limits set by the General and the Program Chairman the Session Organizers are responsible for the content of their sessions and appoint appropriate Session Chairmen.

SPONSORING SOCIETIES:

American Institute of Chemical Engineers
(1976 Conference)

American Nuclear Society
(1977 Conference, Washington, D.C.)

Society of Automotive Engineers
(1978 Conference, San Diego, CA)

American Chemical Society
(1979 Conference, Boston, MA)

American Institute of Aeronautics and Astronautics
(1980 Conference, Seattle, WA)

American Society of Mechanical Engineers
(1981 Conference)

Institute of Electrical and Electronic Engineers
(1982 Conference)

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Message from the General Chairman

Today throughout the world, there has been a de-emphasis in energy conversion projects simply to satisfy government requirements, and a realization that energy conversion must make sense in the marketplace. We as engineers, must consider how our projects are eventually going to be used, and how they will be eventually incorporated into products that people will buy and use.

For the last 18 years, the Intersociety Energy Conversion Engineering Conference (IECEC) has been a marketplace for ideas for potential products. Here, gathered together in one meeting, are the latest reports on technologies of diverse natures which will eventually compete for the marketplace. If your product is electricity for instance, you can evaluate the state of technology of several different types of heat engines, such as Stirling, Brayton Cycle, Rankine Cycle to operate different types of electric generators. You can see how photovoltaics, thermonics, and thermoelectric, MHD, and possibly other methods are doing in the direct conversion area. You can determine how wind energy, tidal energy, ocean thermal energy might fit into your needs. Possibly a new type of energy conversion will be discussed which you have never heard of before. As a marketplace for ideas, the Intersociety Energy Conversion Engineering Conference is ideal.

The utility of having one meeting for all use-related energy conversion technologies was recognized by the major engineering societies and related professional societies back in 1966. The result is the organization of the IECEC, to eliminate duplication of separately sponsored meetings. Each year, one of the sponsoring societies takes its turn to supervise and run this Conference. This year, the society is AIChE. The continuity of this Conference is provided by a Steering Committee composed of two representatives of each of the societies. The intent of the IECEC is to avoid subjects that are appropriate for established conferences on conventional power systems. It also intends to compliment all the specialist conferences that are meetings of experts in a limited area of energy conversion.

Orlando is an attractive vacation spot, and the meeting is scheduled before school starts. Therefore, we have not scheduled any late afternoon or evening activities at the conference, so that you may attend many of the internationally known attractions with your family or associates.

Since this meeting fulfills world-wide needs to learn how to do more with less by means of improved energy conversion, it has grown into an important international meeting. Particularly, we have important contributions from Europe and Japan in many technical areas. This year, the Japan Society of Mechanical Engineers is becoming one of the co-operating societies who help sponsor the IECEC. These co-operating societies do not take turns sponsoring one of the meetings, but do support the meetings with publicity to their members and do receive the privilege of registering at a reduced rate. However, whether you are a member of a sponsoring group or not, I am glad you were able to attend and partake of this meeting. If you are here as a specialist, we hope you will be interested to some degree in the whole field in energy conversion.

W. R. Martini
General Chairman

Message from the Program Chairman

This year's conference is the 18th in the series. Reflection on the changing national energy interests and priorities reveals that the energy conversion field has evolved from one of strong orientation toward military and aerospace applications to one of greater breadth that recognizes a wide spectrum of terrestrial and private-sector requirements. This shift has brought with it greater concern for the economics of the marketplace. Hence this year's theme "Energy for the Marketplace."

Superimposed on the shift discussed above is the present federal policy of emphasis on longer-range R&D, coupled with a de-emphasis of government-funded demonstration and commercialization projects. These added constraints have placed new and difficult challenges before the energy conversion engineering field. It is in this new atmosphere of difficult financial and policy constraints that we present the 18th IECEC.

The program in this Proceedings shows the areas of current interest, many of which lie in the private sector. I think that the spectrum of topics represents a healthy balance among the technical fields, and among the potential markets. Some of them are in healthy competition; others complement one another. Frank McLarnon and I hope that you find this program interesting and informative. Thank you for joining us for a successful 18th IECEC.

Elton J. Cairns
Technical Program Chairman

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839235

A SURVEY OF FUTURE NAVY ELECTROCHEMICAL POWER SOURCES REQUIREMENTS/PROGRAMS

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Abstract

Future naval systems will require electrochemical power sources improved by orders of magnitude over present operational batteries in active life, energy and power density along with reliability, lower cost and maximum safety. Three ambient temperature lithium systems with the potential for 5 to 10 times the specific energy of non-lithium batteries are under investigation: Li/SO_2, Li/$SOCl_2$, and Li/AgO. An alloy of lithium and boron has been found which provides the high energy of lithium as an anode in a thermal battery and is physically and chemically stable in the presence of molten salts. Relatively low temperature nitrate thermal batteries employing Li/B anodes are being investigated for use in missile systems. Advanced rechargeable lead-acid batteries are also being studied with an aim to increasing service life from five to ten years and increasing specific energy by about 20 percent. Further advances in the energy density of rechargeable systems will include a study of rechargeable lithium systems.

