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CYCLING CHARACTERISTICS OF SILICON ENHANCED AND BORONATED LAC KNIFE NATURAL FLAKE GRAPHITE FROM QUEBEC, CANADA IN LITHIUM ION BATTERIES

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Lac Knife Graphite Project

OUTLINE

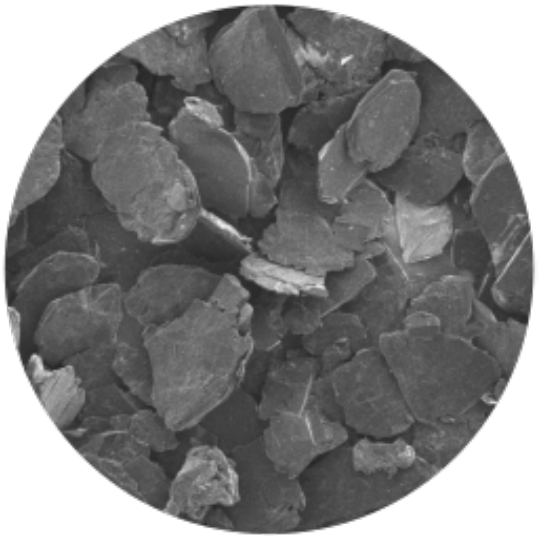
- Development of Grades of Lac Knife Flake Graphite
- Previous work on Silicon Enhanced Spherical Graphite (SPG)
- Results from Additional Cycling Studies on Si Enhanced SPG
- Initial Work on Boronated Lac Knife Flake Graphite
- Key Benefits of Lac Knife Flake Graphite

Fig. 1 DEVELOPMENT OF GRADES OF LAC KNIFE FLAKE GRAPHITE

Lac Knife Ore

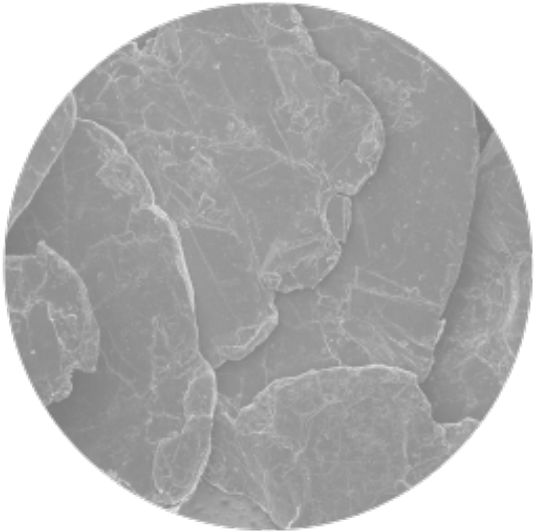
15.1% Cg

Flotation Concentrate



98.3% Cg

Purified Flake Graphite



99.98%+ Cg

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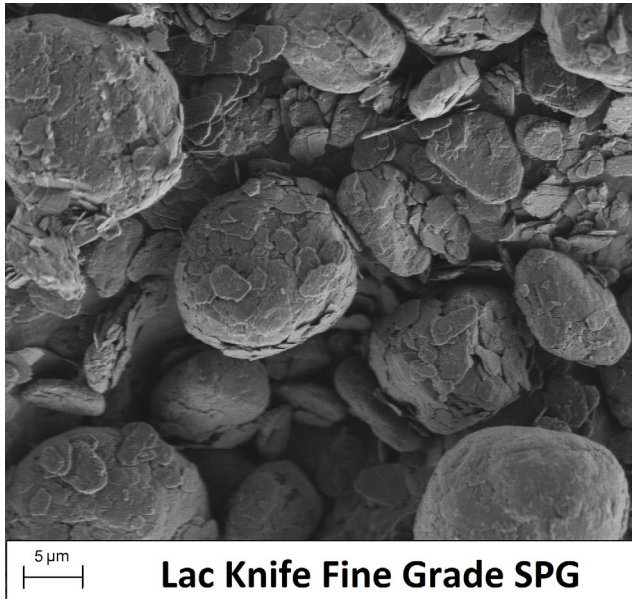
Fig. 2 FORMATION AND GRADES OF LAC KNIFE SPHERICAL GRAPHITE



