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Nickel Zinc Battery Evaluation at Crane

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5/3/17

Nickel Zinc Battery History

- Originally developed and patented by Thomas Edison in 1901
- Performance was limited by cyclic capability and stability of the rechargeable system
- Used occasionally in railcars in early part of 20th century; interest for electric vehicles from the 1970s onward
- US Company, PowerGenix (PGX), developed new Intellectual Property beginning in the 2000s
- EnerSys signed license and technology development agreement with PGX in 2012

Nickel Zinc Electrochemistry

- **Anode Material:** Zinc / Zinc Oxide
- **Electrolyte:** Aqueous Potassium Hydroxide
- **Cathode Material:** Nickel-Oxyhydroxide / Nickel-Hydroxide

Anode:	$Zn + 2OH^-$	discharge → / ← charge	$Zn(OH)_2 + 2e^-$	$E^\circ = -1.24\ V$
Cathode:	$2NiOOH + 2\ H_2O + 2e^-$	discharge → / ← charge	$2Ni(OH)_2 + 2OH^-$	$E^\circ = 0.49\ V$

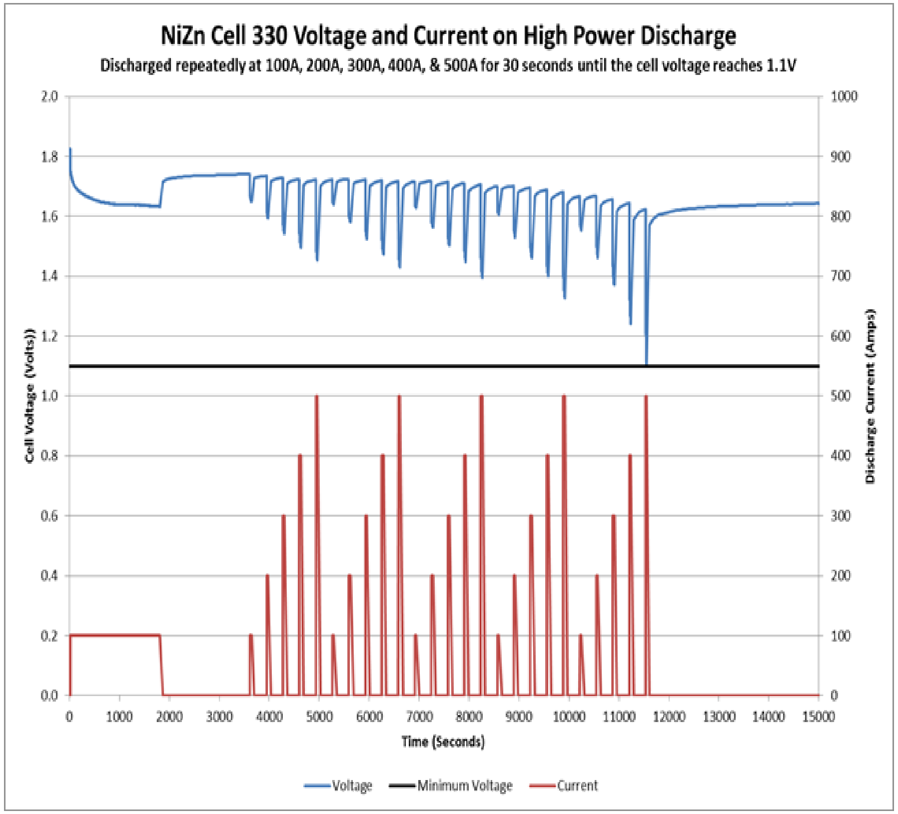
- Nominal voltage of 1.73 volts
- Discharge reaction is exothermic

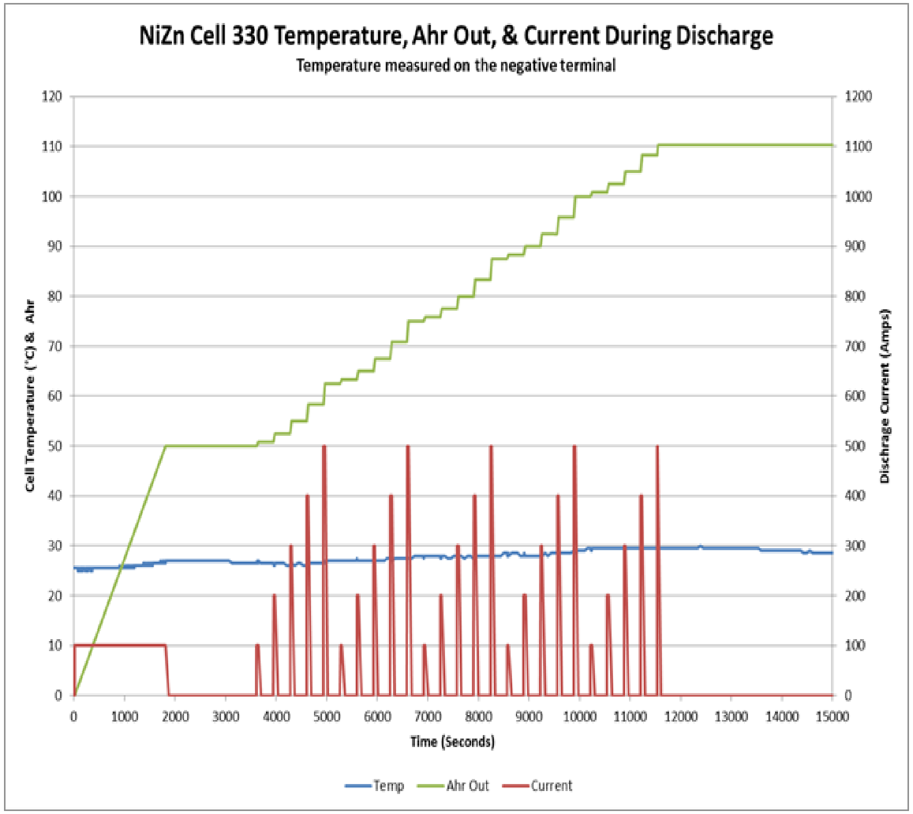
Nickel Zinc Cell Features

- Prismatic single cell
- Rated capacity of 100Ah at 10-hour rate
- Maintenance-free (no top-up or refill required)
- Specific energy - 66 Wh/kg
- Energy density - 136 Wh/liter

