Development of Low Cost Light-Weight Automotive Battery at Oxis Energy

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1. Automotive challenges

The design requirements for pure electric (EV) and plug-in electric vehicles (PHEV) include three main criteria:

a) Performance
b) Cost
c) Safety

Battery weight or specific energy (gravimetric energy density) is critical for EVs and PHEVs. Whilst a high capacity battery is needed to deliver the highest possible mileage, the weight of the battery itself risks becoming a performance constraint. Conversely, because the battery is large power delivery is less likely to be a problem.

Battery cost is also very important and today is the major obstacle to widespread EV take up.

An EV battery stores a great deal of energy compared to most consumer batteries. Safety is therefore paramount. Protection systems are costly and liable to failure. Safety can thus only be ensured if the battery chemistry itself is inherently safe.

The target figures of specific energy for different car manufacturers may vary. However, the key medium to longer term target is about 150Wh/kg for a full battery pack which translates into specific energy on a cell level of 250-300Wh/kg.

Li-ion struggles to deliver this performance. Even the best performing $LiCoO2$/graphite system will fail to do anything above 180Wh/kg. Safer $LiFePO3$ systems have still lower energy. Any emerging Li-ion couples must improve on safety, but carry a cost of lower energy density. Higher safety in Li-ion batteries can be achieved by using either new higher voltage anode materials, resulting in lower cell voltage, or safer, but lower capacity, cathodes.

2. Lithium-metal in rechargeable batteries

Systems using metallic Li offer the highest specific energy. Sulfur represents a natural 'cathode partner' for metallic Li and a lithium-sulfur couple has theoretical specific energy in excess of 2600Wh/kg, which is nearly 5 times higher than that of Li-ion.

However, limited cycle life especially at room and elevated temperatures (which is most important for automotive industry) has to date restricted lithium-sulfur systems from niche applications. Moreover, there were concerns about the safety of metallic lithium especially after the recent accidents with Avestor Lithium-Metal-Polymer batteries used as telecom power back-ups. However, these batteries used a Lithium-Metal-Polymer system with a vanadium oxide (not sulfur) cathode material. They were designed around a solid polymer electrolyte intended to prevent dendrite growth.

There is scepticism about using solid state layers as anode protection in Li metal batteries. Any reversible reaction involves charge and mass transfer, which inevitably results in repeated mechanical expansion and shrinkage of the electrodes. For that reason one can hardly rely on mechanical protection layers over hundreds of cycles.

3. Oxis's Platform Technology

Oxis Energy Ltd (Oxford, UK) is the specialist in rechargeable Li metal systems. Our philosophy is based on the thermodynamic approach to internal safety providing inherent protection from any internal short-circuits as well as from mechanical and electrical abuse.

The system of Li and sulfur has a number of unique features that are not typical for Li-ion electrochemical couples using intercalation electrodes. The combination of lithium and sulfur is known as a system with a 'liquid cathode', meaning that sulfur, the cathode active material, is also present in the electrolyte in the form of lithium polysulfides at different oxidation levels, depending on the state of charge. This feature has a number of implications for the structures of the positive electrode, separator and electrolyte system, as well as for the general design of the battery.

Oxis Energy has developed its proprietary lithium sulphur technology, branded "Lithium-Sulfide (Li-S)". The technology can be implemented using either a metallic Li anode or using an intercalation anode, such as graphite or another higher capacity material. In the future we will refer to Li-metal sulfide as *Li-metal* and will call the second type as *Li-ion sulfide*.

Both systems share the same cathode, separator, electrolyte system and overall cell design; the only difference is the anode.

Here are the basic reactions for Li-metal and Li-ion sulfide:

Li-metal: $2Li + S \longleftrightarrow Li_2S$

Li-ion sulfide: $Li_2S + 12C \longleftrightarrow 2LiC_6 + S$

The table below gives the theoretical figures of specific energy for those two systems. We assumed by default that for Li-ion sulfide graphite is taken as the anode.