Lac Knife Fine Grade SPG

PSDs of Superfine, Fine and Standard Grades of Lac Knife SPG

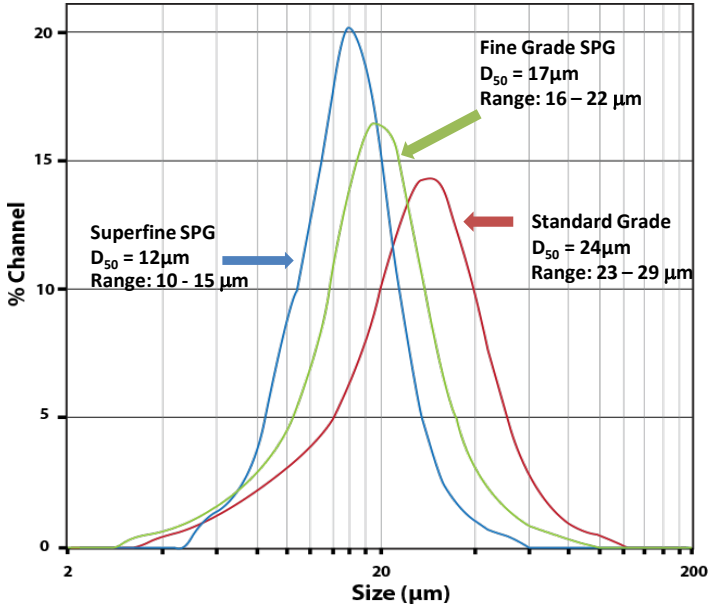


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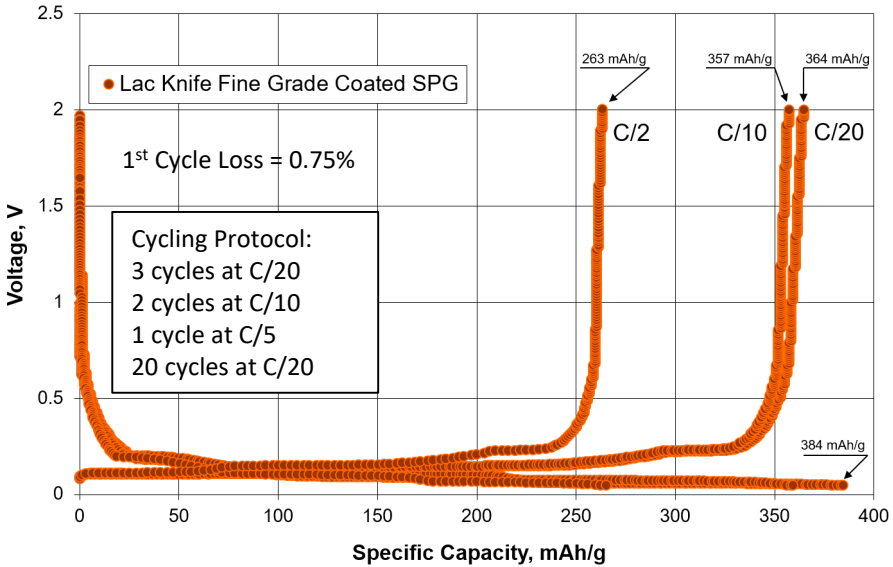
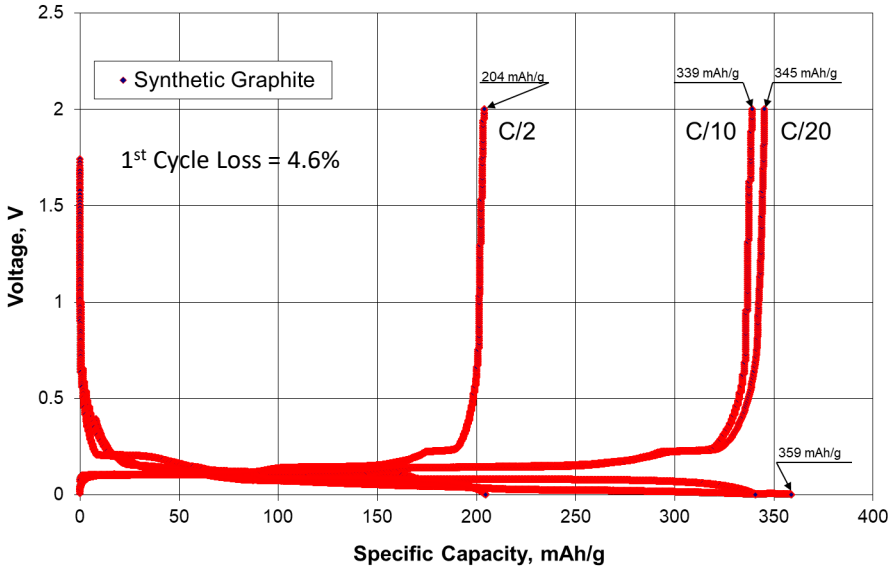
Fig. 3 CHARGE-DISCHARGE CURVES FOR CARBON COATED SPG & SYNTHETIC GRAPHITE AT C/20, C/10, AND C/2 RATES IN CR2016 HALF CELLS