INTRODUCTION

Virtually every modern naval weapons system, in fulfilling its missions/functions, is highly dependent upon the performance characteristics of its electrochemical power source(s) which are shown in Figure 1. As a result of the multiplicity of naval applications (target detection, fuzing, safety and arming, deployment, guidance and control, and propulsion (weapons and vehicles)) involving a wide variety of mission profiles and operational environments, diverse systems requirements exist which dictate the use of electrochemical power sources of different designs and characteristics as noted in Figure 2. In response to these stringent needs, new and innovative technology must and is being developed by the Navy to produce advanced electrochemical power sources with extended performance characteristics. The overall program objectives are to attain long life; high energy and power density; high reliability; lower cost; and maximum safety during life cycle through advances in cell components, materials, thermal management, designs, test and evaluation procedures and new concepts. The specific objectives for pacing naval applications and functions are listed in Figures 3 and 4. In order to accomplish these objectives, the present and future thrusts of the Navy's battery technology program will include the improvement of conventional electrochemical systems and the exploitation and development of new electrochemical systems.

TECHNOLOGY OF PRIMARY AMBIENT TEMPERATURE LITHIUM SYSTEMS

Within the framework stated above, the achievement of safe, reliable, high-energy lithium batteries with sizes and electrical performance characteristics adaptable to various Navy uses (i.e., detection, guidance and control, and weapons propulsion), is considered the single most important Navy battery technology goal. Of all the high-energy lithium battery technologies that are presently available, the three considered most relevant for Navy uses are the Li/SO_2, Li/$SOCl_2$, and Li/AgO electrochemical systems. While all of these are comparatively new and offer five to ten times the specific energy of conventional (non-lithium) battery technologies, they differ in performance, in the nature of their hazards, in their range and scope of Navy uses, and in their state-of-technology development. Presently, the Li/SO_2 and Li/$SOCl_2$ systems are the furthest advanced with Li/SO_2 being used in various Navy applications (buoys and transponders).

As a part of this high priority technology program a research and development effort was undertaken to achieve a safe, reliable Li/SO_2 battery for mine applications (i.e., detection) that will withstand long-term storage. This has been realized by a Naval Surface Weapons Center-Honeywell developed prototype battery (1.2-kWh) of the remotely activated reserve type that incorporates a unique rugged mechanical design. As a result of this achievement, another research and development effort was pursued by NSWC-Honeywell which resulted in the integration of the Li/$SOCl_2$ system within the same battery design concept and reserve configuration.

Another research and development effort was undertaken by the Naval Surface Weapons Center with respect to the elucidation of the chemistry, electrochemistry and thermal phenomena associated with the logistics and use of lithium batteries operating at ambient temperatures. This effort has been coordinated with industry (EIC, Honeywell, Old Dominion University, GTE, and Gould) and will result in determining the ultimate stability and safety of lithium batteries under realistic Fleet conditions.

Several lithium electrochemical systems are presently under consideration for potential use in electric torpedo propulsion applications. To this end a lithium/silver oxide seawater battery is under joint development by the Naval Underwater Systems Center and Gould/OSD, with participating support by Lockheed. The Navy is also pursuing the development of high-rate lithium/thionyl chloride batteries, both in the static electrolyte mode (involving the Naval Ocean Systems Center and ALTUS Corporation), and the flowing electrolyte mode (involving the Naval Surface Weapons Center and GTE). Significant progress is being made and a decision will be forthcoming by October 1985 as to which of these three systems is to be agressively pursued for electric propulsion.

TECHNOLOGY OF MOLTEN SALT SYSTEMS

A second focused electrochemical technology area within the Navy is aimed at advanced thermally-activated batteries for weapon applications that require small, high-rate, short-life electric power sources. With this as an objective, exploratory R&D at NSWC led to the discovery of a new alloy of lithium and boron that exhibits the high-energy electrochemical properties of lithium and is stable (both physically and chemically) in the presence of molten salts. A joint NSWC-General Electric (Neutron Devices Dept.) development effort resulted in improved molten salt battery cells employing this new alloy as the anode. The new molten salt cell also incorporates a newly developed magnesium oxide separator along with non-carcinogenic cathode materials. The goal of this program is to achieve and to assure the future availability of extremely rugged thermally-activated batteries that are non-toxic and are immune to deterioration with age, and that provide specific energy up to 90 Wh/kg at power densities up to 2500 W/kg. It is expected that these advanced thermal batteries will find widespread use as power sources in weapon systems for such functions as deployment, safety and arming, fuzing, guidance and control, and countermeasures. A research and development program is currently ongoing at the Naval Weapons Center to study the feasibility of low-temperature nitrate systems for use in missile systems.

