SAAB

Lithium Ion Battery - Opportunities and Challenges for Submarines

UDT 2019-05-14

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Agenda

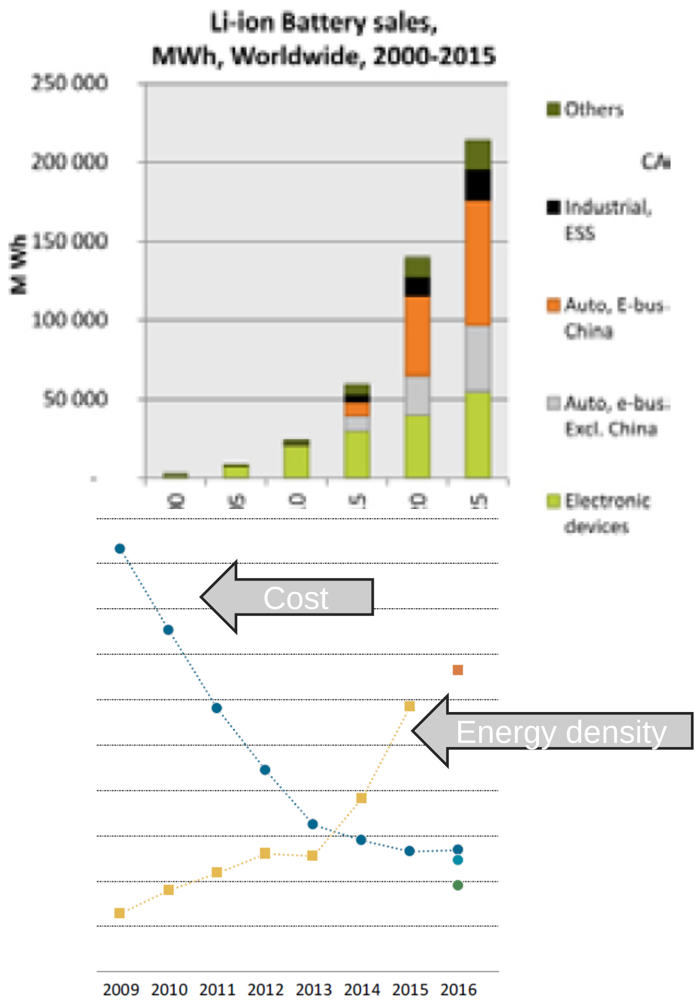
- Background
- Opportunities
- Challenges
- Ongoing project

Background

- Lead acid batteries has been used for energy storage in submarines for more than a century
- The long experience has learnt us to operate the batteries in a safe way by auxiliary systems and proper operating methods
- Li-ion compared to lead acid
  - Higher volumetric and gravimetric energy density
  - Longer life time
  - Lower maintenance
  - Available power independent of state of charge
  - Available energy independent of discharge power

Market trends

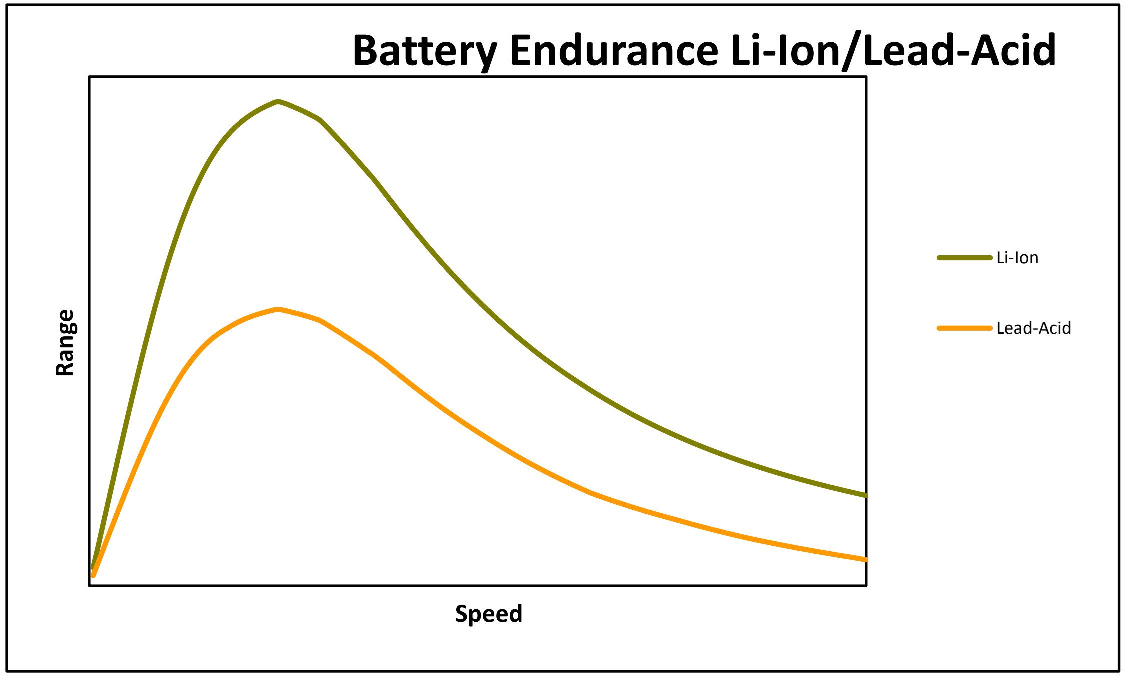
- The continuous electrification of the society increases the need for energy storage
- New battery factories are being built to meet the ever increasing need
- Li-ion battery cost decreases while the energy density increases



