

## Evaluation of TIAX High Energy CAM-7/Graphite Lithium-Ion Batteries at High and Low Temperatures

by Joshua L Allen, Jan L Allen, Samuel A Delp, and T Richard Jow

**ARL-TR-7023** 

August 2014

Approved for public release; distribution unlimited.

### NOTICES

### Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

# **Army Research Laboratory**

Adelphi, MD 20783-1138

August 2014

# **Evaluation of TIAX High Energy CAM-7/Graphite Lithium-Ion Batteries at High and Low Temperatures**

Joshua L Allen, Jan L Allen, Samuel A Delp, and T Richard Jow Sensors and Electron Devices Directorate, ARL

Approved for public release; distribution unlimited.

PROPERTING DATE IN the ADDRESS INTO THE ADDRESS IN THE ADDRESS IN THE ADDRESS IN THE ADDRESS INTO T		REPORT DO	Form Approved OMB No. 0704-0188					
August 2014       Final       11/2013-06/2014         4. TTLE AND SUBTICE       5. CONTRACT NUMBER         Evaluation of TLAN High Energy CAM-7/Graphite Lithium-Ion Batteries at       5. GANT NUMBER         High and Low Temperatures       5. FROGRAM ELEMENT NUMBER         6. AUTHOR(S)       5. FROGRAM ELEMENT NUMBER         Joshua L Allen, Jan L Allen, Samuel A Delp, and T Richard Jow       5. FROGRAM ELEMENT NUMBER         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       10. SPONSOR/MONITOR'S ACRONVM(S)         7. TIN: RDRL-SED-C       2300 Powder Mill Road       ARL-TR-7023         7. DENNSOR/MONITOR'S ACRONVM(S)       11. SPONSOR/MONITOR'S ACRONVM(S)       11. SPONSOR/MONITOR'S ACRONVM(S)         12. DISTRIBUTIONAVAILABLITY STATEMENT       NUMBER(S)       NUMBER(S)       10. SPONSOR/MONITOR'S ACRONVM(S)         13. SUPPLEMENTARY MOTES       14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (forpidet cycle lite) is -800 cycles with 80% capacity retenion. High-loading cells and a C/20 capacity of 2.47 A. h. the projected cycle lite is -800 cycles with 80% capacity retenion. High-loading cells and a C/20	data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.							
A TILE AND SUBTITLE     Evaluation of TIAX High Energy CAM-7/Graphite Lithium-Ion Batteries at     High and Low Temperatures     Sa. CONTRACT NUMBER     SA. CONTRACT NUM	1. REPORT DATE	(DD-MM-YYYY)	2. REPORT TYPE			3. DATES COVERED (From - To)		
Evaluation of TIAX High Energy CAM-7/Graphite Lithium-Ion Batteries at       5. GRANT NUMBER         Sc. PROGRAM ELEMENT NUMBER       5. PROGRAM ELEMENT NUMBER         6. AUTHOR(S)       5. TASK NUMBER         Joshua L Allen, Jan L Allen, Samuel A Delp, and T Richard Jow       5. TASK NUMBER         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)         2800 Powder Mill Road       Addlphi, MD 20783-1138       8. PERFORMING ORGANIZATION RECOMMENTION S ACRONYM(S)         11. SPONSORMONITORING AGENCY NAME(S) AND ADDRESS(ES)       10. SPONSORMONITOR'S ACRONYM(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT         Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life is a secondary corcle in excess of 400 cycles with 80% capacity retention. At -20° C, standard-loading cells displayed a lower C/20 and C/50 capacity (1.8 and 1.65 A:h). At 50° C, standard-loading cells had a C/20 capacity of 2.3 A:h is the projected cycle life is a secondary concern.         4. ABSTRACT       Vith a fade rate of 0.05% we per cycle at a C/20 capacity of 2.6 A h and the capacity loss betwee 2.5 and -20° C was more severe (31% vs. 20% for standard-loading, but they had a larger final capacity (1.72 A:h). The fade rate for high-loading cells had a C/20 capacity of 2.6 A h and the capacity loss	August 2014		Final			11/2013-06/2014		
High and Low Temperatures       5. GRANT NUMBER         6. AUTHOR(S)       5. PROGRAM ELEMENT NUMBER         Joshua L Allen, Jan L Allen, Samuel A Delp, and T Richard Jow       5. FASK NUMBER         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       5. FASK NUMBER         9. VORK UNIT NUMBER       5. FASK NUMBER         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION         10. S. Army Research Laboratory       ATTN: RDRL-SED-C         2800 Powder Mill Road       Addlphi, MD 20783-1138         9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)       10. SPONSOR/MONITOR'S ACRONYM(S)         11. SPONSOR/MONITOR'S REPORT       10. SPONSOR/MONITOR'S REPORT         NUMBER(S)       11. SPONSOR/MONITOR'S REPORT         12. DISTRIBUTION/AVAILABILITY STATEMENT       Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES       11. SPONSOR/MONITOR'S REPORT         14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life is a secondary color and undy be reycle at a C2/O capacity (2.12 LA +, Ith projected cycle life is a secondary color and undy be reycle at a C2/O capacity (2.12 LA +, Ith projected cycle life is a secondary concern.         14. ABSTRACT       20% Capacity retention. High-loading cells had a C2/O capacity (2.3 and 5) "C, respectively Josi Ha and L65 A-b). At 50 "C, standard-loading cells had a C2/O capaci	4. TITLE AND SUE	BTITLE				5a. CONTRACT NUMBER		
	Evaluation of 7	ГIAX High Energ	y CAM-7/Graphite	Lithium-Ion Bat	teries at			
AUTHOR(\$)     Joshua L Allen, Jan L Allen, Samuel A Delp, and T Richard Jow	High and Low	Temperatures				5b. GRANT NUMBER		
Joshua L Allen, Jan L Allen, Samuel A Delp, and T Richard Jow 50. TASK NUMBER 51. WORK UNIT NUMBER 52. WORK UNIT NUMBER 54. WORK UNIT NUMBER 55. TASK NUMBER 54. WORK UNIT NUMBER 54. WORK UNIT NUMBER 55. TASK NUMBER 56. TASK NUMBER 56. TASK NUMBER 57. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 59. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 50. SPONSOR/MONITOR'S ACRONYM(S) 10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S ACRONYM(S) 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells and 1.65 A-h). At 50 °C, capacity tention. At -20 °C, standard-loading cells had a C/20 capacity of 2.21 A-h; the projected cycle life is -800 cycles with 80% capacity tention. At -20 °C, standard-loading cells had a C/20 capacity of 2.21 A-h; the projected cycle life is -800 cycles with 80% capacity tention. At -20 °C, standard-loading cells had a C/20 capacity of 2.21 A-h; the projected cycle life is -800 cycles with 80% capacity tention. At -20 °C, standard-loading cells had a C/20 capacity of 2.67 A-h and the capacity (1.52 A-h). At 50 °C, standard-loading cells had a C/20 capacity of 2.67 A-h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A-h). The fade rate for high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern. 15. SUBJECT TERMS CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery 16. SECURITY CLASSIFICATION OF: 17. LINITATION 18. NUMBER 19. NAME OF RESPONSIBLE PERSON 10. SUBBER (Include area ccdd)						5c. PROGRAM ELEMENT NUMBER		
5e. TASK NUMBER         5. TASK NUMBER         5. WORK UNIT NUMBER         5. WORK UNIT NUMBER         1.3. Army Research Laboratory         ATTN: RDRL-SED-C         2800 Powder Mill Road         Adelphi, MD 20783-1138         9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)         10. SPONSOR/MONITOR'S ACCONYM(S)         11. SPONSOR/MONITOR'S ACCONYM(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT         Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A-1; the projected cycle life is -800 cycles with 80% capacity retention. At -20 °C, standard-loading cells life) at a d - (20 capacity of 2.21 A-1; the projected cycle life is -800 cycles with 80% capacity retention. At -20 °C, standard-loading cells life) at a C/20 capacity of 2.67 A-h and the capacity (1.52 A-h). The fade rate for high-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A-h and the capacity (1.52 A-h). The fade rate for high-loading cells are ideal for applications (even in extreme conditions) where cycle life is a	6. AUTHOR(S)					5d. PROJECT NUMBER		
7. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$)       5. WORK UNIT NUMBER         U.S. Army Research Laboratory       REPORT NUMBER         ATTN: RDR.JSED-C.       ARL-TR-7023         2800 Powder Mill Road       ARL-TR-7023         Adelphi, MD 20783-1138       10. SPONSOR/MONITOR'S ACRONYM(\$)         3. SPONSORING/MONITORING AGENCY NAME(\$) AND ADDRESS(E\$)       10. SPONSOR/MONITOR'S ACRONYM(\$)         11. SPONSOR/MONITOR'S AGENCY NAME(\$) AND ADDRESS(E\$)       11. SPONSOR/MONITOR'S ACRONYM(\$)         12. DISTRIBUTION/AVIALABILITY STATEMENT       Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES       11. SPONSOR/MONITOR'S REPORT         14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.1 A-h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells had a clovated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. At -20 °C. Standard-loading, but they had a larger final capacity (1.72 A-h). At 50 °C, standard-loading cells had a clovatel is hidicate that standard-loading cells are ideal for high-loading cells are ideal for high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-ion, Li-NiO <sub>2</sub> , hig	Joshua L Aller	n, Jan L Allen, Sai	nuel A Delp, and T	Richard Jow				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION         U.S. Army Research Laboratory       ATTN: RDRL-SED-C         2800 Powder Mill Road       Adelphi. MD 20783-1138         3. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)       10. SPONSOR/MONITOR'S ACCONYM(S)         11. SPONSOR/MONITOR'S REPORT       NUMBER(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT       Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES       11. SPONSOR/MONITOR'S REPORT         14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C vith a fade rate of 0.025% per cycle and a C/20 capacity of 2.11 A: ht; the projected cycle life is -8.00 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A-h). At 50 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A-h). At 50 °C, standard-loading cells had a c/20 capacity of 2.21 A-h in the projected cycle life is -8.00 cycles with 80% capacity retention. High-loading, cells had a c/20 capacity of 2.02 (-7.4) and the capacity (1.72 A-h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C. Tespectively) with a projected cycle life of ~350 and ~20 °C. These results indicate that standard-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-			-			5e. TASK NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       8. PERFORMING ORGANIZATION         U.S. Army Research Laboratory       ATTN: RDRL-SED-C         2800 Powder Mill Road       Adelphi. MD 20783-1138         3. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)       10. SPONSOR/MONITOR'S ACCONYM(S)         11. SPONSOR/MONITOR'S REPORT       NUMBER(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT       Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES       11. SPONSOR/MONITOR'S REPORT         14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C vith a fade rate of 0.025% per cycle and a C/20 capacity of 2.11 A: ht; the projected cycle life is -8.00 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A-h). At 50 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A-h). At 50 °C, standard-loading cells had a c/20 capacity of 2.21 A-h in the projected cycle life is -8.00 cycles with 80% capacity retention. High-loading, cells had a c/20 capacity of 2.02 (-7.4) and the capacity (1.72 A-h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C. Tespectively) with a projected cycle life of ~350 and ~20 °C. These results indicate that standard-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-								
U.S. Army Research Laboratory ATTN: RDRL-SED-C 2800 Powder Mill Road Adelphi, MD 20783-1138       REPORT NUMBER ARL-TR-7023         3. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)       10. SPONSOR/MONITOR'S ACRONYM(S)         11. SPONSOR/MONITOR'S ACRONYM(S)       11. SPONSOR/MONITOR'S ACRONYM(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.       13. SUPPLEMENTARY NOTES         14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A-h; the projected cycle life is -800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A-h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle life is -800 cycles with 80% capacity retention. High-loading, but they had a larger final capacity (1.72 A-h). The fade rate for high- loading cells was larger (0.06% for standard-loading), but they had a larger final capacity (1.72 A-h). The fade rate for high- loading cells was larger (0.06% for standard-loading), but they had a larger final capacity (1.72 A-h). The fade rate for high- capacity retention. High-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       17. UMTATION OF ABSTRACT       18. NUMBER OF ABSTRACT       19a. NAME OF RESPONSIBLE PERSON Joshua L Allen         a. REPORT       b. ABSTRACT						5f. WORK UNIT NUMBER		
U.S. Army Research Laboratory       ARL-TR-7023         ATTN: RDRL-SED-C       ARL-TR-7023         2800 Powder Mill Road       ARL-TR-7023         Adelphi, MD 20783-1138       10. SPONSOR/MONITOR'S ACRONYM(S)         11. SPONSOR/MONITOR'S ACRONYM(S)       11. SPONSOR/MONITOR'S ACRONYM(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT       NUMBER(S)         Approved for public release; distribution unlimited.       13. SUPPLEMENTARY NOTES         14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (~20°C), room (25°C), and high temperature (50°C). Standard-loading cells cycled well at 25°C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A·h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20°C, standard-loading cells displayed a lower C/20 and C/S capacity (1.81 and 1.65 A·h). At 50°C, standard-loading cells had a c/20 capacity of 2.67 A·h and the capacity loss between 25 and -20°C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20°C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.81 and 1.65 A·h). At 50°C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50°C. These results indicate that standard-loading cells are ideal for high-loading cells are ideal for high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS	7. PERFORMING	ORGANIZATION NAM	E(S) AND ADDRESS(ES	5)		8. PERFORMING ORGANIZATION		
2800 Powder Mill Road       ARL-1R-/023         Adelphi, MD 20783-1138       II. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES)         9. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES)       II. SPONSOR/MONITOR'S ACRONYM(S)         11. SPONSOR/MONITOR'S ACRONYM(S)       II. SPONSOR/MONITOR'S REPORT NUMBER(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT       Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES       II. SPONSOR/MONITOR'S REPORT         14. ABSTRACT       We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A-h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A-h). At 50 °C, standard-loading cells had a C/20 capacity of 2.67 A-h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A-h). The fade rate for high-loading cells had a C/20 capacity of 2.67 A-h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.81 and 1.65 A-h). At 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       II. LIM	U.S. Army Res	search Laboratory				REPORT NUMBER		
2800 Powder Mill Road         Adelphi, MD 20783-1138         9. SPONSORING/MONITORING AGENCY NAME(\$) AND ADDRESS(E\$)         10. SPONSOR/MONITOR'S AGENCY NAME(\$) AND ADDRESS(E\$)         11. SPONSOR/MONITOR'S REPORT         NUMBER(\$)         12. DISTRIBUTION/AVAILABILITY STATEMENT         Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. At jeb loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more sever (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for high-loading cells are ideal for applications where cycle life is a secondary concern.         15. SUBJECT TERMS       17. LIMITATION OF ABSTRACT       19a. NAM						ARI -TR-7023		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)       10. SPONSOR/MONITOR'S ACRONYM(S)         11. SPONSOR/MONITOR'S REPORT         12. DISTRIBUTION/AVAILABILITY STATEMENT         Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycle well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A-h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A-h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. At jeb-loading cells had a C/20 capacity of 2.67 A-h and the capacity (1.72 A-h). The fade rate for high-loading cells had a C/20 capacity of 2.67 X-h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A-h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 ocycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is a secondary concern.         15. SUBJECT TERMS       17. LIMITATION OF ABSTRACT       18. NUMBER or RESPONSIBLE PERSON John L Allen         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       19. NAME OF RESPONSIBLE PERSON John								