TECHNOLOGY OF HIGH-ENERGY SECONDARY SYSTEMS

One other focused technology area is aimed at advanced rechargeable batteries (non-lithium) for submarines and deep submergence research vehicles. The Navy goals for lead-acid batteries that are used in nuclear submarines are to increase service life from five to ten years and increase specific energy by about 20 percent. To accomplish this, a joint NSWC-Gould R&D program is being conducted to develop and characterize metal-matrix composite battery grids fabricated from pure lead reinforced with nonmetallic fibers. Initial results look promising, and successful completion of this effort will provide reliable submarine batteries with higher volumetric energy density and longer service life. A research and development program to study the corrosion rate of lead and lead alloy electrodes is also being pursued to provide an alternative method and data base for optimization of electrodes for submarine batteries. The Navy goals for secondary or rechargeable batteries with zinc, iron, or cadmium electrodes are to increase by a factor of two to five the number of deep charge-discharge cycles that can be reliably obtained, to achieve up to five plus years of wet-stand life without substantial loss of discharge capacity, and to achieve reliably a specific energy up to 100 Wh/Kg.

Small diesel-electric submarines may also be a part of the future Fleet. The challenge will be to provide rechargeable electric power systems with long cycle life, acceptable cost, and with higher specific energy and power than lead-acid batteries. A reliable secondary electrochemical system having these characteristics remains an elusive goal at present that may be achievable in the future with a rechargeable lithium system. This possibility will be studied in the near future.

SUMMARY

Present and future naval system electrochemical power requirements indicate the need for aggressive battery development programs. Multiple development thrusts based on lithium anode systems (both ambient temperature and thermal) are addressing these needs. Half of a total budget of $11M(shown in Figure 5), supports advanced and engineering development. The remaining $5M is split between research and exploratory development with research getting the heavier support. Independent research programs selected by Navy activities mainly support investigation of specific problem areas in exploratory development.

Exploratory development activities cover efforts on:

a. high-rate lithium primary batteries for weapons propulsion (both aqueous and thionyl chloride types) and for arming, safety, and fuzing (molten salt types);
b. low to mid rate lithium batteries for detection, guidance and control;
c. programs directed toward the improvement of non-lithium systems.

Lithium battery safety is a major concern in battery scale, especially with high capacity batteries discharged at high rates. There are active Navy programs to determine acceptability of lithium power sources for service use, to review lithium battery programs for safety and to investigate accidents of which there have been a significant number.

The advanced development program includes diverse efforts in support of weapon and platform power source applications. Significant programs include lead-acid battery improvement for submersible auxiliary and propulsion power, silver oxide-zinc characterization, and lithium thionyl chloride development for missile power. There are also three major programs to design and test high-rate propulsion batteries, two based on lithium/thionyl chloride, the other, an aqueous system, based on lithium/silver oxide.

In conclusion, the Navy battery R&D program is a comprehensive effort which includes the exploitation of the specific energy advantages of lithium anode electrochemistry for both low and high discharge rate systems. Successful scale-up of non-aqueous lithium batteries to high capacities and high discharge rates is contingent on resolution of the safety risk. The Navy battery research and development program also addresses the improvement of non-lithium systems such as the lead-acid system where improvements may provide another generation or more of reliable use. Where non-lithium systems have clear disadvantages not susceptible to correction, an attempt is being made to replace them with higher performance lithium batteries. An example is the silver oxide-zinc system in which silver oxide degrades under thermal stress and must be protected from environmental heat. Replacement with a lithium system will be a breakthrough in the solution of this problem.

FIGURE 1.
BATTERIES FOR NAVAL APPLICATIONS —PRINCIPAL FUNCTIONAL AREAS

DETECTION	FUZING	PROPULSION	GUIDANCE & CONTROL
MINES	MINES	MINES	MINES
BOMBS	BOMBS	TORPEDOES	GUIDED MISSILES
TORPEDOES	FUZES	SUBMARINES	TORPEDOES
GUIDED PROJECTILES	GUIDED MISSILES	TORPEDO TARGETS	GUIDED PROJECTILES
DEPTH CHARGES	GUIDED PROJECTILES	SUBMERSIBLES	TORPEDO TARGETS
TELEMETRY	TORPEDOES	SWIMMER DELIVERY VEHICLES	SUBMERSIBLES
SURVEILLANCE BUOYS	LASER DESIGNATORS	LIFE SUPPORT SYSTEMS	LASER DESIGNATORS
SONOBUOYS	DEPTH CHARGES		
SOUND SOURCES			
ACOUSTIC TRANSPONDERS			
FIELD COMMUNICATIONS			
MONITORING BALLOONS			
LASER DESIGNATORS			

