A Survey of Available Underwater Electric Propulsion Technologies and Implications for Platform System Safety

Clinton Winchester, Justin Govar, Julie Banner, Tracey Squires, Patricia Smith, and Peter Keller

AUV2002 Energy Systems Workshop
June 20-21, 2002
South Western Research Institute, San Antonio, TX

Naval Surface Warfare Center, Carderock Division
Code 644, Power Systems Branch
9500 MacArthur Blvd
West Bethesda, MD 20817-5700

Disclaimer and Limitation

- This talk presents information on the subject of electrochemical power system safety for platform integration, including but not limited to various lithium based chemistries and the safety requirements, testing protocols, and the integration requirements for use in US Navy applications and from US Navy platforms
- Nothing in this presentation shall be construed as contractual or technical direction to current, ongoing or future contracts

Background

- This presentation is intended to familiarize and reacquaint the audience with aspects of using high energy power sources and implications for Platforms
- Some of the images and videos shown in this presentation are the results of deliberate, extreme and aggressive battery performance evaluations and abuse tests.
- These examples depict events that can and have occurred during routine Navy activities.

AUVs and Power Systems

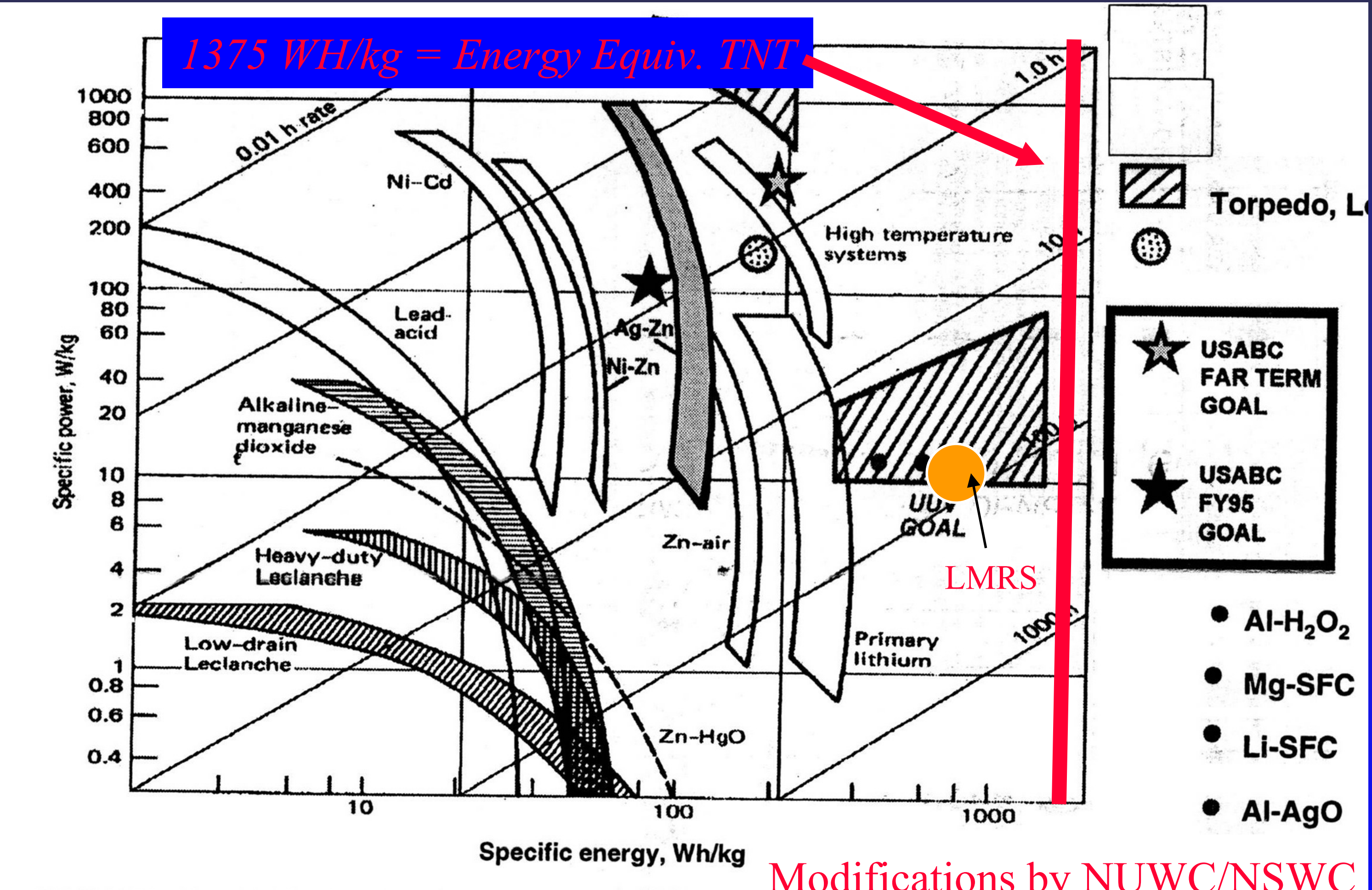
- Higher endurance AUVs permit
  - Cost effective missions
  - Enables missions not otherwise possible
- Higher endurance AUVs require higher energy density storage
  - Larger AUV with scale-up
  - Higher energy density power systems
    - Electrochemical (battery, fuel cells)
    - Thermal engines (hot-rock turbines, SCEPS, AIP)
- *Higher Energy Density means greater risks and challenges in system integration*

