F-16 CANOPY JETTISON ROCKET MOTOR PROPELLANT REPLACEMENT WITH EC-10 PROPELLANT

ALPHA BRAVO COLLINS

AEROSPACE REDEFINED

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F-16 CJRM PROPELLANT REPLACEMENT WITH EC-10

The Rocket: F-16 Canopy Jettison Rocket Motor (CJRM)

- The F-16 CJRM 1517-30 is cast with UPCO-2217P propellant and UPCO-44-055C liner
  - Both the composite propellant and the liner contain the carboxy-terminated polybutadiene polymer Butarez, which has not been manufactured for over 30 years.
  - One of the curatives, a tri-functional aziridine, also acts as a bonding agent.
  - It uses a combination of fine AP and some potassium perchlorate to achieve high burning rate

- The F-16 CJRM 1517-31 is cast with EC-10 propellant and MIL-DTI-32123 Ty.3 liner
  - The composite propellant and liner both contain the hydroxy-terminated polybutadiene R-45M, and are cured with an isocyanate curative.
  - EC-10 uses the bonding agent Tepanol, which has amine groups that are adsorbed into the surface of ammonium perchlorate, producing ammonia gas.
  - The ammonia gas must be removed, or it will react with the isocyanate curative.

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Our Unique Mixing/Casting Process

- Collins uses shaker mixers, and cast directly from the mix bucket
- Most of the industry uses vertical blade mixers. There are pros and cons to the shaker
  - **Pros:** The process is very efficient for the small motors used in CAD/PAD. Clean up is minimal. Mix and cast is typically complete in ~3 hours.
  - **Cons:** Difficult to remove dissolved gasses. Propellant heats up fast.
- The evolution of ammonia during the EC-10 mix is a challenge for the shaker mixer

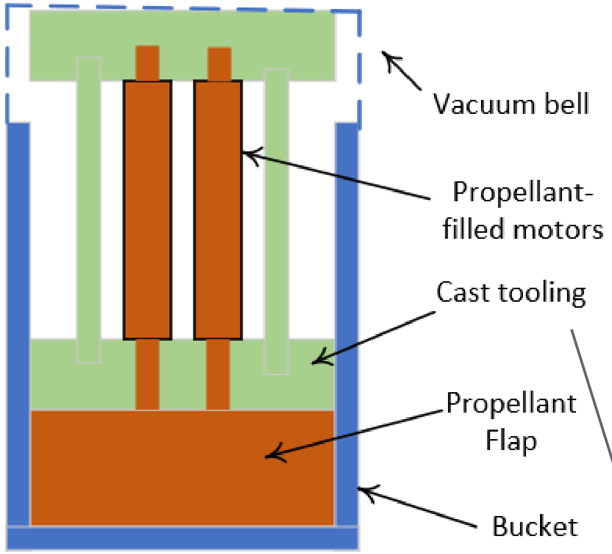

Illustration of our casting process

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History leading to EC-10 development

- 1970's UPCO-2217P propellant and UPCO-44-055C qualified in 1517-30 motors
- 1997 - Plan initiated to replace CTPB/MAPO propellant in MK109 CJRM with an HTPB propellant lead to development of EC-08 propellant
- 1999 - IHTR 2163 FAT report for EC-08 in MK-109
- 2001-2005 Producibility issues with EC-08 lead to EC-10
- 2004-2007 - UPCO Arizona develops EC-10 process using a Ross vertical mixer
- 2008 - UPCO AZ closes and moves to UPCO Fairfield. Ross mixer was not transferred.

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History of EC-10 at Collins in Fairfield

- 2010-2013 Adapted the mix process for the shaker mixer
  - Developed a tri-modal oxidizer blend to achieve burning rate, and a multi-day mix process to remove ammonia
- 2013 Mar 2013 – Collins successfully casts F-16 CJRM batch 1569-01
- 2013 Nov 12 – DIL-WS-35703 Material Spec for EC-10 Propellant approved
- 2017-2018 – Anomalies detected in CJRM motors from EC-10 batch 1741-02, some attributed to unmixed propellant inclusions that were <u>not detectable by X-ray</u> inspection
- 2019 – Unsuccessful effort to develop a 1-day mix process that would avoid the formation of unmixed inclusion
- 2020 – Developed bimodal oxidizer blend that produced the same burning rate as trimodal
- 2022 – Demonstrated screening process to eliminate unmixed inclusions in propellant