NiZn Cell Performance – High Power Pulse Discharge

- HPPD with variable discharge current pulses and voltage responses at various states of discharge
- HPPD with variable discharge current pulses and cumulative Ah output at isotherm conditions

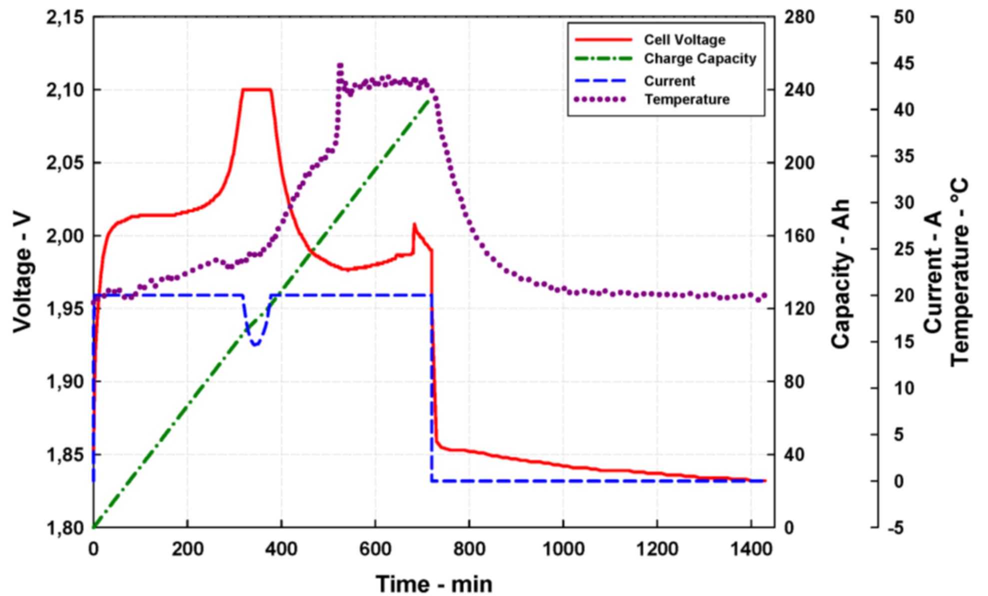


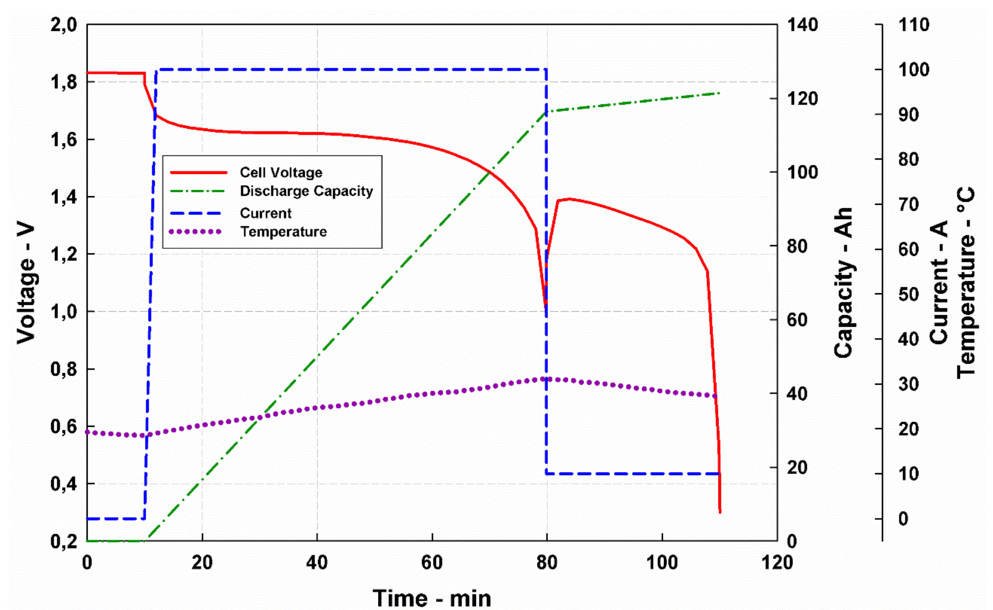


5C starting power available when as low as 92%DOD, or about 8%SOC

NiZn Cell Performance – Overcharge/Over-discharge

