Choosing the Right Battery Technology

Nigel Calder

Common battery types and efficiencies:

- Wet cells (~60% efficient):
  - Cranking versus deep cycle
  - Golf cart/Trojan
- Gel cells (~75% efficient)
- 'Advanced' Absorbed Glass Mat (AGMs) (~85% efficient):
  - Lifeline
  - TPPL (EnerSys/Odyssey; Northstar)
  - Carbon-enhanced (Northstar)
  - Carbon super capacitor ('Ultra' from East Penn)
  - Carbon negative plate grid (Firefly)
  - Lead crystal ??? (Betta; ~85%-90% efficient?)
- Lithium-ion (~95% efficient)

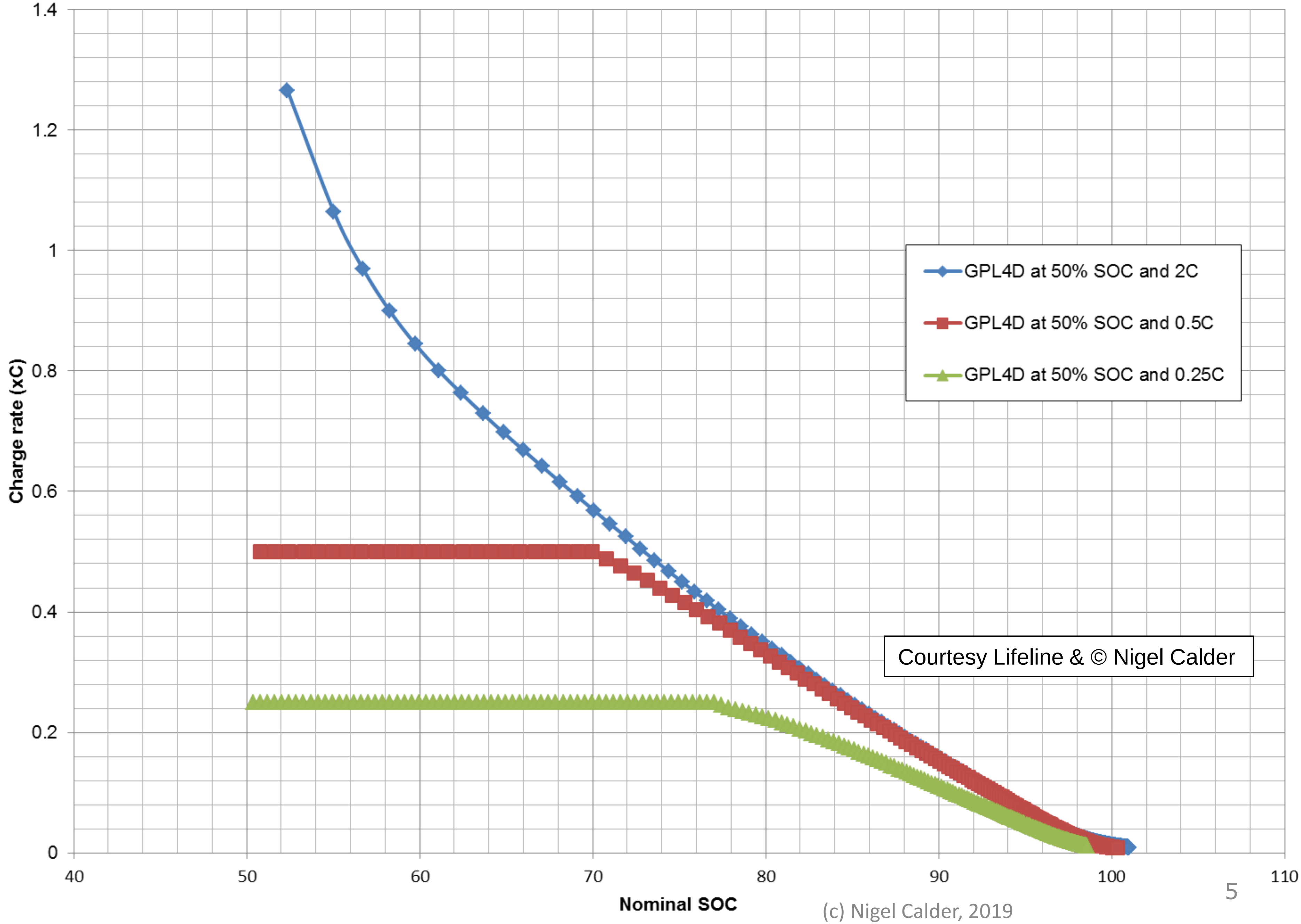
PbA chemistry:

- Positive active = porous lead dioxide; negative = finely-divided lead (sponge lead); electrolyte is sulfuric acid
- Discharge: both electrodes = lead sulfate
- At the negative, initially, sulfates small: high surface area + electroactive
- Crystals coalesce: less surface area + less electroactive
- At the positive plate sulfate crystals diminish into a sludge that is hard to charge and sheds
- The positive plate grid corrodes at the top of the charge cycle throughout the life of the battery

What is wrong with lead-acid (PbA)?

- Low CAR, especially at high SoC
- Capacity loss (sulfation) if not fully recharged
- Poor active material utilization – high volume & weight per Wh of usable capacity
- Relatively low cycle life
- On paper, lithium-ion does not suffer from any of these