Source: IEA, Global EV outlook 2017

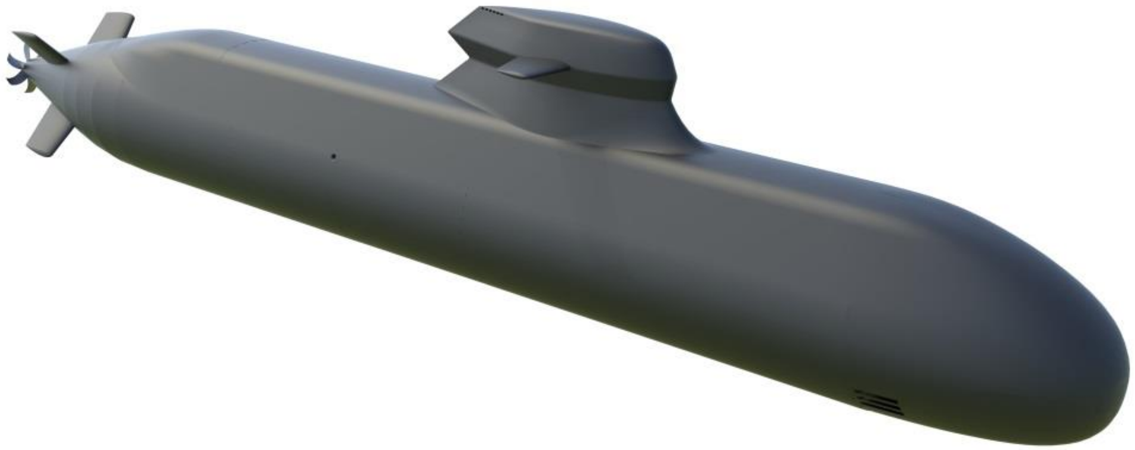
Opportunities for submarines

- Increased energy storage
  - Increased endurance
  - If replacing lead acid, the endurance can be maintained with a smaller battery. Freed up volume can be used for increased storage of diesel and LOX to increase AIP endurance
- Higher performance
  - Better energy efficiency, lower indiscretion ratio
  - Full performance available at lower state of charge



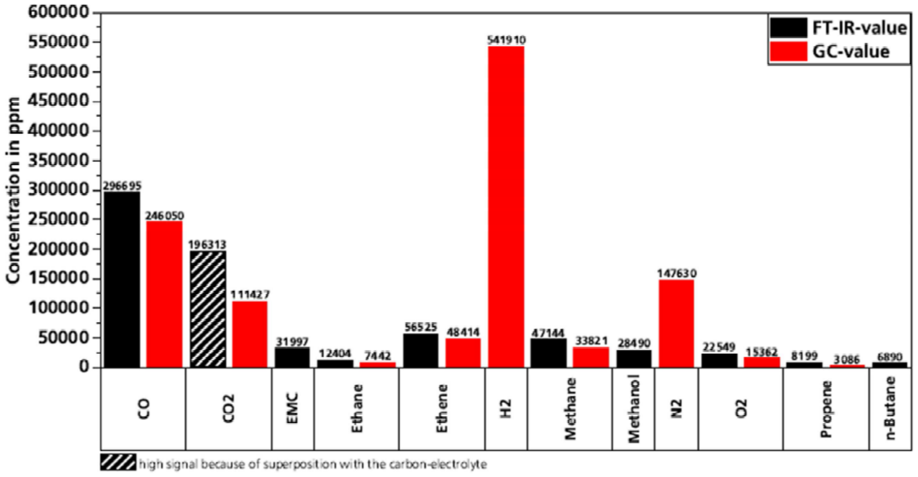
Opportunities for submarines

- Decreased maintenance
  - No gas charging
  - No water filling, cleaning, manual measurements…
- Longer lifetime
  - Fewer battery replacements
- Higher availability of the submarine