Various AUV Systems Sizes

Electrochemical Systems Demonstrated and used in AUVs

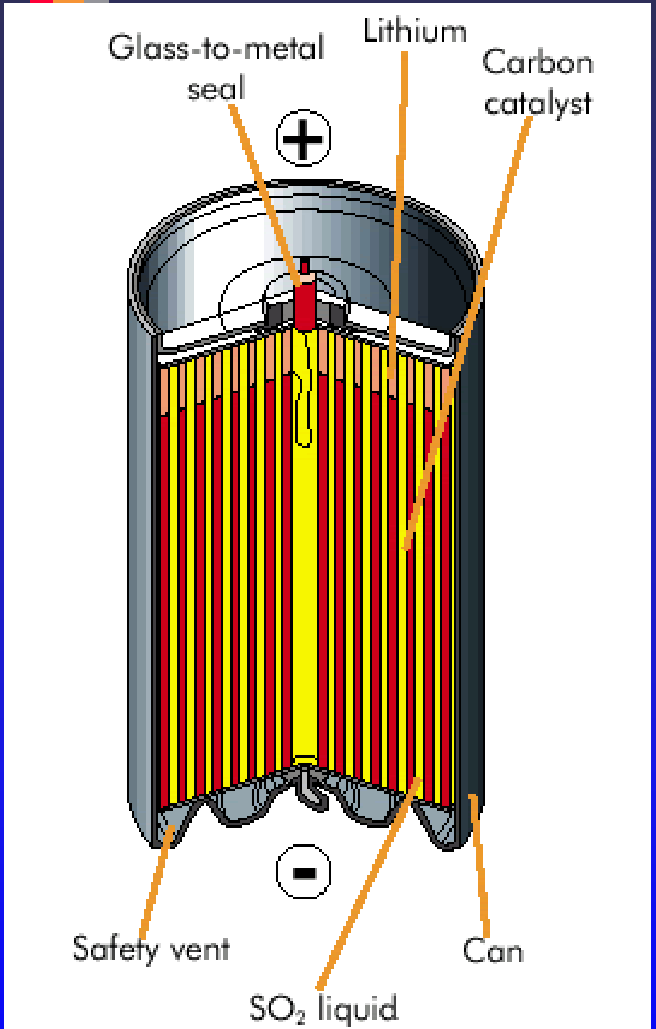
- Battery systems
  - Reserve – Li/SOCl2, Al/AgO, Ag/Zn, Thermal, Mg/AgCl2
  - Primary – Li/SOCl2, Li/SO2, Alkalines,
  - Rechargeable – Li-Ion, Na/S, Ag/Zn, NiCad, Pb-Acid, NiMH
- Fuel Cells and Semi-Cells
  - Mg/Seawater and Al/O2
  - H2/O2 PEMFC, AFC