FIGURE 2. ELECTROCHEMICAL SYSTEMS USED (PRESENT AND FUTURE) IN NAVY BATTERIES

$C{-}MnO_2/NH_4Cl,ZnCl,H_2O/Zn$

$C{-}MnO_2/MgBr_2,Mg(ClO_4)_2,H_2O/Mg$

$HgO/KOH,H_2O/Cd$

$HgO/KOH,H_2O/Zn$

$PbO_2/H_2SO_4,H_2O/Pb$

$AgO/KOH,H_2O/Zn$

$AgCl/SEAWATER/Mg$

$PbO_2/HBF_4,H_2O/Pb$

$CaCrO_4/LiCl{-}KCl/Ca$

Li/SO_2

$Li/SOCl_2$

Li/AgO

Li/FeS_2

FIGURE 3.
AUXILIARY PRIMARY BATTERIES

FUNCTIONS	DETECTION		FUZING & DEPLOYMENT		GUIDANCE & CONTROL	
PACING APPLICATIONS	MINES, BUOYS		MISSILES, MINES PROJECTILES		MISSILES	
PRESENT TECHNOLOGY	LECLANCHE, MERCURY, MAGNESIUM		THERMAL BATTERY, RESERVE ENERGIZER		SILVER-ZINC, THERMAL BATTERY	
RELEVANT EXPLORATORY DEVELOPMENT PROGRAMS TO ACHIEVE GOALS	A*		B*		A*, B*	
CAPABILITIES	PRESENT	GOAL	PRESENT	GOAL	PRESENT	GOAL
ENERGY DENSITY (W-HR/KG)	44 TO 110	660	22	88	22-44	88-440
POWER DENSITY (W/KG)	220	1100	880	2640	660	3300
CYCLE LIFE (CYCLES)	N/A		N/A		N/A	
OPERATIONAL LIFE	1 YR	1 YR	10 SEC-5 MIN	10 SEC-20 MIN	2-15 MIN	2-30 MIN
STORAGE LIFE (YEARS)	2-5	10	15	20	5-15	10-20

RELEVANT EXPLORATORY DEVELOPMENT PROGRAMS

A* PRIMARY AMBIENT TEMPERATURE LITHIUM SYSTEMS

B* MOLTEN SALT MATERIALS AND SYSTEMS

FIGURE 4.
PROPULSION BATTERIES

	PRIMARY		RECHARGEABLE	
	WEAPON		VEHICLE	
	(ONE-SHOT)		(CYCLE USE)	
PACING APPLICATIONS	TORPEDOES		SUBMARINES, DSRV	
PRESENT TECHNOLOGY	SILVER-ZINC, Mg-AgCl		LEAD-ACID SILVER-ZINC	
RELEVANT EXPLORATORY DEVELOPMENT PROGRAMS TO ACHIEVE GOALS	A*		B*, C*	
CAPABILITIES	PRESENT	GOAL	PRESENT	GOAL
ENERGY DENSITY (W-HR/LB)	66-88	220-440	22-44	26-220
POWER DENSITY (W/LB)	440	2200	N/A	
CYCLE LIFE (CYCLES)	N/A		20-200	100-500
OPERATIONAL LIFE	2-10 MIN	2-10 MIN	1-5 YRS	3-10 YRS
STORAGE LIFE (YEARS)	5-10	10	N/A	

A* PRIMARY AMBIENT TEMPERATURE LITHIUM SYSTEMS

B* ADVANCED LONG-LIFE RECHARGEABLE BATTERIES (NON-LITHIUM)

C* RECHARGEABLE AMBIENT TEMPERATURE LITHIUM SYSTEMS

FIGURE 5.
FUNDING SUMMARY OF NAVY BATTERY R&D PROGRAMS

	$K	
	82	83
RESEARCH (6.1)	3,203.4	3,218.6+
EXPLORATORY DEVELOPMENT (6.2)	2,587.	2,164.
ADVANCED DEVELOPMENT (6.3)	5,370.	5,796.
TOTALS	11,160.4	11,178.6+

839236

POTENTIAL OF FUEL CELL POWER PLANTS FOR UNDERSEA VEHICLE PROPULSION

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ABSTRACT

Fuel cells can provide a high energy density power source for undersea applications, thus providing extended mission endurance capability. The solid polymer electrolyte fuel cell technology is described, and conceptual fuel cell power plants for 13 and 1818 metric ton submersible vehicles are presented as defined in a study conducted for the Canadian Defense Research Establishment.

INTRODUCTION

Fuel cells were first developed to meet the need for an efficient, high energy density power source which could operate in the hostile environment of space, and they have been very successful in meeting this need. In many ways the power source needs for certain undersea applications face similar constraints and, consequently, may be able to benefit from the technological advancements that have occured in fuel cell development during the past twenty years.

General Electric's solid polymer electrolyte fuel cells were first adapted for undersea applications during the late 1960's when two small power sources were developed for the U.S. Navy for submerged buoy applications. More recently, several studies have been made regarding the potential application of fuel cells for propulsion of undersea vehicles. These studies have shown that, in applications for which a nuclear power plant is not appropriate, a fuel cell power system can provide a long submerged endurance within restrictive weight and volume constraints.

The results of one study, conducted for the Canadian Defense Research Establishment (1), are summarized for different classes of vehicle, -- a small 13 metric ton submersible, for research and exploration, and a larger 1818 metric ton submarine capable of extended submerged operation.