- The Lac Knife cells exhibit significantly higher specific capacities than the synthetic cells at all cycling rates.
- The lower C/2 Rate values are due to design limitations of the coin cells and not the performance of the graphite.

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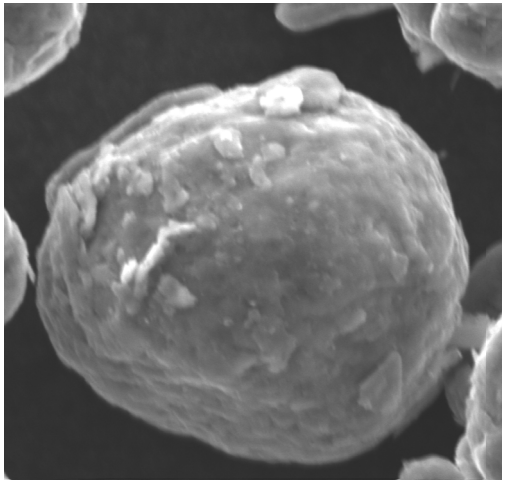
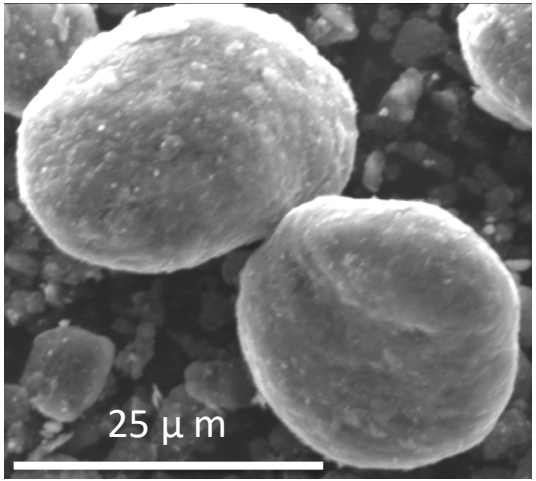
Fig. 4 SEMs OF SILICON ENHANCED LAC KNIFE SPHERICAL GRAPHITE