Power and Energy Comparisons – AUV Needs

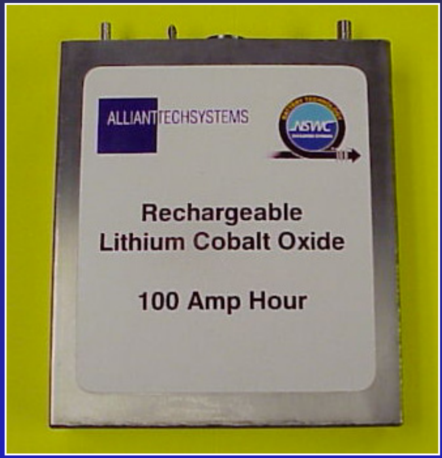


SOURCE: David Linden Handbook of Batteries, 2nd ed, 1995

Classic Battery Description



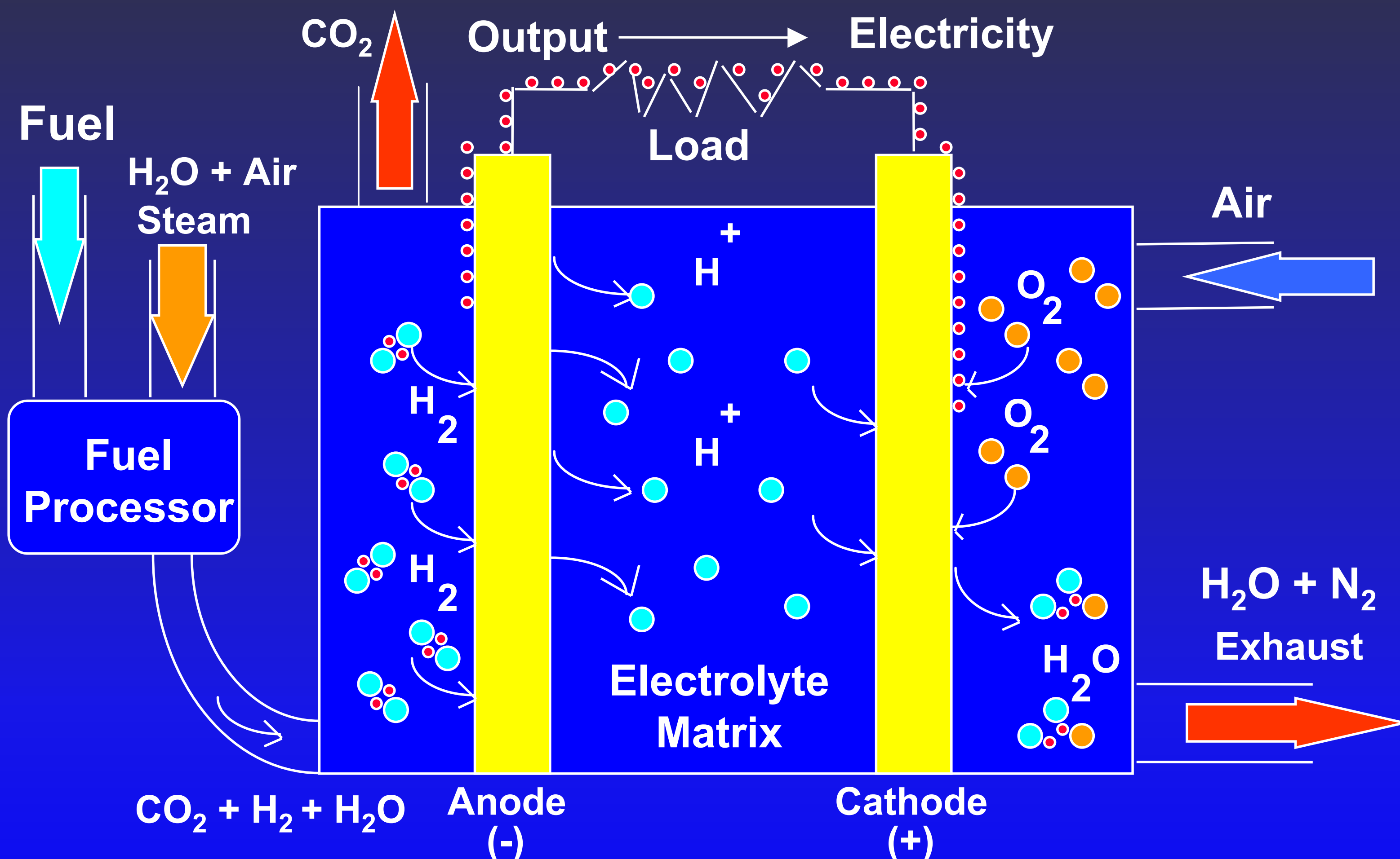
Spiral construction (LO)



