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Proceedings of the Workshop on Power Sources for Distributed Autonomous Systems

JILL P. DAHLBURG

Senior Scientist for Science Applications
Executive Directorate

KAREN S. SWIDER-LYONS

Surface Chemistry Branch
Chemistry Division

LEONARD M. TENDER

Laboratory for Molecularly Engineered Materials and Surfaces
Center for Bio/Molecular Science and Engineering

HAROLD J. BRIGHT
RICHARD T. CARLIN

Office of Naval Research
Arlington, VA

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*Laboratory for Molecularly Engineered Materials and Surfaces, Center for Bio/Molecular Science and Engineering
†Surface Chemistry Branch, Chemistry Division
‡Office of Naval Research, 800 North Quincy Street, Arlington, VA 22217-5660

14. ABSTRACT

The Workshop on Power Sources for Distributed Autonomous Systems was held on 23-24 February 2004 at the Naval Research Laboratory in Washington, DC. The purpose was to explore otimization, utilization, and integration of power and energy sources to enable new and high-value DoD distributed autonomous systems capabilities. Four central consensus conclusions emerged.

The realization of future and high-value Department of Defense (DoD) distributed autonomous systems capabilities will require significant focus on power integration. All components of autonomous systems, including power and energy sources, should be considered at design inception and carried through fruition in a concerted effort. Current availability of capable miniature/low-power sensors, communications hardware, data storage and processing tools, platform mobility elements, energy and power awareness, and R&D-oriented systems design provides an expeditious opportunity to achieve new and useful distributed autonomous systems capabilities. Highest likelihood for success is by means of enfranchising multiple small, applications driven, interdisciplinary development teams of scientists, engineers, and DoD customers.

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Proceedings of the Workshop on Power Sources for Distributed Autonomous Systems

SECTION 1: OVERVIEW

The Workshop on Power Sources for Distributed Autonomous Systems was held on 23-24 Feb 2004 at the Naval Research Laboratory [NRL] in Washington DC. The purpose was to explore optimization, utilization, and integration of power and energy sources to enable new and high value Department of Defense [DoD] distributed autonomous systems capabilities. The workshop organizers were Jill Dahlburg, Karen Swider-Lyons, Leonard Tender, Harold Bright, and Richard Carlin. Eighty registered participants -- from NRL, the Office of Naval Research [ONR], the Defense Advanced Research Projects Agency [DARPA], Naval Undersea Warfare Center [NUWC], Naval Surface Warfare Center-Carderock, and selected Universities – attended, representing expertise in areas of power sources, systems integration and military applications. The workshop comprised nine invited talks, two discussion sessions (each with three concurrent sessions, on the subjects of applications: land, sea, and air-based systems; and of power ranges: <1 Watt, 1 to 500 W, and > 500 W-based systems); two poster sessions; and, a "speak-out session" where each participant expressed ideas for future directions.

This workshop provided a unique forum for extensive, focused dialogue on topics relevant to power integration for autonomous systems. Four central consensus conclusions emerged concerning realization of future and high value DoD distributed autonomous systems capabilities:

(1) Increased energy and power density are critical for success of autonomous systems applications for the DoD. Numerous opportunities exist to significantly increase energy and power density which must be pursued.

(2) Increased energy and power efficiency are critical for success of autonomous systems applications for the DoD. Application of recent developments in information technologies (IT), chip design, nano-engineered and polymeric materials, and biomimetics provide good starting points to significantly increase energy and power efficiency, particularly for small devices.

(3) All components of autonomous systems including power and energy sources should be considered at design inception and carried through fruition in a concerted effort. Such a concerted systems approach contrasts with the standard approach as perceived by many workshop participants in which energy and power sources are considered late in design, are therefore highly constrained and may limit overall capabilities of the system.

(4) Current availability of capable miniature/low power sensors, communications hardware, data storage and processing tools, platform mobility elements, energy and power awareness, and R&D-oriented systems design, provides an expeditious opportunity to achieve new and useful distributed autonomous systems capabilities. Highest likelihood for success is by means of enfranchising multiple small, 'application driven' interdisciplinary development teams of scientists, engineers, and DoD customers.

Manuscript approved November 19, 2004.

The workshop schedule is provided in Chart 1, following. Abstracts of the opening presentations, background for the workshop discussion, are given in Sec. 2. In Sec. 3 the breakout discussion sessions are summarized. Remarks from the concluding “speak-out session” are highlighted in Sec. 4. Appendices provide a list of posters and a short bibliography of germane power sources references.