11. SPONSOR/MONITOR'S REPORT NUMBER(S)         12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A.h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A.h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle line excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A.h and the capacity (1.72 A.h). The fade rate of nigh- loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is imperative, while high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS         CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:       17. LIMITATION ABSTRACT PAGES       19a. NUMBER (Include area code)         16. REPORT       b.ABSTRACT       c. THIS PAGE       UU       20 <td>-</td> <td></td> <td></td> <td></td> <td></td> <td></td>	-							
NUMBER(\$)         12. DISTRIBUTION/AVAILABILITY STATEMENT         Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.1 A+h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A+h). At 50 °C, standard-loading cells had a 1.62 A+b). At 50 °C, standard-loading cells had a 1.62 A+b). At 50 °C, standard-loading cells had a C/20 capacity of 2.67 A+h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A+h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life or ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       19. NUMBER (Include area code)         16. REPORT       b. ABSTRACT       c. THIS PAGE       19. NUMBER (Include area code)	9. SPONSORING/	MONITORING AGENC	Y NAME(S) AND ADDR	ESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
Approved for public release; distribution unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A·h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is imperative, while high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS         CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:         a. REPORT       b. ABSTRACT         c. THIS PAGE       UU         20       19b. TELEPHONE NUMBER (Include area code)								
13. SUPPLEMENTARY NOTES         14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A-h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells dale rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A-h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A-h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is a secondary concern.         15. SUBJECT TERMS       Temperature       17. LIMITATION OF:       18. NUMBER OF ABSTRACT       0 responsible person Joshua L Allen         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       18. NUMBER OF RESPONSIBLE PERSON Joshua L Allen       19a. NAME OF RESPONSIBLE PERSON Joshua L Allen	12. DISTRIBUTION/AVAILABILITY STATEMENT							
14. ABSTRACT         We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A ·h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF: PAGES       18. NUMBER OF RESPONSIBLE PERSON Joshua L Allen         a. REPORT       b. ABSTRACT       c. THIS PAGE       UU       20			tribution unlimited.					
We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A·h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is imperative, while high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       18. NUMBER OF RESPONSIBLE PERSON Joshua L Allen         a. REPORT       b. ABSTRACT       c. THIS PAGE       UU       20       19b. TELEPHONE NUMBER (Include area code)	13. SUPPLEMENT	ARY NOTES						
We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A·h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is imperative, while high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       18. NUMBER OF RESPONSIBLE PERSON Joshua L Allen         a. REPORT       b. ABSTRACT       c. THIS PAGE       UU       20       19b. TELEPHONE NUMBER (Include area code)								
We evaluated lithium-ion battery cells (standard- and high-loading) from TIAX, LLC to determine the capacity and fade rate (projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A·h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is imperative, while high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS       CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       18. NUMBER OF RESPONSIBLE PERSON Joshua L Allen         a. REPORT       b. ABSTRACT       c. THIS PAGE       UU       20       19b. TELEPHONE NUMBER (Include area code)	44 40070407							
(projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C         with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A·h; the projected cycle life is ~800 cycles with 80%         capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is imperative, while high-loading cells are ideal for high-energy applications (even in extreme conditions) where cycle life is a secondary concern.         15. SUBJECT TERMS         CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:         a. REPORT       b. ABSTRACT         c. THIS PAGE       UU         20       19a. NAME OF RESPONSIBLE PERSON         Joshua L Allen       19b. TELEPHONE NUMBER (Include area code)			11. (standard	d h: - h 1 d:) d		I C to determine the second its and fode sets		
CAM-7, Lithium-ion, Li-ion, LiNiO <sub>2</sub> , high energy density, high temperature battery, low temperature battery         16. SECURITY CLASSIFICATION OF:         a. REPORT       b. ABSTRACT         c. THIS PAGE         UU       20         19b. TELEPHONE NUMBER (Include area code)	(projected cycle life) at low (-20 °C), room (25 °C), and high temperature (50 °C). Standard-loading cells cycled well at 25 °C with a fade rate of 0.025% per cycle and a C/20 capacity of 2.21 A·h; the projected cycle life is ~800 cycles with 80% capacity retention. At -20 °C, standard-loading cells displayed a lower C/20 and C/5 capacity (1.81 and 1.65 A·h). At 50 °C, standard-loading cells had an elevated fade rate of 0.048% per cycle, but are expected to cycle in excess of 400 cycles with 80% capacity retention. High-loading cells had a C/20 capacity of 2.67 A·h and the capacity loss between 25 and -20 °C was more severe (31% vs. 20% for standard-loading), but they had a larger final capacity (1.72 A·h). The fade rate for high-loading cells was larger (0.06% and 0.09% per cycle at 25 and 50 °C, respectively) with a projected cycle life of ~350 and ~250 cycles at 25 and 50 °C. These results indicate that standard-loading cells are ideal for applications where cycle life is secondary concern.							
16. SECURITY CLASSIFICATION OF:     17. LIMITATION OF ABSTRACT     18. NUMBER OF ABSTRACT     19a. NAME OF RESPONSIBLE PERSON Joshua L Allen       a. REPORT     b. ABSTRACT     c. THIS PAGE     UU     20     19b. TELEPHONE NUMBER (Include area code)			NiO2, high energy (	lensity, high tem	perature hatte	ry, low temperature battery		
16. SECURITY CLASSIFICATION OF:     OF ABSTRACT     OF PAGES     OF Joshua L Allen       a. REPORT     b. ABSTRACT     c. THIS PAGE     UU     20       19b. TELEPHONE NUMBER (Include area code)			(102, ingh chergy (		-			
a. REPORT b. ABSTRACT c. THIS PAGE UU 20 19b. TELEPHONE NUMBER (Include area code)	16. SECURITY CLASSIFICATION OF:			OF	OF			
Unclassified Unclassified Unclassified 20 301-394-0049	a. REPORT b. ABSTRACT c. THIS PAGE					19b. TELEPHONE NUMBER (Include area code)		
	Unclassified	Unclassified	Unclassified	00	20	301-394-0049		