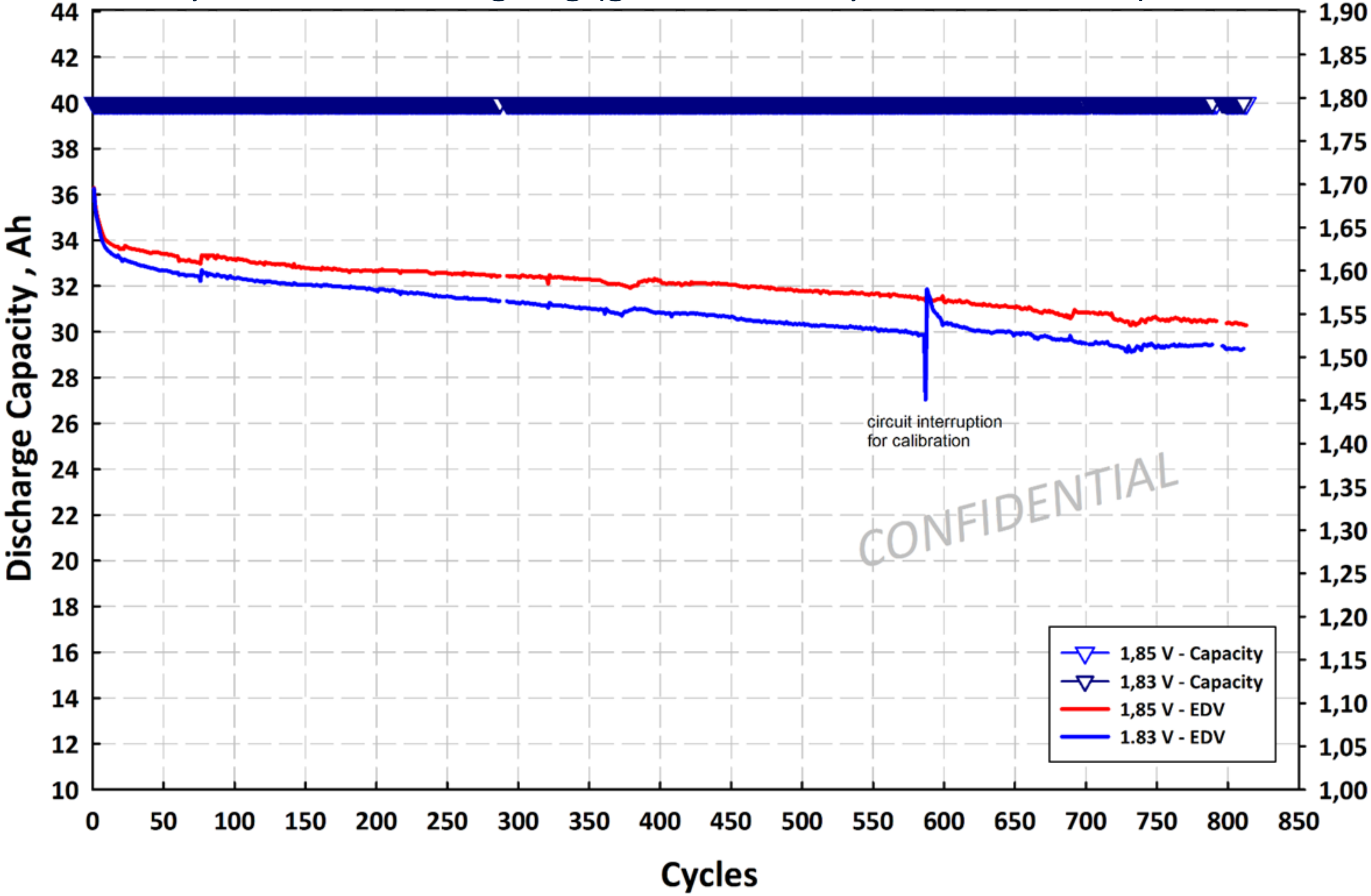
- Overcharge test – no physical damage or thermal runaway
- Over-discharge test – no physical damage observed and cell could be recharged after 21 day extended storage
- Recharge recovery after 21 day extended storage at 0% SOC – recharge input 125Ah and subsequent discharge delivered 100Ah capacity





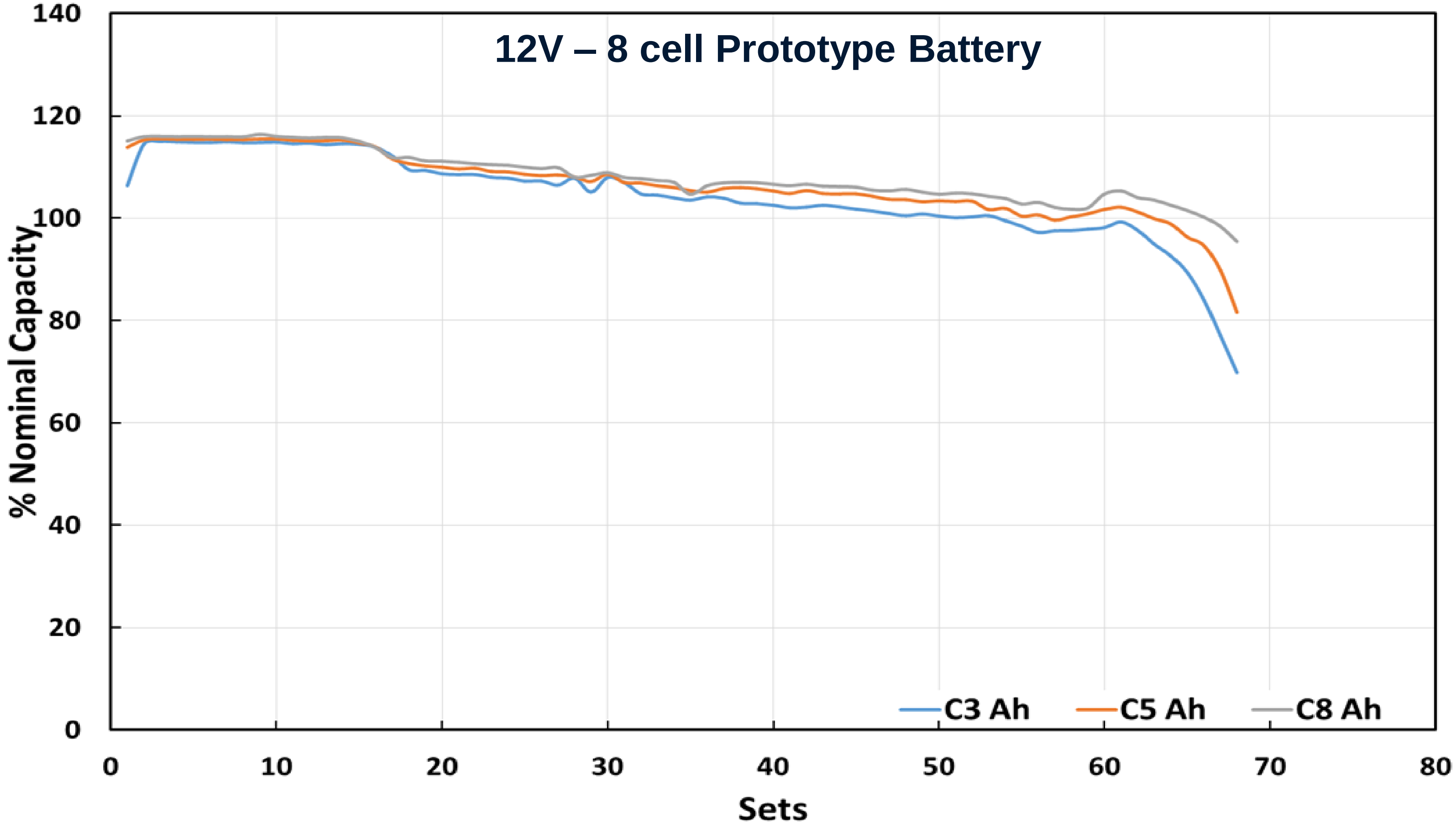
NiZn Cell Performance – Shallow Cycle Life Using Float Charge Conditions

