Agenda

- 30mm Inbore/Hangfire Investigation
  - Apache M230 Weapon System Basic Information
  - Reported Problems
    - Total Incident Types / #’s & Groupings
    - Resultant Damage Examples
  - Investigation Team
  - Methodology Employed
  - Most Likely Causes & Actions Taken
  - Additional Recommendations
  - Summary
Apache M230 Weapon System

• Aircraft System
  – Turret Mounted Weapon
  – Closed Loop Linkless Feed System
  – Weapon Mounted Uploader/Downloader; ‘D’ Model Aircraft have Additional Ammunition Sideloader
  – First In/Last Out Ladder/Rail Magazine

• M230 Weapon
  – Externally Powered w/Electric Drive Motor
  – Single Barrel, Chain Driven Automatic Cannon
  – 625 ± 25 Shots per Minute Firing Rate

• M789 High Explosive Dual Purpose Cartridge
  – Aluminum Cartridge Case w/Electric Primer, IB52 Booster System & Double Base WC855 Ball® Powder
  – High Strength 4130 Steel Projectile w/PBXN-5 Explosive Fill
  – Spin Compensated Shaped Charge Liner
  – Point Initiating, Base Detonating Nose Mounted Fuze
• **Hangfire** – Ballistic functioning of the cartridge occurs outside of the dwell time of the weapon. Operating group & sometimes receiver damaged.
  – 23 Incidents since Aug 97

• **Inbore Detonation** – Premature initiation in the barrel under the barrel support shroud. Barrel bulges, sometimes ruptures.
  – 21 Incidents since Aug 97

• **Severed Barrel** – Premature initiation in the barrel near the muzzle. Muzzle is completely lost.
  – 2 Incidents Since Aug 97
Typical Damage
“Minor Event” - Hangfire
Typical Damage
“Severe Event” - Hangfire
Typical Damage Inbore Detonation

- Damage Similar to or Identical to Severe Hangfire/High Pressure Plus Barrel Cracking & Muzzle Break Impacts by Fragments
Typical Damage
Bullet on Bullet

Severed Barrel

Severed & Ruptured Barrel

1/130th

2/101st
In-Bore/Hang-fire Investigation Team Participation

In-Bore/Hang-fire Investigation Team Encompasses Elements From Across Area Weapon System, and is a Total System Approach to Solving LW30mm Field Issues
IHIT Methodology

- Team Used A System Engineering And Six Sigma Approach
  - Interviews w/Field Units (Shooters, Ground Crews, Supply)
  - Re-work Previous Root Cause Analysis for Inbore Detonations
  - Use Failure Mode Effects Analysis (FMEA) Process
  - Collect Data (Modeling, Simulation, Testing) To Fill Data Gaps & Populate Fault Tree For Each Failure Mode
  - Conduct Design Of Experiments (DOE) And Verification Testing
  - Incorporate Changes Into TDP
UNIT VISIT & INCIDENT
KEY INFORMATION

- No Incident Resulted from the 1st Round Fired
- Ammo Usually Stays in A/C Until Scheduled Phase Maintenance - Some Units Reloaded in Reverse Order of Download
- Manual Mode for Sideloader & Uploader/Downloader are Still Used Infrequently
- Feed System Jams While Uploading are Still Occurring Resulting in Punctured Cartridge Cases
A Total System Approach

121 Potential Causes

Cannon, Handling System & Aircraft Systems

121 Potential Causes

Ammunition Handling & Storage

3 Potential Causes

Ammo Metal Parts Manufacture

55 Potential Causes

215 Total Potential Failure Modes Identified

Six Sigma Tools:
- Continuous Black Belt Consultation
- Failure Modes Effect Analysis
- Fault Tree Analysis
- Design of Experiments

Identified Three Major Root Causes

Ammunition LAP

36 Potential Causes

- Cross Functional/Cross Organizational IPT
- Co-Leaders from PM-MAS & PM-Apache
- User Involvement & Feedback
- Systems Engineering
Hangfire/High Pressure
Ignition System DOE Phase I

