cool by design

Electric Water Craft Battery Thermal Runaway Considerations

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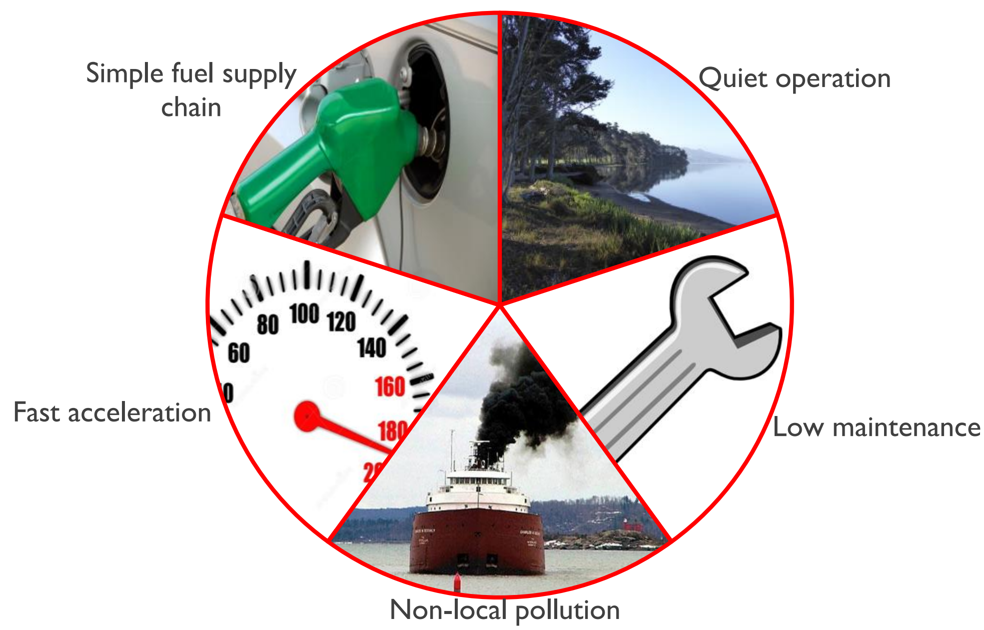
The Value of Electric Water Craft

The electric water craft market is expected to grow from $2.6 billion in 2014 to $7.3 billion in 2024, with equal contribution from underwater vehicles and surface craft.[i]

Public and private sectors are both driving growth as electric water craft provide unique capabilities for passenger applications as well as unmanned military and commercial uses. Depending on the application, an electric water craft could provide value from the following attributes:

Benefits of Electric Water Craft



- **Quiet operation:** Resort communities, tour boats in scenic areas, crew coaching and military
- **Low maintenance:** Less moving parts than combustion engines
- **Non-local pollution:** Air and water quality
- **Fast acceleration:** High torque at zero RPM
- **Simple fuel supply chain:** Recharge from grid, generator, on-board solar

While electric water craft have provided the above attributes for some time, the advancement of lithium-ion batteries has lowered the cost and increased the range of the vehicles, significantly opening the market. This applies to all sizes of vehicles: small underwater unmanned vehicles can require batteries less than 100 Wh in capacity, while large ferries can require batteries in excess of 4 MWh[ii].

Lithium-ion's Role in Electric Water Craft

The emergence of lithium-ion batteries is an improvement over the legacy lead acid or nickel based systems due to lower volume and weight, longer life, less maintenance, and improved monitoring of battery health. With prices falling, the most notable downside to lithium-ion technology is the flammability of battery cells. High profile incidents such as the Boeing 787 Dreamliner battery fires illustrate the volatile nature of even high quality lithium-ion batteries.

Like aerospace, the marine industry has little tolerance for fire. The significant risk to human life in a manned vessel or loss of an expensive unmanned vessel places a higher value on safety than ground transportation vehicles require. Possibly the highest profile marine incident was a 2008 lithium-ion fire in the Advanced SEAL Delivery System that cost the US Navy hundreds of millions of dollars.[iii]

Figure 1: Navy ASDS[iv]