Table 1: Comparative theoretical data for Li-metal, Li-ion sulfide and Li-ion ($LiCoO_2$)

	Li-Metal (Oxis)	**Li-ion Sulphide (Oxis)**	Li-ion (LiCoO2)
Open Circuit Voltage	2.35	2.3 – 2.4	3.8
Theoretical Specific Capacity, Ah/kg	1165	282	135
Theoretical Capacity density, Ah/l	1900	540	320
Theoretical Specific Energy, Wh/kg	2735	680	513
Theoretical Energy density, Wh/l	4465	1300	1216

4. Safety and Environmental Benefits

Conventional electrochemical wisdom holds that the use of lithium metal is risky. Indeed, even Li-ion batteries suffer major safety concerns associated with the growth of spiky lithium dendrites resulting in an internal short circuit, followed by uncontrolled energy release. A common belief is that any rechargeable lithium metal system would sooner or later generate uncontrolled dendritic lithium. Potentially, during charging, some lithium may remain suspended in the electrolyte rather than plated onto the anode, thus creating precursors for dendritic lithium.

Fortunately, this is not the case for the lithium-sulfur battery of Oxis Energy. Lithium sulfide electrolytes provide an effective mechanism for the passivation of suspended or 'mossy' lithium by creating instantaneously a Li_2S film on metallic lithium. Passivated lithium may form during charge and it is scavenged during discharge or battery rest periods. This inherent protection mechanism is supported on the chemical level and is associated with the so called 'sulfide cycle'. Lithium sulfide (Li_2S) has a melting point of 938C and is a good insulator. The failure mode for

Oxis's Li-metal battery is the full loss of capacity due to the loss of conductivity between electrodes because of the excessive formation of non-conductive and highly stable passivated lithium.

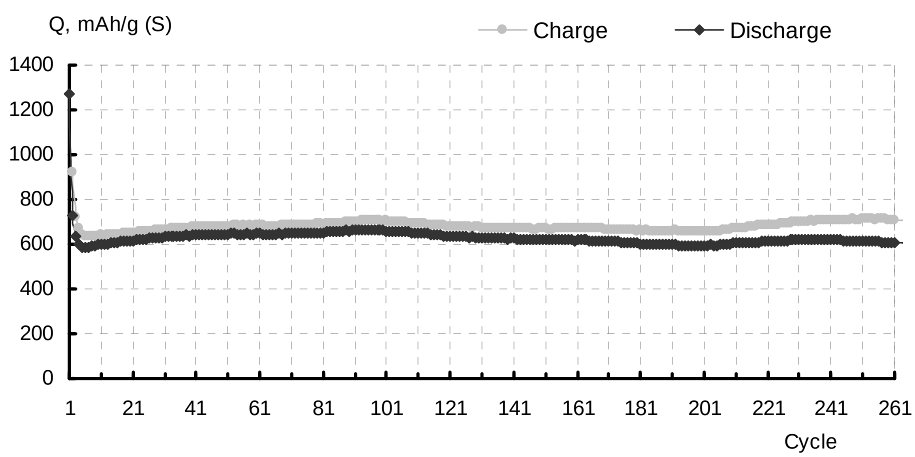
Oxis's batteries use 'heavy' electrolytes with high flash points. Our prototypes have demonstrated safe performance from room temperatures to 140C, albeit with reduced capacity at the top end of this range. Nail penetration tests both on freshly assembled and cycled pouch cells (0.5Ah capacity) did not result in any noticeable increase in temperature. Significantly, post mortem examination confirmed that there was no localised temperature increase at the point of puncture. This is due to the rapid spread of the reaction across the full surface of the Li electrode producing effective heat dissipation.

The chemistry inside Oxis's cells is benign and ultimately biodegradable, electrode active materials and electrolyte components convert into minerals under natural conditions.

5. State-of-the-art in Li-metal and Li-ion sulfide.

Oxis Energy has managed to significantly extend the cycle life of Li-metal batteries. Capacity fade is known to result from loss of sulfur from the positive electrode, excessive passivation of the lithium anode and degradation of the electrolyte system. Each of these causes has its own solution and these are covered by Oxis's IP and know-how. A year ago we demonstrated capacity fade as low as 0.04% - 0.06% per cycle. More recent data are presented on Fig 1. This shows charge discharge capacity per gram of sulfur measured at 30^{o}C and rated at C/10.

