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Thermal Battery Development – Reduced Product Variability Through Six Sigma and Materials Finger-Printing

Authors:

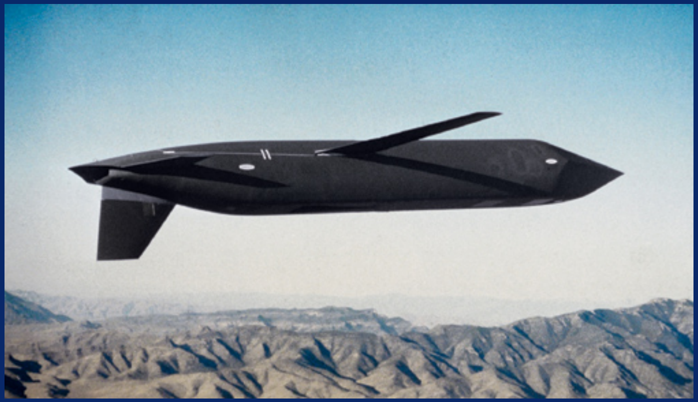
Paul F. Schisselbauer	215-773-5416	ATK OS Power Sources Center
John Bostwick	215-773-5428	ATK OS Power Sources Center

Agenda

- Overview
  - Thermal Batteries and Applications
- Performance Comparison
  - Thermal Batteries Versus Ambient Temperature Batteries
- Process Definition Using Six-Sigma
- Thermal Battery Description
- Manufacturing Processes
  - Process & Materials Control
  - Materials Characterization
- Cost Reduction Initiatives
- Benefits of End-Product Consistency
- Summary

Overview

- Thermal Batteries are used on a variety of weapon systems, including:
  - Bombs
  - Projectiles
  - Missiles, etc.
- Proper battery function is often of critical importance in meeting a weapon system's mission requirements.



CALCM

ERGM Projectile

- Thermal batteries have a proven track record and are capable of meeting the most demanding requirements.

M830A1

Overview

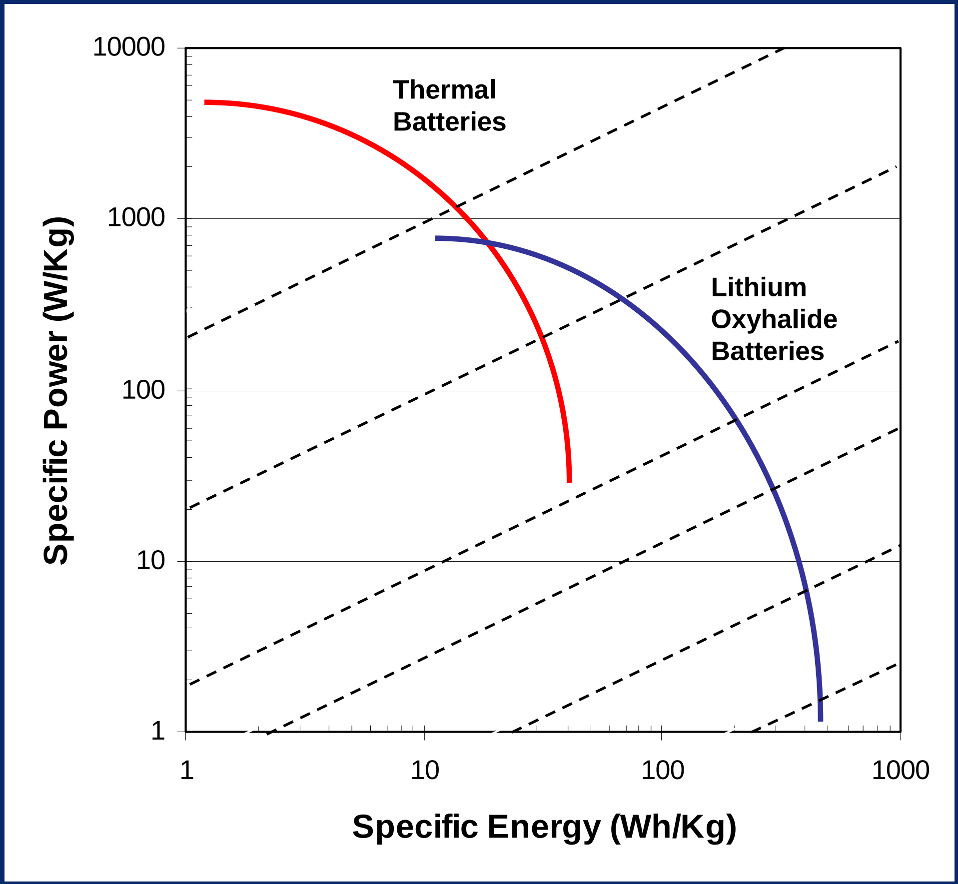
- Correct battery function depends on its design and manufacture, both of which present some challenges.
  - Design subtleties affecting performance can be overcome using test verification
  - Manufacturing or materials subtleties, on the other hand, often cause issues even after they were thought to have been taken care of.
- This paper presents a thermal battery development effort where product variability is reduced through the use of six-sigma tools, materials characterization or “finger-printing”, and automation.
- The battery developed by this effort can be used on several applications, including the DSU-33 Proximity Sensor and the Precision Guided Mortar Munition (PGMM).