Spiral
Pouch
Stack Prismatic
Circular Stack Plate

Variety of Battery Configurations

Fuel Cell Operation



$$H_2 \longrightarrow 2H^+ + 2e^- \qquad O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$$

Stored Electrochemical Energy

- Batteries
  - Primary (alkalines, lithium)
  - Rechargeable (Li-ion, Ag/Zn, NiCd)
  - Reserve (Li/SOCl2, Ag/Zn, Thermal)
- Readily available, cheap
- Conceptually easily designed, installed, used
- Can support all levels of conceptual usage

Stored Electrochemical Energy

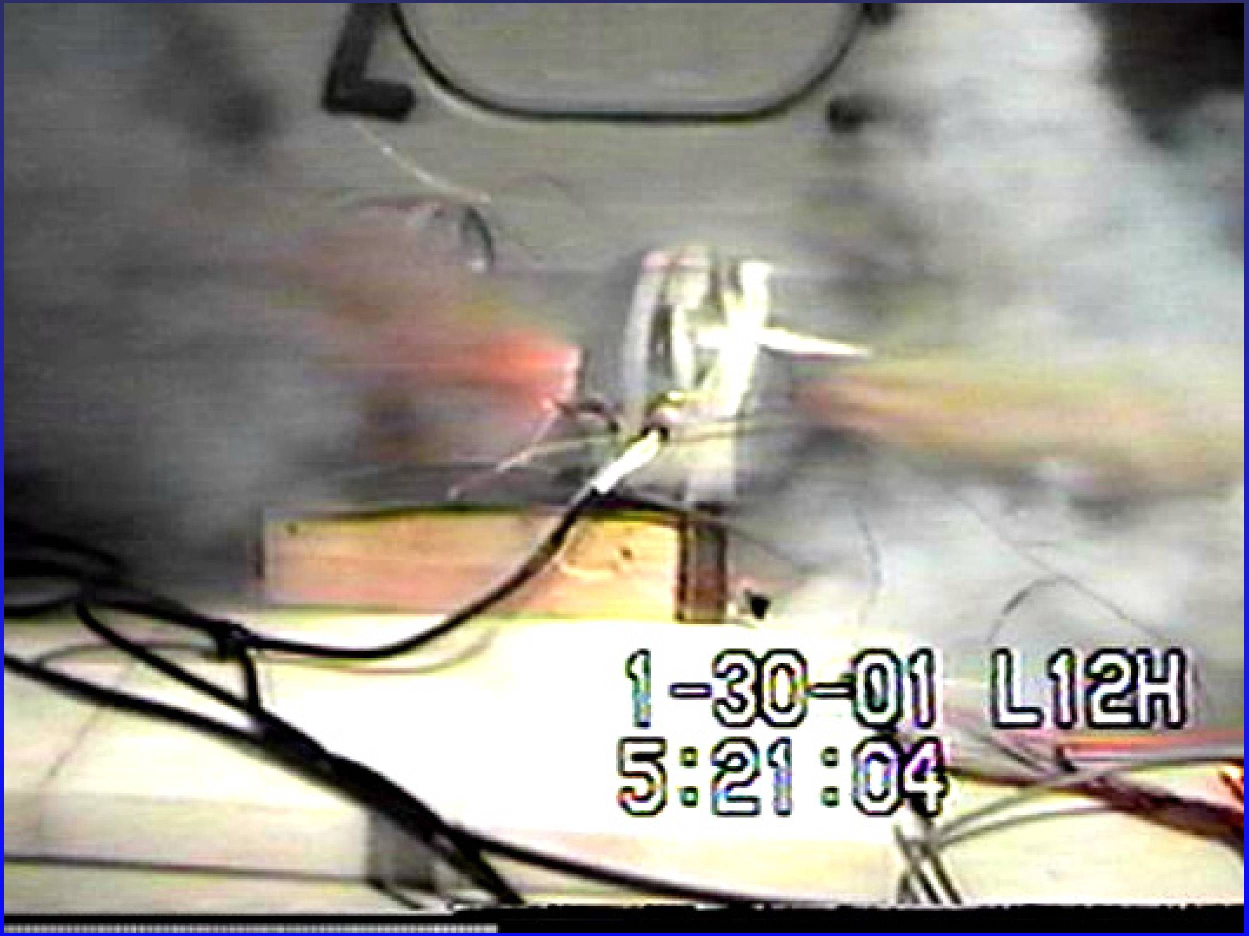
- Fuel Cells
  - Gas-gas feed reactants (H_2/O_2 PEM, Alkaline)
  - Semi-FC (metal anode with replaceable cathode reactant)
  - Gas-Air or reformed basic organic fuel
- Potentially higher energy density than batteries
- Limited power/mass (more like bobbin cell)
- Large storage of unreacted materials kept separate
  - Maybe safer
- Novel, expensive, developmental, not yet reduced to practice except in stationary power systems