Challenges for submarines, safety

- Cell faults can cause emissions of explosive and/or poisonous gasses and a large amount of thermal energy
- Faults caused by external abuse (electrical, thermal, mechanical) can be mitigated by management and protection systems and packaging…
- …but internal faults can not
  - Even though the probability of a fault might be low, the consequences can be devastating in the submarine's enclosed environment



Challenges for submarines, safety

- Demonstrating safety for a full life cycle of a submarine is not practical and would come at a high cost, and the cell would probably be obsolete after the test
- The system must be fault tolerant
  - The consequences from a cell fault must be managed
  - Propagation of faults must be prevented
  - Emissions to the submarine's atmosphere must be avoided

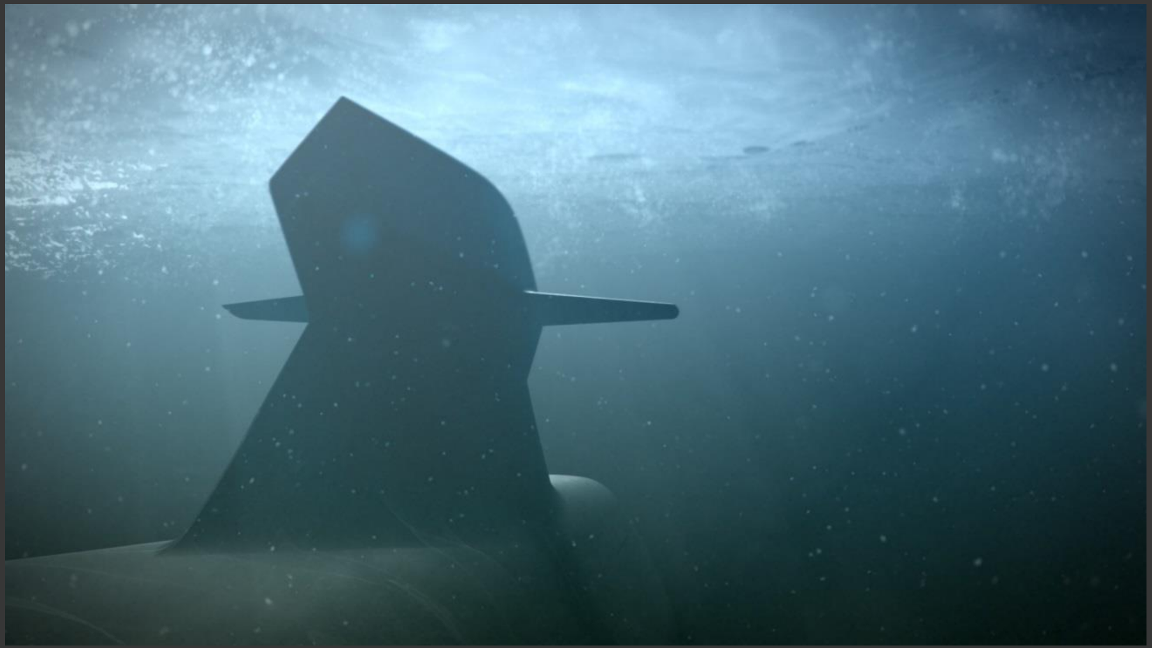
Challenges for submarines, electrical

- Short circuit currents for Li-ion cells are much higher than for lead acid, and have shorter rise times
- The breakers used today on submarines does not provide sufficient breaking capability
- New design of protection system is required, providing selective clearance of faults

Challenges for submarines, summary

- An intricate optimization problem to find a system design that
  - provide attractive capability enhancements
  - can be integrated into a submarine and maintain an acceptable level of safety and complexity
  - fulfills submarine specific requirements, i.e. shock and signatures
  - can continuously leverage of the ongoing cell development
  - can be maintained during the long service life of a submarine
  - can be realized to an acceptable through life cost

