Project Number: 901215

Project Start: Jan. 1, **2012** **Project Duration (in years):** **1**

Please indicate what type of project is being proposed (mark only one).

x				
Feasibility/Scoping [Less than 100 days effort]	**Development**[1]	**Research**	**Infrastructure**[1]	**Education**
	Time Series	**Institute Initiative**		

Project Manager[2]: Ed Mellinger

Principal Investigator: Jim Bellingham

Lead Scientist: Ken Smith

Lead Engineer: Jon Erikson

Project Title: Feasibility Study to Develop Safety Guidelines for the Failure Modes of Lithium Batteries

[1] Development and infrastructure projects must complete the risk matrix (see item #5 at the end of the proposal form).
[2] Not all projects will require all four titles to be filled in. Please indicate individuals only for those titles that are appropriate for your project.

1) ABSTRACT (new projects only)

This project is a feasibility study to explore the failure modes of the secondary lithium batteries that MBARI uses so that a set of safety guidelines can be established. The project is motivated by the growing number of high energy density batteries in use at MBARI, and the prospect of a battery accident and possible harm to personnel or property. The Battery Safety Committee has developed extensive contacts with the battery industry, and it is clear that work in the electric car industry has begun to address many of our concerns in that failure modes are better understood and battery testing methods are better defined. Our intent is to extend this work to understand a) what safety measures should be taken when putting lithium ion batteries in a pressure vessel, and b) what design principles are involved in minimizing the chance of failure propagation from an individual cell to an entire pack. This will result in a set of guidelines that can be used by MBARI engineers in projects using these types of batteries.

2) PROPOSAL

a) <u>New Projects</u>

Statement of the problem, why it is important

Lithium-ion batteries are the highest energy density secondary (rechargeable) batteries commercially available, and hence are very attractive and extensively used for untethered, uncabled, or autonomous ocean instruments and platforms. These batteries can fail for a variety of reasons ranging from electrical or mechanical abuse, to latent manufacturing defects that need no outside event to trigger. Due to their energy density, failure frequently results in battery cells bursting, followed by high-intensity fire. If the fire involves many cells in a large battery pack, there is a very large energy release and a significant safety hazard to personnel and property.

Lithium-ion cells are widely used, a few at a time, in cell phones and portable computers, with a good though far from perfect safety record. Unfortunately, little guidance exists for safe use of these batteries in large (hundreds of cells) packs, in a marine environment, or inside deep-sea pressure vessels, all of which are typical of oceanographic applications. Manufacturers design the cells to survive several abuse scenarios, but provide almost no information on failure modes, or actual thermal and chemical release rates in the event of a failure.

Growing interest in electric road vehicles has resulted in considerable industry effort to understand the failure modes of large Lithium-Ion battery packs. Similarly, the U.S. Navy has fielded large battery systems with varying results, and has developed and continually evolved safety standards to reduce the risk of using these systems aboard ships. Both of these outside activities address aspects of MBARI's use of Lithium-Ion batteries that have not previously been addressed by the battery industry itself, such as using large assemblies of cells, or using them inside of pressure vessels.

As large Lithium-Ion battery systems become more attractive and more accessible to MBARI engineers, there is a need for design guidelines to minimize the safety hazards that come with these batteries' high energy density. It appears that there may now be enough knowledge emerging from recent industry efforts to develop such guidelines here at MBARI. This project proposes to summarize those industry efforts, test available batteries to characterize their failure modes, and then to propose a set of basic design guidelines tailored for the unusual aspects of MBARI's battery applications.

How does it relate/contribute to MBARI's mission and strategic plan?

This project focuses on a safety issue, and is therefore supportive of MBARI's ongoing field activities. Since other organizations also face this problem, our efforts may constitute a valuable contribution improving safety across the community.

How does it relate/contribute to the Packard Foundation's Ocean Visions Grantmaking policies?
(See http://mww.mbari.org/oed/OED_Documents3.htm#Packard for documents.)

This project does not directly impact Packard Foundation activities. However, the activity is intended to improve the safety of MBARI activities undertaken in support of the Packard Foundation vision.