CHART 1. WORKSHOP SCHEDULE

Monday Feb 23rd, 2004

0900 - 0915:	Jill Dahlburg (NRL): DAS Introduction
0915 - 0940:	Robert Nowak (Consultant): DARPA Palm Power Program
0940 -1005:	Richard Carlin (ONR): Electric Power Sources for the Navy and Marine Corps
1005 –1025:	Robert Rosenfeld (DARPA): Power Sources for Autonomous Systems
1045 - 1110:	Maria Medeiros (NUWC): Magnesium-solution phase catholyte semi-fuel cell for undersea vehicles and future UUV requirements
1100 - 1135:	Karen Lyons (NRL): Selecting a power source for a microair vehicle
1135 - 1200:	John Harb (Brigham Young Univ.) Hybrid micropower for microsensing systems
1300 - 1325:	Leonard Tender (NRL): Opportunities for energy harvesting on the seafloor
1325 - 1350:	Adam Heller (UT-Austin) Bioelectrocatalysts & Biological Energy Harvesting Fuel Cells
1350 - 1510:	POSTER SESSION
1515 - 1700:	1st Breakout session – LAND, SEA, and AIR
1700 - 1730:	Present results of 1st breakout session

Tuesday Feb 24th, 2004:

0900 - 0915:	Jill Dahlburg (NRL): Welcome Day 2
0915 - 1130:	2nd break out sessions – <1 W; 1 to 500 W; and, >500 W
1130 - 1200:	Report summaries of 2nd breakout session
1200 - 1300:	LUNCH and “speak-out” session
1300:	Adjourn, take down posters

BREAKOUT SESSION GUIDANCE:

The purpose of this workshop is to identify research opportunities in power and energy for autonomous systems over the next twenty years. Critical areas include solutions for: creating more effective power sources; conserving power and energy; efficient energy use; and, optimal integration of power sources with applications

1st Breakout Session

To achieve these goals, the 1st breakout session will consist of the following three discussion groups denoting regimes of autonomous systems operation (discussion leaders in parentheses)

Sea (Tender, Carlin, and Anderson); Land (Nowak, Schuette); Air (Kellogg, Lyons)

As a starting point, each discussion group of the 1st breakout session should define:

unmet applications – 5 to 20 years;
power regimes of each application (e.g. <1 W, 1-500 W);
energy issues (e.g., energy limits, lifetime, cost, and signature).

2nd Breakout Session

The 2nd breakout session will consist of the following three discussion groups denoting regimes of power required by autonomous systems (discussion leaders in parentheses)

<1 W (Tender, Anderson); 1 to 500 W (Kellogg, Nowak); >500 W (Medeiros/Lyons)

As a starting point, each discussion group of the 2nd breakout session should define:

solutions for creating more power/energy;
solutions for more efficient energy use;
solutions for conserving power/energy; and,
practical integration issues.

SECTION 2: SUMMARY OF OPENING BRIEFINGS

Jill Dahlburg *(NRL Senior Scientist for Science Applications)*
DAS Introduction: Dr. Dahlburg noted the purpose of the workshop, which follows in the tradition of Navy new directions R&D technical meetings: to provide a forum for the discussion of scientific advances and opportunities in the production, storage, exploitation and integration of power for future applications of DoD as well as other civilian sectors that require lightweight, long-lived, and possibly ubiquitous power sources. Autonomous systems enable precise placement of sensors to enable real-time situational awareness and volumetric management. They range from systems with a few nodes, in which sensors, communication and agents are combined on single platforms, to those with a multitude of distributed nodes that have 'high performance computing in the loop.' Many-node Distributed Autonomous Systems [DAS] will enable volumetric control in situations that range from the systematic to the ad hoc. In the latter systems, environment will be largely unpredictable or unconventional, and DAS mobility will be needed to provide an ability to adjust. Although significant work has been ongoing for some time in the wider areas of distributed sensor systems, to date few concepts have tried to exploit large-N (1000's or more) DAS; few have exploited short standoff distances made possible by the large-N concept; none have exploited sensor modalities that are uniquely enabled by these new modalities; and, few have attempted to address full-scale integrated systems. Dr. Dahlburg posed the question: 'we have massively parallel computers; why not also massively parallel distributed autonomous systems for real world volumetric control?' She noted that central to DAS developments are issues of power, primarily optimal integration of power sources, both for defined applications and also for developments starting from specific power source identification. She concluded by observing that for rapid advances toward large-N DAS deployments, DAS-focus systems integration – with the issues of power central and possibly foremost – may be the key next R&D activity.

Robert Nowak *(consultant, formerly NRL, ONR, and DARPA)*
DARPA Palm Power Program: (program manager: Dr. Valerie Browning). The goal of the Palm Power Program is to create portable power sources with 10 to 20 times the specific energy of batteries for 3 - 240 hour missions at 20 Watts average power. Such power sources are required to provide energy for legacy systems or those under development for which batteries are inadequate. Energy conversion devices that employ liquid hydrocarbon fuels are the most promising route to achieving the Palm Power goals. Compact direct methanol fuel cells have been developed and are now being evaluated by the military. A robust rapid start up, 20W tubular solid oxide fuel cell that operates on butane/ propane was discussed.