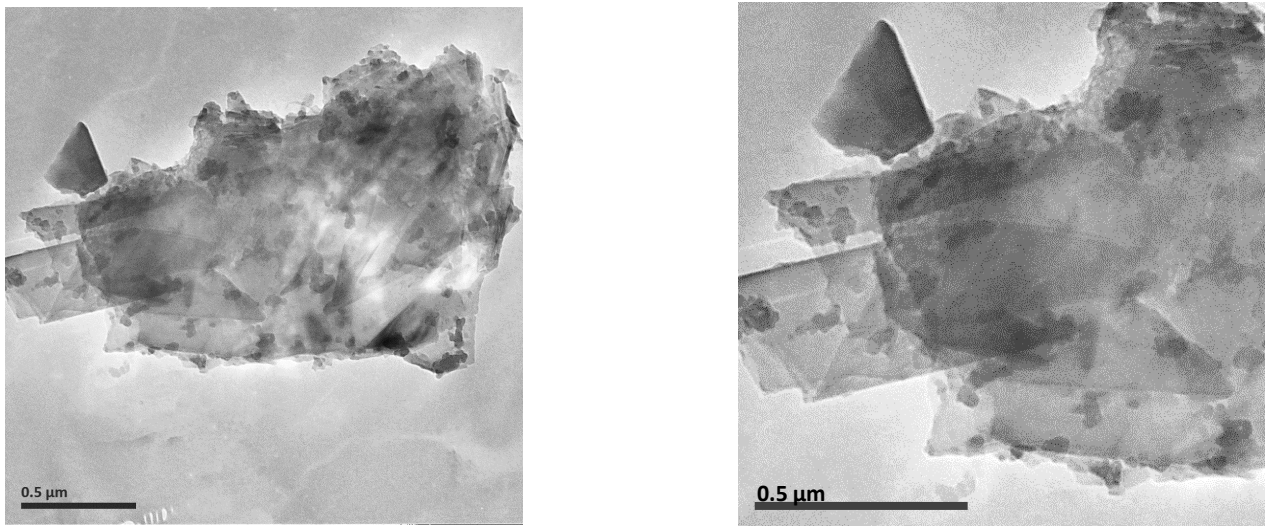


4.5% Si Carbon Coated SPG
Lac Knife Graphite



18% Si Carbon Coated SPG
Lac Knife Graphite

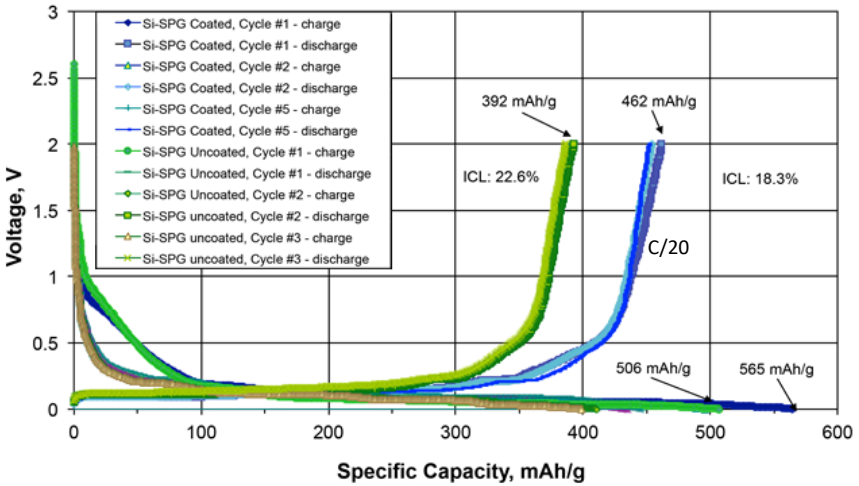
Fig. 5 TEMs OF SILICON ENHANCED LAC KNIFE GRAPHITE