Lifeline charge rate vs nominal SOC, 14.4v absorption voltage



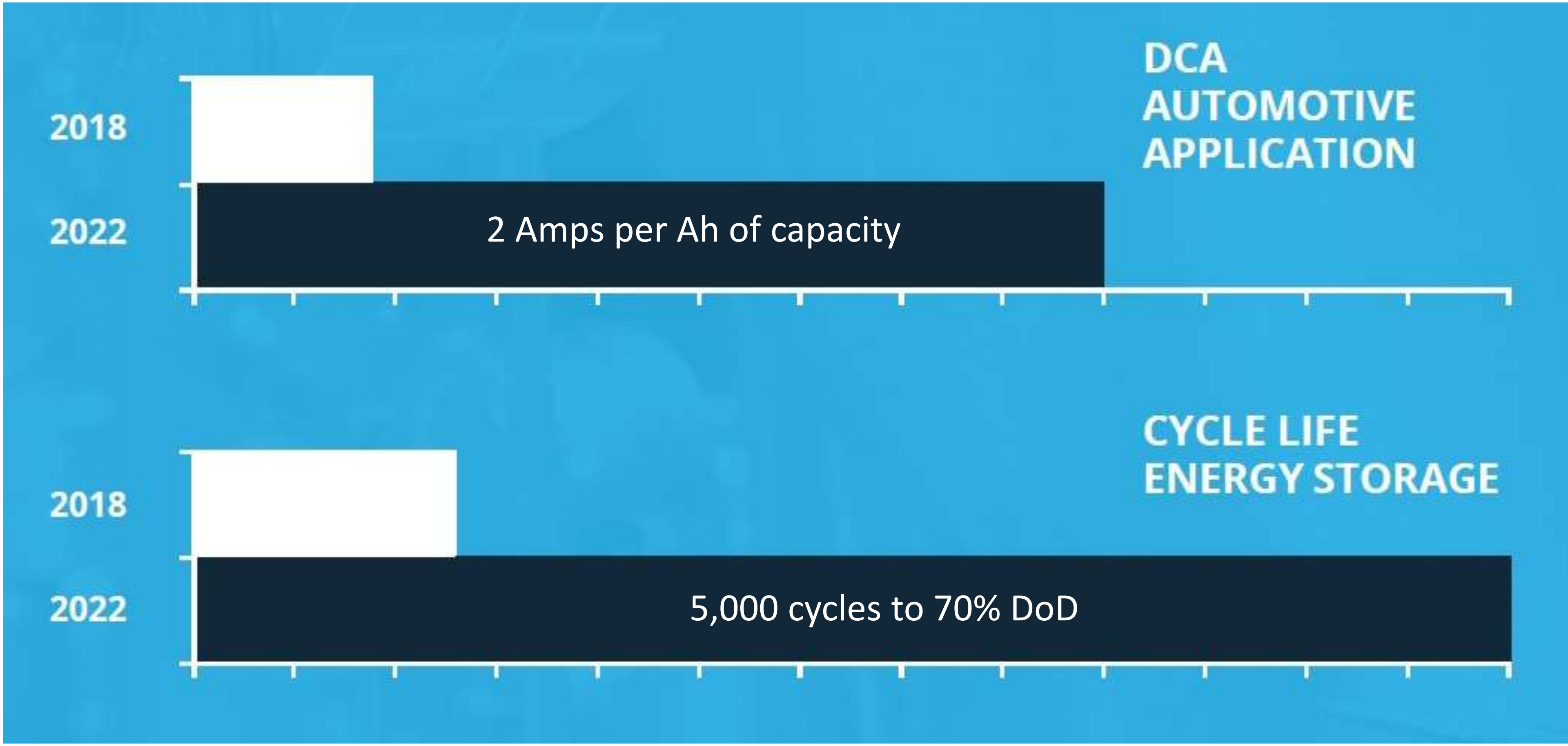
Principal PbA failure modes in marine:

- Sulfation from pSoC operation; primarily affects the negative plate (crystal growth…)
- Plate grid corrosion; primarily affects the positive plate, especially with overcharging
- Dissolution of the active material/plate shedding; primarily affects the positive plate (aging)
- Drying out the electrolyte (lack of maintenance; overcharge)

Drivers of change:

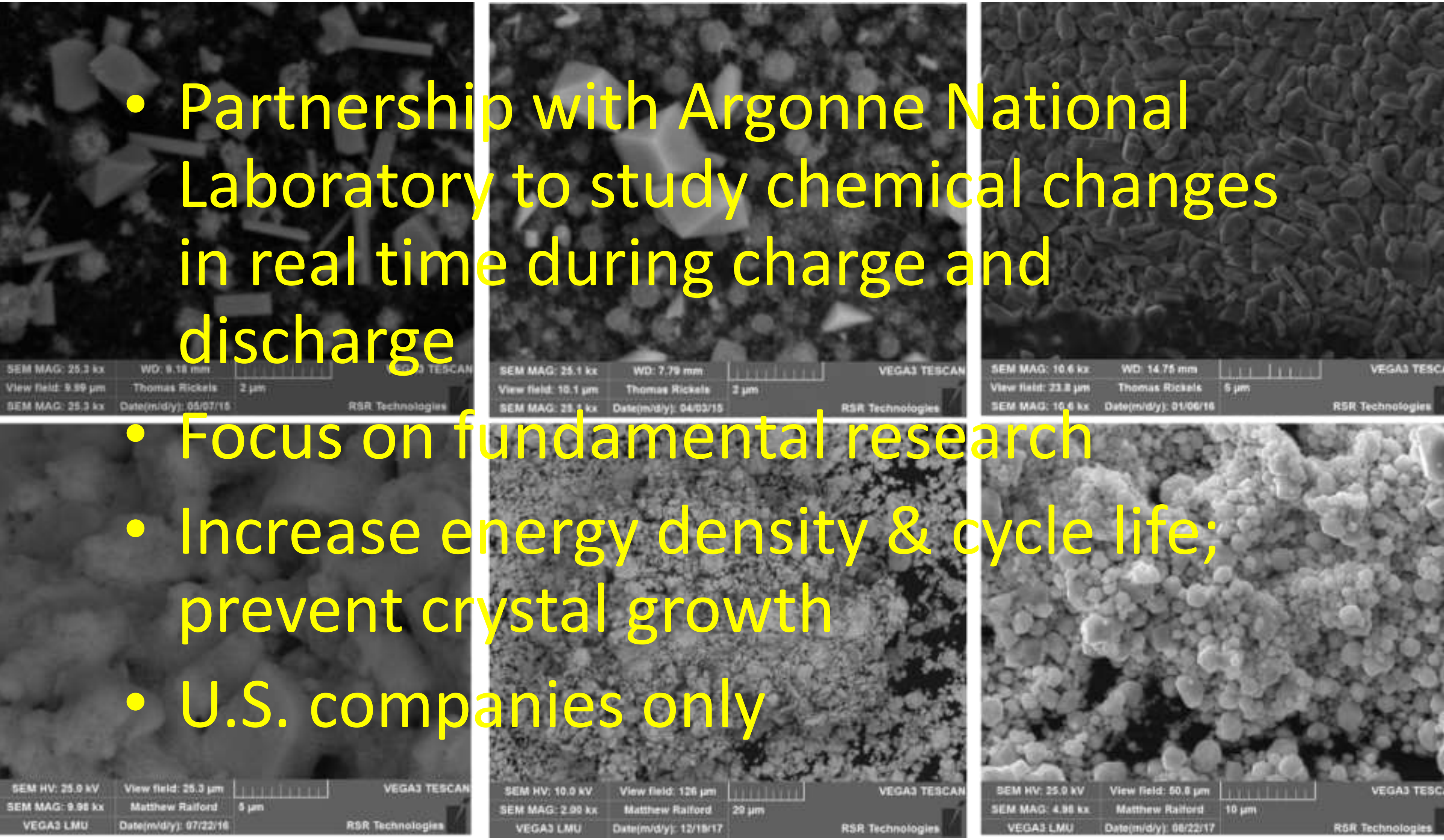
- 85% of lead goes into batteries; li-ion inroads
- Start/stop mild and micro hybrids
- Grid stabilization with wind & solar vs spinning reserve
- Peak power management
- Require pSoC operation & high CAR to high SoC

ALABC short-term objectives:



DCA = Dynamic Charge Acceptance (Charge acceptance in relation to state of charge)

Lead Battery Science Research Consortium:



- Partnership with Argonne National Laboratory to study chemical changes in real time during charge and discharge
- Focus on fundamental research
- Increase energy density & cycle life; prevent crystal growth
- U.S. companies only