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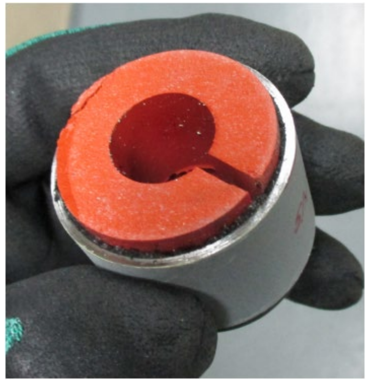
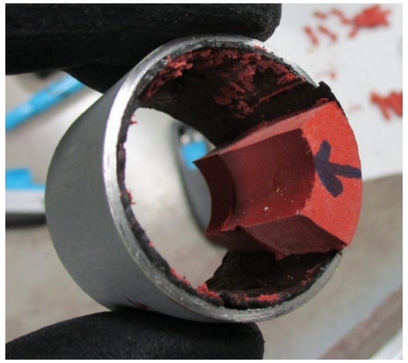
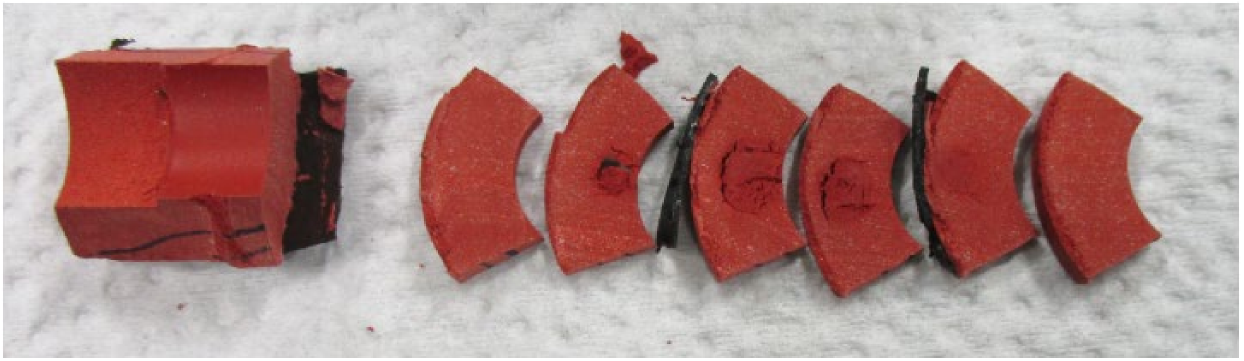
Anomalies Identified in Qualification Grains

- In 2017 some anomalies were detected in grains that had been aged
  - The anomalies were not present in the X-rays that were taken before aging.
  - The anomalies appeared as dark semi-circular rings, indicating low-density regions
- The grains were cut apart and the anomaly regions were dissected
  - They were identified as round regions of soft propellant, with distinct transitions between the soft and firm propellant







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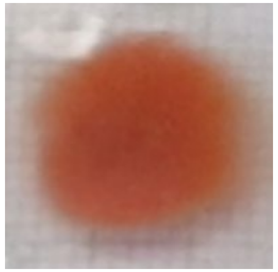
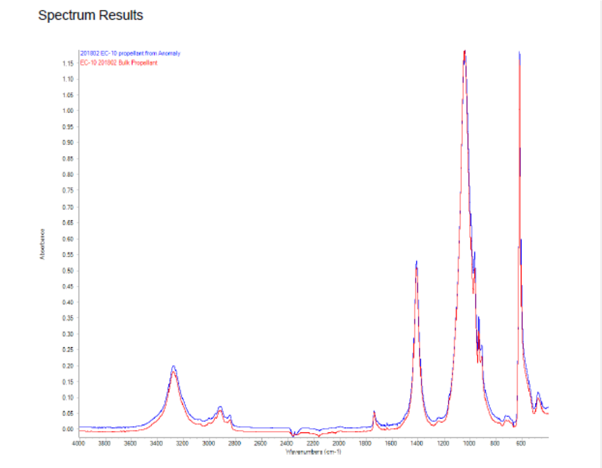
Anomalies Identified in Qualification Grains – Identifying the Cause

- The anomalies were round regions of soft propellant, with distinct transitions between the soft and firm propellant
- The soft propellant regions dissolved in toluene
  - Indicates that there was no crosslinking present
  - The largest anomaly was about 0.25”, which is the diameter of the inlets that the propellant is cast through.
- Preliminary hypothesis:
  - The sharp border between soft and firm propellant and complete absence of crosslinking suggested that the anomalies were formed before the curative was added and never absorbed curative
  - An uncured region caused by a side reaction with a side reaction during cure would not have such well-defined edges.