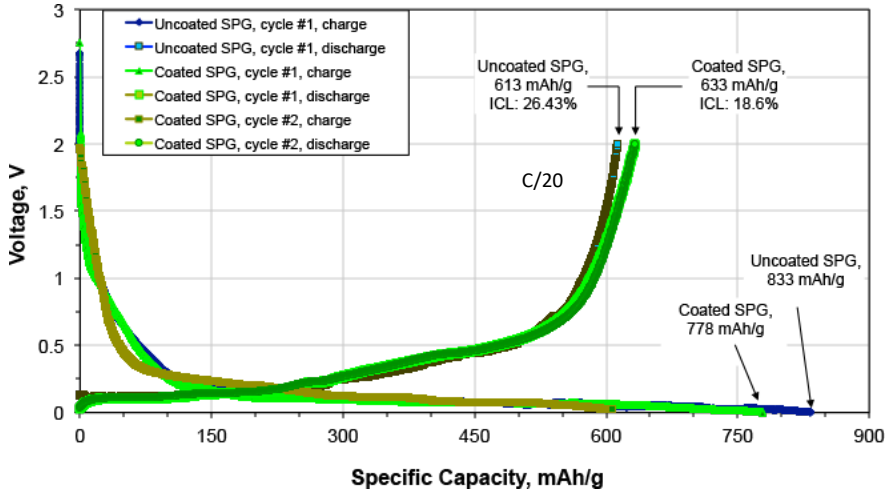
4.5% Si Carbon Coated Lac Knife SPG

Fig. 6 EFFECT OF Si CONTENT ON REVERSIBLE CAPACITY AND IRREVERSIBLE CAPACITY LOSS OF SILICON-ENHANCED LAC KNIFE GRAPHITE

4.5 wt % Silicon



18 wt % Silicon



- Coating the SPG with carbon increases the reversible capacity from 392 to 462 mAh/g which is 24% higher than the theoretical capacity of graphite alone.
- Carbon Coating also reduces the Irreversible Capacity Loss (ICL) from 22.6% to 18.3%

- Reversible Capacity of Carbon Coated SPG is 633 mAh/g, 70% higher than the theoretical capacity of graphite.
- ICL of Carbon Coated SPG is 18.6%

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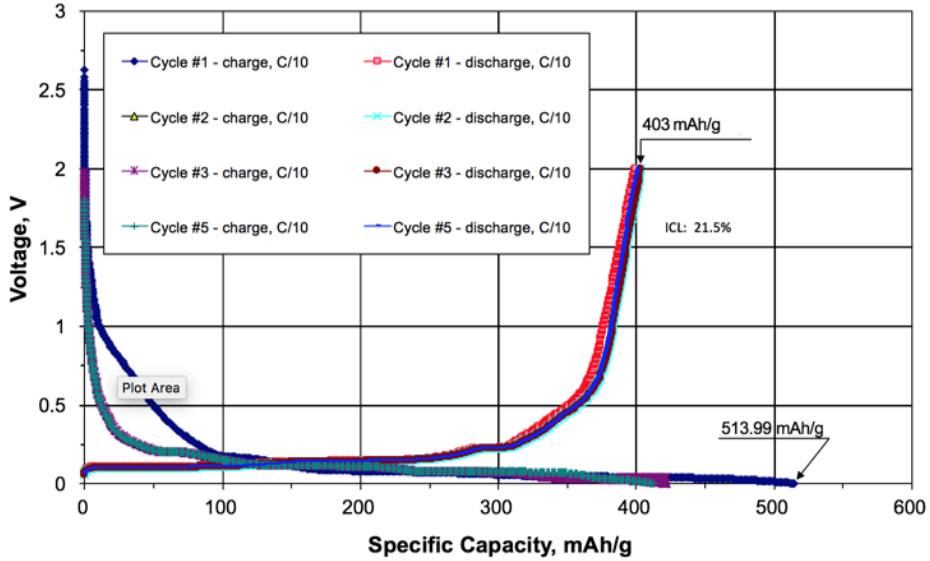
Fig. 7 GALVANOSTATIC CURVES AT C/10 RATE FOR CARBON COATED LAC KNIFE SPG AT 4.5 wt% SILICON ADDITION



- Silicon Enhanced Graphite SPG exhibits highly stable cycling performance at a C/10 rate for 5 cycles.
- The 403 mAh/g achieved at 4.5 wt% Si is 19% higher in capacity than the 339 mAh/g capacity reached for coin cells made with the untreated synthetic graphite shown in Fig. 3 at a C/10 rate.