SOLID POLYMER ELECTROLYTE FUEL CELL TECHNOLOGY

Solid polymer electrolyte fuel cells are unique in that there is no liquid electrolyte to present problems of leakage, corrosion, or normality control, or to present any possible hazard or safety concern in the event of an accident or spill. The electrolyte used in the SPE® cells is a solid sheet of plastic, similar to teflon Ⓣ, which has been sulfonated to give it ion-exchange properties that enables it to conduct hydrogen ions. Being a solid material, it also provides a rugged barrier between the hydrogen and oxygen reactants which can withstand substantial pressure differentials; further assuring the safety of the system under both normal and potential abnormal operating conditions.

The electrode structures are merely thin films of catalyst pressed onto the electrode surface. On the cathode side a thin wetproofing film is placed over the electrode to prevent the product water, which forms at this electrode, from filming over the surface and obstructing the access of oxygen to the electrode. This cell construction and the electrochemical reactions are shown in Figure 1. Cells of this type have been life tested for more than 60,000 hours with minimal performance degradation.

SPE fuel cells were originally used during the Gemini spacecraft program in the early 1960's where two 1-KW units provided the onboard electrical power needed during orbital operations. This type of fuel cell was also used in the Biosatellite spacecraft, and Figure 2 shows another 3-KW unit that was developed for the U.S. Navy for a high altitude balloon program. More

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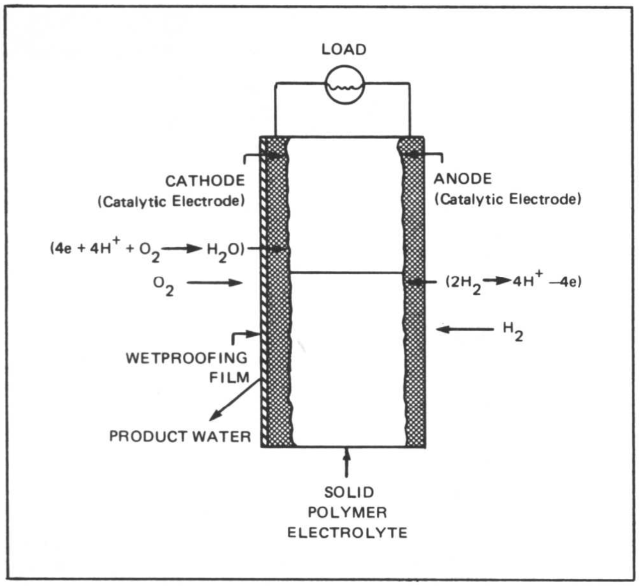

Figure 1. The Solid Polymer Electrolyte Fuel Cell

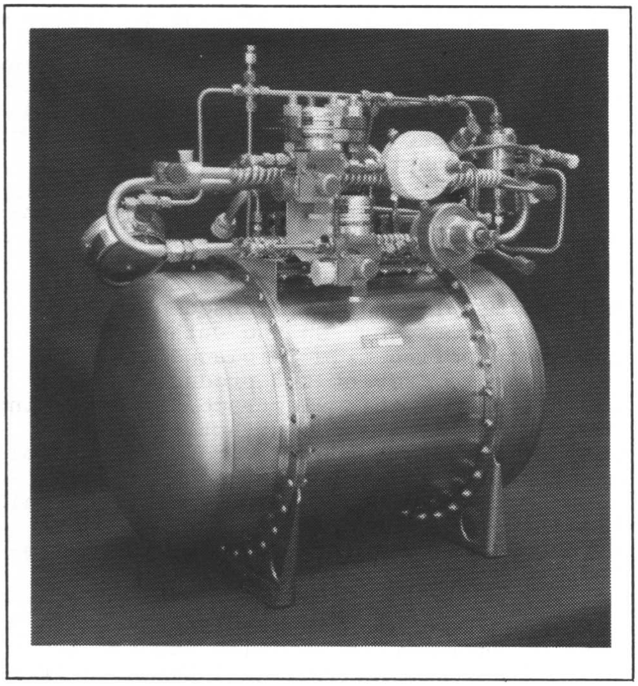

Figure 2. 3 kW Fuel Cell Module

recently a 4 kW advanced design module has completed 2000 hours of operation under a continuing technology development program with NASA's Manned Space Center, and is presently installed in a breadboard regenerative fuel cell system which is being evaluated by NASA as a potential high density energy storage system for future space station applications.

SPE water electrolysis units have also been developed for aerospace, military, and commercial applications using the same basic technology and cell design features as used in the SPE fuel cells. The above regenerative fuel cell system includes an electrolysis unit as well as the fuel cell, and SPE electrolyzers have also been developed for generating hydrogen and oxygen for orbital maintenance propulsion.

The U.S. Navy also plans to use SPE electrolyzers on board nuclear submarines to generate oxygen for their life support systems, and SPE electrolyzers are also in commercial production. Figure 3 shows a prototype of the Navy system which is currently undergoing qualification and reliability testing, preparatory to commencing sea trials in 1984.