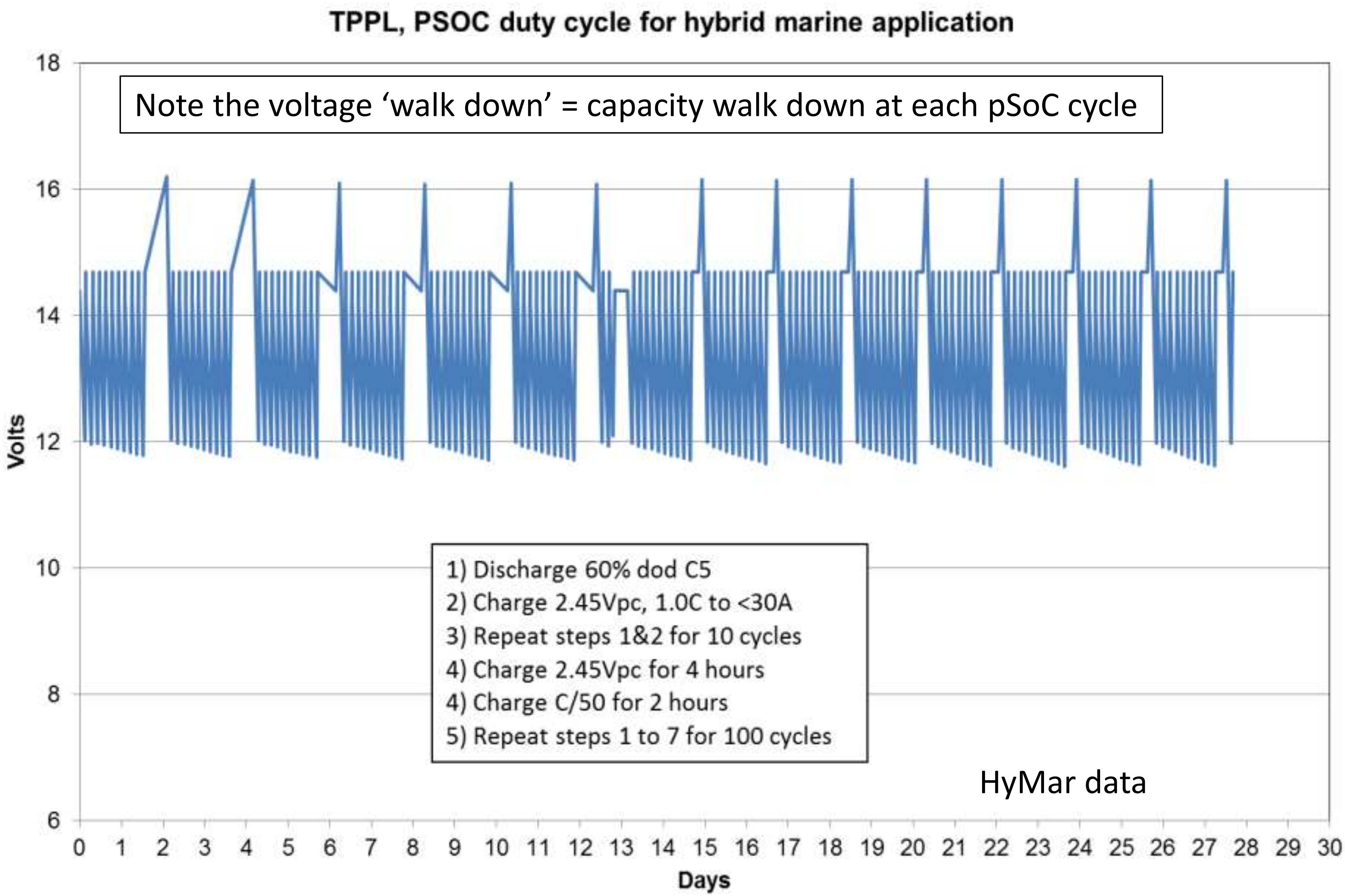
RSR TEchnologies

Thin Plate Pure Lead (TPPL):

- Been available for ~15 years; Enersys (Odyssey & SBS) and Northstar
- High purity stamped lead grid minimizes corrosion of the positive plate grid which enables thinner grids to survive in cycling applications
- Thin plates result in high CAR
- Combines cranking characteristics with deep cycle capability
- Still sulfation but can be recovered with conditioning cycles but only on a limited basis

7. Assembled by robots

What the robots are doing:

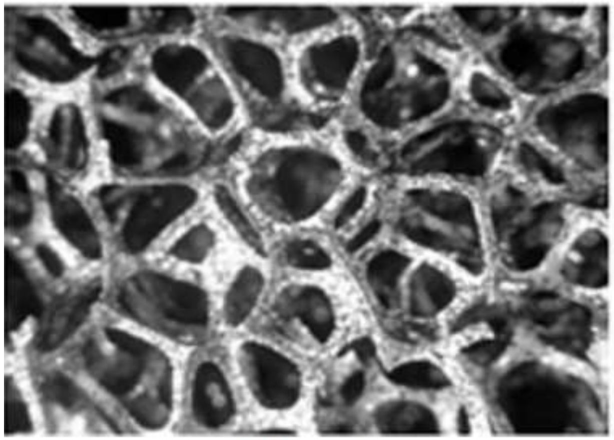

TPPL, PSOC duty cycle for hybrid marine application
Note the voltage 'walk down' = capacity walk down at each pSoC cycle
Volts
18
16
14
12
10
8
6
Days
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
1) Discharge 60% dod C5
2) Charge 2.45Vpc, 1.0C to <30A
3) Repeat steps 1&2 for 10 cycles
4) Charge 2.45Vpc for 4 hours
4) Charge C/50 for 2 hours
5) Repeat steps 1 to 7 for 100 cycles
HyMar data

Carbon-doped negative active material:

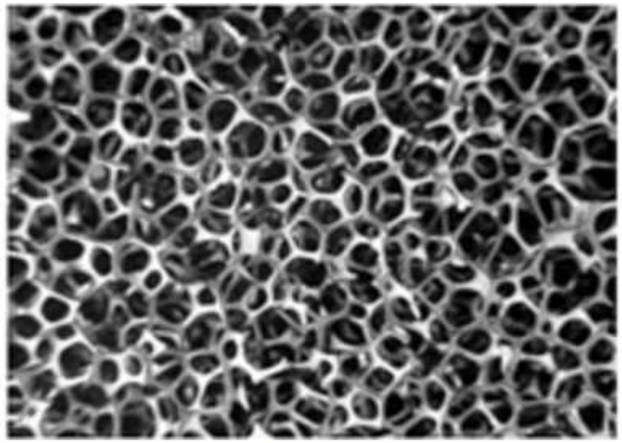
- Been available for ~10 years; Northstar ‘Blue’ batteries
- TPPL with carbon-doped active material in the negative
- Carbon inhibits sulfation
- Claim 2,000 cycles at 50% DoD & 25˚C with 12-year life if “optimal charge” (drops to ~500 cycles with “standard charge”); 2 year life at 45˚C
- In pSoC operation: “Every second week the battery shall be equalized using a 16h equalization charge at 2.41 VPC”

Carbon-foam negative plate grid:

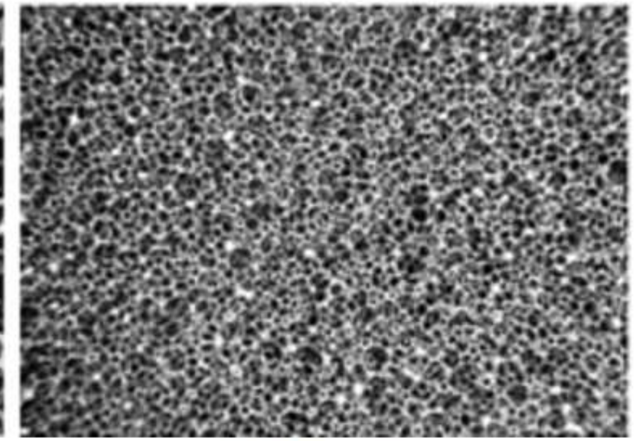
- Patented technology owned by Firefly & distributed by OceanPlanet Energy
- Negative plate grid a carbon foam – radically different to all other PbA batteries
- Pore structure of foam prevents negative plate sulfation; high cycle life
- Can be operated in a pSoC indefinitely
- CAR similar to other AGMs
- ArcActive carbon felt from New Zealand?