Standard Form 298 (Rev. 8/98) Prescribed by ANSI Std. Z39.18

## Contents

Lis	t of F	ligures	iv
Lis	t of I	ables	iv
1.	Intr	oduction	1
2.	Арр	oroach	2
3.	Res	ults	4
	3.1	Standard-Loading Electrodes	4
	3.2	High-Loading Electrodes With/Without Optimized Cell Hardware	7
4.	Cor	iclusions	10
Lis	t of S	ymbols, Abbreviations, and Acronyms	12
Dis	tribu	tion List	13

## List of Figures

Fig. 1 Calculated specific energy (left) and energy density (right) of fixed volume 18650 cell designs with 5 mA h cm <sup>-2</sup> active material loading. Data provided by TIAX	2
Fig. 2 Voltage profile and specific capacity of cathode materials with a Li metal anode (C/20 rate). Average discharge potential given in parentheses. Data provided by TIAX	2
Fig. 3 Room temperature (25 °C, cycles 1–20) and low temperature (–20 °C, cycles 21–24) rate cycling and room temperature cycle life testing (25 °C, cycles 25–127) of standard-loading cells (2.7–4.2 V)	5
Fig. 4 Room temperature (25 °C) differential capacity of 18650 cells with standard-loading electrodes. Cycles 1–100 every 10 cycles shown.	6
Fig. 5 High temperature (50 °C) cycle life testing (2.7–4.1 V; Charge: C/2 CC, CV to C/20; Discharge: C/5 for 1 <sup>st</sup> and 102 <sup>nd</sup> cycle, 1C for 2 <sup>nd</sup> –101 <sup>st</sup> cycle)	7
Fig. 6 Room temperature (25 °C, cycles 1–20) and low temperature (–20 °C, cycles 21–23) rate cycling of high energy 18650 cells	8
Fig. 7 Room temperature (25 °C) cycle life testing (2.7–4.2 V; Charge: C/5 CC, CV to C/20; Discharge: C/10 for 1 <sup>st</sup> and 52 <sup>nd</sup> cycle, C/2 for 2 <sup>nd</sup> -51 <sup>st</sup> cycle) of high energy 18650 cells.	9
Fig. 8 High temperature (50 °C) cycle life testing (2.7–4.1 V; Charge: C/5 CC, CV to C/20; Discharge: C/10 for 1 <sup>st</sup> and 52 <sup>nd</sup> cycle, C/2 for 2 <sup>nd</sup> -51 <sup>st</sup> cycle) of high energy cells	.10