The initial undersea application for the SPE fuel cell was as a power source for an underwater sonobuoy. Two different units were developed, one having a 1.8 KWH capacity and the other 44 KWH. Operating on solid chemical reactants, these units were designed to provide continuous electrical power in a sealed enclosure for durations up to one year. Figure 4 shows the 1.8 KW unit being deployed for undersea testing.

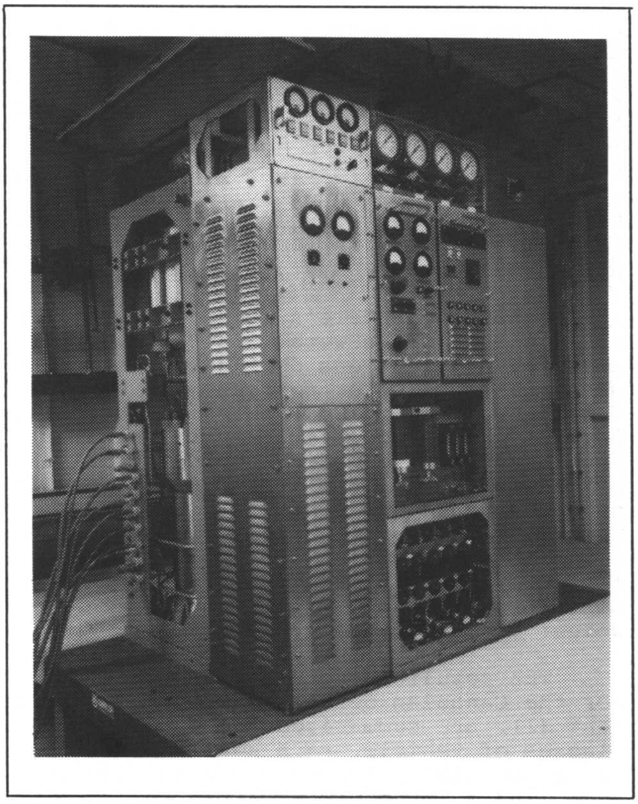

Figure 3. U.S. Navy Submarine Oxygen Generation System

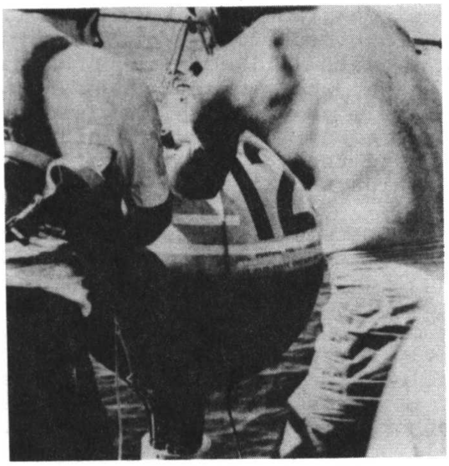

Figure 4. Unit No. 1A in Process of Seawater Installation

Applicability to Propulsion of Undersea Vehicles

A fuel cell powerplant, although not of the solid polymer electrolyte type, has been tested by the U.S. Navy in their deep submergence rescue vehicle and has demonstrated the basic compatibility between fuel cell operating characteristics and the vehicle propulsion system. General Electric has conducted several preliminary studies to define the characteristics of suitable SPE fuel cell power plants for a number of potential undersea vehicle applications. Typical examples include a small 13 metric ton submersible, with a power requirement in the neighborhood of 17 KW to provide power for propulsion, heating, and emergency life support, and a larger 1818 metric ton submarine which requires a power plant of around 2.6 MW capacity. In both cases, the fuel cell appears to be an attractive candidate for the application. (2, 3)

SPE fuel cells are particularly attractive for application in a manned submersible because of the absence of hazardous or toxic liquid electrolytes. SPE cells have also demonstrated a potential life capability in the range of 40,000 to 100,000 hours, which may preclude the need for planned module replacement or refurbishment during the operational life of the vehicle.

17 KW (96 KWH) Power Plant. Three different mission power profiles were defined for the 13 metric ton deep diving submersible, each of which impose quite different requirements on the power plant. The limiting mission, which actually established the power plant sizing is shown on Figure 5. The primary requirements for carrying out these missions are as follows:

Max. steady state power	17 KW
Min. steady state power	0.5 KW
Voltage	105-127 VDC
Maximum weight	1016 kg
Maximum volumn	1 m^3

The fuel cell module proposed to meet these requirements was an adaptation of an advanced hydrogen/ oxygen cell stack being developed for NASA for future spacecraft applications. Figure 6 shows an 18-cell module of this configuration, with .1 m^2 active area cell. This module containing 18 cells was rated at 7 KW. For the 17 KW rating at 120 volts, a stack of 130 similar cells of 0.03 m^2/ cell active area would be used, which would result in a module size approximately 20 cm x 20 cm x 117 cm as shown on Figure 7. The performance of the module is shown on Figure 8.