Table 1 **COMPARISON OF ELECTROCHEMICAL PERFORMANCE OF LAC KNIFE SPG WITH SILICON ENHANCED SPG**

Focus Graphite Cell Test Samples	Reversible Capacity (mAh/g)	Irreversible Capacity Loss %	Surface Area (m^2/g)
Standard Carbon Coated SPG Grade (D_{50}=23.9µm)	364	1.4%	0.5
Fine Carbon Coated SPG Grade (D_{50}=17.4µm)	365	1.0%	1.1
Superfine Carbon Coated SPG Grade (D_{50}=11.9µm)	360	1.2%	0.9
4.5% Si Carbon Coated Standard Grade SPG	462	18.3%	2.7
18% Si Carbon Coated Standard Grade SPG	633	18.6%	4.8

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Fig. 8 SEMs OF CARBON MATERIALS USED IN ANODES

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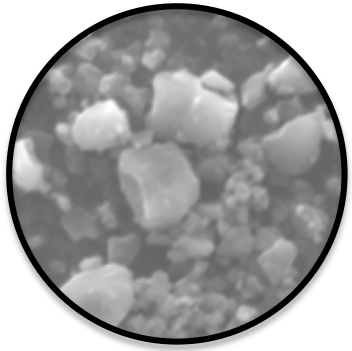
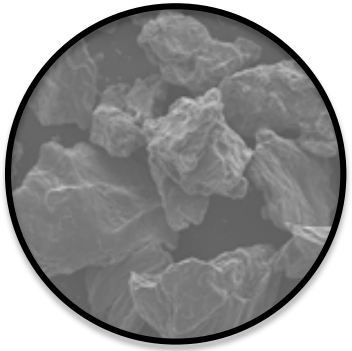
Hard Carbon



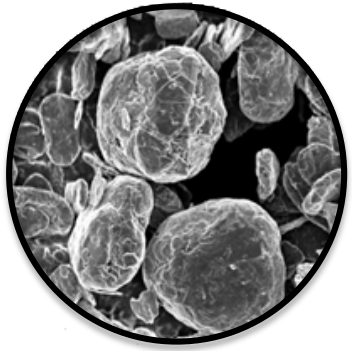
0.54 g/cc

Synthetic Graphite



0.88 g/cc

Lac Knife SPG



0.98 g/cc

- Lac Knife's spherical particles provide for maximum packing and volumetric densities.
- Hard Carbons and Synthetic graphite are comprised of irregularly- shaped particles.