**Control Factors**

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Mix</td>
<td>100%</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Primary Charge</td>
<td>With</td>
<td>Without</td>
<td></td>
</tr>
<tr>
<td>Flashtube Pellets</td>
<td>Pellet</td>
<td>Powder</td>
<td></td>
</tr>
<tr>
<td>Propellant Level</td>
<td>100%</td>
<td>50%</td>
<td>25%</td>
</tr>
</tbody>
</table>

**Pareto Chart of the Standardized Effects**

(response is Action Time, Alpha = .05)

- **Propellant**
- **Booster**
- **Primary**
- **Booster & Propellant Interaction**

**MANN BARREL TEST**
Damaged IB52 Pellets/Flash Tube

Open Air High-Speed Video of Flash Tube Venting

Normal Flash Tube

Damaged IB52

WC855 in Tube

Gas Velocity From Flash Tube

Normal

Damaged IB52

Crushed IB52

WC855 in Tube

Some Damage IB52 Pellets

Broken Lacquer Seal with WC855 in Tube

Live Propellant 30-mm Gun Simulator

WC855 in Flash Tube has Given Greater Than 40 ms Ignition Delay

Normal IB52

hot

ambient

cold

Crushed IB52

cold and ambient

hot
Hot Temperature Storage Led to DPA Depletion

- Over time, the original stabilizer, DPA, depletes and converts to daughter products – 2NDPA, NNODPA; DPA reaction rate increases as temperature increases

- DPA concentration of the 1995 Lot had depleted to half the concentration of the 2006 Lot at time = 0

- AT 71°C, DPA concentration depleted to 0 within 22 days of storage
• Ballistic testing conducted at ambient. All data corrected with reference ammunition. Data is the average of 5 shots.

• Variation in pressure performance attributed to migration of DBP deterrent
**Aged WC-855 for DOE Factor 6**

Casemouth Pressure vs Days Aged - 2006 Propellant Lots Conditioned at 71 deg C
(Test RFAAP 07-004 & 005)
IHIT Propellant Aging Study - Ballistic Testing at Radford 4-5 January 2007

- Test Firing order randomized for 55 cartridges in test group
- Data corrected to reference rounds
- Data sorted by Age - 0 to 33 days
- Error bars represent +/- 1 SD

Based on data from Test 2430, estimated Casemouth and Chambre Pressure for charge weight of 51.5 grams at 20 days at 71 deg C. (Propellant conditioned in drum not cartridge for Test 2430. Recommend subjecting sufficient qty of this aged WC-855 to extended conditioning at 71C at ATPG to attain Chamber Pressure in range of "On" setting for DOE Factor 6 (470-490 MPa). Based on the propellant aging study data shown here, expect to get to desired pressure in <10 days.

Estimated Casemouth Pressure at 51.5 grams based on fit at 3 charge weights from Test 2430 (y = 14.718x - 338.55)

SOW - LSL for 470-490 MPa Chamber Pressure ("On" Setting DOE Factor 6)

SOW - USL for 470-490 MPa Chamber Pressure ("On" Setting DOE Factor 6)

Estimated Chamber Pressure at 51.5 grams based on fit at 3 charge weights from Test 2430 (y = 15.045x - 336.07)

2006 Propellant Lot aged @ 71°C

Linear (2006 Propellant Lot aged @ 71°C)
## Headspace DOE

### Phase I Test Matrix

<table>
<thead>
<tr>
<th>Firing Order of Rounds</th>
<th>No. of Rounds</th>
<th>High Pressure (approx 500 Mpa)</th>
<th>Nominal Pressure</th>
<th>Nominal Headspace</th>
<th>Headspace 0.025&quot;</th>
<th>Headspace 0.031&quot;</th>
<th>Hot Barrel (180°F)</th>
<th>Ambient Barrel</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
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<td></td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
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<td>5</td>
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<tr>
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<td>6</td>
<td>5</td>
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<td></td>
<td>X</td>
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<td>X</td>
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<tr>
<td>8</td>
<td>5</td>
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<td></td>
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<td></td>
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<td>X</td>
</tr>
</tbody>
</table>