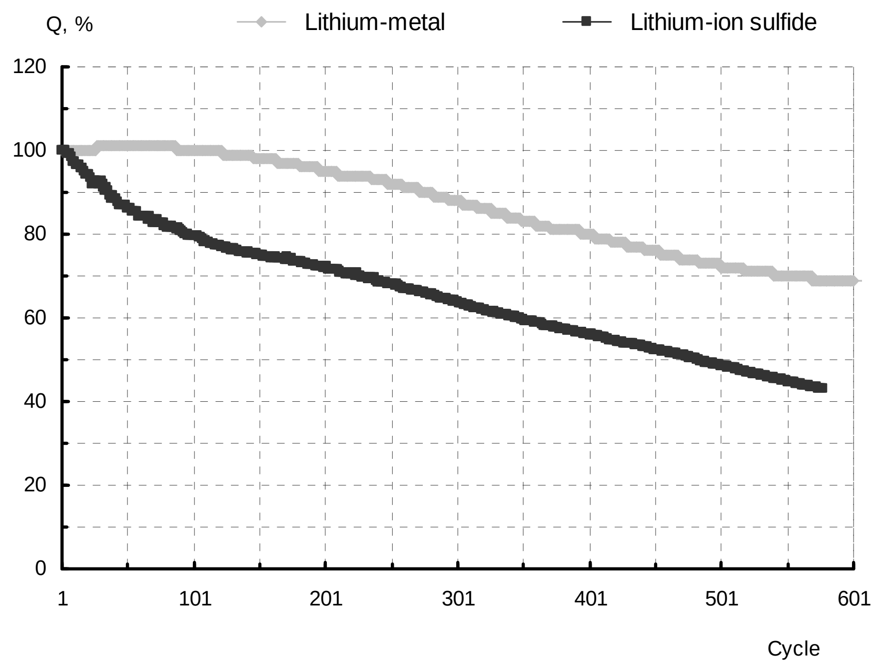
Fig 1: Capacity fade for Li-metal (Li-S Oxis Energy)



At the end of the last year we introduced a changed design of the Li-S cell and a new modification to our platform electrolyte system. Both changes produced a significant increase in specific energy. On a cell level they gave an equivalent of 350Wh/kg. The safety features of the electrolyte and the battery system as a whole were not compromised. We did not need to use lighter solvents to achieve better ion conductivity at a cost of decreased safety at room and elevated temperatures.

The comparison data of Li-metal (graphite anode) and Li-ion sulfide is presented on Fig 2. It shows normalised discharge capacity measured at 30^{o}C at C rates of C/10 – C/5. For Li-ion sulfide on a cell level it corresponds at the 300th cycle to a rated specific energy of 195 Wh/kg and the volumetric energy density of 240Wh/l.

Fig 2: Normalised discharge capacity for Li-metal and Li-ion sulfide (Oxis Energy)



6. <u>Cost considerations</u>

The bill of materials for both technologies benefits from low cost cathode materials such as sulfur and carbon. For Li-metal sulfide batteries in volume manufacture this will show a cost saving of 20%-30% compared with Li-ion.

Li-ion sulfide looks even more attractive. The absence of metallic lithium means that both electrodes can be made of carbon and graphite, whilst lithium is introduced into the system via low cost electrolyte salts. This may bring the cost of Li-ion sulfide down to that of AGM lead acid batteries.

7. <u>Summary</u>

The Li-metal sulfide technology of Oxis Energy is capable of meeting the specific energy targets for full EVs and plug in hybrids (300Wh/kg). There has been significant progress in improving the cycle life. Li-metal is optimised for 8-10 hours charge time and thus suitable for overnight charging. Faster charge may compromise the cycle life, but not battery safety.

Li-ion sulfide has the strengths of both Li-metal sulfide and Li-ion. It has a performance advantage of 50% over Li-ion systems and excellent safety characteristics. At the same time in volume manufacture it can be cost competitive with advanced lead-acid batteries.

Both systems are at the R&D and early prototyping stage. More data points are being collected and both systems need further refinement to improve power ratings and cycle stability under various conditions.