PGMM

DSU-33 Proximity Sensor

Performance Comparison

- Certain battery systems are ideally suited to military applications.
  - Cold Operating Temp. (-45F)
  - Long Shelf Life (>20 years)
- Lithium Oxyhalide Batteries are best suited to applications that require extended life.
  - Lithium/Thionyl Chloride
  - Lithium/Sulfuryl Chloride
  - Lithium/Sulfur Dioxide
- Thermal Batteries are best suited to applications that require high power.
  - Lithium Silicon/Iron Disulfide
  - Lithium Silicon/Cobalt Disulfide



Ragone Plot Comparing Thermal Batteries to Lithium Oxyhalide Batteries.

(Approximate data - plot for illustration purposes only)

Performance Comparison – General Features

Parameter	Thermal Batteries	Lithium/Oxyhalide Batteries
Description	Self-contained, hermetic, electrochemical power source	Self-contained, hermetic, electrochemical power source
Storage Life	20 years	20 years
Storage Mechanism	They achieve dormancy by utilizing electrolytes which require elevated temperature to become ionically conductive.	They achieve dormancy by physically separating the active components, i.e., the lithium foil anode and the electrolyte (catholyte).
Strength	Provide **high current** density for high power applications.	Provide **high energy** density for extended mission times
Reliability	High	High
Thermal Management	Important design consideration	Minimal issues
Cost	Moderate to high	Low to Moderate – cost effective in high volume production

Performance Comparison

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	Ambient Temperature Batteries			Thermal Batteries	
	Lithium Metal / Thionyl Chloride ($Li/SOCl_2$)	Lithium Metal / Sulfuryl Chloride (Li/SO_2Cl_2)	Lithium Metal / Sulfur Dioxide (Li/SO_2)	Lithium Silicon / Iron Disulfide ($LiSi/FeS_2$)	Lithium Silicon / Cobalt Disulfide ($LiSi/CoS_2$)
Energy Density (Wh/kg)	Reserve: 50 to 150 Active: 300 to 440	Reserve: 45 to 135 Active: 265 to 387	Reserve: 32 to 95 Active: 200 to 280	Reserve: 20 to 45 Active: N/A	Reserve: 20 to 75 Active: N/A
Power	Moderate to High	Moderate to High	Moderate	High	High
Working Voltage Per Cell (Volts)	3.0 to 3.9	3.0 to 4.2	2.7 to 2.9	1.6 to 2.1	1.6 to 2.1
Temperature	-45F to +160	-45F to +160	-45F to +160	-45F to +160	-45F to +160

Process Definition Using Six-Sigma

Concept Development
- Project Management (milestone planning, risk evaluation
- Voice of Customer
- Concept & Development
- Product Mapping

Product & Process Design
- DFM & DFA
- Process Mapping
- Design FMEA
- Process Capability
- Design of Experiments (DOE)

Product & Process Optimization
- DFM & DFA
- Process Design

Product & Process Capability
- Capability Analysis

Product Maturity

Thermal Battery Description

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Concept Development → Product & Process Design → Product & Process Optimization → Product & Process Capability

G3190B1 Thermal Battery (DSU-33 Application)

Performance

Voltage (V): 22 to 32.0
Current (mA): 350
Rated Capacity (mAh): 20
Activation Time (ms): < 500
Initiation Approach: Electric Igniter
Operating Temp. Range (°F): -65 to +221
Storage Temp. Range (°F): -65 to +221