Richard Carlin *(ONR 333 Division Head)*
Electric Power Sources for the Navy and Marine Corps: Dr. Carlin discussed how improved power sources are needed over a broad range of power levels to fulfill Naval needs. ONR has recognized the overall need for improved power sources in the "Grand Challenge" for electric power. ONR is looking at solid-state energy conversion devices, and has a new energy and power initiative. He described the complexity of using a fuel cell for ship service and for undersea vehicles, and stressed that the system must be

carefully considered. Oxygen storage is a major issue for the undersea operation of fuel cells and other air-breathing devices. ONR is also investigating opportunities in new fuels to help develop the Navy after Next.

Robert Rosenfeld *(DARPA TTO Program Manager)*
Power Sources for Autonomous Systems: Dr. Rosenfeld described many of the autonomous systems currently in development in DARPA's Tactical Technology Office, including both air and ground vehicles. A regenerative fuel cell may serve as both an energy storage device and source of propellant in space (using H_2 and O_2). Novel small engines are being developed, with a focus on using hydrocarbons as the fuel. Dr. Rosenfeld discussed the considerations needed in development of a power source, by defining the requirements (e.g. need for voltage, current, torque, endurance, power bursts, etc). Hybrid systems can be used to achieve numerous power and energy demands, as in the Combat Hybrid Power Systems (CHPS) program. Dr. Rosenfeld emphasized that the system environment, space, air, land or sea, will also dictate what power source can be used.

Maria Medeiros *(NUWC)*
Magnesium-solution Phase Catholyte Semi-fuel Cell for Undersea Vehicles and Future UUV Requirements: Dr. Medeiros discussed ongoing research at NUWC to replace the silver-zinc batteries currently used in unmanned undersea vehicles with a power source having 10x greater capacity. Research is focused on power sources for new-generation torpedoes, 21" Unmanned Underwater Vehicles [UUVs], and Mission Reconfigurable [MR]UUVs. Researchers at NUWC are targeting magnesium semi fuel cells to achieve 4-5X the proposed goal. The magnesium electrodes use seawater as the electrolyte and peroxide as the oxidant, Nafion membranes, and new Pd/Ir catalyst at the cathode. NUWC has been testing the cells in specialized facilities and has also created new cell module designs necessary for the UUV application. The performance of the cells can be optimized with system modeling. She also presented the system environment for MRUUVs (operating temperature, salinity range, pressure, etc). The energy of the missions is from 50 to 100 kWh, and must be confined to specific dimensions and weights. The system must have a specific energy of at least 130 Wh/kg, but preferably be as high as 500 Wh/kg. A polymer fuel cell is being investigated for the mission. Fuel and oxidant storage and replenishment pose major technical issues.

Karen Swider Lyons *(NRL, Chemistry Division)*
Selecting a Power Source for a Micro Air Vehicle: Dr. Swider-Lyons described a new effort at NRL to fly a small air vehicle with a proton exchange membrane fuel cell (PEMFC) for 8 hours at night. She outlined many of the criteria that must be used to determine whether the mission can be successful. In order to meet the mission goals and outperform state-of-the-art batteries, the entire fuel cell system (stack, pumps, and fuel source), must be light and be operated at high efficiency. As a fuel source, both hydrogen gas and chemical hydrides are being considered, both of which have positive and negative attributes. Lastly, the cost of the whole system must be kept reasonable to be practical to the military. Dr. Swider-Lyons emphasized that it is important to build the device around the power source, so that the appropriate trades in design can be accommodated. The project team includes NRL experts in fuel cells and air vehicles, and

researchers from Directed Technologies of Arlington VA who are modeling the system for optimum performance. A demonstration test flight is expected in June of 2004.

John Harb *(Brigham Young University)*
Hybrid Micropower for Microsensing Systems: Professor Harb discussed research at BYU for "systems on a chip." As part of this effort, they have are developing and assimilating components for autonomous operation of micro-sensing systems, including energy storage, energy harvesting, and control/interface circuitry. Micro-sensing systems require milliWatt bursts of power, which can be achieved with Ni/Zn thick film batteries. The micro-fabricated batteries are optimized via modeling for high performance, and have been operated over several weeks for thousands of cycles. To recharge the batteries, they can be integrated with a solar cell. The team has developed low-power circuitry to allow the battery to be charged evenly with variations in solar power. The batteries can also be linked in arrays. In addition, BYU researchers have developed micro-sensing switches and thermal actuators, which can be integrated with the micro-batteries, or be used independently as sensors.