Batteries and Fuel Cells Are Stored Energy

- Controlled transfer of energy
  - Discharge or Charge
- Uncontrolled transfer of energy
  - Venting with report, spontaneous rapid disassembly, structural failure with deflagration and fumes
  - "Explosion"
- Difference between two occurrences is dependent on how well we understand and control the cell, battery and system.

Sometimes Things Go Wrong

Sometimes Things Go Wrong



Cautionary Tales

- Blind Mans Bluff (1999)
  - Describes a plausible scenario involving a "hot run" Mk37 torpedo captive in sub
  - Reserve Ag/Zn battery may have "cooked-off" due to self-discharge
  - Resulted in ignition of warhead
- Robust technology, encapsulated in ordnance (or near ordnance) had unintended consequences due to minor design oversight

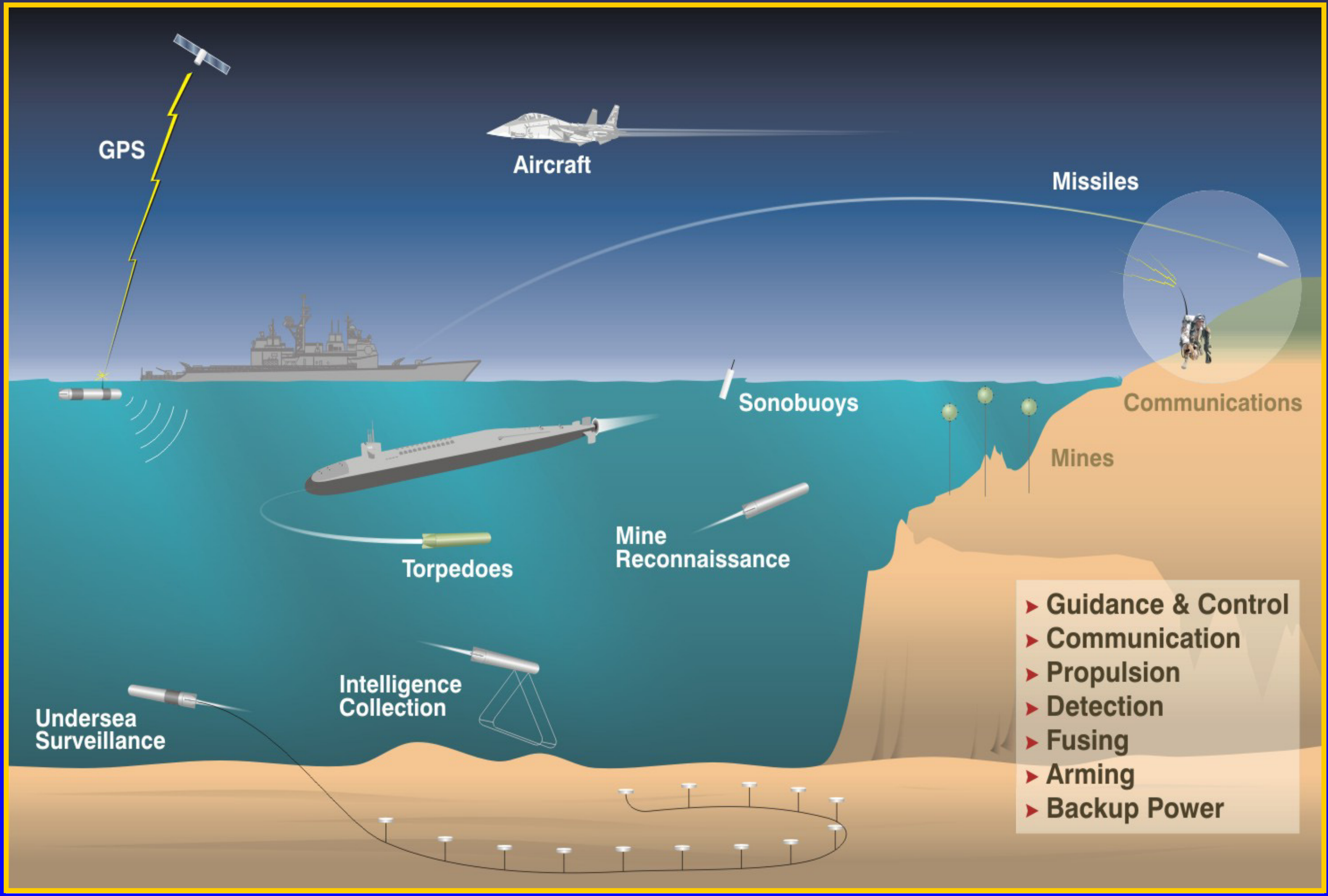
Engineering and Application Issues

- Scale-up is not always predictable
  - Thermal management, kinetics and form-factors vary with design of cell, battery and application
  - Non-linear impact with size of application
  - Trial-and-error approach still used

Engineering and Application Issues

- Battery configurations are challenging conflict of maximizing performance without sacrificing safety
  - Potting and vent pathways and environmental hardening
  - Thermal management in close-packed configurations
  - Multicell series/parallel behavior
  - Charge control for secondary batteries - cycle life vs performance

System Integration Challenges



AUV Platforms of Military Interest and Carriage Integration Issues

- Surface Ships
  - Surface or below deck stowage?
  - Magazine stowage?
- Aircraft
  - Fixed Wing
    - Inboard or wing/outboard carriage and launch
  - Rotary Wing
    - Inboard or external load carriage launch
- Submarines
  - External store
  - Internal store
    - Co-location with ordnance?

Torpedo “Room”

There is no free “room”

SSN 761 Springfield from WGBH Boston NOVA Website

Helo's and Planes

- Can't walk away easily
- May not be able to dispose of item

Large Electrochemical Power Source AUV Platform Integration Issues

- Performance and Environments
- Integration with platform systems
- Integration with platform handling logistics