Ongoing project



Ongoing project

- Saab Kockums has an ongoing project developing a lithium ion battery suitable for installation on a conventional submarine
- The project is funded by FMV
- A strong project team has been formed together with PMB Defence (AU) and EST-Floattech (NL)
- This integrated systems team approach ensures complete coverage of cell research, technology selection, battery system design, submarine integration, operational analysis and commercial longevity for low cost of ownership

Project setup

- FMV
  - Project owner
  - Design authority
  - Operational analysis
- Saab Kockums
  - Overall project lead
  - System requirements
  - Submarine integration

PMB Defence

- 30-year history of manufacturing lead acid batteries for Australia’s Collins class submarines
- Has conducted research and development activities on new technology batteries, such as Li-ion, for many years
- Responsible for module design and integration

EST-Floattech

Project objectives

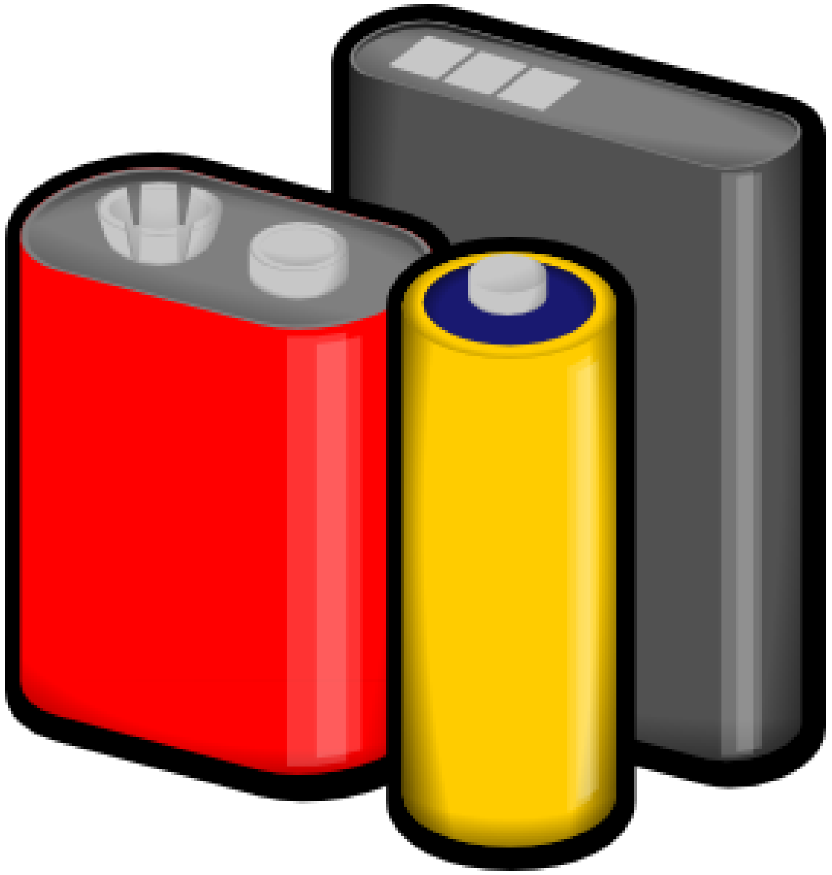
- Design and build a battery system based on a standard format, commercially available cell and an existing battery management system
- The system's performance shall be significantly superior to the available lead acid submarine batteries
- The system shall be possible to integrate on both existing as well as future submarines, and be able to utilize the ongoing improvements in cell chemistry and energy density without major re-design
- Acceptable safety level and life cycle cost

Fundamental design decisions

- The cell shall be of a well-used standard format
- The system must be tolerant to a worst case single cell fault
- The emissions from such a fault shall be contained, and not released into the submarine's atmosphere
- A single cell fault shall not cause a cascading fault