Lenny Tender *(NRL, Center for Bio/Molecular Science and Engineering)*
Opportunities for Energy Harvesting on the Sea Floor: Dr. Tender described the opportunities for electrochemical power generation on the seafloor for the eventual powering of stationary autonomous distributed systems nodes. The common feature of these opportunities is the proximity of fuel and oxidant on the seafloor and their straight-forward utilization to electrochemically generate sustained electrical power indefinitely. One such opportunity centers on oxidation of sediment organic matter with seawater oxygen. Throughout most of the continental margins, organic matter resulting primarily from sedimentation of phytoplankton detritus accounts for 0.1% – 10% of sediment weight. Typical organic matter content of sediment of these environments is ~2%. As a point of reference, the energy density of such sediments based on complete oxidation of organic matter content with oxygen is ~ 17,000 watt-Hr per cubic meter; equivalent to that of ~ 1100 alkaline D-cell batteries weighing ~152 kg and occupying ~62 L. This is enough energy to operate autonomous device requiring 1.0 watt time averaged power for ~1.9 years not taking into account sedimentation of additional organic matter or diffusion from adjacent sediment. Dr. Tender has demonstrated that a 2-electrode device (the so called "BUG" – Benthic Unattended Generator), consisting of an anode imbedded in marine sediment and connected by an external electrical circuit to a cathode in overlying seawater, can accomplish this reaction and capture the concomitant electron transfer as electrical current though an external circuit which could used to power such devices. This approach is ultimately limited by mass transfer (diffusion and convection) of fuel (sediment organic matter) and may be well suited only for sub 1-Watt applications. Dr. Tender subsequently described abundant features on the seafloor (such as seeps, vents, and hydrate outcrops) where fuel mass transfer is orders of magnitude greater and therefore the prospect for orders of magnitude greater power generation exists. He recommended that mission-relevant unattended sensors should be a priori designed and developed in ways that take advantage of these vast undersea natural power resources.

Adam Heller *(UT-Austin)*

<u>Bioelectrocatalysts and Biological Energy Harvesting Fuel Cells:</u> Dr. Heller described a bioelectrotrocatalyst superior to platinum in the electroreduction of oxygen to water near neutral pH and proposed safe and simple plastic packaged metal-air cells, of high energy density and higher power density than that of the zinc-air cell. He also described his recent advances in design of miniaturized bio-fuel cells that utilize selective 3 dimensional catalysts of electro-oxidation and electro-reduction of biochemicals. The catalysts are based on electrically connecting ("wiring") the reaction centers of immobilized redox enzymes to electrodes through electron conducting redox hydrogels. The wired enzymes enable applications in vivo and miniaturization of electrodes. Dr. Heller described a fuel cell consisting of two such electrodes, that when inserted into a whole grape, could generate electrical power from oxidation of glucose and reduction of oxygen contained within the grape. This fuel cell operates at a temperature and alkalinity close to those of normal blood and produces about the same amount of power as a wristwatch battery (~1.9 microwatts). Such bio-fuel cells could eventually power miniature glucose sensors for monitoring diabetics, autonomously monitor a wide range of other physiological parameters (stress, heart rate, temperature, etc) of a warfighter for remote assessment of their condition/situation.

SECTION 3: SUMMARY OF BREAKOUT SESSIONS

Session I: Regimes of Autonomous Systems Operation

BREAKOUT DISCUSSION SESSION (I-a): SEA

The subject area of sea-based autonomous systems include a wide range of devices, with broad functionality and operational environments. This breakout group focused on defining several of the applications. One vision of future sea-based distributed autonomous systems capabilities is total control of littoral environments (and beyond) involving passive monitoring and reporting and soft killing abilities. Realization of such visions requires a high density of many autonomous system nodes (> $100/km^2$). A clear distinction with respect to energy and power needs can be made between stationary (fixed station) nodes (e.g., SEPTR) and those that move about (propelled nodes). A further distinction can be made among propelled nodes: those utilize active propulsion (e.g. MIRV) and those that drift (e.g., an ARGO float). A total sea-based Distributed Autonomous System would involve a network of many different nodes, each presenting unique energy and power needs that must be optimally satisfied. Furthermore, designing a node around unique energy/power sources (e.g. energy harvesting) may result in high-value capabilities not yet predicted. Specific points raised by discussion session participants include:

- Dissolved oxygen in sea water should be explored as viable oxidants for sensors requiring milliWatts
- Energy conservation with respect to propulsion of UUVs leads to the question: can UVVs benefit with respect to reduced drag by moving in formation like birds/cyclists/race cars?
- Better Mg or Zn/seawater batteries should be explored
- Enzyme–based electrodes (see Heller's invited talk) should be explored as a viable means to plant nodes on fish and other creatures where such nodes derive their power from circulating glucose, and in blood stream
- Nuclear power should be explored for use in persistent sensing systems
- In situ oxidation of sulfide and ethane flux associated with seep, vents and hydrates should be examined for persistent power > 1 kiloWatt
- Energy harvesting should be explored for persistent power < 1 Watt
- Drawing from behavior of microorganisms, quorum sensing should be explored as an effective means for autonomous soft kill capabilities. Here, individual nodes detect presence of other nodes, which initiates a response. Free drifting nodes could be designed, for example, to detect and destroy mines. Such nodes could detect mines by paramagnetism or chemical signature and attach to them. When a critical number of nodes attach a single mine, each node could detect the presence of others (by low power acoustics, for example) and simultaneously self-destruct. (Quorum Sensing should be explored for land-based applications as well.)
- Nature/biology is full of examples of efficient sea-based propulsion. We should study and learn from these examples.

- In the design of any sea-based system, it is important to consider: deployment; stealth and covertness; miniaturization; energy conservation/ management; efficient transduction of power to the surface; and efficient real-time telemetry as related to power loading.

BREAKOUT DISCUSSION SESSION (I-b): LAND

The breakout session looking at land requirements focused on defining what capabilities were desired, attributes, and technology solutions. The overall finding was that a system design approach that incorporates the attributes of the power source, power sink and mission profile is highly desirable.

“Soft kill” capabilities were identified as requiring low power (e.g., <100 W). This class of devices would include those for multimodal surveillance (monitoring, perimeter protection) and would be positioned for detection of radiation (0 – Thz), Chem/Bio and nuclear hazards, and physical or seismic changes. The devices would have to be able to function in both a continuous mode and be able to fluctuate with a state of change. They should also be undetectable so they can be operated in denied areas of operation, have long operational duration, be tamper proof, and be able to serve in a multifunctional network.

A key technology needing improved power sources is communication. Line-of-sight communications include optical and RF, but an infrastructure is required (e.g., 1 W for Low Earth Orbit). Non-line-of-sight communications include relays and devices that can function at low data rates.

Power sources for sensors must also be developed. Typical sensors operate at 1 W today, but are likely to operate at the mW and μW levels in the future.

Unattended devices will require energy harvesting hybrids, e.g., photovoltaics, thermo-electrics, mechanical (MEMS, piezoelectric) coupled with an energy storage devices, such as batteries and/or capacitors. Nuclear power sources might also be an option for long-duration mission. They would also have to be integrated with a battery or capacitor for load leveling.

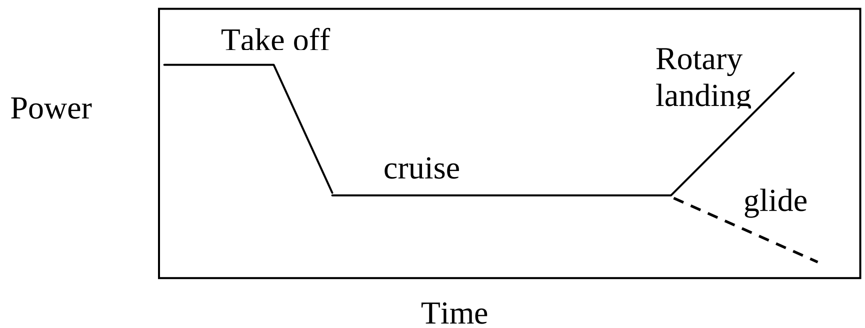
The relationship between power and time must be considered when coupling power sinks and sources. High power (Watts) will be needed for any devices requiring mobility. High energy (Watt-hours) is needed for devices that must operate unattended for a long duration.

Power conservation is critical in all of the missions. Methods must be devised to either turn off the power consumption of the power sinks, or use the power more efficiently. For the latter case, the use of hybrid systems can also be beneficial, as the efficiency of sources can vary with load (current), so several systems can be used to higher efficiency. By considering the power source during the design of the device, engineers can seek solutions in energy conservation that will not compromise the mission.

BREAKOUT DISCUSSION SESSION (I-c): AIR

This breakout session identified power and energy issues specific to air vehicles. It was focused mainly on non-space applications. The main criteria for air vehicles is that they have the power and energy for speed, height, range and terrain covering.

Missions for air vehicles tend to be unique, as they start at high power for several minutes during launch, followed by typically a cruise period at a much lower power level (3 to 10x lower). At the end of the mission, the power either falls off if the vehicle glides to land, or it can increase in the case of helicopters, which need to increase their blade speed for a controlled landing. A typical power profile is shown in the figure below.



During the cruise period, there may also be a need for additional power to accommodate course changes. In contrast, an electronic device would operate at a certain power, with short bursts (seconds) for transmission or other functions. The flight mission requires the extended periods of high power coupled with the low power.