- Integration with platform personnel
- Casualty procedures
- Emergency recovery procedures
- Emergency compatibility with ships systems (Hard/Software, Life support)

Safety and System Integration

- Hazard analysis and system integration are required per Mil-Std-882
- Energetics must be understood
  - Both in normal and abnormal function
  - Abused reactions
  - Energetics are not just explosives – include pressure bottles and batteries (all types)
- System integration may include such subtle issues as microgram/cm2 out-gassing of coatings inboard a sealed stowage area

HAZARD RISK INDEX
Mil-Std-882

FREQUENCY OF OCCURRENCE	HAZARD CATEGORIES I CATASTROPHIC	II CRITICAL	III MARGINAL	IV NEGLIGIBLE
(A) Frequent	1A	2A	3A	4A
(B) Probable	1B	2B	3B	4B
(C) Occasional	1C	2C	3C	4C
(D) Remote	1D	2D	3D	4D
(E) Improbable	1E	2E	3E	4E

HIGH
(CAE (ASN-RDA) USSOCOM)

SERIOUS
(PEO)

MEDIUM
(PM)

LOW
(PM)

Some Governing Documents and Requirements for Platform Integration

- NAVSEA Technical Manual S9310-AQ-SAF-010
- MIL-STD-810F Environmental Standard
- MIL-STD-2105 Hazard Characterizations for Non-Nuclear Ordnance
- Ship and Submarine Fire Fighting Instructions
- Nuclear Powered Submarine Atmosphere Control
- MIL-S-901D Shipboard Shock
- Naval Ships Technical Manual
- MIL-STD-167 Shipboard Vibration
- MIL-STD-882 Hazards Analysis
- NAVAIR 00-80R-14 Aircraft Firefighting Manual
- Software System Safety Technical Review Panel
- Weapon System Explosives Safety Review Board

New Focus for the WSESRB

- Previously the focus was limited to systems associated with ordnance as stand alone
- New focus emphasizes “Ship Integration”
  - Shipboard
    - (No submunitions!)
  - Submarine
  - Aircraft
- Focus has also captured importance of software integration and interoperability

Mission of the **W**eapon **S**ystem **E**xplosives **S**afety **R**eview **B**oard (WSESRB)

- The WSESRB has responsibility for independent oversight of the safety effort associated with all ordnance items, weapon devices, or systems used, handled, stored or tested aboard a Navy ship or aircraft.
- Convenes once a month for 2-4 days to adjudicate and express opinions to programs on their specific safety analyses and impacts