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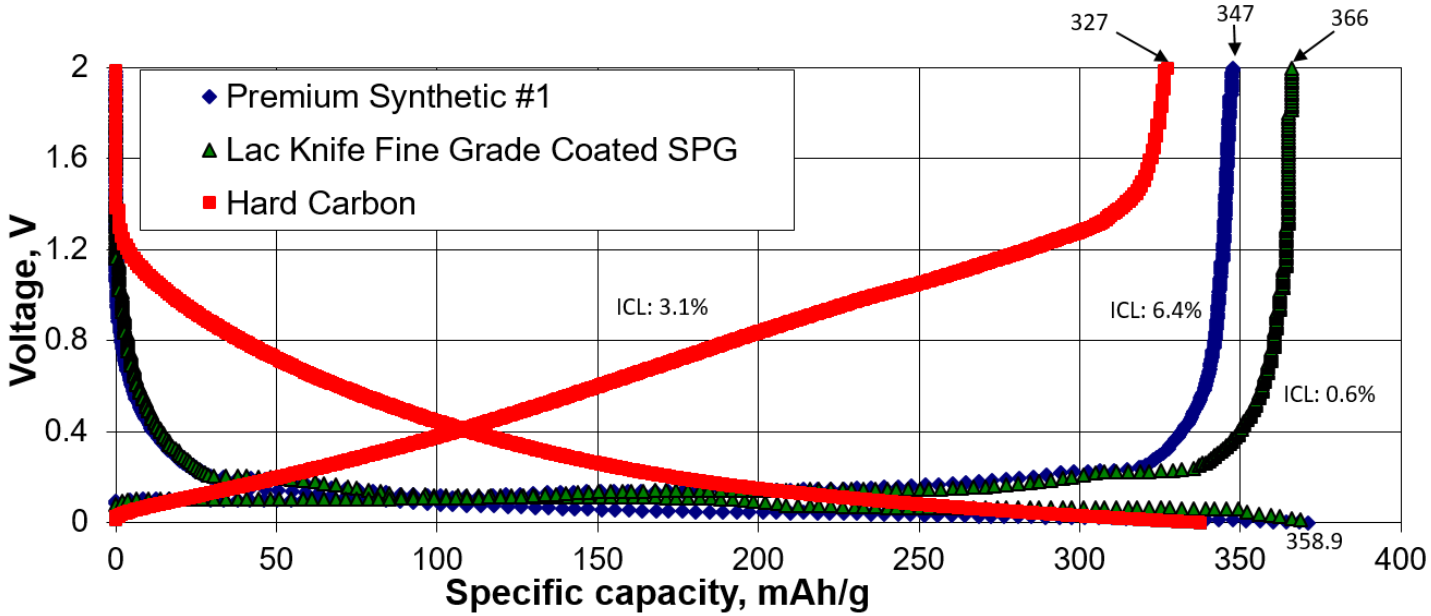
Fig. 9 COMPARISON OF THE ELECTROCHEMICAL PERFORMANCE OF LAC KNIFE FLAKE GRAPHITE WITH HARD CARBON AND SYNTHETIC GRAPHITE



- Synthetic Graphite has a similar voltage profile to the Lac Knife SPG but with a lower reversible capacity and higher ICL.
- Hard Carbon's voltage profile is much different and behaves similar to a capacitor in a high rate application but with a lower capacity than can be achieved with Lac Knife graphite.

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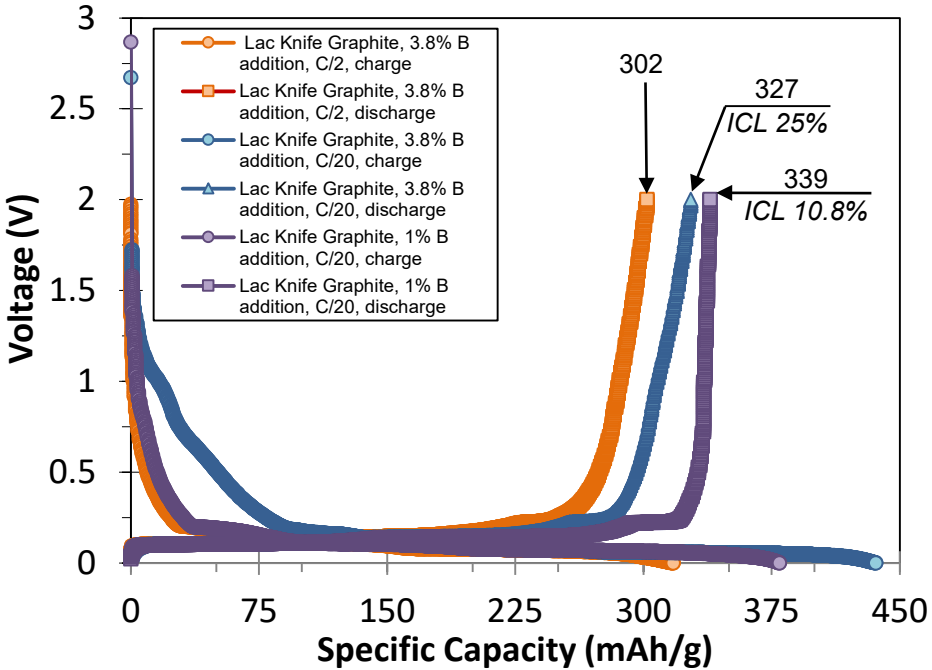
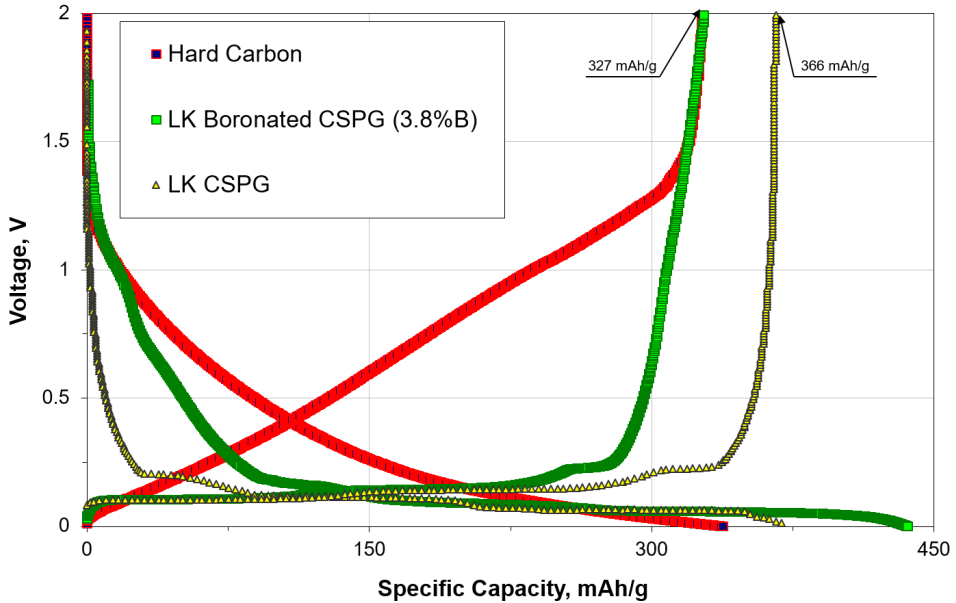
Fig. 10 **GALVANOSTATIC CURVES FOR CARBON COATED LAC KNIFE SPG AT 1.0 and 3.8 wt% BORON ADDITIONS**