Control EC-10 in toluene



Anomaly EC-10 in toluene



Control EC-10 RED

Anomaly EC-10 BLUE

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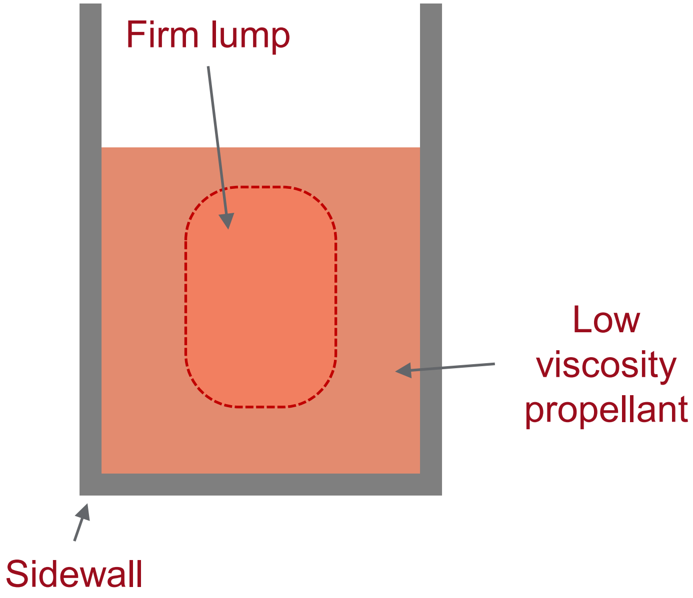
Anomalies – Testing the hypothesis

- A batch of EC-10 was mixed, and observed carefully during the mix
  - The viscosity of the EC-10 is relatively low, but it was found that the mixture packed down when it was held overnight
  - When it was mixed the next morning, it appeared to fluidize rapidly, but when probed it was found that a large lump of firm propellant remained in the center
  - The low-viscosity propellant near the sidewalls was inefficient at transferring the force of the shaker to the firm lump in the center, so the lump broke up gradually.
  - At the end of mixing, some small remnants of the “lump” were still found in the mix



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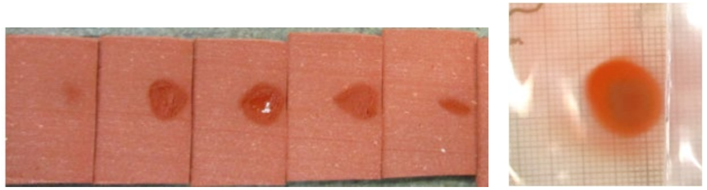
Anomalies – Testing the hypothesis

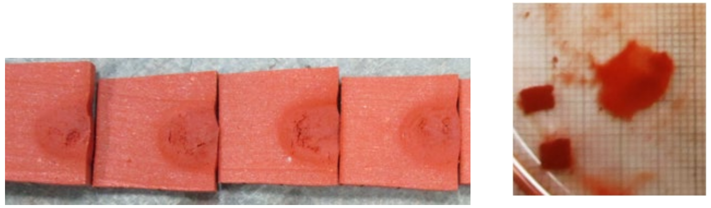
- Samples were cast with imbedded impurities that might cause soft propellant regions

Unmixed propellant “lump”	A drop of water	A drop of curative
Dried decomposition product of the curative	A drop of the bonding agent	A drop of the plasticizer

  - The lumps were nearly invisible in X-ray, and dissolved in toluene. The edges were abrupt.
  - The water drops formed regions that were more apparent in X-ray and did not completely dissolve in toluene. The edges were more transitional.
  - The bonding agent formed a smaller region than the water that did not dissolve in toluene.
  - The curative and its decomposition product did not form soft regions.