The weight of the power source is critical for successful air missions, since the weight directly affects the viability of flight. The trend in air vehicles is that the technology will get smaller, which poses new problems with power sources: they tend to decrease in specific energy and power as they become smaller (due to the larger surface area to volume ratio). This effect makes the search for the versatile power-dense source more complicated. Efforts to utilize new technologies (e.g. MEMS) that can offer weight reduction must be explored.

One route to conserving energy in small flight vehicles is to modify their mission so that they can periodically rest and harvest energy. Such vehicles might fly and perch, or hop and wait. These would require a hybrid system with a high specific power energy storage device, plus a means for recharging from the environment (solar energy, energy harvesting/ piracy, etc). The benefit of such systems might be realized through modeling, which could trade the weight of the storage and harvesting components vs. the required power and energy of the mission.

Hybrid systems might also be useful for addressing the power profile above, for instance by coupling batteries rated for high and low power, or batteries and capacitors. Hybrid engine/battery systems might be to generate the combination of torque, cruising power and electrical power needed for helicopters. Again, modeling would be able to show whether the vehicle could accommodate the weight of the hybrid systems (two power sources and the electronics for their management). The group recognized that facile software for modeling would be a benefit for the design of new systems.

Other additional considerations for flight missions are to minimize noise and IR signature. It is also important to consider the environmental impact of the system. An environmentally benign system might save energy by not returning home at the end of a mission and simply degrading or self-consuming.

Session II: Regimes of Power Required by Autonomous Systems

BREAKOUT DISCUSSION SESSION (II-a): < 1W

Sub 1 Watt-based Autonomous Systems represents a wide open field with unlimited opportunities for high value Distributed Autonomous Systems. One only needs to look at the diversity of hand held consumer electronics devices to begin to appreciate this point. It is clear that batteries will be the dominate energy source in this power regime for the foreseeable future. It is important to note here that a device consuming an average of 1 Watt for a year requires ~8770 Watt—Hrs on energy, or ~440 Alkaline D-cells. Higher energy and high power density batteries must therefore be developed in order to optimize/miniaturize sub 1 Watt devices. Energy harvesting approaches should be explored as means to greatly extend operational lifetimes of such devices beyond those achievable by batteries. Two examples of energy harvesting were presented at the workshop (Tender and Heller, Sec.2 above) which may significantly impact Sub 1 Watt applications. Energy harvesting on the seafloor (Tender) may enable persistent operation of 1000's of sub 1 Watt system nodes on the seafloor, and enzyme-based bio-fuel cells (Heller) could enable devices to be powered by whole fruit, living organisms, or other abundant advantageous energy supplies. Solar, wind, thermal, and mechanical energy sources need to be/ should be optimized as well.

Specific points raised by discussion session participants include:

- Short-term mission/disposable/low cost/devices
- Nano-batteries should be explored (for smart dust)
- High number/distributed sensors
- Membranes that concentrate oxygen
- Bio-telemetry
- Random, deployed drifting/parasitic sensors
- Submarine to deploy fish with bio-fuel cell powered devices
- Environmentally benign and/or biodegradable
- No signature
- Micro UUVs deployed by mini UUVs
- Better solid state batteries
- Enzyme engineering
- Bacteria-based sensors
- Energy harvesting

- Hybrid systems for energy storage

BREAKOUT DISCUSSION SESSION (II-b): 1 to 500 W

The 1 to 500 W power regime encompasses a range of devices and missions currently used by the military. 1 to 10 W is needed for stationary platforms, sensors, low bandwidth communication, and “burglar-alarm”-type reactions. Power from 10 to several hundred watts is necessary for high bandwidth communication, active sensors, and locomotion of small autonomous vehicles (aircraft and robots). The present military power sources for the 1 – 500 W power regime are $LiSO_2$ primary batteries and lithium-ion rechargeable batteries. Whereas improvements in present power sources are likely, they will only extend current capabilities. To enable new capabilities, new advances power sources are needed.

Logistics fuels are energy dense, and new power sources are being developed that can convert the energy of the fuel into electricity. Diesel fuel has a capacity of 12,000 Wh/kg, the 100 to 300 Wh/kg of most Li batteries; however, the mass of the energy conversion device and efficiency will lessen this number. Solid oxide fuel cells may be able to operate on logistic fuel at approximately 30% efficiency, as discussed in Dr. Nowak’s presentation, and a total system (20 to 150 W) may be able to achieve >1000 Wh/kg for 3 day missions. New Stirling engines also show promise, and may also operate in excess of 20% system efficiency when configured with a JP8 or diesel burner.

Energy harvesting may be a viable source of power for devices operating at 1 to 10 W. Opportunities lie in the areas of solar power, fluid motion, and bio-harvesting. The mission must be carefully considered for energy harvesting systems, as the energy/fuel availability can vary.