## List of Tables

Table 1	Battery specifications and description of testing performed	.3
Table 2	Description of testing procedures used to evaluate cell performance	.3
	Capacity and specific energy of standard- and high-loading cells at 25 °C and °C with discharge rates of C/20, C/10, C/5, C/2, and 1C	.8

### 1. Introduction

The objective of this effort is to evaluate prototype lithium (Li)-ion battery cells provided by TIAX LLC in November 2013 for high and low temperature cycleability in accordance with the requirements set forth in Phase II of the Small Business Innovation Research (SBIR) program, solicitation topic code OSD09-EP5 (contract number W911QX-12-C-0001).

Commercial Li-ion batteries are readily available with a specific energy in excess of 200 W·h/kg. Such batteries are based upon cathode chemistries that typically include lithium cobalt oxide (LiCoO<sub>2</sub> or LCO) and lithium nickel cobalt aluminum oxide (LiNi<sub>x</sub>Co<sub>y</sub>Al<sub>z</sub>O<sub>2</sub> or NCA). The commercialization of Li-ion battery cells in excess of 200 W·h/kg has enabled the development of next-generation plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs), and fully electric vehicles (EVs), and has provided power improvements to consumer electronics. Although the military requirements for Li-ion battery specifications are very similar to those used in EVs or consumer electronics (i.e., greater specific energy [W·h/kg] and energy density [W·h/L]), there are some notable challenges associated with the military implementation of commercial "state-of-the-art" Li-ion batteries.

Batteries used in military applications must be lightweight, compact rechargeable batteries that are capable of operating over a wide temperature range. A critical limitation of commercial Liion batteries is their poor low temperature performance (< -20 °C), due to decreased ionic conductivity, and instability at higher temperatures (>50°C), due to the degradation of the electrolyte, dissolution of the cathode active materials in the electrolyte, and/or breakdown of the cathode materials resulting in steady performance degradation including capacity fade and impedance rise in the cells.

The prototype cells provided by TIAX LLC in November 2013 include their patented layeredstructure dopant-stabilized lithium nickel oxide (LiNiO<sub>2</sub> or LNO) cathode, referred to as CAM- $7^{TM}$  by TIAX, a graphitic anode, and a proprietary electrolyte. When compared with commercially available cathode materials, including lithium manganese oxide (LiMn<sub>2</sub>O<sub>4</sub> or LMO), lithium iron phosphate (LiFePO<sub>4</sub> or LFP), lithium nickel cobalt manganese oxide (LiNi<sub>x</sub>Co<sub>y</sub>Mn<sub>z</sub>O<sub>2</sub> or NCM), LCO, and NCA, CAM-7 based 18650 cells have a higher specific energy and energy density (Fig. 1). The low end-of charge potential for CAM-7 (4.3 V vs. Li compared to >4.8 V for high voltage materials such as lithium nickel manganese oxide [LiNi<sub>0.5</sub>Mn<sub>1.5</sub>O<sub>4</sub> or LNMO] and lithium cobalt phosphate [LiCoPO<sub>4</sub> or LCP]) is beneficial for reducing the irreversible oxidation of the electrolyte and thus enables a long-cycle life. The higher specific capacity of CAM-7 yields an impressive specific energy when compared with the state-of-the art cathodes (Fig. 2). The room temperature performance of the CAM-7/graphite system has been well studied and compared with similar cathode materials. This report evaluates the high and low temperature performance of CAM-7/graphite 18650 cells to determine if they are suitable for extreme environmental conditions.



Fig. 1 Calculated specific energy (left) and energy density (right) of fixed volume 18650 cell designs with 5 mA·h cm<sup>-2</sup> active material loading. Data provided by TIAX



Fig. 2 Voltage profile and specific capacity of cathode materials with a Li metal anode (C/20 rate). Average discharge potential given in parentheses. Data provided by TIAX.

### 2. Approach

CAM-7 based 18650 cells were provided by TIAX LLC in two batches. Batch 1 (JA428–JA431) consists of four cells (two sets of duplicate cells) with standard-loading electrodes, carbonate-

based electrolyte, and a high porosity separator. Batch 2 (JA402–JA407) consists of six cells (three sets of duplicate cells) with high density and high active material loading electrodes, a carbonate-based electrolyte, and a high porosity separator. Cells JA402 and JA403 also contain an engineered 18650 hardware that improves the specific energy by reducing the weight of the inert materials. The specifications of the prototype Li-ion cells are provided in Table 1. The testing procedures for evaluating the cell performance are provided in Table 2.

Cell ID	C/20 (A·h/W·h)	Cell Weight (g)	Test Description
JA428	2.2/8.1	40.36	DT rote IT Consoity DT Cycle Life
JA429	2.2/8.3	40.57	RT rate, LT Capacity, RT Cycle Life
JA430	2.2/8.2	40.33	UT Cruele Life
JA431	2.1/7.9	40.38	HT Cycle Life
JA402	2.7/10.0	40.28	DT Data IT Consister
JA403	2.7/10.0	40.43	RT Rate, LT Capacity
JA404	2.7/9.9	42.42	DT Carala Life
JA405	2.7/9.9	42.33	RT Cycle Life
JA406	2.7/10.0	42.25	UT Cruele Life
JA407	2.7/10.0	42.39	HT Cycle Life

Table 1 Battery specifications and description of testing performed

Table 2	Description of tes	ting procedures used	to evaluate cell performance
---------	--------------------	----------------------	------------------------------