- Tested ok
- Incident 1
- Incident 2

### Phase II Test Matrix

<table>
<thead>
<tr>
<th>Firing Order of Rounds</th>
<th>No. of Rounds</th>
<th>High Pressure (approx 415 Mpa)</th>
<th>Nominal Headspace (0.022&quot;)</th>
<th>Maximum Headspace (0.031&quot;)</th>
<th>Ambient Barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Hangfire signature has been replicated without an actual hangfire event.
  Excessive headspace
  Elevated pressure (~ 500 Mpa)
  Hot barrel

• Propellant gases vented from the chamber area can damage the operating group and receiver.

• Damage created similar to that seen in HE-Inbore events, except no barrel bulge and generally no Blast Suppressor damage.

• Not all “hangfires signatures” are necessarily actual hangfires.
Hangfire/High Pressure

- **Most Likely Causes**
  - **Extended Vibration** Damages Cartridge Ignition System (Replicated)
    - No Rounds Showed Physical Damage After 144 Hours
    - 30% Showed Some Damage After 192 Hours
  - **Extended High Temperature Exposure** Changes Propellant Characteristics (Replicated)
    - Significant Pressures Measured after 432 Hours @ 71° C (160° F)
  - **Cartridge Cases are Punctured and Propellant is Lost or Contaminated** (Replicated)

- **Actions Taken to Date to Reduce/Eliminate Issues**
  - 1980s Production Placed into Condition Code ‘N’
    - Removed to Strategic Reserve in Kuwait, Planned for Demilitarization When Stockpile has been Replenished
  - Aviation Safety Action Message (ASAM) and AIN issued
    - Requires Download and Inspection of Ammo at Aircraft Regularly Scheduled Maintenance
    - Requires Rotation of Ammo When Reloaded into Aircraft to Minimize Prolonged Exposure to Vibration and Extreme Temperatures
  - Initiated Design Improvement Program to Improve Robustness of the Ignition Train
Inbore Detonation
Explosive Reaction and Response

Low Order Time Lines

35 μs  55 μs  75 μs  100 μs

Barrel from Arizona Incident

Data from Incidents, Experiment and Modeling

Signature matches an initiation at rear of warhead
Dynamic Signature Replication
Bullet-on-Bullet

Violence and location reveal that bullet on bullet scenario not likely scenario for bulge…

Tests conducted:
- HE round → HE round (3 times)
- HE round → HE round (dummy fuze)
- HE round → TP round

Implies rear bullet initiation

Follow-on shot with solid fuze result was an in-bore with incorrect signature
Dynamic Signature Replication Set Forward

Result is g-load on order of $10^3$-$10^5$ with no reaction of projectile (Fuze ripped off body)

Liner / Retainer gaps
- Gap > 0.032 in (from x-ray)
- Defuzed
- 8 shots, no in-bores

Fuzed
- No defects as determined from x-ray
- Standard, fuzed rounds
- 5 shots, no in-bores
Dynamic Signature Replication High Pressure (Body Failure)

Rationale
- Structural analysis found weak area in rear
- Bullet-on-bullet tests at APG:
  - 4 out of 4 shots went low order
  - Initiation from rear of projectile

Procedure
- Single projectile of increased mass
- Replace fuse with tungsten weight
- Provide data for fracture model

Mass taken to over double (2.25x) of projectile with subsequent increase of base pressure – NO initiation of explosive
Dynamic Signature Replication Foreign Material (aka Putty)

M789 LW30mm HEDP round

Shot 1

Bulged barrel centered at < 8 inches from breech

Dummy fuze replaces live fuze (with putty to match mass)
Foreign Material in Liner Cavity

<table>
<thead>
<tr>
<th>Sample AA</th>
<th>Fragment</th>
<th>Mass (mg)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
<td>48</td>
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<tr>
<td></td>
<td>2</td>
<td>51</td>
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<td></td>
<td>3</td>
<td>53</td>
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<td></td>
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<tr>
<td></td>
<td>5</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>51.8</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>311</td>
</tr>
</tbody>
</table>