10 ppi

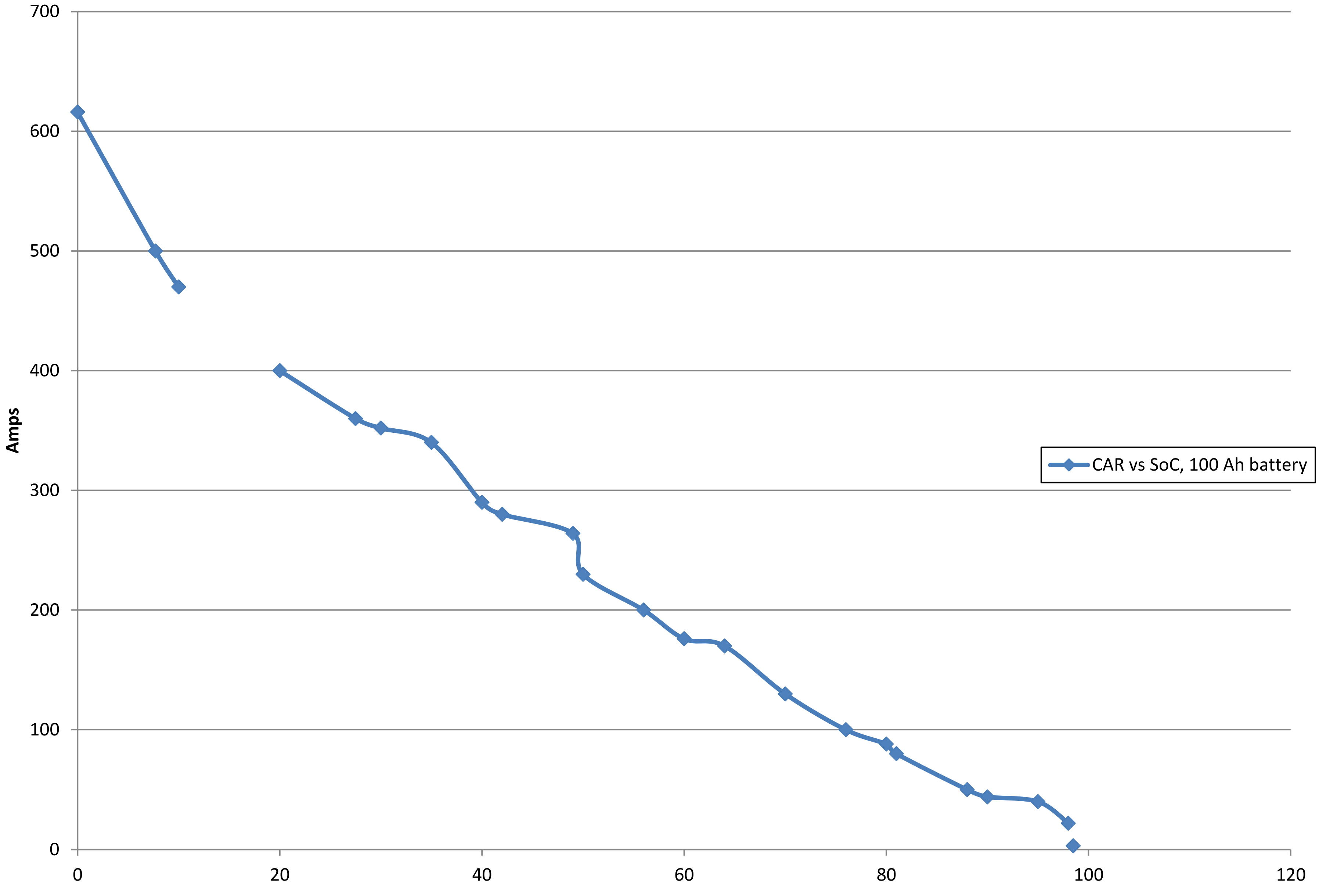


45 ppi

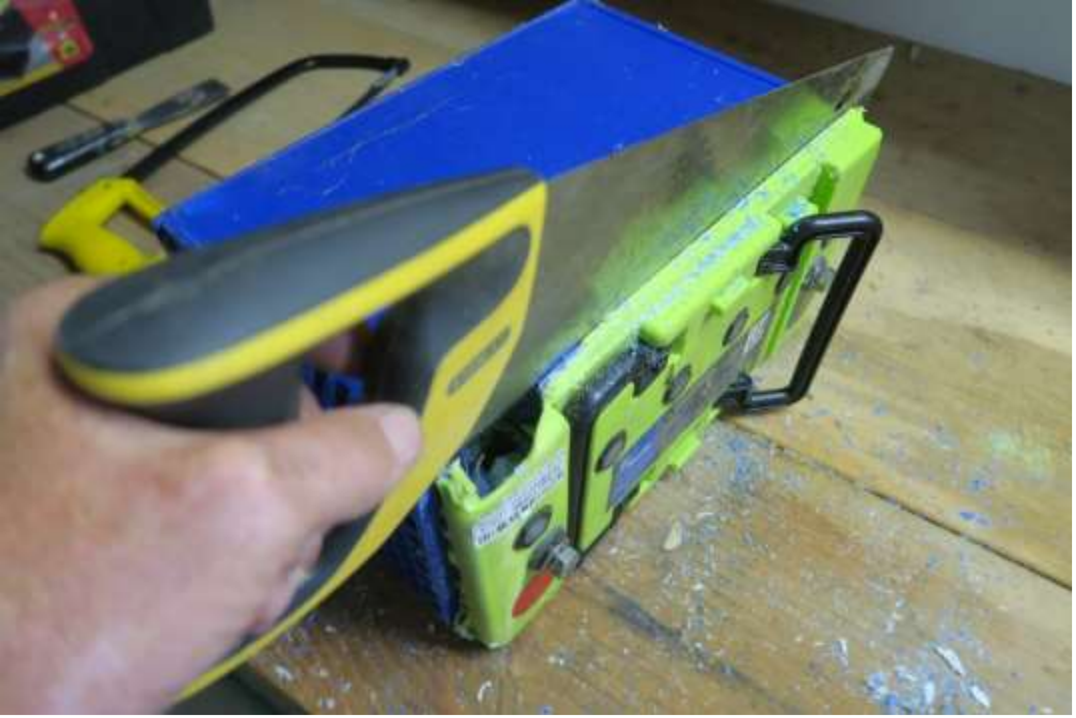


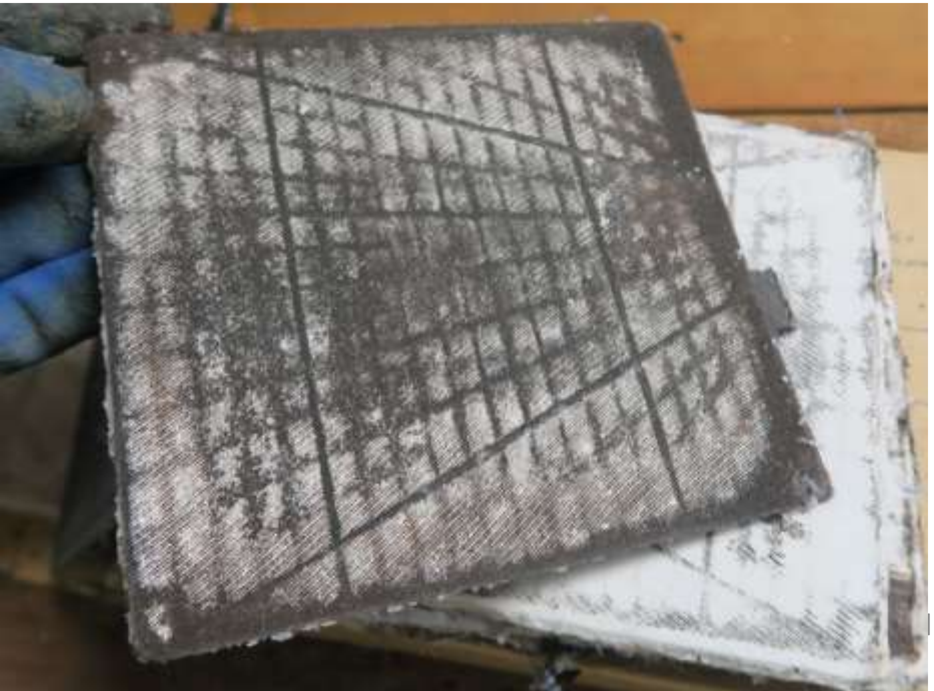
100 ppi