Cell ID	Testing Procedures
JA428 JA429	<ul> <li><i>RT Rate (25 °C)</i></li> <li>Charge: C/2 CC to 4.2 V, CV with C/20 cutoff</li> <li>Discharge: to 2.7 V at C/20, C/10, C/2 and 1C</li> <li><i>LT Capacity (-20 °C)</i></li> <li>Charge (at RT): C/2 CC to 4.2 V, CV with C/20 cutoff</li> <li>Discharge (at LT): to 2.7 V at C/20, C/10, C/5 and C/2</li> <li><i>RT Cycle Life (25 °C)</i></li> <li>Charge: C/2 CC to 4.2 V, CV with C/20 cutoff</li> <li>Discharge: to 2.7 V at C/5 1<sup>st</sup> and last cycle</li> <li>Discharge: to 2.7 V at 1C x 100 cycles</li> </ul>
JA430 JA431	<ul> <li>HT Cycle Life (50 °C)</li> <li>Charge: C/2 CC to 4.1 V, CV with C/20 cutoff</li> <li>Discharge: to 2.7 V at C/5 1<sup>st</sup> and last cycle</li> <li>Discharge: to 2.7 V at 1C x 100 cycles</li> </ul>
JA402 JA403	<ul> <li><i>RT Rate</i> (25 °<i>C</i>)</li> <li>Charge: C/5 CC to 4.2 V, CV with C/20 cutoff</li> <li>Discharge: to 2.7 V at C/20, C/10, C/5 and C/2</li> </ul>
Improved Hardware	<ul> <li>LT Capacity (-20 °C)</li> <li>Charge (at RT): C/5 CC to 4.2 V, CV with C/20 cutoff</li> <li>Discharge (at LT): to 2.7 V at C/20, C/10 and C/5</li> </ul>
JA404 JA405	<ul> <li><i>RT Cycle Life (25 °C)</i></li> <li>Charge: C/5 CC to 4.2 V, CV with C/20 cutoff</li> <li>Discharge: to 2.7 V at C/10 1<sup>st</sup> and last cycle</li> <li>Discharge: to 2.7 V at C/2 x 50 cycles</li> </ul>
JA406 JA407	<ul> <li>HT Cycle Life (50 °C)</li> <li>Charge: C/5 CC to 4.1 V, CV with C/20 cutoff</li> <li>Discharge: to 2.7 V at C/10 1<sup>st</sup> and last cycle</li> <li>Discharge: to 2.7 V at 1C x 50 cycles</li> </ul>

Note: HT = high temperature, LT = low temperature, and RT = room temperature

### 3. Results

#### 3.1 Standard-Loading Electrodes

The first batch of 18650 cells provided by TIAX LLC consisted of standard-loading electrodes with a carbonate-based electrolyte. The variable rate testing (Fig. 3) yielded a cell discharge capacity of 2.23, 2.12, 2.03, and 1.97 A h at a discharge rate of C/20, C/5, C/2, and 1C, respectively. The corresponding specific energies of these cells were 203, 191, 181, and 172 W·h/kg at discharge rates of C/20, C/5, C/2, and 1C, respectively. To test the low temperature performance, the cells were charged at room temperature (CCCV at C/2 with C/20 cutoff) and transferred to an environmental chamber that was maintained at -20 °C. The cells were allowed to equilibrate for 1 h and discharged at various rates. The cell discharge capacity obtained was 1.83, 1.76, 1.66, and 1.39 A  $\cdot$  h for discharge rates of C/20, C/10, C/5, and C/2, respectively (Fig. 3). After testing the room temperature and low temperature rate performance of the cells, the room temperature cycle life was tested to see if the variable rate or low temperature had any effect on the cell cycleability. A single C/5 cycle was performed to verify the capacity is consistent with the cycles performed during the room temperature rate testing; the cells actually displayed a higher C/5 capacity of 2.12 A·h, compared with the 2.09 A·h capacity previously obtained. The cycle life of the cell was tested by performing 100 cycles at 1C and finally testing the C/5 capacity again to compare with the previous results. The 1C capacity of the cells decayed from 1.99 to 1.94 A h after 100 cycles, a fade rate of ~2.5% over 100 cycles or ~0.025% per cycle. This indicates the system projects to be capable of ~800 cycles while still maintaining 80% of the original capacity. The final C/5 cycle is consistent with the previous results with a fade rate of ~2.4% after 100 cycles (2.01 A  $\cdot$  h for the final C/5 cycle).



Fig. 3 Room temperature (25 °C, cycles 1–20) and low temperature (–20 °C, cycles 21–24) rate cycling and room temperature cycle life testing (25 °C, cycles 25–127) of standard-loading cells (2.7–4.2 V)

To better demonstrate the electrode material's stability, the differential capacity of the room temperature cycle life test was plotted as a function of the full cell voltage. The data in Fig. 4 are highly consistent through the 100 cycles with the only change between the individual cycles being a slight decrease in the reduction peak at 3.9 V. The loss in capacity observed at 3.9 V is likely the cause of the 0.025% per cycle fade rate and may be due to slight structural changes within the cathode material or loss of cycleable lithium to side reactions at the anode. It is noteworthy that no polarization was observed in Fig. 4, suggesting that stable passivation layers were formed and perpetual electrolyte decomposition did not occur (which would lead to impedance build-up and cell polarization).



Fig. 4 Room temperature (25 °C) differential capacity of 18650 cells with standard-loading electrodes. Cycles 1–100 every 10 cycles shown.