Energy scavenging also arose as a key opportunity for devices operating in the 1 – 500 W regime. Autonomous vehicles might be designed to extract power from power lines, cell phone towers (microwaves), gas pipelines, and fiber-optic lines that carry power for repeaters.

In addition to the development of new power sources, the group concluded that gains could be had from improving the integration of the power sources and energy management. Power source integration can be improved simply via modeling and the implementation of hybrid systems for load following of power peaks. The power source can also be integrated better by taking advantage of the vehicle/platform structure as part of its packaging and thereby lower the weight and volume of the power source. Both of these routes imply a knowledge of expected operations, and also of ongoing collaborative research with fielded prototypes. Power source integration, particularly in weight-sensitive expeditionary development regimes, is very mission and system specific.

Energy management can also be improved by modeling and the use of hybrids. Small (1 to 10 W) autonomous systems might also be built to go to sleep to conserve energy and power, and hybrid systems can be exploited to match power levels efficiently.

BREAKOUT DISCUSSION SESSION (II-c): > 500 W

Many of the military's unmanned vehicles require power in the 1 to 5 kW range, including UUVs (unmanned undersea vehicles), USCs (unmanned surface craft), UGVs (unmanned ground vehicles), and UAVs (unmanned air vehicles), to name a few. The Navy is also investing in improved power plants for ship service, which, although is a "manned" mission, might enable the use of less oversight. In this power regime, there is no goal for decreasing the power of the mission – most missions would actually benefit from power sources with higher power to enable more capabilities.

Batteries and engines are the power sources that are currently used in the 1 to 5 kW power regimes. There may be opportunities in the future for fuel cells. The capacity of batteries can only be increased moderately (factors of 2-5). Fuel conversion systems (engines and fuel cells) have the most opportunity if they can be efficient and compact. The use of new alternative fuels (metals, refined hydrocarbons, etc) might facilitate the specific power and energy of engines and fuel cells. Note that the need for oxygen complicates the use of fuel conversion systems for undersea applications.

The development of new power sources in this power regime requires a high level of pre-engineering and systems integration. Unfortunately, the commercial need for 1 to 5 kW power sources is low (only auxiliary power), and batteries are typically optimized for portable power, and engines/turbines for power plants, leaving a significant development gap for military needs. The breakout group discussed that 6.4 development programs can fail due to a lack of 6.2 research on modeling or pre-engineering. Furthermore, there are still research opportunities on power sources in the 1- 5 kW range (e.g. for engines) that have not been fully explored, and may have unusual thermodynamic cycles.

Some of the key problems for power sources in the 1- 5 kW region are shared across all power regimes, such as efficiency, noise, and inadequate materials. There are also more unique problems in this regime, such as the management of waste heat, which is exacerbated by inefficient or poorly engineered power sources. The waste heat problem scales with size, as the surface area to volume ratio decreases, and becomes an increasing burden. Another problem that is specific to military missions is the unique power profile: the need for energy at a constant power, interspersed with periods (3 to 10 min) of 10 to 100x more power. This power profile is necessary for military vehicles that need to cruise, and then exert high power for propulsion (see discussion above for the AIR break-out session). The duty cycle of the mission prevents the use of capacitors or electrochemical capacitors, which are adequate for power bursts from milliseconds to several seconds. Generally speaking, consumer products do not have such a power profile, making this a military specific problem.

Solutions to developing more effective power sources would be to develop or utilize alternative fuels, rigorous pre-engineering and modeling of system and vehicle design performed in tandem with the field customer, and the implementation of hybrid power sources.

SECTION 4: "SPEAK OUT SESSION" HIGHLIGHTS

At the end of the workshop, the participants were asked to concisely voice their findings from the workshop. Many of these statements are paraphrased below, as informal workshop summary.

- We need to look to solar cells and beyond for energy harvesting: huge opportunities lie in photovoltaics, biochemistry and bio-electrochemistry, and there are untapped prospects for chemical and mechanical harvesting.

- People talk about building the device around the power source but it rarely happens, either one has a new power source with no mission or a mission with no power source. This mindset needs to change for successful new developments: we need to 'marry' the vehicle and the power source together early in development, by means of scientists, engineers and DoD customers working together in small 'application driven' teams that have as goal systems prototyping and testing.

- The Navy can play a fundamental role in developing realistically useful distributed autonomous systems [DAS]. It brought into existence the nuclear fleet by recognizing power to be the integral and primary issue. This perspective may also be valid for DAS deployments.

- The new power sources, and efficient and integrated systems that have been envisioned in this workshop will provide very high value to future military operations. Their ubiquitous development is possible, and it is thus critically important for the DoD to engage this opportunity.