CAR versus SoC, 100Ah battery, 14.4v




Extreme
31 - PC2150
Extreme



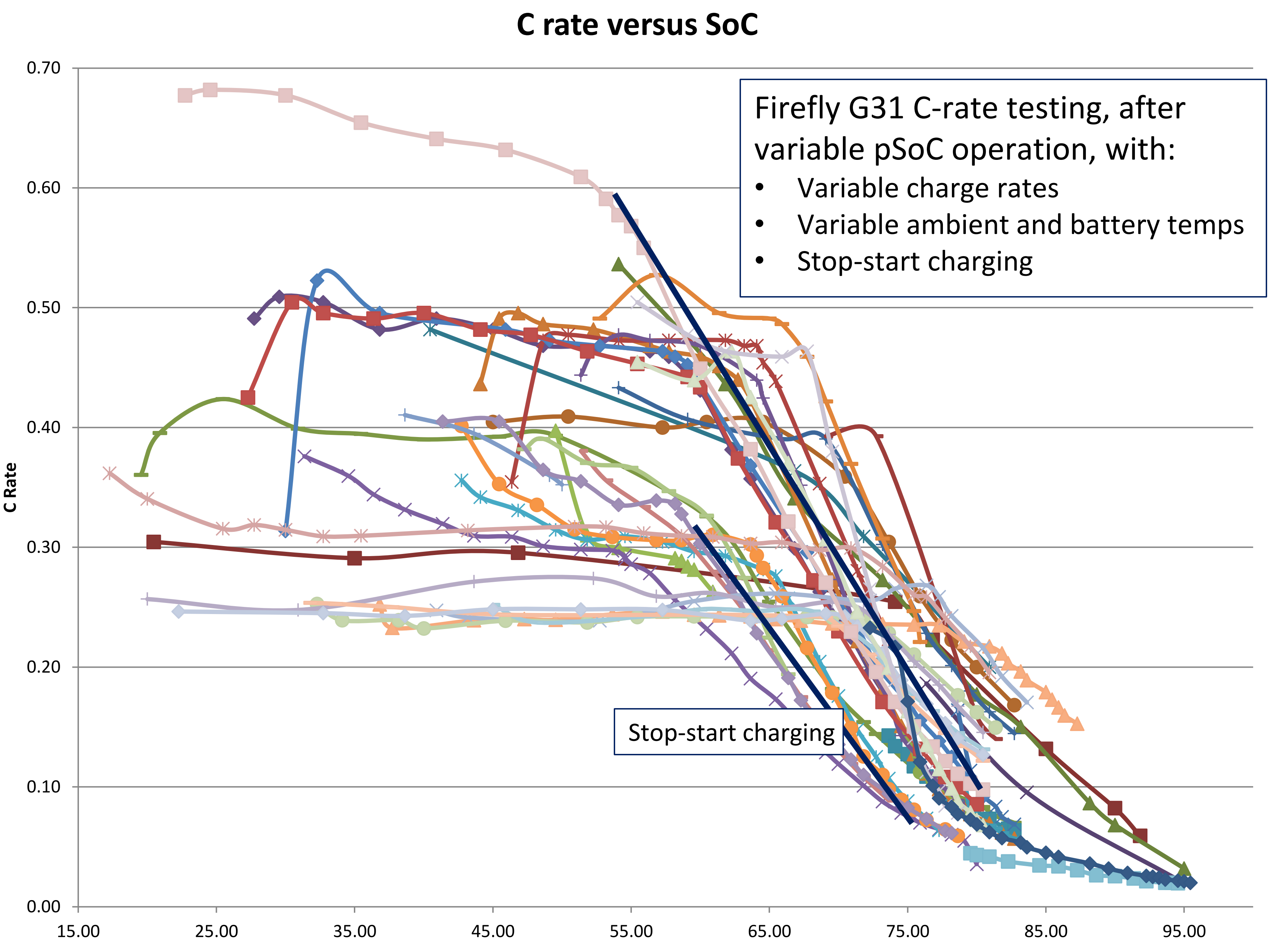




METRIC
1
2
3
4

Real-world testing:

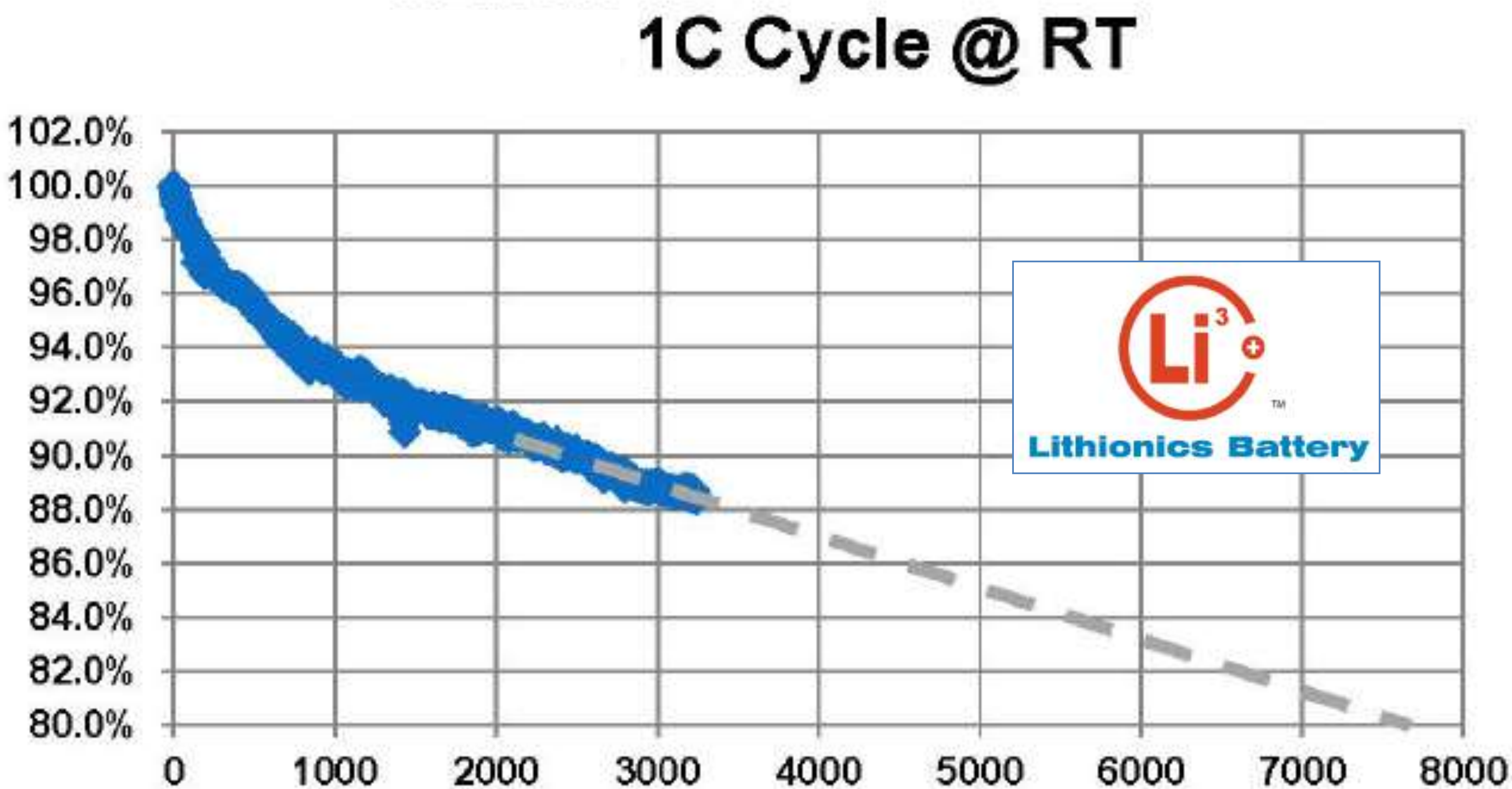
- Capacity ‘walk-down’ in pSoC; recovered with normal full-charge cycle
- Months of pSoC operation with high C-rates
- If charge stopped & restarted, CAR drops
- Discharged to 35% SoC, left for 8 months, capacity recovered with normal full-charge
- There have been QC and supply problems
- **This is by far the best lead-acid technology on the market for pSoC cycling applications**


C rate versus SoC
Firefly G31 C-rate testing, after variable pSoC operation, with:
• Variable charge rates
• Variable ambient and battery temps
• Stop-start charging
Stop-start charging
C Rate
SoC
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
15.00
25.00
35.00
45.00
55.00
65.00
75.00
85.00
95.00

Then there's lithium-ion:

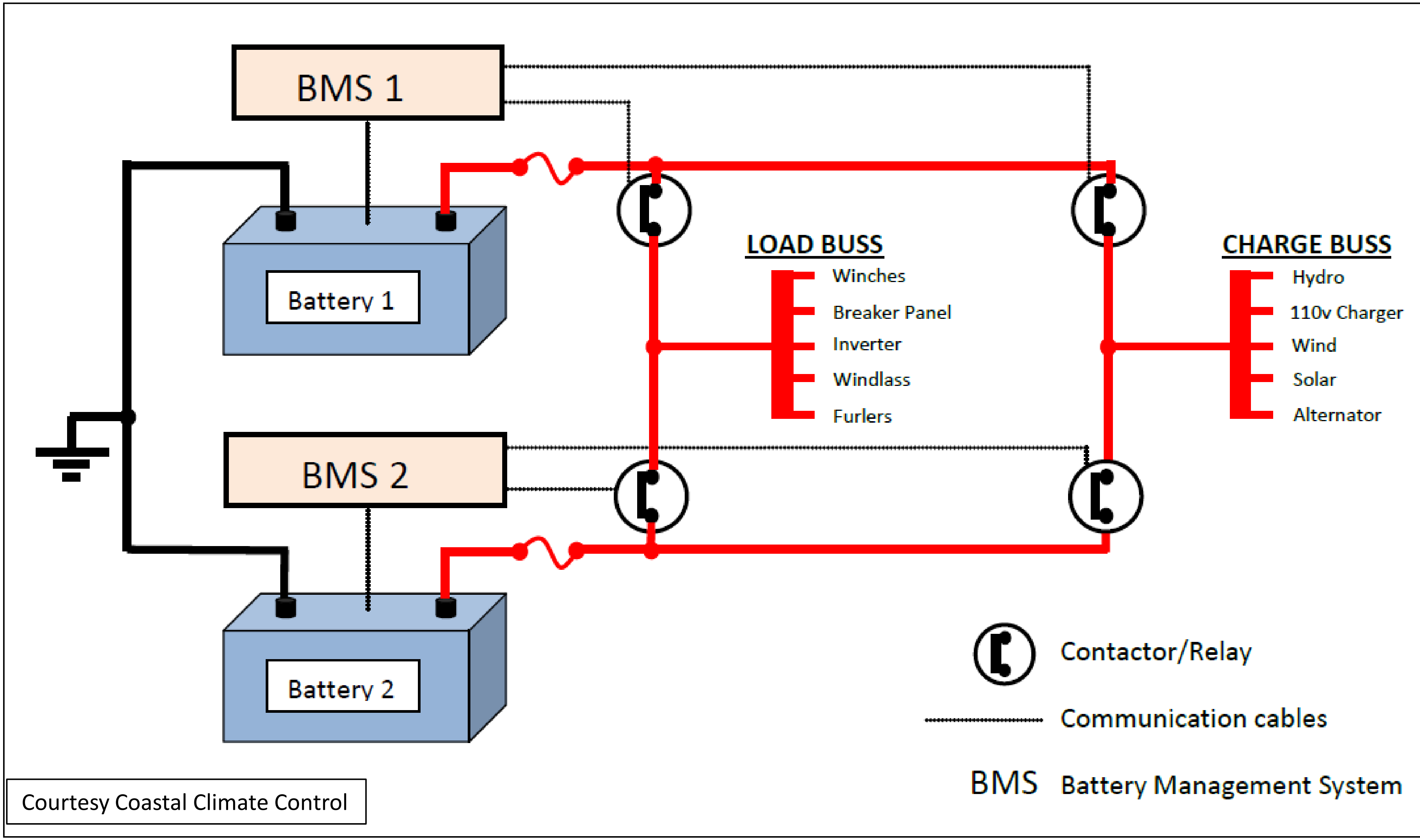
- High energy density with light weight
- *Potentially*, very high CAR to high SoC
- Immune to sulfation (and prefer pSoC)
- Tolerate deep discharges
- Depending on chemistry, very high cycle life
- Chemistries: LFP, NMC, NCA
- Potential exothermic reactions with flammable electrolyte
- Quality construction with appropriate BMS is critical
- An ESS, not a battery…