The second set of cells was tested at high temperature (50  $^{\circ}$ C). High temperature testing is commonly used to demonstrate the cell's overall stability to high temperature (electrolyte decomposition kinetics increase with temperature) as well as to accelerate the life cycle of the cell. The high temperature testing of cells JA430–JA431 can be seen in Fig. 5. The cells were cycled at C/5 for the first and last cycle with 100 cycles of C/2 charge and 1C discharge in between. Although the cells were similar in design and content, cell JA431 displayed a lower capacity (see Table 1). Due to the differing capacity, and the fact that both cells were cycled at the same rate (2A discharge), the efficiency of the cells varied with the lower capacity cell (JA431) having a lower efficiency due to the higher discharge rate (1.05C for JA431 vs. 1.1C for JA430). The average capacity and efficiency is plotted in Fig. 5 with error bars demonstrating the high-low values. The average cell capacity of the first 1C cycle is  $1.98 \pm 0.02$  A·h. After 100 cycles at 1C, the cell average fades to  $1.90 \pm 0.01$  A·h, suggesting the cell fades at a rate of ~4.8% total through 100 cycles, or at a rate of 0.048% per cycle. Although the fade rate of 0.048% per cycle is roughly double the fade rate at room temperature (0.025\% per cycle), the cells still project to be able to cycle ~400 cycles until the capacity fades to 80% of the initial average capacity ( $\sim 1.58 \text{ A} \cdot \text{h}$ ).



Fig. 5 High temperature (50 °C) cycle life testing (2.7–4.1 V; Charge: C/2 CC, CV to C/20; Discharge: C/5 for 1<sup>st</sup> and 102<sup>nd</sup> cycle, 1C for 2<sup>nd</sup>-101<sup>st</sup> cycle)

#### 3.2 High-Loading Electrodes With/Without Optimized Cell Hardware

Three sets of duplicate cells were provided by TIAX LLC with high-loading electrodes. The first set of cells (JA402–JA403) included an engineered hardware that improved the overall specific energy. Room temperature and low temperature variable rate testing was performed on the cells and the results are shown in Fig. 6. The cell capacities at room temperature are 2.67, 2.59, 2.51, and 2.36 A·h for discharge rates of C/20, C/10, C/5, and C/2, respectively. When the cell was reduced to -20 °C, the cell discharge capacity was reduced to 2.14, 2.02, and 1.72 A·h for discharge rates of C/20, C/10, and C/5, respectively. The specific energies of the improved hardware cells at 25 °C were 240, 232, 221, and 201 W·h/kg at discharge rates of C/20, C/10 C/5 and C/2, respectively. At low temperature (-20 °C), the specific energy drops to 189, 174, and 144 W·h/kg for C/20, C/10, and C/5, respectively. A comparison of the variable rate capacity and specific energy at 25 °C and -20 °C of the standard- and high-loading cells is shown in Table 3.



Fig. 6 Room temperature (25 °C, cycles 1–20) and low temperature (–20 °C, cycles 21–23) rate cycling of high energy 18650 cells

Table 3 Capacity and specific energy of standard- and high-loading cells at 25 °C and -20 °C with discharge rates of C/20, C/10, C/5, C/2, and 1C

		JA428/429 Standard-Loading					JA	420/403	3 High-I	Loading	
		C/20	C/10	C/5	C/2	1C	C/20	C/10	C/5	C/2	1C
	25°C	2.23	_	2.12	2.03	1.97	2.67	2.59	2.51	2.36	_
Capacity (A·h)	-20°C	1.83	1.76	1.66	1.39	_	2.14	2.02	1.72	_	_
Specific Energy	25°C	203	_	191	181	172	240	232	221	201	_
$(W \cdot h/kg)$	-20°C	164	155	142	112	—	189	174	144	—	_

The second pair of cells (JA404–JA405) was tested at room temperature for cycle life. Since these cells contained high-loading, thicker and shorter electrodes, the transport of Li<sup>+</sup> ions through the electrodes and the separator is hindered and thus the rate performance is reduced. If one compares the C/20 and C/2 capacity from Fig. 3 (1.81 and 1.65 A·h, respectively) with the C/20 and C/2 capacity from Fig. 6 (2.67 and 2.36 A·h, respectively), the capacity decline when increasing the rate from C/20 to C/2 is ~8.8% with the standard-loading cells compared to 11.6% for the high-loading cells. Since the high-loading electrodes have diminished Li<sup>+</sup> ion transport, the cells are less able to delithiate fully at the point when the cell reaches the end voltage (i.e., the cell becomes polarized due to the slower kinetics). Due to the polarization phenomenon, the high-loading cells display a higher fade rate compared with the standard-loading cells. The cycle life of the high-loading cells is shown in Fig. 7. The capacity of the cells fades from an initial capacity (C/2) of 2.40 A·h to a final capacity of 2.32 A·h (after 50 cycles). The fade rate of the cells is ~3.3% over the 50 cycles or 0.06% per cycle. With an initial capacity of 2.40 A·h and a fade rate of 0.06% per cycle, the high-loading cells project to be able to be cycled ~350 cycles and still maintain 80% capacity retention (~1.92 A $\cdot$ h).



Fig. 7 Room temperature (25 °C) cycle life testing (2.7–4.2 V; Charge: C/5 CC, CV to C/20; Discharge: C/10 for 1<sup>st</sup> and 52<sup>nd</sup> cycle, C/2 for 2<sup>nd</sup>-51<sup>st</sup> cycle) of high energy 18650 cells

The high-loading cells were also tested for high temperature stability (JA406–JA407). The high temperature cycle life results can be seen in Fig. 8. The high temperature cells (50 °C) were cycled with a lower upper charging limit (4.1 V vs. 4.2 V for the room temperature cycle life testing) in order to limit electrolyte oxidation and therefore display a lower overall capacity when compared to the room temperature tests. The initial capacity (C/2) of the high temperature cells was 2.34 A·h. After 50 cycles, the cells faded ~4.7% to a final capacity of 2.23 A·h; the fade rate was ~0.09% per cycle. Based on the initial capacity of 2.34 A·h and a fade rate of 0.09% per cycle, the high-loading cells project to be capable of being cycled ~250 cycles and still maintain 80% capacity retention at 50 °C.