Large Non-Ordnance Battery Powered System on Submarines

- Proposed system is a torpedo “look a-like” with NO explosive components
  - However, it will be stored and launched from torpedo tubes and may be highly energetic and represent hazards to the sub
  - WSESRB decided that this program must undergo a full WSESRB safety review complete with an emphasis on SSSTRP (Software System Safety Technical Review Panel)

Basic System Requirements for Integration into a Torpedo Room

- The UUV and battery component need to:
  - Be compatible with torpedo room operations
  - Permit easy swap-outs *
  - Be safe to carry fresh and spent *
  - Be easily acquired and easily refurbished *
  - Be energy dense
  - Be safe under all logistical environments

*Assumes recovered and refurbished in torpedo room

Mine Countermeasure System for Air Carriage and Deployment

- Foreign military Non-Developmental Item (NDI) with Li/SO_2 batteries
  - Original system designed for ship carriage and deployment
    - 45 Li/SO_2 “D”-cell powered
    - 4 pound shape-charge warhead
  - Current proposed system is internally carried and deployed from a helicopter
  - Stowage is in the ships Magazine!

Basic System Requirements for Aircraft Carriage

- The system and battery component need to:
  - Be compatible with aircraft and flight operations
    - Be compatible under all flight vibrations and temperatures
  - If launched from crew space must be compatible with flight clearance requirements
  - Example: EMATT
    - Li/SO2 batteries may pose severe hazard to crew
    - Must be safe under all conditions

Focus on Energetic Material Use in the Navy

- All non-explosive energetics have a higher visibility in overall system safety
  - What was formerly a ✓ is now an area for critical review and evaluation
  - Batteries and fuel cells captured
  - Thermal engine systems also
- System location and system interoperability is now as critical a concern as what is in it
  - Non explosive devices, if they have potential impact on ordnance or personnel, are now critically reviewed

Summary

- Advanced mission AUVs require increase in energy density over available electrochemical systems
- The energy density and rate capability may make the energetic more less stable than "ordnance"
- System integration is not easy, is not straight forward and has many hurdles
- Care, common sense, jaundiced eyeballs and appropriate paranoia have useful functions as AUVs increase in capability and performance

Acknowledgements

- PMS403 Unmanned Undersea Vehicle Office (Dan Templeman)
- NUWC Newport (Chris Egan)
- NOSSA (Sidney Andrews, Steve Bennett, Ed Kratovil)
- NAVSEA 05 (Dave Bernhardt, Andy Miles, Dave Satterfied, Rich Hagar)
- NSWC Carderock (Unmanned Vehicle Office)
- NSWC Crane (Don Mains)
- NAWC Aircraft Division (Bill Johnson)
- Boeing UUV Systems (Damian Drozd)

PROSPECTS FOR FUTURE POWER AND PLATFORM SAFETY

- Presently the average PRIMARY BATTERY yields 25 to 40% of the Theoretical Energy Density
  - This reduction is structural overhead (case, separators, supporting electrolyte)
  - This reduction is electrochemical inefficiency vs. equilibrium potential
- Presently the Average RECHARGEABLE BATTERY yields 10% to 20% of the Theoretical Energy Density
  - This reduction is structural overhead (case, separators, supporting electrolyte)
  - This reduction is electrochemical inefficiency during discharge vs. equilibrium potential
  - Additional inefficiency from recharge losses (dispersal of reactants in the bulk volume)
- VEHICLE energy packaging usually has a 30% to 60% overhead
  - The AUV is doing very well if we get 10% of the Energy out we should by weight
- Primary battery efficiency may be increased by 50% (to 60 to 70%)
  - Requires extensive modeling and structural analysis at the electrode level
  - Requires extensive use of nanophase electrochemical materials
    - Corollary is the cathode is an energy dense solid reactant or reaction site for solution phase material
- Secondary battery may be increased by 30 to 50 % (to a 35% efficiency)
  - Requires extensive modeling and structural analysis at the electrode level
  - Requires extensive use of nanophase electrochemical materials
- AUV energy packaging can be increased
  - Conformal energy supplies (no more square pegs in round holes)
  - Pressure tolerant systems (no heavy wall structures)
  - Integrated hull-section/power supply (no separate battery)
- With respect to safety and handling
  - The higher the energy densification, the greater the risk of cascading response
  - The higher the densification, the greater the need for thorough system integration