Cell cycle life testing, courtesy Lithionics:



Emerging limitations:

- Published CAR frequently ~0.3C (energy vs power)
- Problematic thermal limits: no charging below 0˚C and above 45˚C… (no active cooling in our applications); critical temperature thresholds at the cell level
- Cranking issues in sub-freezing temperatures
- BMS protects the battery at the expense of the boat (need to control charging sources; dual bus; back-up PbA)
- NMC capacity loss if kept fully charged
- Self discharge during lay-up requires capacity buffer
- Shaving capacity at both ends reduces effective capacity
- Lack of a marine standard to provide guidance



Courtesy Coastal Climate Control

Courtesy Coastal Craft

Extended lay-ups (over 3 months):

- Self discharge rate ≤ 3% per month
- Reduce the battery voltage to…50% SoC +/- 10%
- Turn the battery off
- Store in temps no higher than 30˚C
- Every 3 months, charge to 100%, discharge to LVC, then recharge to 50% +/- 10%

Lithium-ion considerations:

- What chemistry to use?
  - Appropriate charging, especially dockside with NMC?
  - Extended lay-ups?
- BMS:
  - Is it suitable for marine applications?
  - Appropriate cell balancing in extended pSoC service
  - Cell balancing in series connections (e.g. 48v systems)
  - Will the boat's energy monitor accurately track SoC & warn of/prevent impending disconnect
- Battery versus boat:
  - Temperature constraints
  - Dual bus
  - Backup batteries?
- Standards & third party testing: UL 1426 & 1973; UN 38.3; ABYC

My criteria:

- UL 1973 or
- Established marine brand with a solid history and reputation
- Other batteries may be perfectly OK but how do we tell? I will not bet my boat on them…

How much do batteries really cost?

- Upfront cost + installation + maintenance
- # of cycles before failure
- Energy delivered at each cycle in kWh (Ah x voltage)
- Lifetime ‘kWh throughput’ (kWh per cycle x life cycles)
- Cost/kWh of throughput
- This is a purely parasitic cost in an energy system…

Battery 'throughput' calculations:

- Calculate kWh capacity of a battery (Ah x voltage, e.g. 83 Ah @ 12v = 1 kWh; approximately a Group 27 battery)
- Let's assume $250/kWh of installed & maintained capacity
- Assume 500 cycles to 80% DoD ('high end' AGM)
- Assume recharge to 95% SoC (i.e. 75% of capacity used at each cycle = 0.75 kWh)
- Total energy 'throughput' is 0.75 kWh x 500 = 375 kWh
- Cost/kWh = ($250/375) = $0.67 per kWh

Battery 'throughput' costs: the importance of high cycle life

€/kWh through-put cost	Cost/kWh of battery capacity (€)							
	100.00	150.00	200.00	250.00	300.00	350.00	400.00	450.00
	Life cycles, assuming 80% DoD at each cycle and no efficiency losses through the battery							
0.01	12,500	18,750	25,000	31,250	37,500	43,750	50,000	56,250
0.02	6,250	9,375	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	28,125
0.03	4,167	6,250	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	18,750
0.04	3,125	4,688	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14,063
0.05	2,500	3,750	5,000	6,250	7,500	8,750	10,000	11,250
0.06	2,083	3,125	4,167	5,208	6,250	7,292	8,333	9,375
0.07	1,786	2,679	3,571	4,464	5,357	6,250	7,143	8,036
0.08	1,563	2,344	3,125	3,906	4,688	5,469	6,250	7,031
0.09	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6,250
0.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.2	625	938	1,250	1,563	1,875	2,188	2,500	2,813
0.25	500	750	1,000	1,250	1,500	1,750	2,000	2,250
0.3	417	625	833	1,042	1,250	1,458	1,667	1,875
0.35	357	536	714	893	1,071	1,250	1,429	1,607
0.4	313	469	625	781	938	1,094	1,250	1,406
0.45	278	417	556	694	833	972	1,111	1,250
0.5	250	375	500	625	750	875	1,000	1,125
0.6	208	313	417	521	625	729	833	938
0.7	179	268	357	446	536	625	714	804
0.8	156	234	313	391	469	547	625	703
0.9	139	208	278	347	417	486	556	625
1	125	188	250	313	375	438	500	563

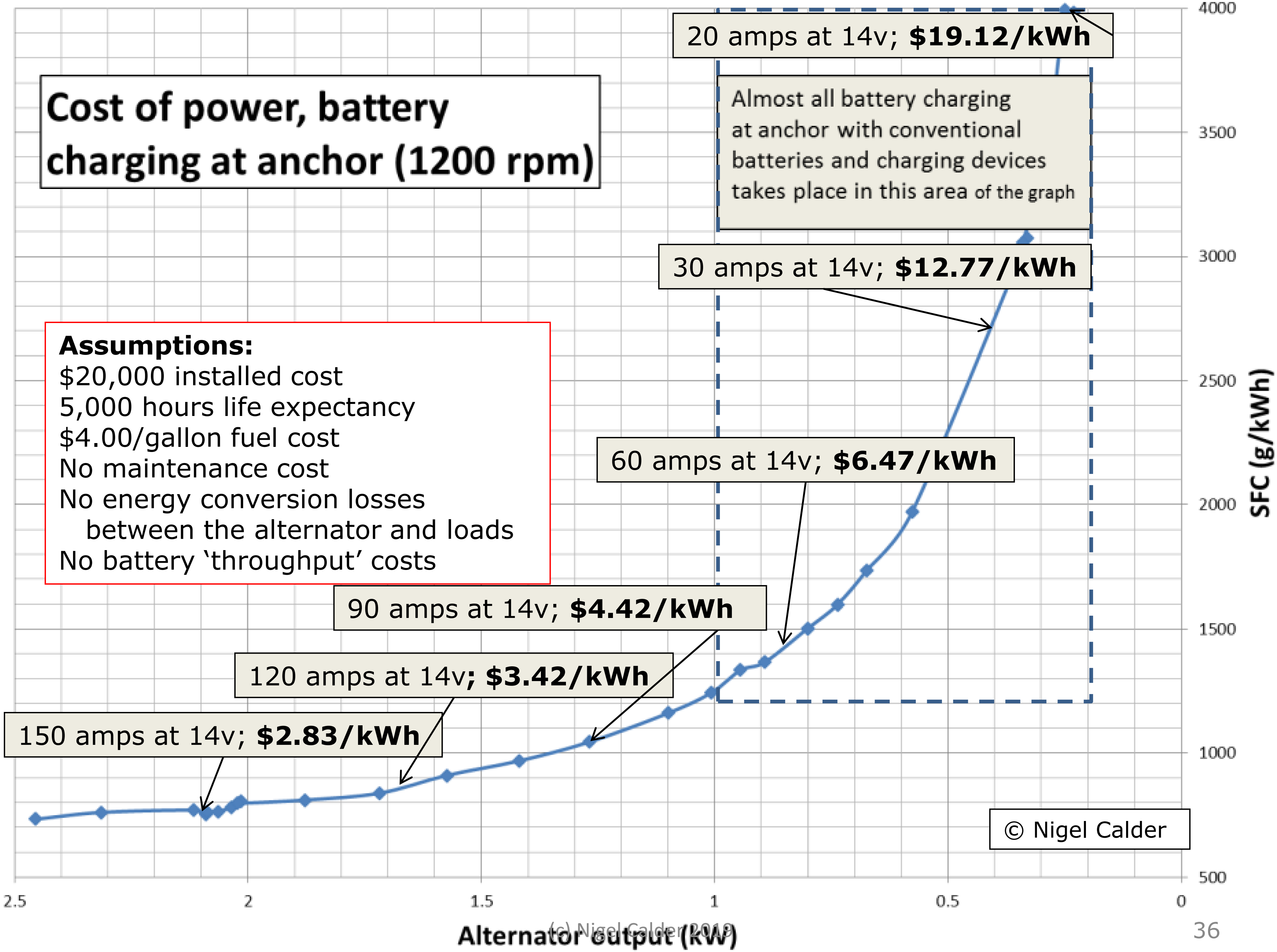
E.g. 8D 12v battery rated at 250 Ah, costs $400, with 400 cycles to 80% DoD:
Capacity is 12v x 250 Ah = 3,000Wh = 3kWh
Cost is $400/3 = $133.33/kWh
80% DoD = 200 Ah = 200 Ah x 12v = 2.4 kWh
400 cycles = 2.4 kWh x 400 cycles = 960 lifetime kWh
'Throughput' cost = $400/960 kWh = $0.42/kWh
The assumption of a 100% recharge is unrealistic…
There will be additional costs associated with the losses in charging & discharging…