Fig. 8 High temperature (50 °C) cycle life testing (2.7–4.1 V; Charge: C/5 CC, CV to C/20; Discharge: C/10 for 1<sup>st</sup> and 52<sup>nd</sup> cycle, C/2 for 2<sup>nd</sup>-51<sup>st</sup> cycle) of high energy cells

### 4. Conclusions

Five sets of duplicate cells were provided by TIAX LLC for evaluation at high and low temperatures as part of the requirements set forth in the Phase II SBIR contract. The cells consisted of two sets of standard-loading cells and three sets of high-loading cells. The standard-loading cells cycled well at room temperature with a fade rate of only 0.025% per cycle and a C/20 capacity and specific energy of 2.21 A·h and 203 W·h/kg, respectively. The low fade rate suggests the standard-loading cells are capable of up to 800 cycles while maintaining 80% of the initial capacity. Although the C/20 capacity of the cells at -20 °C was reduced by only 18% (1.81 A·h), the slower ionic conductivity had a more dramatic effect at higher rates, reducing the C/5 capacity from 2.09 A·h at room temperature to 1.65 A·h at -20 °C (a 21% reduction).

The high temperature cycle life of the standard-loading cells faded more dramatically, as expected, due to increased electrolyte oxidation and/or structural changes within the cathode/anode. With an initial capacity of 1.98 A · h and a fade rate of 0.048% per cycle, the high temperature cells are still project to be able to cycle ~400 cycles while maintaining 80% capacity retention. The ability of the standard-loading electrodes to cycle at low temperature, as well as the impressive cycle life at room temperature and high temperatures, marks an improvement over the state-of-the-art Li-ion battery.

In order to improve the specific energy of the cells, TIAX LLC provided three sets of cells containing higher-loading electrodes. Although these cells do have a significantly higher specific energy (240 W·h/kg vs. 203 W·h/kg for standard-loading), the rate performance and cycle life of the cells suffer. A summary of the room temperature and low temperature discharge capacity and specific energy is shown in Table 3. The capacity of the standard-loading electrodes decreased from 2.23 A  $\cdot$  h (C/20) to 2.12 A  $\cdot$  h (C/5), a decrease of ~4.9%, while the higher-loading electrodes decreased from 2.67 A ·h (C/20) to 2.51 A ·h (C/5), a decrease of 6.0%. Furthermore, the low temperature performance of the high-loading cells is worse due to the compounding effects of the decreased electrode conductivity, higher current density through the separator, and reduced ionic mobility through the higher-loading electrodes. The capacity of the higher-loading cells decreased from 2.67 A·h (RT) to 2.14 A·h (at -20 °C) for C/20, a decrease of 20%, and from 2.51 A ·h (RT) to 1.72 A ·h (at -20 °C) for C/5, a decrease of 31%. Comparing the standardloading (20% C/5 capacity decrease) and higher-loading (31% C/5 capacity decrease) cell designs, there is a more significant decrease in capacity due to the operation at low temperature with higher-loading electrodes. It is notable that even with the larger relative capacity decrease of the higher-loading cell compared with the standard-loading cell; the capacity of the cell is still larger at 1.72 A $\cdot$ h versus 1.66 A $\cdot$ h for the standard-loading cells (at C/5 discharge). Thus, any decrease in rate performance is more than offset by benefits in overall specific energy.

The room temperature and high temperature cycle life tests for the high-loading cells display an initial (C/2) capacity of 2.40 and 2.34 A  $\cdot$  h, respectively. The fade rates of the cells were 0.06% and 0.09% per cycle for the room temperature and high temperature cells, respectively. With the initial capacity and fade rates listed previously, the cycle life of the cells were calculated to be ~350 and ~250 cycles for the room temperature and high temperature, respectively, while still maintaining an 80% capacity retention.

The CAM-7/graphite cells provided by TIAX LLC demonstrate standard- and higher-loading electrode designs that could meet the needs of different military applications. The standard-loading electrode cell designs display a lower specific energy than the higher-loading designs, but have a lower fade rate that enables a significantly longer cycle life (up to 800 cycles with 80% capacity retention). These cells are ideal for applications where cycle life is imperative, even in extreme conditions. The higher-loading cell designs, in contrast, provide a specific energy of up to 240 W·h/kg (at C/20 discharge rate) and also display an improved low and high temperature capacity. The higher-loading cells, however, suffer from an increased fade rate that limits their projected cycle life to ~350 and ~250 cycles (for RT and 50 °C) while maintaining 80% capacity retention. These cells are ideal for high energy applications (even in extreme conditions) where cycle life is a secondary concern. The CAM-7/graphite system is well suited for low and high temperature applications and offers many benefits over the state-of-the-art Lion battery cells.

# List of Symbols, Abbreviations, and Acronyms

EVs	electric vehicles
HEVs	hybrid electric vehicles
HT	high temperature
Li	lithium
LiCoO <sub>2</sub> or LCO	lithium cobalt oxide
LiCoPO <sub>4</sub> or LCP	lithium cobalt phosphate
LiFePO <sub>4</sub> or LFP	lithium iron phosphate
LiMn <sub>2</sub> O <sub>4</sub> or LMO	lithium manganese oxide
LiNiO <sub>2</sub> or LNO	lithium nickel oxide
$LiNi_{0.5}M_{1.5}O_4$ or $LNMO$	lithium nickel manganese oxide
LiNi <sub>x</sub> Co <sub>y</sub> Mn <sub>z</sub> O <sub>2</sub> or NCM	lithium nickel cobalt manganese oxide
LiNi <sub>x</sub> Co <sub>y</sub> Al <sub>z</sub> O <sub>2</sub> or NCA	lithium nickel cobalt aluminum oxide
LT	low temperature
PHEVs	plug-in hybrid electric vehicles
RT	room temperature
SBIR	Small Business Innovation Research

- 1 DEFENSE TECHNICAL (PDF) INFORMATION CTR DTIC OCA
- 2 DIRECTOR
- (PDF) US ARMY RESEARCH LAB RDRL CIO LL IMAL HRA MAIL & RECORDS MGMT
- 1 GOVT PRINTG OFC
- (PDF) A MALHOTRA
- 4 DIRECTOR
- (PDF) US ARMY RESEARCH LAB RDRL SED C JOSHUA L ALLEN JAN L ALLEN SAMUEL A DELP T RICHARD JOW

INTENTIONALLY LEFT BLANK.