Physical Characteristics

Chemistry: $LiSi/FeS_2$
Size: 1.50” Dia. by 2.38” Length
Weight (g): 210

Environmental

MIL-STD-331 Environments

Thermal Battery Description

Concept Development → **Product & Process Design** → Product & Process Optimization → Product & Process Capability

- The G3190B1 device is a reserve primary lithium silicon/iron disulfide thermal battery.
- It is a self-contained, hermetic unit, capable of being stored in excess of 20-years and then being activated on demand.
- The battery's electrochemistry is based on Sandia's proven $LiSi/LiCl\text{-}KCl/FeS_2$ system.
- Overall Cell Reaction:

$$Li_4Si + FeS_2 \rightarrow 2Li_2S + Fe + Si \qquad (1.6V \text{ to } 2.1V)$$

- This system easily meets both power and energy requirements of the DSU-33 fuze application.

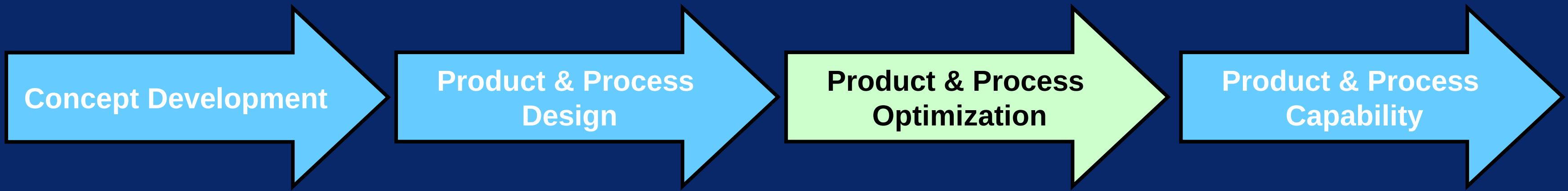
Thermal Battery Description

Concept Development → Product & Process Design → Product & Process Optimization → Product & Process Capability

LiSi/FeS_2 Battery for DSU-33

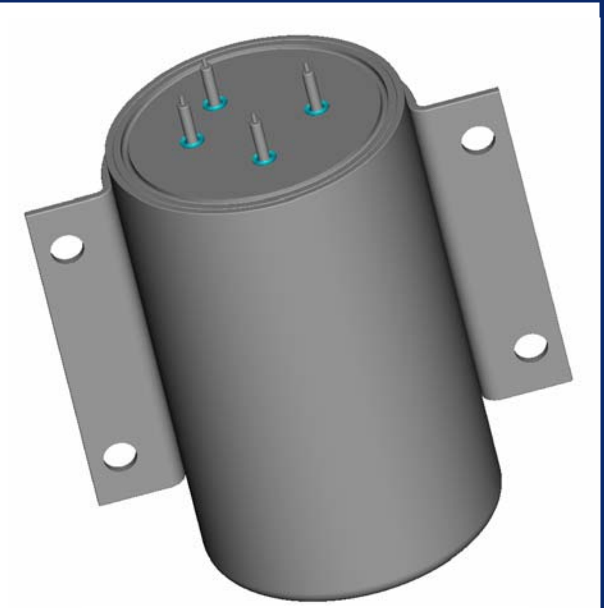
- Battery uses 15 cells in series
  - Voltage: 31.5V max.
  - Working voltage per cell: 1.8 V nom per cell
- Application requires a power of 7.7 Watts
  - Battery power significantly exceeds requirement due to the relatively high intrinsic electrode capabilities and battery size.
  - Initial battery projection approximately 150 watts.
- Application requires a capacity of 19.44 mAh
  - Battery capacity significantly exceeds requirement due to manufacturing limitations for minimum electrode thicknesses.
  - Initial battery projection 120 mAh capacity.

Thermal Battery Description



LiSi/FeS_2 Battery for DSU-33

- Design uses a lithiated cathode to compensate for electro-active impurities.
- Electrolyte uses a eutectic binary composition of lithium chloride-potassium chloride to achieve lower temperature operation.
- Center fire initiation using an igniter.
- Operating Temperature Range: 352°C to 550°C.