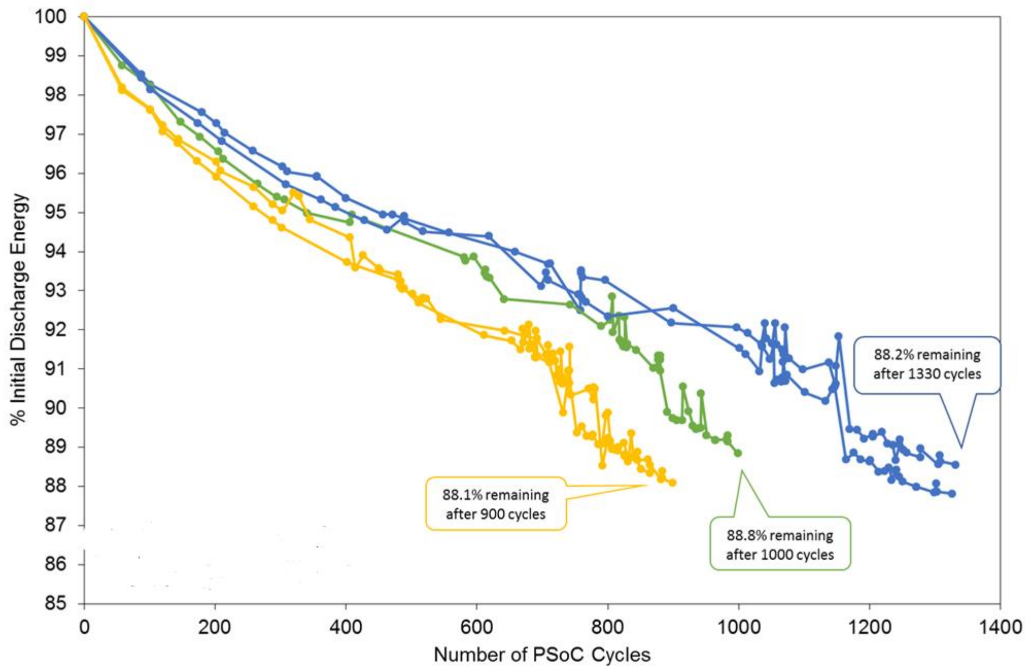
Standardized cell format

- Using a standardized cell format gives a larger freedom in choosing the appropriate cell
- Multiple possible suppliers and chemistries
- The cell can be changed without major re-design of the system
- Cell improvements can be included in later stages, as long as thermal safety limits are met



Performed testing

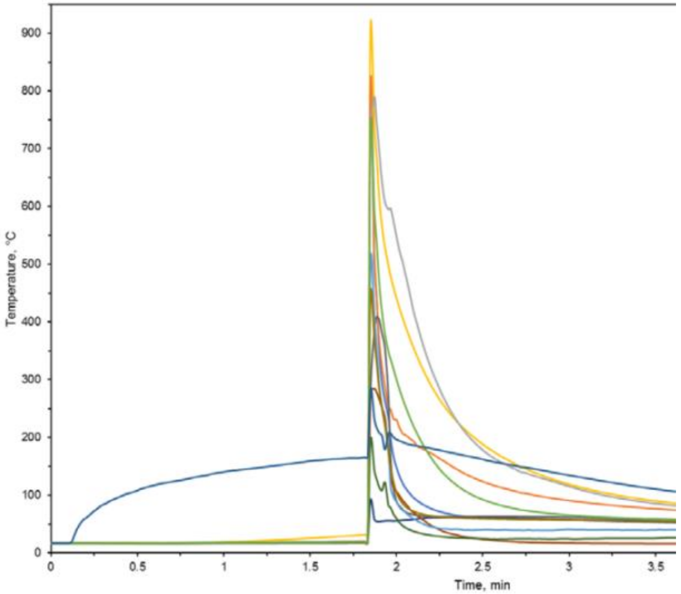
- Cell characterization
- Abuse testing
- Cycle-life tests
- Propagation prevention
  - Faults triggered in various positions inside module to ensure that adjacent cells are protected against thermal stress and ejected material