Because of the relatively small amount of reactants required for the 96 KWH capacity, it was concluded that for this application, high pressure gas cylinders would be the best way to store the reac-

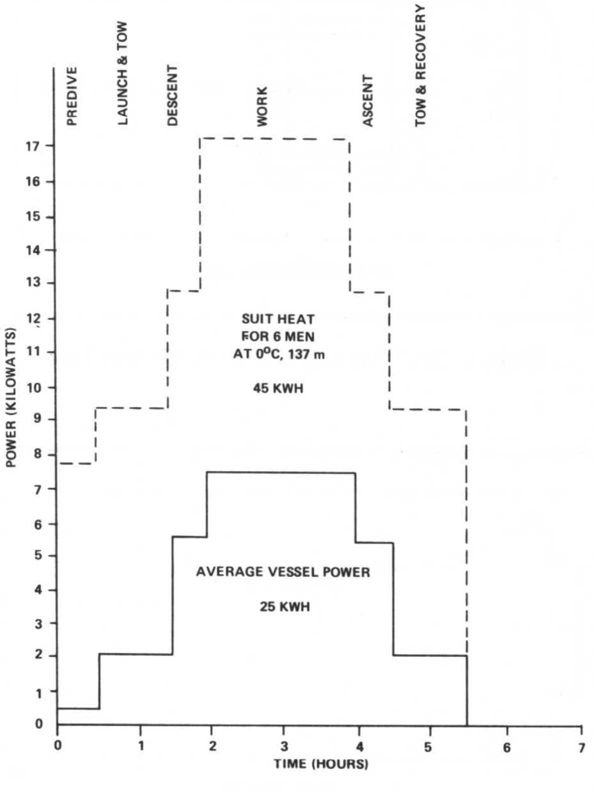

Figure 5. SDL-1 Power Profile Lockout Mission

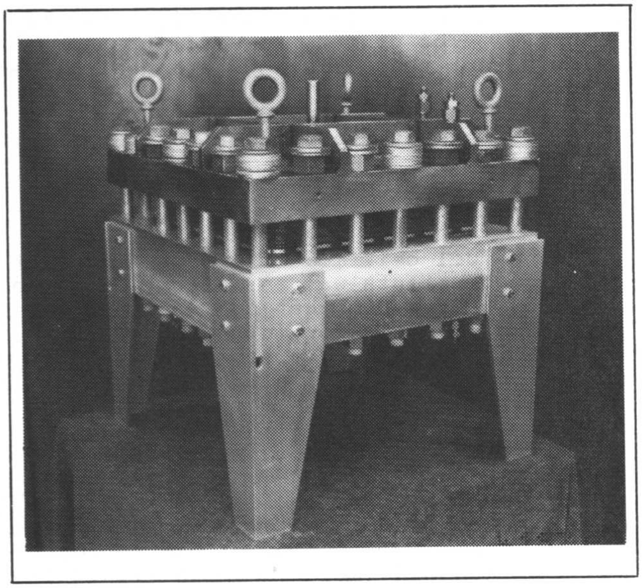

Figure 6. 7 KW NASA Advanced Fuel Cell Developmental Module

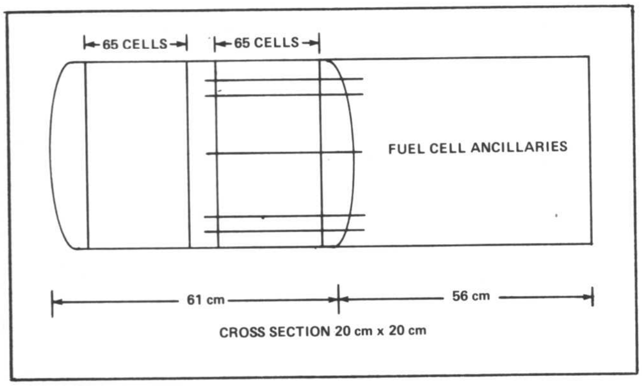

Figure 7. Fuel Cell Module Outline

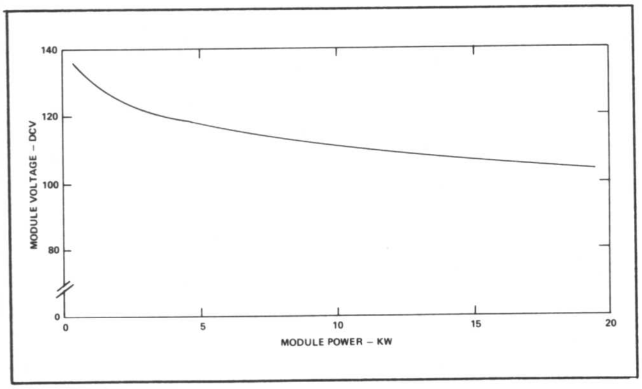

Figure 8. Fuel Cell Module Performance

tants. Four standard 1A cylinders of oxygen and six cylinders of hydrogen will provide the required capacity. The weight of these cylinders (filled) is approximately 825 kg which, when added to the 99 kg for the fuel cell and its ancillaries, results in a total power plant weight of 924 kg. This is more than 91 kg lighter than the specification requirement.