- IEC 60896-21 clause 6.13: float with daily discharge of 20 amps for 2 hours (40%DoD C/2)
- Float voltages of 1.83 volts and 1.85 volts used
- Over 810 cycles to date – ongoing (goal of >800 cycles at 40%DOD)



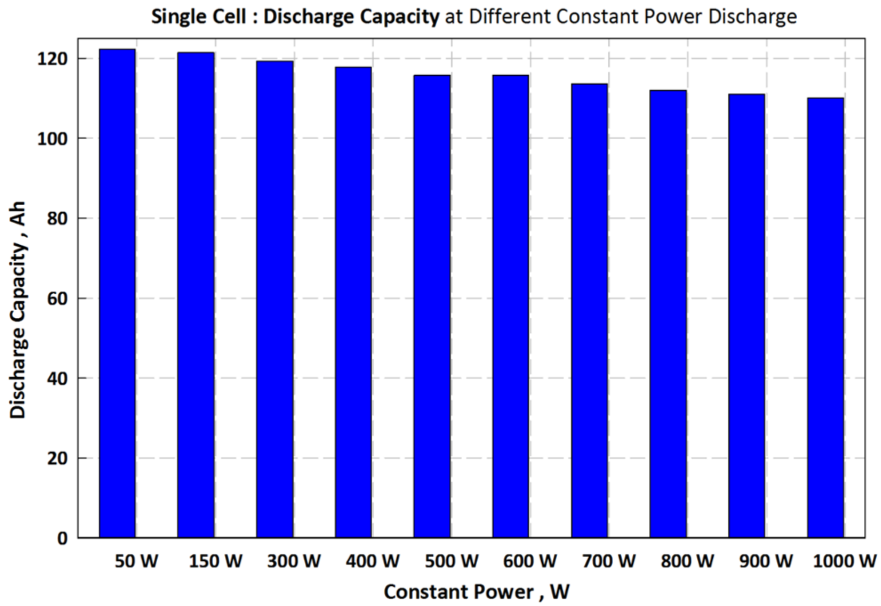
NiZn Cell Performance – 100% DOD Cycle Life

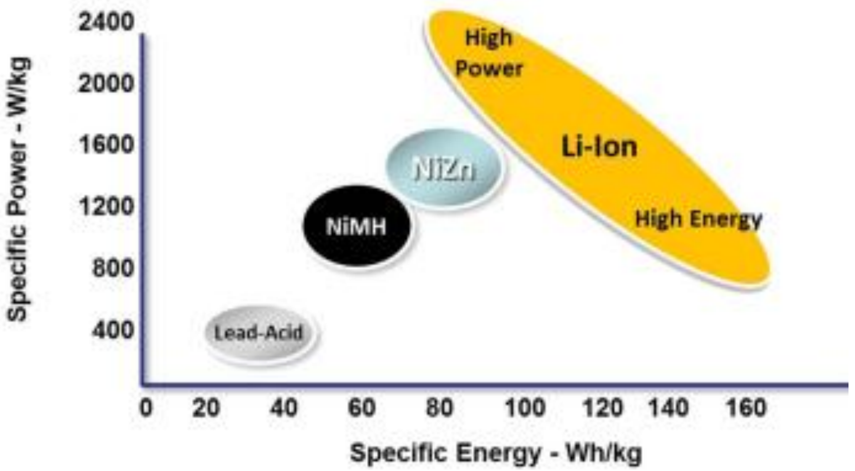
- Telcordia GR-4228: Clause 5.14 cycling test
- Comprised of C/3, C/5, C/8 discharges per set = three 100% DOD cycles per set
- 65+ sets achieved to 80% EOL at C/3 rate and 68+ sets achieved to 80% EOL at C/5 rate
- Total of 195+ cycles to C/3 EOL and 204+ cycles to C/5 EOL – all at 100% DOD cycling
- Note: all discharges equivalent to 100Ah at all rates (i.e. C/3=33.3A, C/5=20A, C/8=12.5A)



Why Nickel Zinc?