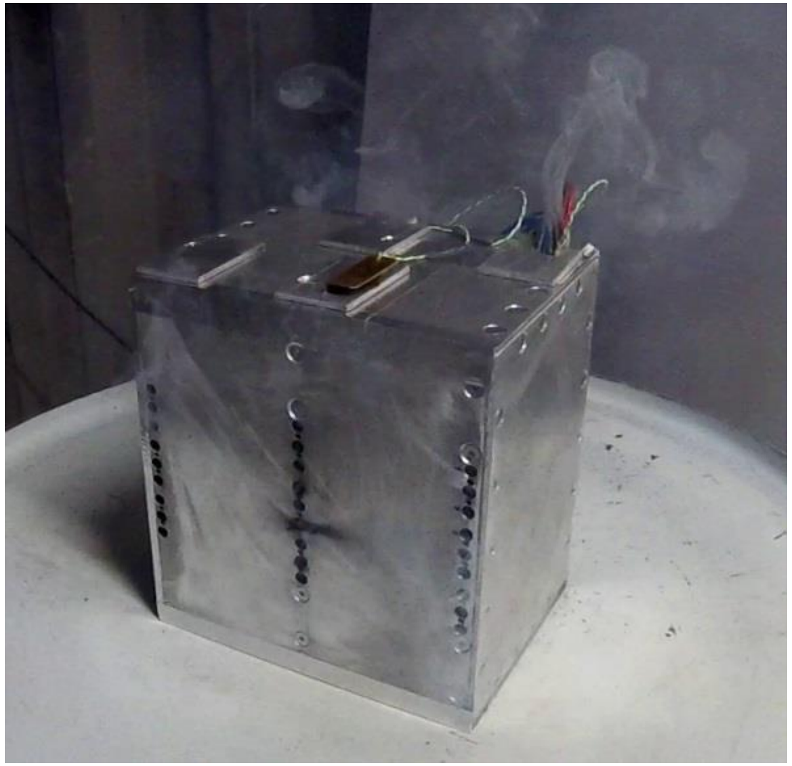
Thermal design

- Through careful and innovative use of design and materials, the released energy can be absorbed and propagation to adjacent cells avoided
- Thermal management during the fault is handled within the module and not dependent on external systems

Thermal runaway on single cell



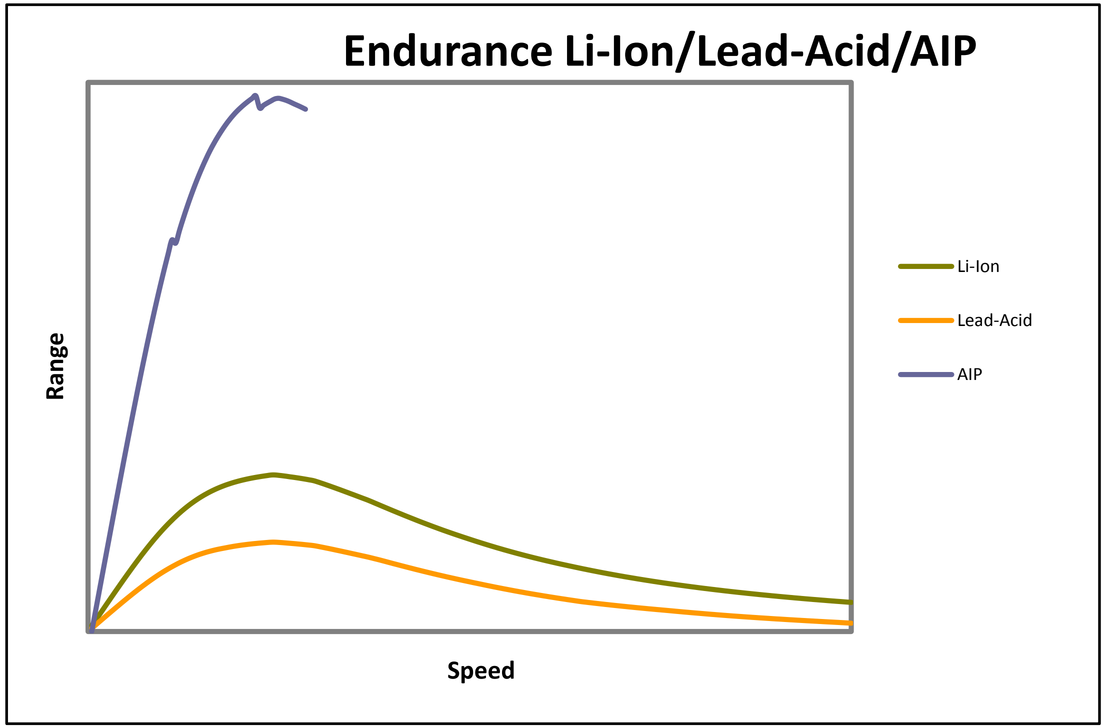
Measured temperatures



Thermal runaway inside sub-module

Demonstrator system

- A demonstrator system has been built and tested at PMB's premises in South Australia
- Integrates the cell, packaging and EST's BMS and is supervised by Saab Kockums Ship Control and Monitoring System
- Charge and discharge rates representative of a submarine have been run at different temperatures
- The results show that the designed system can be integrated, meets the functional and performance requirements, and provides the predicted energy density
  - Approximately 3 times lead acid for high power, 2 times for low power



Next steps

- Next project phase is progressing and includes
  - Design optimizations
  - Further integration studies
  - Comprehensive long-time test program
  - Design of large scale land based test site for system qualification before sea-trials

Full scale qualification to be performed before customer acceptance

Questions?