- Addition of Boron to the structure of Lac Knife graphite changes the shape of the galvanostatic curve to resemble that of hard carbons.
- Impressive rate capability of 92.4% is observed with boronated graphite at the C/2 over C/20 ratio - excellent capacity retention for coin cell tests.

Fig. 11 COMPARISON OF GALVANOSTATIC CURVES AT C/20 RATE FOR LAC KNIFE CSPG AND BORONATED CSPG WITH HARD CARBON



- The addition of 3.8 wt% boron to LK Carbon Coated SPG shows a positive trend in the slope of the discharge curve similar to hard carbon and capacitor type performance.
- Work is continuing on improving the performance of LK boronated SPG while recognizing its excellent potential for high rate applications on par with hard carbons.

Table 2 KEY BENEFITS OF USING LAC KNIFE FLAKE GRAPHITE IN LITHIUM ION BATTERIES

Lac Knife Carbon Coated Spherical Graphite	
High Purity	• Reversible Capacities of 360 to 365 mAh/g are close to Theoretical Capacity of Graphite at 372 mAh/g • Low Irreversible Capacity Losses of 0.6 to 1.4%
High Crystallinity	• Reduced Capacity Fade During Long Term Cycling • High Electrical Conductivity of Graphite Provides Potential for Increasing Battery Capacity by Improving Utilization of Cathode Active Material
Modified Lac Knife Spherical Graphites	
Silicon Enhanced Lac Knife Spherical Graphite	• Increases Capacity from 462 to 633 mAh/g at 4.5% and 18% Si Additions, 24% to 70% Beyond Theoretical Limits of Graphite Alone • Exhibits Stable Cycling Characteristics After First Cycle Losses of 18.3 to 18.6%
Boronated Lac Knife Spherical Graphite	• Increases Rate Capability of Flake Graphite for High Power Applications • Exhibits Excellent Capacity Retention Characteristics Over a Wide Range of Cycling Rates

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THANK YOU

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