- Fast recharge capability
- Cycle life
- Maintenance free (no top-up or refill)
- Consistent capacity (Ah) as power increases
- Specific Energy 60Wh/kg
- Energy Density 130Wh/l
- US Company, PowerGenix (PGX), developed new Intellectual Property beginning in the 2000s
- EnerSys signed license and technology development agreement with PGX in 2012
- Recent technical developments (additive) have improved stability and cyclic capability
- EnerSys is investing in NiZn optimization and industrialization to provide solutions for these markets in the future





Sources: Ricardo Consulting, AABC, PowerGenix estimates

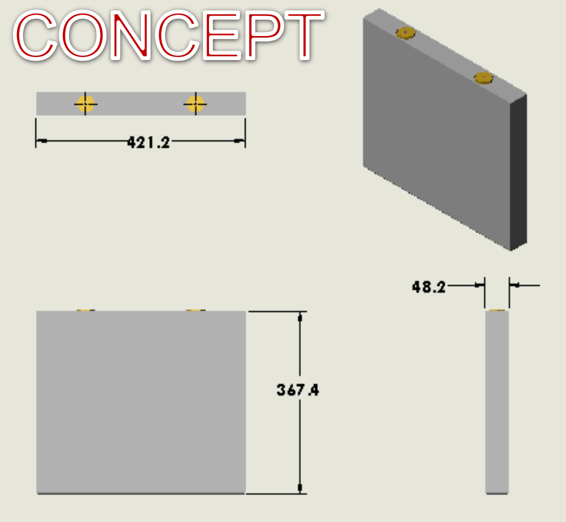
Evaluation of NiZn Technology

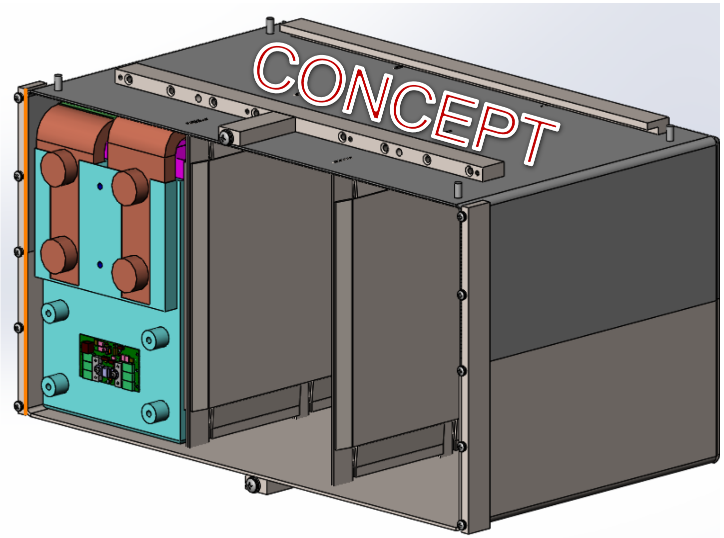
- Submarine Application
  - More Power!
  - 102% increase in 1C capacity over large format lead acid cell
  - 65% increase in C/3 capacity
  - 29% increase in C/10 capacity

	Cell Characteristics		Dual C Size Module		
C Type Module Performance	C-Type LA Cell	Narrow C NiZn Cell	2 Series LA Cell	3 Series NiZn Cell	% Change
Upper Voltage	2.4 V	1.9 V	4.8 V	5.7 V	19%
Nominal Voltage	2.0 V	1.7 V	4.0 V	5.1 V	28%
Lower Voltage	1.7 V	1.25 V	3.4 V	3.75 V	10%
Capacity @ 2,225 A 1C	2,225 Ah	4,500 Ah	2,225 Ah	4,500 Ah	
Capacity @ 965 A C/3	2,895 Ah	4,770 Ah	2,895 Ah	4,770 Ah	
Capacity @ C/10 (Ah)	3,850 Ah	4,950 Ah	3,850 Ah	4,950 Ah	
Energy @ 2,225 A 1C	4,450 Wh	7,700 Wh	8,900 Wh	22,800 Wh	156%
Energy @ 965 A C/3	5,790 Wh	8,200 Wh	11,580 Wh	24,300 Wh	110%
Energy @ C/10 (Ah)	7,700 Wh	8,500 Wh	15,400 Wh	25,200 Wh	64%
Nominal Mass	218 kg	163 kg	515kg	587 kg	19%

Evaluation of NiZn Technology

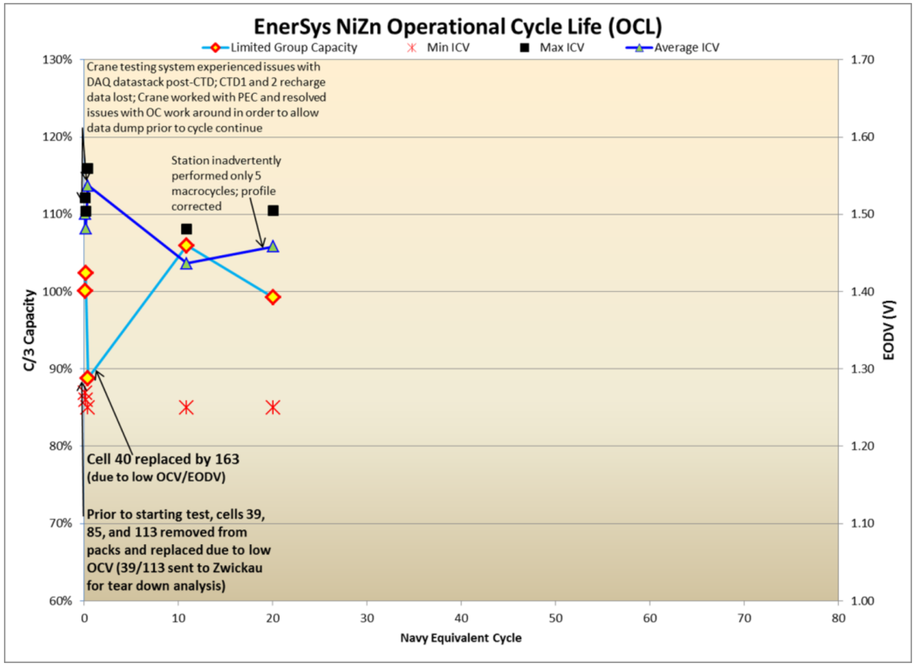
- Phase 1
  - ISEA/EnerSys developed test plan through Q4 FY2018
  - EnerSys provided 260-**100Ah** test cells in Q3 FY16
  - Completion of 12+ tests to characterize technology through shelf life testing, operational cycle life, temperature characterization, and accelerated aging
- Phase 2
  - EnerSys will develop **900Ah** cell
  - Concept will package 3 NiZn blocks, each with 5 parallel 900Ah NiZn cells