APPENDIX A: LIST OF POSTERS

Biocomposite Nano-Architectures: Protein Superstructures as Artificial Mitochondrial Energy Sources: Jean Marie Wallace, Jane K. Rice, Kristin B. Eden, Rhonda M. Stroud, Jeremy J. Pietron, Jeffrey W. Long, and Debra R. Rolison, NRL Surface Chemistry and Sensors and Materials Branches

Communication Networking Techniques Can Provide Improved Energy-Aware Performance: Energy-Aware Broadcasting and Multicasting in Wireless Networks: Jeffrey E. Wieselthier and Gam D. Nguyen, NRL Code 5521; Anthony Ephremides, E&CE Dept., UMD.

Designing Hybrid Nano-structured Electrode Platforms for High-Performance Electrochemical Capacitors: Jeffrey W. Long, Todd M. McEvoy, Brett M. Denning, Christopher P. Rhodes, & Debra R. Rolison, NRL Code 6171

Flexible Organic Solar Cells: Gary P. Kushto, Heungsoo Kim, Woohong Kim, Alberto Piqué, Zakya H. Kafafi, NRL

Improvements on Li-ion Batteries as Autonomous Power Souces: Arnold Stux, Jeremy Pietron, and Karen Swider-Lyons, NRL Code 6171

Laser Printing of Integrated Micropower Sources: A. Piqué[1], H.S. Kim[1], M. Ollinger[1], R.C. Auyeung[1], C.B. Arnold[2] and T.E. Sutto[3]
[1] NRL Code 6364; [2] Department of Mechanical and Aerospace Engineering, Princeton University; [3] NSWC-Dahlgren Division, Code B54, Dahlgren, VA 22448

Nanostructured Catalyst Architectures for Improved Fuel Cell Performance: Terence L. Schull (PI), Walter J. Dressick, Susan L. Brandow, Mu-San Chen, NRL Code 6900; Karen Swider-Lyons, Christopher Klug, NRL Code 6171

Photovoltaic Powered Optical Data Links for Autonomous, Miniature Sensor Systems: Robert Walters, NRL Code 6818; Charmaine Gilbreath, NRL Code 7215; William Rabinovich, NRL Code 5652; Glenn Creamer, NRL Code 8231; Phillip Jenkins, Ohio Aerospace Institute; Mark Smith, Ohio Aerospace Institute; David Wilt, NASA Glenn Research Center

Status of SiC Switches and Converters: Fritz Kub, Code 6880

Selecting a Power Source for a Microairplane: Karen Swider Lyons and Peter Bouwman, NRL Code 6171; Danielle White, Matt Panaro, Jim Kellogg , NRL Code 5712; Greg Ariff and Brian James, Directed Technologies, Arlington VA

Ultra Light Weight High Power Density Photovoltaic Device: Nikolai Lebedev and Scott Trammell, NRL Code 6900

APPENDIX B: POWER SOURCES BIBLIOGRAPHY

Tutorials on fuel cells, batteries, photovoltaics:
http://voltaicpower.com/Site-Map.htm

NAS, Energy Efficient Technologies for the Dismounted Soldier, 1997:
http://www.nap.edu/books/0309059348/html/index.html

JASON, Portable Energy for the Dismounted Soldier, JSR-02-135, June 2003
Free download: http://www.fas.org/irp/agency/dod/jason/porten.pdf

DOE, Fuel cell handbook (sixth edition):
www.fuelcells.org/fchandbook.pdf

DOE, Education on fuel cells and hydrogen
http://www.eere.energy.gov/hydrogenandfuelcells/education.html

LANL, Fuel cell tutorial: Green power:
education.lanl.gov/resources/fuelcells/fuelcells.pdf

NAS, the Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs Report Feb 2004
http://www.nap.edu/books/0309091632/html/

DOE, Workshop on Portable Power, 15-17 Jan 2002
http://www.eere.energy.gov/hydrogenandfuelcells/fc_portable_power_workshop.html

NSF-IC Report on Approaches to Combat Terrorism (ACT) (October 2003)
www.mitre.org/public/act/10_22_final.pdf

The CD proceedings below are available at the following web site:
http://nrlbio.nrl.navy.mil/Research/TenderInfo/Tender.asp

- ONR, Workshop on fuel cells for unmanned undersea vehicles, 29-31 Oct 2003 (CD)
- ONR Grand Challenge Workshop: Electric Power Sources for the Navy and Marine Corps, 16-18 Nov 1999 (CD)
- ONR Grand Challenge Workshop: Naval Fuels 4Jun 2001 (CD)
- Soldier Power and Energy Workshop Oct 2002 (CD)
- IEEE AUV 2002 (CD)
- ONR, Electric ship workshop May 2002 (CD)