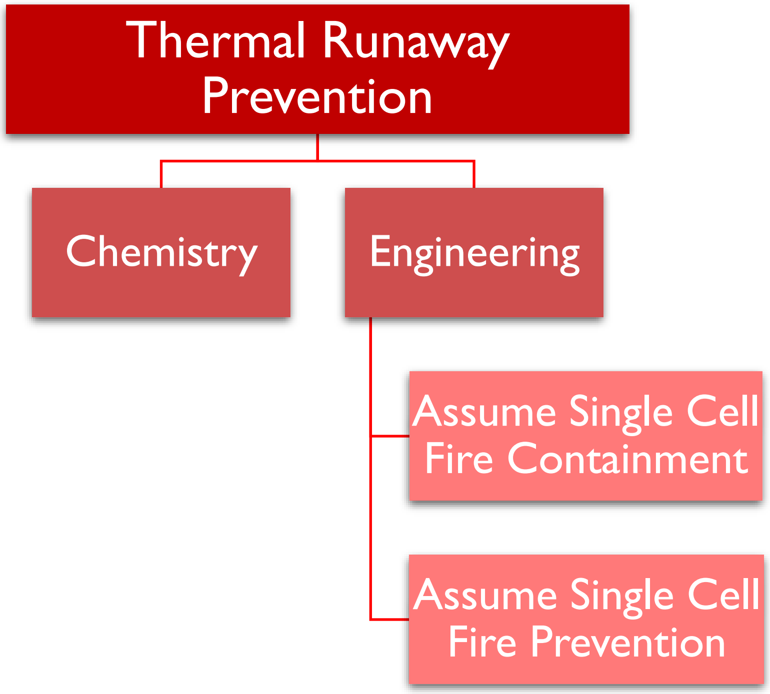
Safety: Chemistry vs. Engineering

Battery fire prevention can come primarily from two categories: advanced chemistry and engineering solutions. The advanced chemistry approach is the holy grail for lithium-ion component, cell, and pack manufacturers. An inherently safe battery chemistry provides wide latitude for system design and quality. Lithium iron phosphate and lithium titanate cells have the highest cell level safety, but are still capable of entering thermal runaway[v] due to flammable electrolyte and are significantly heavier and larger than other lithium-ion chemistries.

Within lithium-ion battery cells, the electrolyte is the primary flammable element and responsible for most of the heat generated during thermal runaway. As of publication of this document, no commercially available lithium-ion cells contain non-flammable electrolyte and the authors are unaware of any conference presentations or journal publications indicating the commercial availability of non-flammable electrolytes before 2020. This suggests that an engineering solution is required until a chemistry solution is developed.

Can You Prevent Single Cell Failure?
Engineering solutions can be broken into two approaches:

- Assume single cell thermal runaway can be prevented
- Assume single cell thermal runaway can't be prevented



Until recently, many companies employed the theory that they could design a way to prevent a single cell from going into thermal runaway, so engineering efforts were focused in that direction. Driven by a number of high profile failures of this approach, the battery industry is pivoting to the assumption that no design can guarantee prevention of a single cell thermal runaway event.

Working under that assumption, battery makers then perform risk analysis to determine the consequences of a single cell thermal runaway and use that to drive design. Solar street lights and smart grid meters are applications that could accept more risk of complete battery pack fires due to limited risk for fire to cause physical or financial harm. Aerospace and marine applications are on the other end of the spectrum due to the extreme nature of the consequences of a full pack fire.

How to Design to Prevent Propagation
To prevent thermal runaway propagation, engineers must design to either absorb heat within the pack or reject to the outside (or some combination thereof). In situations where it is easy to reject heat to the outside environment, isolating heat from neighboring cells while rejecting it to the environment can be effective. In more confined spaces or challenging environments, spreading heat and absorbing in the full thermal mass of the battery pack can substitute for lack of heat rejection to the environment. In marine applications, where batteries are often in water tight compartments, heat rejection is challenging, making the heat spreading and absorbing approach more attractive.

To effectively spread and absorb heat without compromising on the fundamental lithium-ion benefits, it is ideal to have a thermal management system that has the following attributes:

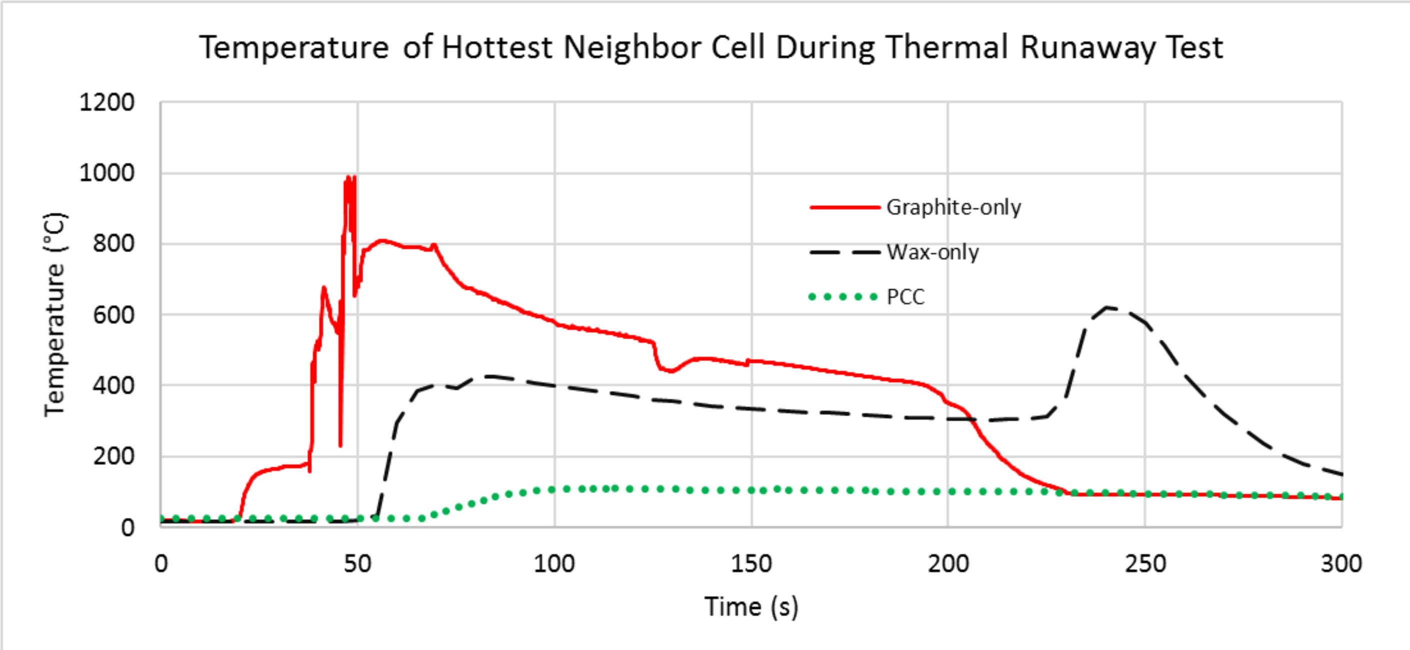
1. High thermal conductivity or convection
2. High thermal mass
3. High efficiency
4. Low weight
5. Reliable in electrical or mechanical failure
6. Low cost

The following matrix compares different thermal management options against those criteria. The material developed by the authors of this paper is the fourth column "AllCell Phase Change-Graphite Composite (PCC)":

		Thermal Management Option			
		Aluminum or Graphite Heat Sink	Liquid Cooling	Paraffin Wax	AllCell PCC
Performance Characteristic	High conductivity or convection	✓	✓	✗	✓
	High thermal mass	✗	✓	✓	✓
	High Efficiency	✓	✗	✓	✓
	Low weight	–	–	✓	✓
	Reliable in electrical or mechanical failure	✓	✗	✓	✓
	Low cost	–	–	✓	✓

Perhaps unsurprisingly, the material invented, patented, and commercially manufactured by the authors of this white paper is the only option that fully satisfies all conditions. That, however, shouldn't be translated into blind prejudice for one's own solution. Test data also verifies the findings.

In thermal runaway testing of a 450 Wh lithium-ion battery pack, the following graphs show the peak temperature of the cell adjacent to the trigger cell for thermal management systems that were: graphite-only, PCM-only, and PCM-graphite composite. It can be seen that the PCC pack is the only one that prevents thermal runaway propagation as the neighboring cell does not exceed 120°C.



Conclusion

The electric water craft market is growing quickly, driven by private and public sectors; manned and unmanned craft; on and below surface. The technical and commercial advances in lithium-ion battery technology is playing a big role in this growth but is also increasing the safety risks as it is a volatile chemistry. It is becoming apparent that it is currently impossible to guarantee that a single cell fire won't occur, so designs must be made to prevent the spread of the fire. Spreading the heat quickly to a large thermal mass is an effective way to prevent the spread of fire without sacrificing vehicle weight, cost, or performance.

Contact

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[i] IDTechEx report, "Electric Boats, Small Submarines and Autonomous Underwater Vehicles (AUV) 2014-2024"
[ii] http://www.businesswire.com/news/home/20150610005460/en/Leclanch%C3%A9-Deliver-4.2-MWh-Battery-System-Worlds
[iii] http://evworld.com/news.cfm?newsid=19865
[iv] http://www.navy.mil/view_imagex.asp?id=185950&t=1
[v] http://www.sciencedirect.com/science/article/pii/S0306261916312697