Cycle life may be a red herring:

- Cycle life is only relevant to the kWh throughput cost if it can be fully utilized
- No recreational marine application is likely to be able to use 5,000 cycles…
- The battery will likely fail from other causes first
- The kWh throughput cost needs to be based on the ***cycles used***…

Impact of ‘kWh input’ costs:

- Need to know the energy source for charging the battery (e.g. shorepower, solar, onboard engine)
- Calculate the cost per kWh of the input energy
- *If an engine is run solely for battery charging, the ‘kWh input’ cost will be much higher than the battery’s ‘kWh throughput’ cost*
- **The key factors in total energy costs become:**
  - **Battery CAR & efficiency**
  - **The ability to exploit high CAR rates (high output alternators; Integrel system)**
- If the high CAR rate of lithium-ion can be exploited the kWh throughput cost is less than that of PbA


Cost of power, battery charging at anchor (1200 rpm)
20 amps at 14v; $19.12/kWh
Almost all battery charging at anchor with conventional batteries and charging devices takes place in this area of the graph
30 amps at 14v; $12.77/kWh
Assumptions:
$20,000 installed cost
5,000 hours life expectancy
$4.00/gallon fuel cost
No maintenance cost
No energy conversion losses between the alternator and loads
No battery 'throughput' costs
60 amps at 14v; $6.47/kWh
90 amps at 14v; $4.42/kWh
120 amps at 14v; $3.42/kWh
150 amps at 14v; $2.83/kWh
© Nigel Calder
SFC (g/kWh)
4000
3500
3000
2500
2000
1500
1000
500
2.5
2
1.5
1
0.5
0
Alternator output (kW)

Cost of power from generators, $/kWh

SFC	€/kWh	Electrical output, kW									
(g/kWh)	(fuel)	0.25	0.5	0.75	1	2	4	6	8	10	15
		€/kWh, including amortization									
200	0.35	8.35	4.35	3.02	2.35	1.35	0.85	0.68	0.60	0.55	0.48
220	0.39	8.39	4.39	3.05	2.39	1.39	0.89	0.72	0.64	0.59	0.52
240	0.42	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.62	0.55
260	0.46	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.66	0.59
280	0.49	8.49	4.49	3.16	2.49	1.49	0.99	0.82	0.74	0.69	0.62
300	0.53	8.53	4.53	3.19	2.53	1.53	1.03	0.86	0.78	0.73	0.66
325	0.57	8.57	4.57	3.24	2.57	1.57	1.07	0.90	0.82	0.77	0.70
350	0.61	8.61	4.61	3.28	2.61	1.61	1.11	0.95	0.86	0.81	0.75
375	0.66	8.66	4.66	3.32	2.66	1.66	1.16	0.99	0.91	0.86	0.79
400	0.70	8.70	4.70	3.37	2.70	1.70	1.20	1.03	0.95	0.90	0.83
450	0.79	8.79	4.79	3.45	2.79	1.79	1.29	1.12	1.04	0.99	0.92
500	0.88	8.88	4.88	3.54	2.88	1.88	[illegible]	[illegible]	[illegible]	[illegible]	1.01
550	0.96	8.96	4.96	3.63	2.96	1.96	[illegible]	[illegible]	[illegible]	[illegible]	1.10
600	1.05	9.05	5.05	3.72	3.05	2.05	[illegible]	[illegible]	[illegible]	[illegible]	1.18
700	1.23	9.23	5.23	3.89	3.23	2.23	[illegible]	[illegible]	[illegible]	[illegible]	1.36
800	1.40	9.40	5.40	4.07	3.40	2.40	[illegible]	[illegible]	[illegible]	[illegible]	1.53
900	1.58	9.58	5.58	4.24	3.58	2.58	[illegible]	[illegible]	[illegible]	[illegible]	1.71
1000	1.75	9.75	5.75	4.42	3.75	2.75	2.25	2.08	2.00	1.95	1.88

Assumptions:
$10,000 installed cost
3,000 hours life expectancy
$5.00/gallon fuel cost
85% electrical efficiency…
No maintenance costs
No energy conversion losses between the generator and loads
No battery throughput costs

‘Take home’ messages:

- If charging times are limited, high CAR and/or partial state of charge (pSoC) operation are by far the most important battery attributes
- *Where weight and volume are not critical factors*, ‘advanced’ PbA should not be written off in high CAR, pSoC applications; capabilities are improving all the time
- All batteries have a relatively high ‘kWh throughput ‘ cost, & potentially a very high ‘kWh input’ cost
- *If the capabilities of lithium-ion can be fully exploited*, in many applications the cost of energy supplied by the battery will be less than with any PbA battery
- There are more constraints on the SOE* of lithium-ion batteries than are often recognized…

* SOE = Safe Operating Envelope

Lifestyles will trump other factors:

- Ability to have overnight aircon without running a generator
- Getting the generator and its associated maintenance off the boat
- Getting the propane system off the boat (a single fuel boat)
- Advanced PbA batteries & lithium-ion batteries coupled to advances in alternators & solar panels now make this possible

Questions?

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