P-t Curves from Test 2410

1st in-bore

6 loose fragments at 71C: 2/2 in-bores
All other conditions: 0 / 33

Notes:
- Testing at ATPG 5/2/06
- Casemouth pressure measured (trace#2); chamber pressure port (trace#3) n/a for this test series
- Pressure values corrected based on calibration of transducer #C14607 from ATPG test data sheet.
Test vs. Field Incidents - Profile

Reference Line approx. 9.5" from end of barrel
## Fault Tree Probabilities for In-Bore DOE Factors

<table>
<thead>
<tr>
<th>Block Description</th>
<th>Reliability</th>
<th>Prob. of Failure</th>
<th>Final Probability</th>
<th>Priority Ranking</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>#504 Setback initiation due to debris in cavity</td>
<td>1</td>
<td>1.0005E-05</td>
<td>1.0005E-05</td>
<td>A1.11</td>
<td></td>
</tr>
<tr>
<td>#65 Thin sidewall body fails on setback</td>
<td>1</td>
<td>7.8400E-07</td>
<td>7.8399E-07</td>
<td>A1.12</td>
<td></td>
</tr>
<tr>
<td>#502 Particles embedded in HE cause HE to initiate at setback</td>
<td>1</td>
<td>5.0000E-07</td>
<td>4.9998E-07</td>
<td>A1.15</td>
<td></td>
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<tr>
<td>Normal projectile 7</td>
<td>0.9914</td>
<td>9.9137E-01</td>
<td>4.5107E-08</td>
<td>A2.1</td>
<td></td>
</tr>
<tr>
<td>#504 Setback initiation due to debris in cavity 0.9999</td>
<td></td>
<td></td>
<td>1.6300E-09</td>
<td>A2.11</td>
<td></td>
</tr>
<tr>
<td>#1 Thin BCP flange fails on setback</td>
<td>1</td>
<td>1.1000E-09</td>
<td>1.1000E-09</td>
<td>A1.17</td>
<td>Factor 2</td>
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<tr>
<td>#307 Projectile Base deformed by propulsion gases</td>
<td>1</td>
<td>6.6700E-10</td>
<td>6.6699E-10</td>
<td>A1.9</td>
<td>Factor 3</td>
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<tr>
<td>#303 baseplug Vibrates loose</td>
<td>1</td>
<td>3.3400E-10</td>
<td>3.3399E-10</td>
<td>A1.2</td>
<td>Factor 1</td>
</tr>
<tr>
<td>#80 Cut Cartridge Case</td>
<td>1</td>
<td>1.0000E-10</td>
<td>9.9998E-11</td>
<td>A1.3</td>
<td>Factor 5</td>
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<tr>
<td>Improperly secured HE moves back and detonates at setback</td>
<td>1</td>
<td>2.0000E-11</td>
<td>2.0000E-11</td>
<td>A1.16</td>
<td>Factor 6</td>
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<tr>
<td>#503 High pressure event</td>
<td>1</td>
<td>8.3400E-07</td>
<td>8.3400E-07</td>
<td>A1.17</td>
<td>Factor 6</td>
</tr>
<tr>
<td>PBXN-5 Develops cracks in storage #51</td>
<td>1</td>
<td>1.0001E-11</td>
<td>1.0001E-11</td>
<td>C1.1</td>
<td></td>
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<tr>
<td>Voids in explosive pellet #52</td>
<td>1</td>
<td>1.0000E-11</td>
<td>1.0000E-11</td>
<td>C1.3</td>
<td></td>
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<tr>
<td>DOE Factor Special Purpose Test</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Redundant with a Prior Element Being Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **In-bore demonstrated in Test 2410**
- **Factor 4**
- **Factor 2**
- **Factor 3**
- **Factor 1**
- **Factor 5**