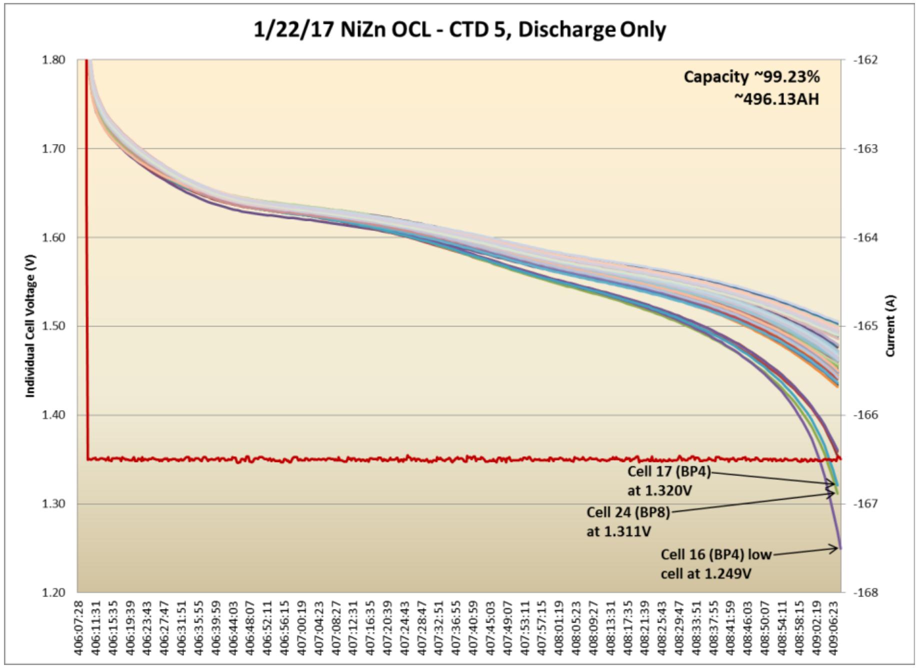




Phase 1 Evaluation of NiZn, OCL Testing

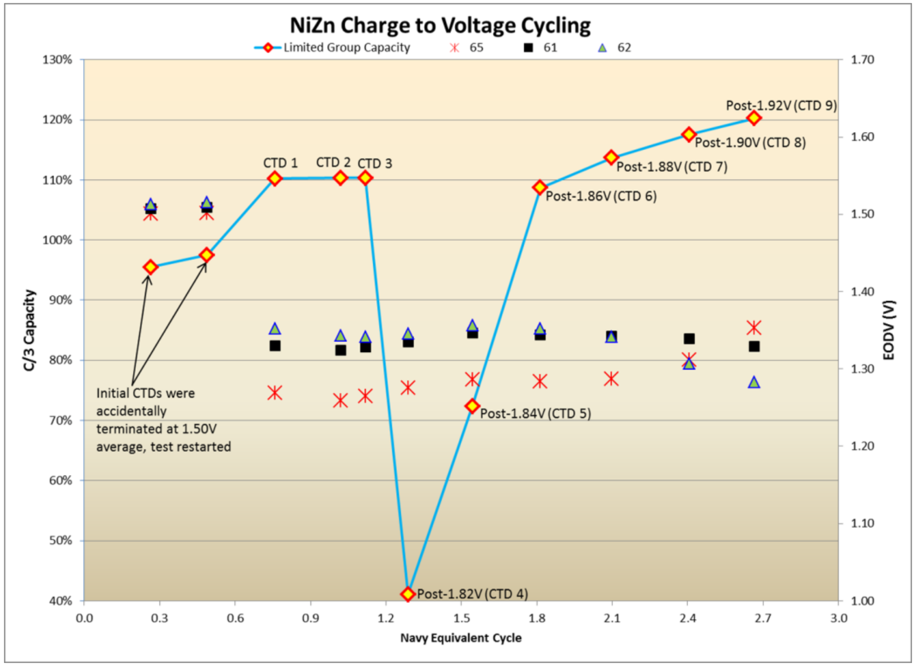
- NiZn 100 Cell OCL test to determine long term performance with testing profile that mimics submarine operations
- CTD 4 and CTD 5 completed and returned 105.95% and 99.23% capacity, respectively (limited by single cell cutoff)
- Cell performance has improved as cells become more balanced during discharges/charges
- Charge voltage was increased from 1.88Vpc to 1.89Vpc per EnerSys request