G3190A1 Battery with Mounting Bracket

Manufacturing Processes

Concept Development → Product & Process Design → Product & Process Optimization → Product & Process Capability

Manufacture Components

Heat Pellet

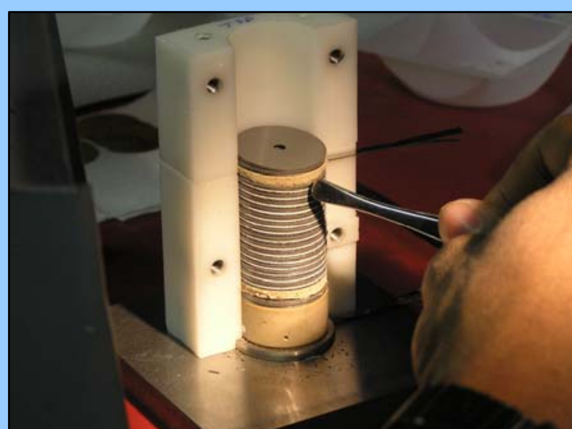
Anode Pellet

Separator Pellet

Cathode Pellet

Manufacture Subassemblies

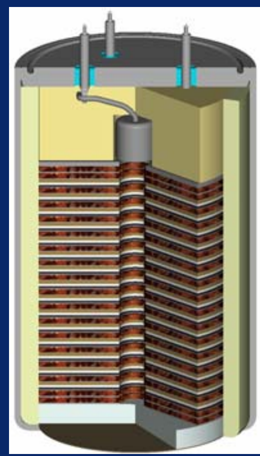
TP/Igniter Assembly



Cell Stack Sub-assembly

Final Battery Assembly

Battery Closure Weld



Cut-away View of Thermal Battery

Process & Material Control

Concept Development → Product & Process Design → Product & Process Optimization → **Product & Process Capability**

Thiokol's "Fingerprinting" Program

- The diagnostic combination of analytical methods for detailed characterization of key materials

Value of a material fingerprint

- A fingerprint can be used to identify a material, to differentiate it from similar looking materials, or lead to its source
- Important for acceptance of materials, qualifying a change in a manufacturing process, location, or supplier

General Benefits of Fingerprinting

- Increases reliability and consistency of end product
- Fundamental understanding of critical materials
- Provides baseline chemical profile of materials in use
- Lot-to-lot consistency can be monitored and changes flagged
- Material changes can be traced to their source
- Acceptance testing for small supplier who cannot afford lab support
- Instills technical ownership for critical materials
- Enhance requalification of changes in vendor or production site
- Improved supplier relationship through data sharing
- Database available for failure analyses

Materials Characterization

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Concept Development → Product & Process Design → Product & Process Optimization → **Product & Process Capability**

Analytical Tests

Test	Description	Use
SEM	Scanning Electron Microscopy	Direct observation
Raman	FT - Raman Vibrational Spectroscopy – Laser Excitation	Identifies molecules
ICP/OES	Inductively Coupled Plasma with Optical Emission Spectroscopy Identification	Trace metal analysis
EDS	X-ray Diffraction Spectroscopy	Elemental composition
Metallurgical Analyses	Materials Analysis	Direct observation
Other Tests	Pyrotechnic Burn Rates Pressure Generation Versus Time Electrolyte Leakage Tests Mechanical Properties	Various