Unmixed propellant “lump” embedded in propellant



Propellant cured with a drop of water added

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Anomalies – Resolution

- The observations indicated that the multi-day mix process gives the propellant the opportunity to pack down firmly in the bowl. The packed material around the edges becomes fluid very quickly when shaking starts, but that fluid region dampens the shaking force so that it is not transmitted efficiently to the center. This is unique to the EC-10 mix process.
- **This is very troubling because, if not mitigated, we could have undetected unmixed regions in any motor.**
- A screen was added to either trap unmixed regions, or to break them into sizes too small to cause significant weak regions in the propellant grain.
- We also changed from a trimodal oxidizer blend to a bimodal blend, which reduced the packing that occurs overnight, and we have not detected that big lump that formed in the center since the change.

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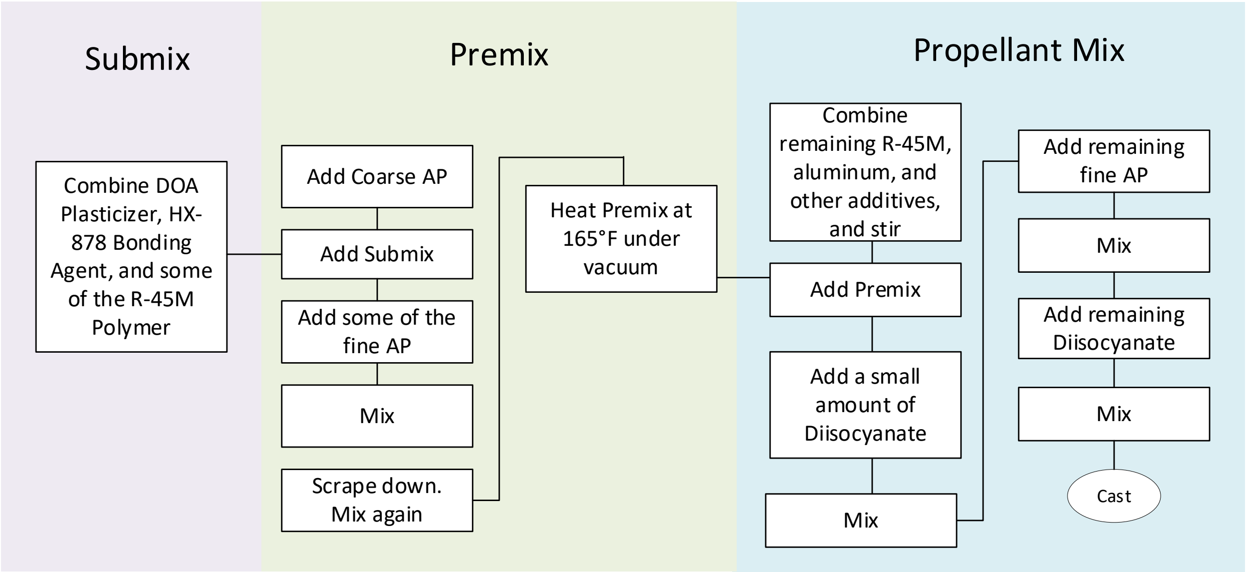
Studying an Alternative Method to Mitigate Unmixed Propellant Anomalies

- A process to pre-react the bonding agent with the oxidizer was evaluated
  - The process took time, but was less labor intensive than the long mix cycles
  - If successful, this method would eliminate the formation of anomalies that were undetectable in X-rays
  - There were some very promising results, but the process was not robust



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Switching from Tri-Modal to Bi-Modal Oxidizer Blend

- We inadvertently found a different process improvement while investigating the mix process improvement
  - We began with a legacy tri-modal blend of ammonium perchlorate oxidizer, which included a FEM-ground 6-micron fraction, but another program consumed our supply of FEM-ground AP.
  - We developed a bimodal blend as a temporary work-around until we got more of the FEM-ground AP, but it worked better than we expected and was easier to produce.
- To translate trimodal into bimodal -
  - Since all the fractions are the same material, and the surface area of a spherical particle divided by its volume is proportional to 1/(radius), the relative surface area contribution of each size fraction can be simplified to the weight % divided by the diameter

Oxidizer Blend							
Batch	Course		Medium		Fine		
	Median Size, µ	Weight Ratio	Median Size, µ	Weight Ratio	Median Size, µ	Weight Ratio	
Trimodal	50	37.4%	18	36.7%	5.8	25.8%	
Bimodal	50	57.2%	-	-	7	42.8%	
Surface Area Relative Contribution							Sum
Trimodal	0.75		2.04		4.45		7.24
Bimodal	1.14				6.12		7.26

We knew we could grind ~7-micron AP in-house, so we calculated a bimodal blend that would use 7-micron AP to get about the same surface area as our legacy trimodal blend.