Approach to the problem
Our approach is predicated on two assumptions: 1) that failure of single Lithium-Ion cells cannot be absolutely prevented, merely minimized, and 2) that it should be possible to design undersea battery systems that can survive a cell failure, by preventing propagation of individual cell failures to other cells in the larger battery pack. These assumptions are prompted by a series of conversations with representatives of the electric car industry, and by review of industry literature. The remaining questions are how to prevent propagation, which requires knowledge of the cell failure modes, and whether these failures can be safely contained within an oceanographic pressure vessel.

We plan to determine how much gas is released when a typical cell fails, and how much heat energy is directed at adjacent cells. We will also attempt to determine how much heat the cells can sustain before they fail, and if there are ways to minimize the probability of cell failure in cascade. Finally, we will investigate how a typical pressure vessel is affected by a battery failure, and how it could be successfully vented to release internal pressure.

Although our proposal is written as self sufficient, our intentions are to leverage a growing academic focus at NPS on power systems. In this last year, Mr. Joe Farmer of Lawrence Livermore National Laboratory was on sabbatical at NPS and taught a power system class which has now become a part of the NPS curriculum. Through Joe we met a number of NPS faculty, including Prof. Sebastian Oswald, a new faculty in the physics department. Sebastian is developing a research program revolving around battery safety. He is planning on establishing a battery test facility at NPS to characterize failures of batteries. Our intent is to develop a collaborative relationship with Sebastian which might include:

- Combining resources to create a single battery test facility, probably at NPS, accessible to us. This test facility would be substantially more advanced than what is planned in our proposal to support chemical characterization of reaction products and electrical characteristics of cell prior to and during failure.
- Interaction with students supervised by Prof. Oswald, who would use the facility for research on topics of common interest.

- Information exchange with Navy battery safety programs, which are increasingly connected to NPS.
- Establishing a CRADA to provide a formal framework allowing MBARI use of NPS facilities, and allowing collaborative research. CRADAs can also provide a conduit for funding, e.g. from the Navy through NPS to MBARI should that be useful.

Publications (from other projects over the last 5 years)

None on this subject.

a) New and Continuing Projects: Plans for 2012

Engineering/technology development

This is largely a testing program, with the goal of characterizing the failure modes of small (18650) lithium-ion cells, and developing battery pack designs that minimize the likelihood of failure propagation between cells. While this testing proceeds, we will continue tracking safety developments in the battery industry. The overall plan can be summarized in three categories as follows:

1) We will further review evolving battery industry design and safety practices. We hope to converge on a basic set of cell failure modes that are relevant in oceanographic battery packs, and an understanding of the design guidelines industry uses to deal with these failures. We plan to pursue these avenues of inquiry:

- attend Battery Safety 2011 Conference (November 2011)
- review recent Navy standards (if available)
- continue discussions with contacts in electric vehicle industry

2) We plan to deliberately provoke single-cell failures of two or three candidate Li-Ion cells, to characterize their thermal and gas output during failure. Based on the results of these tests, we will develop a battery pack approach that attempts to prevent these failures from spreading between cells in a pack. We will test this approach with instrumented dummy cells, and then with small numbers (two or three) of actual live cells. Finally, we will attempt to develop a pressure housing vent design that is capable of safely releasing the gas flow rates observed during the testing.

3) We will summarize our findings, and the results of these tests, in a preliminary report. This will be coupled with a presentation to MBARI battery user community, to raise awareness of the issues and get feedback on proposed safety measures. Finally, a formal report will make recommendations to the MBARI Safety Officer regarding design and testing standards for large battery packs for use at MBARI.

Specific deliverables

The product of this research will be a set of recommendations to MBARI Management regarding design principles and safety measures that will increase the safety of large lithium battery packs used at

MBARI. This will take the form of a report to the MBARI Safety Officer outlining the tests that were performed, and making recommendations regarding:

- Best industry practice for battery control electronics
- Pack design to reduce chance of failure propagation
- Pressure housing and vent design to reduce chance of explosion
- Storage and handling practices.