Performance

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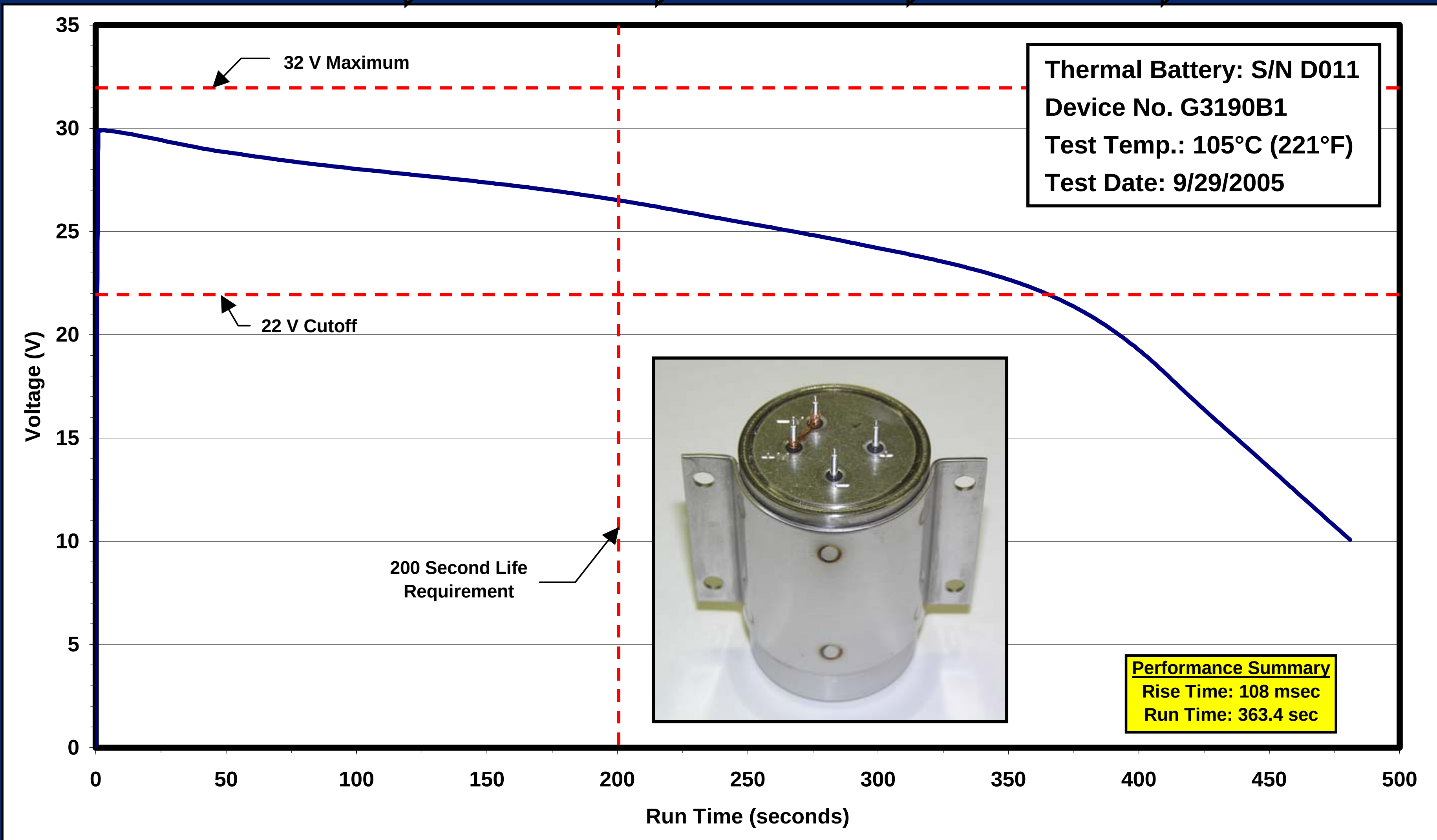
Concept Development → Product & Process Design → Product & Process Optimization → Product & Process Capability



Cost Reduction Initiatives

Concept Development → Product & Process Design → Product & Process Optimization → **Product & Process Capability**

- Automated Mechanical Press
  - High Speed Pressing of pellets
  - Smaller Footprint
  - Good Modularity for Changes in Pellet Size
- FeS_2 Purification
  - Safe & Cost Effective
- Lithium Silicon
  - Manufacture Versus Buy
- Igniters
  - Make/Buy Analysis has Identified Low-Cost Solution that Meets Requirements

Benefits of End-Product Consistency

Concept Development → Product & Process Design → Product & Process Optimization → **Product & Process Capability**

- Increases product reliability
- Improves the consistency in performance, I.e., tighter groupings in performance
- Easier to identify technical issues

Summary

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- A disciplined design and manufacturing approach using Six-Sigma tools has resulted in the success of this thermal battery project.
- Automated manufacturing of thermal batteries is long over due.
- Future power requirements appear to be headed toward higher energy and power densities:
  - Specific Energy: 35 Wh/kg → 70 Wh/kg
  - Specific Power: 750 W/Kg → 1500 W/Kg
- Technical innovations in both performance and manufacturing are required to meet the projected program demands.
- The ***Power Sources Center*** is poised and ready to take on these challenges.