This system weight could be reduced by about 450 kg (to approximately 545 kg) by using light-weight, filament wound high pressure cylinders, resulting in an energy density of about 176 wh/kg. This is significantly better than any available rechargeable battery system, and offers a further advantage in being able to be rapidly recharged for repeated dives. The fuel cell power plant volume would be approximately .76 m^3, about 23% below the specification value.

2.6 MW, (338 MWH) Power Plant. The duty cycle specified for the 1815 metric ton submarine calls for a 1000 hour submerged endurance with 30 hours at the maximum power of 2.6 MW, 320 hours at 0.75 MW and 650 hours at 0.3 MW. The system voltage was specified as 600 to 950 VDC and the maximum power plant weight as 727 metric tons. The use of cyrogenically stored hydrogen and oxygen was stipulated as the baseline system, but alternative reactant systems were also to be investigated.

Considerable flexibility exists in the selection of a fuel cell module size to form a building block for the 2.6 MW power plant. In this case a 325 KW module was selected on the basis of a mission reliability analysis. Twelve of these modules would be used for the complete power plant, connected in a series/parallel matrix such that any eight of the modules would provide the full 2.6 MW power rating.

Each module would consist of 243 cells of .16 m^2 active area per cell. These would be scaled-up versions of the cell described above for the 17 KW module and would comprise a unit approximately 43 cm x 43 cm x 320 cm with a weight of about 563 kg (including ancillaries).

SPE cells have been made in sizes considerably larger than the .16 m^2 active area proposed here with no loss in performance because of scaling. Figure 9 shows a 200 KW SPE water electrolysis module which is comprised of 60 cells of .24 m^2 active area each.

The optimum module size will depend on a detailed analysis of the installation and mission requirements. In another study for a similar power plant rating, the optimum configuration turned out to be the use of a larger number of smaller modules (i.e., in the range of 30 to 50 KW).

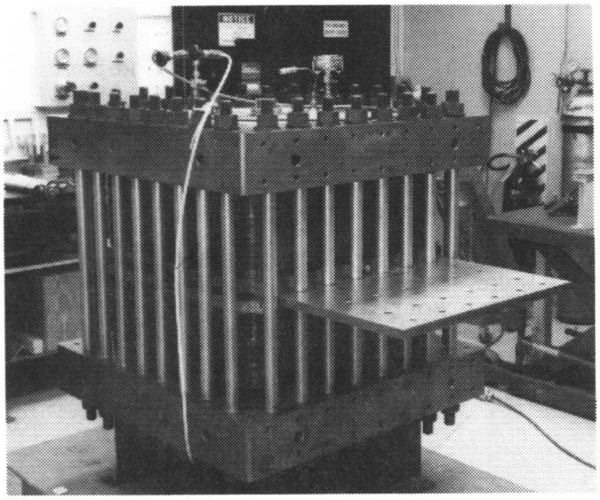

Figure 9. 2000 SCFH (200 kW) SPE Water Electrolysis Module

For the 1000 hour mission, a total of 24,000 kg of hydrogen and 216,000 kg of oxygen are required. These reactants would be stored in 6 commercially available cryogenic dewars each 3.3 m diameter x 18.3 m long, two of these being filled with oxygen and four filled with hydrogen.

Three dewars can fit within the 7.6 m hull diameter along the longitudinal axis and still provide ample space for the fuel cells and other system components.

The total system weight comes out to be around 436 metric tons, which is just over one half on the specified weight of 727 metric tons. However, the required volume is in the neighborhood of 950 m^3 which is almost double the desired value.

Alternate Reactant Sources

While the cryogenic reactant storage was stipulated as the baseline system, there are several other methods for storing hydrogen and oxygen in chemical form which can also be considered. Table I lists a number of alternate combinations of reactant sources, with a comparison of the system weight, volume, initial cost and refueling cost as compared with the baseline system.

The configuration which meets specification requirements for both weight and volume is the one using Sodium Borohydride ($NaBH_4$) as the source of hydrogen, and cryogenic oxygen. However, with this approach, the operating costs would be quite high since the $NaBH_4$ chemical compound is relatively expensive.

CONCLUSIONS

The results of these studies have shown that, for undersea applications in which a nuclear power plant is not practical, an SPE fuel cell power plant can offer a safe, reliable high energy density alter-

TABLE I

COMPARISON OF ALTERNATE REACTANT SOURCES

APPROXIMATE % OF CRYOGENIC SYSTEM VALUE

SYSTEM	I	II	III	IV	V	VI
H_2 System	Cryo	FeTiHx	FeTiHx	$NaBH_4$	MgZnHx	CH_3 OH
O_2 System	Cryo	Cryo	$NaClO_4$	Cryo	H_2 O_2	KO_2
Charged System Weight (kg)	45	338	449	60	259	154
Equipment Volume (m^3)	2.8	.23	3.34	1.3	2.1	2.5
Est. Production Cost (%)	100	102	107	101	95	105
Reactant Cost for Refilling (%)	100	61	406	1872	125	589