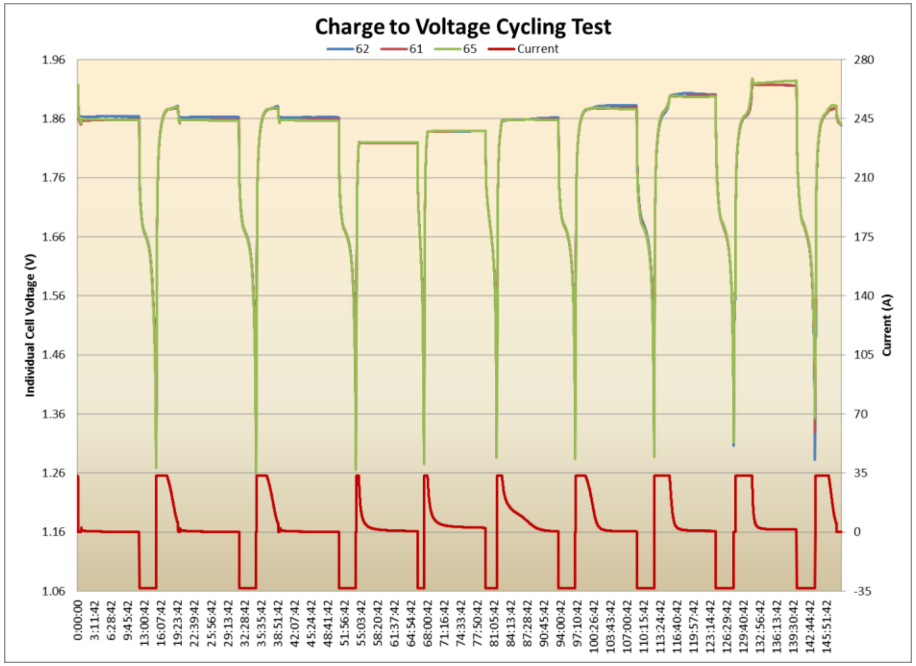




Phase 1 Evaluation of NiZn – Charge to Voltage

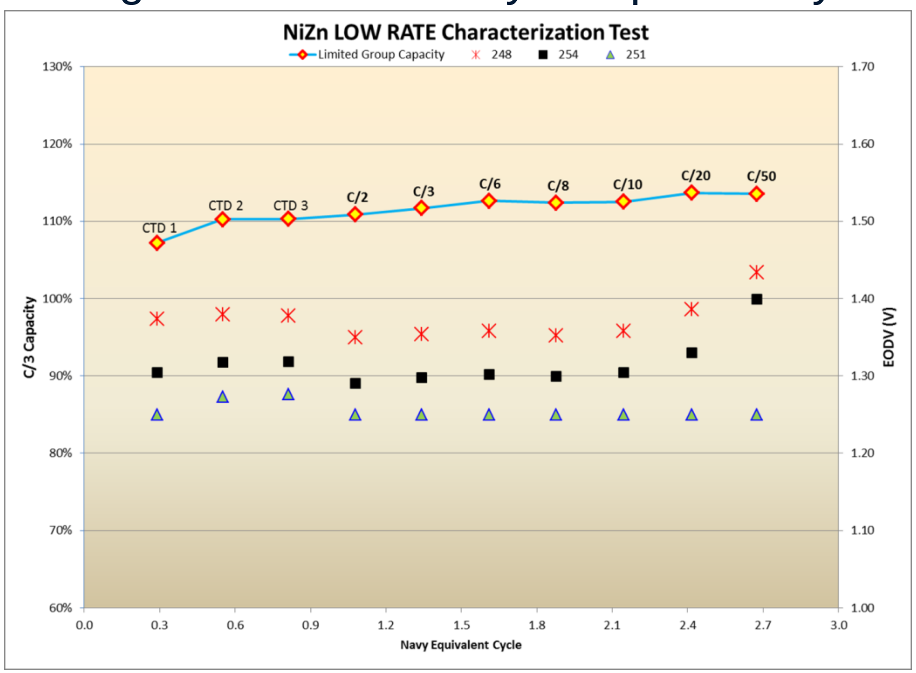
- NiZn Charge to Voltage testing completed December 2016
- Test charged cells for 12hrs at voltages from 1.82V – 1.92V (performing a CTD after each step) to find optimal charge voltage and identify cell capacity at different charge voltages
- Test confirmed that current charge (1.88V and 1.89V) and float (1.86V) values are best choice based on data available; higher charge voltages did return up to ~7% more capacity but may decrease cycle life