**Fault Tree Diagram:**
- **Loose Base Closing Plug in Fuze (Factor 1)**
- **Thin Flange on Fuze Base Closing Plug (Factor 2)**
- **Thin Sidewall due to Eccentric Cavity at Crimp Grooves (Factor 4)**
- **Cut Case (Factor 5)**
- **Thin Dome (Factor 3)**
- **Propellant High Pressure (Factor 6)**
# Main In-bore DOE

<table>
<thead>
<tr>
<th>Factor</th>
<th>Example of “On” Factor Setting</th>
<th>Example of “Off” Factor Setting</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Full Thread Engagement</td>
<td></td>
</tr>
<tr>
<td>Loose BCP</td>
<td>~1/2 Thread Engagement</td>
<td>Full Thread Engagement</td>
<td>80</td>
</tr>
<tr>
<td>Thin BCP Flange</td>
<td>~.015” Flange Thickness</td>
<td>~.044” Flange Thickness</td>
<td>5</td>
</tr>
<tr>
<td>Thin Dome</td>
<td>~.05” Dome Thickness</td>
<td>~.125” Dome Thickness</td>
<td>80</td>
</tr>
<tr>
<td>Eccentric Cavity</td>
<td>Max Eccentricity (~.020”)</td>
<td>Nominal Eccentricity (~.008”)</td>
<td>80</td>
</tr>
<tr>
<td>Cut Cart. Case</td>
<td>Cut through case to proj. body</td>
<td>No Cut</td>
<td>80</td>
</tr>
<tr>
<td>High Pressure</td>
<td>~405 MPa Chamber</td>
<td>~480 MPa Chamber</td>
<td>81*</td>
</tr>
</tbody>
</table>

* 1 shot included thin BCP Flange
Test In-bore Comparisons

Barrel Diameter (inches)

Distance from End of Barrel (inches)

Foreign Material

Thin Flange
P-t Curves from DOE
In-bores (Thin Flange)

- No In-bore
- In-bore #1
- In-bore #2
- In-bore #3 (High Pressure)
Inbore Detonation

• Most Likely Causes
  ★★ Foreign Material from Manufacturing Process in Liner Cavity (Replicated)
  ★ Thin Flange/Spitback Crimp (Replicated)

• Actions Taken to Date to Reduce/Eliminate Issue
  – 1980s Production Placed into Condition Code ‘N’
    • Removed to Strategic Reserve in Kuwait Planned for Demilitarization When Stockpile has been Replenished
  – 1990+ Production
    • Thin Flange on Base Closing Plug Identified as a Critical Defect
      – Additional Testing Added to Verify Design Margin
      – Double Automated Inspections Added to Manufacturing Line
    • Affected Lots (Prior Inbore Detonations) Restricted from Use Until Screened
    • X-Ray Screening to Remove Defective Rounds Being Initiated
    • Manufacturing Process has been Modified to Eliminate Source of Foreign Material
  – AIN & ASAM Issued to Minimize Ammo Exposure to Extreme Temperatures
Bullet on Bullet
A loss of propellant due to punctured case caused:
1. Increased Action Time (5 to 24 ms)
2. Decreased Range
3. Projectiles stuck beyond origin of rifling at ~15% propellant load
4. Projectiles stuck at origin of rifling or failed to debullet at 5-10% propellant load.
• Most Likely Causes
  ★ Cartridge Cases are Punctured and Propellant is Lost
  • Efficiency Loss to a Level of 10-15% (Replicated)

• Actions Taken to Reduce/Eliminate Issue
  – ASAM #AH-64-07-ASAM-13 Issued
    • Emphasizes Use of “Auto” Mode for D Model Apache Sideloader which Minimizes Risk of Creating and Firing Punctured Cases
    • Requires Download and Inspection of Ammunition at Aircraft Regularly Scheduled Maintenance
    • Re-emphasizes the Need for Caution Uploading/Downloading the Aircraft to Avoid Punctured Cartridge Cases
Summary

- Investigation is Completed
- Final Reports are Being Written for Individual as well as Combined Efforts
- Investigation Results are Being Formulated into:
  - Design Changes
  - Manufacturing Process Changes
  - Stockpile, Manual and/or Procedural Changes, as Applicable