Milestones (see last page for personnel classification list)

1) Design and build test chamber/facility
2) Design an example battery system for testing
3) Test cell, and cell group, failure modes in chamber
4) Draft report and present to MBARI battery-user community
5) Final recommendations to Management

	Milestone 1	**Milestone 2**	**Milestone 3**	**Milestone 4**	**Milestone 5**	**Total Resources**[3] for each resource category for all milestones listed here
Milestone Date						
Milestone Description	**Test Chamber**	**Example battery design**	**Test cell failure modes**	**Draft report, presentation**	**Final report**	
EE	**80**	**80**	**80**	**160**	**80**	**480**
SE						
ME	**80**	**80**	**40**	**20**		**220**
EE Tech						
SE Tech						
ME Tech	**320**		**160**			**480**
Machine Shop						
Divers						

[3] This number should be the same number you entered on the resource requests for this particular resource.

Budget justification

Testing will be performed in a metal housing that approximates a typical deep-sea pressure vessel. This housing will be instrumented with temperature sensors (high temperature thermocouples), a gas flow sensor, and pressure sensor. Funds are requested for fabrication of this housing and attendant fixtures, as well as for the temperature and pressure sensors, and conditioning electronics.

Funds are also requested for limited consultation with industry experts, primarily for brief review of our testing plans, and then of our final recommendations.

Materials for Test Chamber	$3,000
Tungsten Fast Response Thermocouples -- 10 @ $100	$1,000
Batteries for test, 100 @ $10 each	$1,000
Materials for test fixtures and battery pack mock-ups	$2,500
Connectors for Test Chamber	$1,500
Flow Meter (Differential Pressure) -- Omega PX760	$1,115
Hot-Wire Anemometer (for calibration) -- Omega HHF2005HW	$645
Thermocouple-input PCI data acquisition board - Omega OMB-DAQTEMP14A	$1,499
1 RT Las Vegas @ $400 plus 4 nights hotel @ $150	$1,000
Battery Safety/Lithium Battery Conf, Nov 9-10 2011, Las Vegas (Academic Rate)	$1,199
Outside Consultants -- 40 hr @ $100/hr	$4,000
Total	**$18,458**

Project team

Ed Mellinger (Electrical Engineer, Project Manager)
Jon Erickson (Mechanical Engineer)
Jim Bellingham (PI)
Ken Smith (Project Scientist)
TBD (Mechanical Tech – Jim Scholfield would be well suited)

Project lab space

Testing will be done in a corner of the Bellingham lab, with the Test Chamber located within the fume hood there.

Data availability outside project team, uniqueness

Test results and recommendations will be made available within MBARI, and as desired, outside.

Risk matrix (development and infrastructure projects only)

	Technical Risk	Organizational Risk	Tech Transfer Risk	Labor Estimate Risk
High	X			

Medium		X		X
Low			X	

Personnel Classifications

Engineer - Mechanical Engineer (Reg)	**Engineer - Electrical Engineer** (Reg)	**Engineer - Software Engineer** (Reg)	**Engineer - Mechanical Tech** (Reg)	**Engineer - Electrical Tech** (Reg)	**Engineer - Software Tech** (Reg)	**Observ Support Technician** (Reg)	**Science – Software Engineer** (Reg)
Jim Birch (2/3)	Mark Chaffey	Dave Caress	John Ferreira	Paul Coenen	Karen S	Mike Kelley	Mike Godin
Larry Bird	Scott Jensen	Danelle Cline	Frank Flores	Tom Marion		Open - TBD	Frederic Py
Jon Erickson	Chad Kecy	Duane Edgington(2/3)	Mike Parker	Jim Montgomery			
Dale Graves (2/3)	Denis Klimov	Kevin Gomes (2/3)	Jim Schofield	Jose Rosal			
Andy Hamilton (2/3)	Paul McGill	Kent Headley (2/3)					
Brett Hobson	Ed Mellinger	Rich Henthorn					
Bill Kirkwood	Craig Okuda	Bob Herlien					
Gene Massion	Alana Sherman	Brian Kieft					
Doug Pargett		Thom Maughan					
Farley Shane		Mike McCann					
		Rob McEwen					
		Tom O'Reilly					
		Wayne Radochonski					
		Mike Risi					
		Brent Roman					
		Carlos Rueda-Velasquez					
		Brian Schlining					
		Rich Schramm					