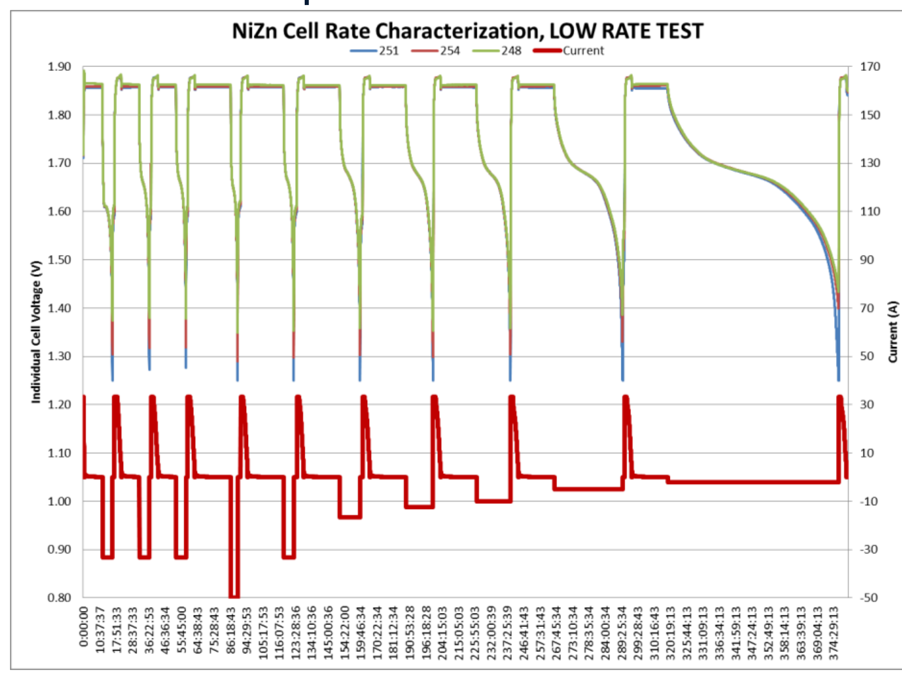




Phase 1 Evaluation of NiZn – Low Rate Characterization

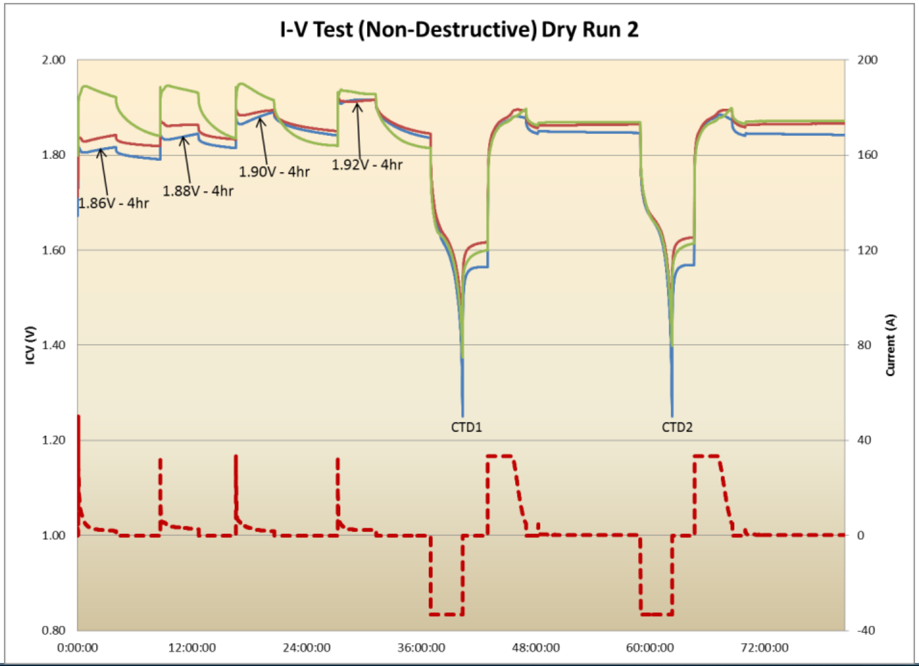
- Test evaluated cell performance at discharge rates representative of SVRLA operational ranges of C/2, C/3, C/6, C/8, C/10, C/20, and C/50
- Cells showed very stable performance at rates normally subjected in submarine battery applications
- Cells displayed less than 3% of rated capacity change in performance from C/2 to C/50 rate discharges; in comparison, SVRLA cells displayed a >40% change in rated capacity from C/3 to C/50 rate discharges
- High rate test recently completed dry run and will be complement test to low rate

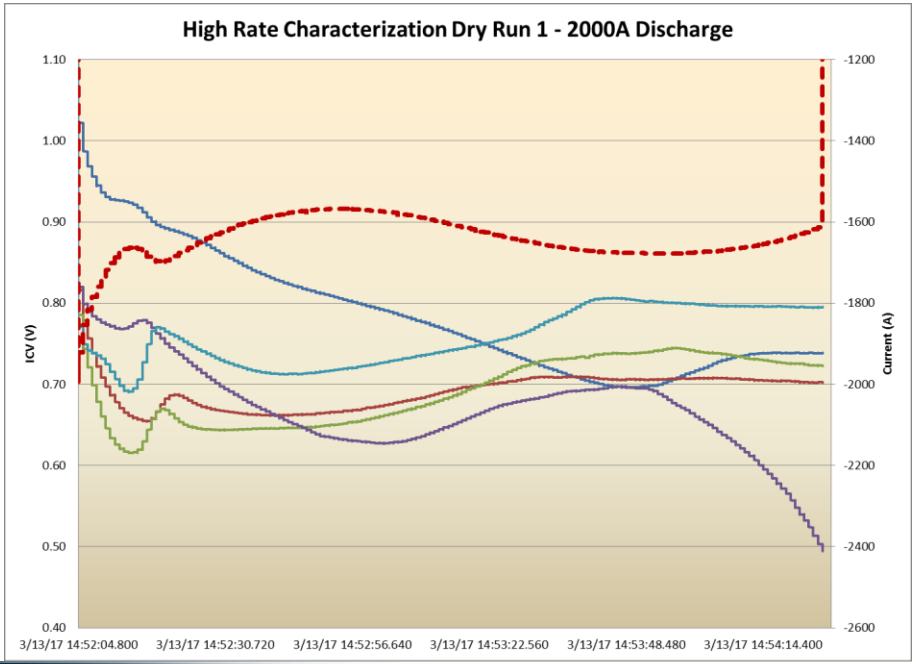




Phase 1 Evaluation of NiZn – Other Tests

- High rate test completed dry run and will begin testing soon
  - Determine cell performance at 1C, 5C, 10C, and 20C
- I-V non-destructive test started – hold voltages and observe current
- I-V destructive (overcharge) test – determine maximum acceptable operating cell voltage; expect irreversible damage
- Long string normal operations, float-only – determine long term float only performance with monthly test discharges





NiZn Cell Performance

- EnerSys and Crane test results demonstrate the potential of NiZn technology in both high and low discharge rate applications
- Stable after overcharge and over-discharge without thermal runaway or other hazardous behavior
- High power availability even at low state of charge
- Excellent recovery after extended deep discharge storage
- Very good cycle life performance at continuous deep cycling and also during shallow cycling using float charging
- Excellent recovery after extended deep discharge storage

Conclusion

- NiZn cell and battery testing is showing many potential performance benefits for a wide range of military and civilian applications
- NiZn has demonstrated safe operation under abusive operational conditions
- EnerSys is investing in NiZn optimization and industrialization to provide solutions for these markets in the future
- Crane to work with EnerSys to optimize manufacturing and consistency in cells
- Crane testing to determine viability of NiZn as future of submarine main storage battery

QUESTIONS?

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Acronyms

- ISEA – In-Service Engineering Agent
- NSWC Crane – Naval Surface Warfare Center Crane
- CTD – Capacity Test Discharge
- Hr – Hour
- Ah – Amp-Hour
- TD – Trickle Discharge
- Wh – Watt-Hour
- V – Volts
- Vpc – Volts per Cell
- A – Amps
- DOD – Depth of Discharge
- NiZn – Nickel Zinc
- OCL – Operational Cycle Life
- SOC – State of Charge
- SVRLA – Submarine Valve-Regulated Lead Acid
- PGX - PowerGenix