This was just supposed to be a temporary work-around to use in development while we waited for the FEM-ground AP to arrive

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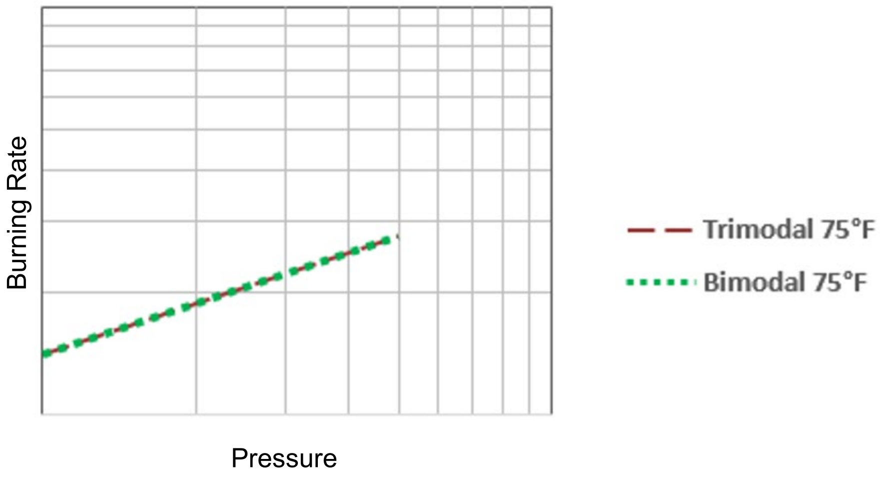
Switching from Tri-Modal to Bi-Modal Oxidizer Blend

- Reasonable expectations were that burning rate would not be reproduced and that the bimodal particle pack would be less efficient and produce higher viscosity
  - In fact, the bimodal burning rate matched the trimodal very well (motor data confirms this)
  - Tap bulk density of the bimodal matched that of trimodal very well too
  - Viscosity increase was minimal
  - …and it appears that the bimodal blend does not pack down as much when held overnight, **reducing the chance of creating the lumps** that were observed during the trimodal mixes.



Tap bulk density comparison of bimodal solids blend, left and trimodal solids blend, right. (With other solids added at nominal ratios)

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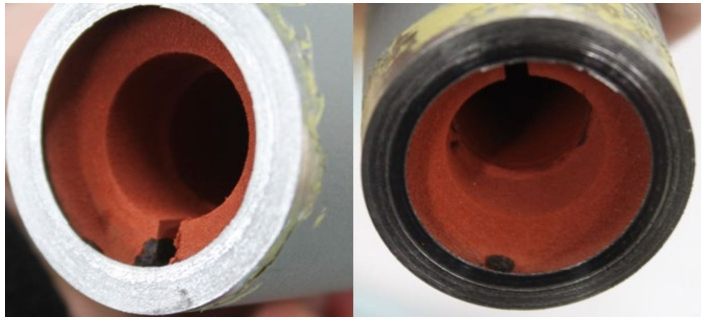
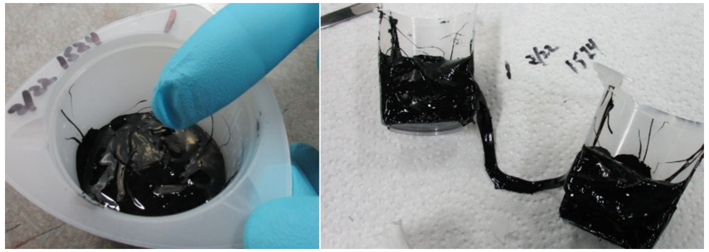
Another, much simpler anomaly that was detected

- Liner defects were observed in X-rays and visual inspection
  - Our liner witness samples were not representative of the liner in the motors. The surface appeared firm when the bulk of the liner was still soft.
  - Ultimately we found out that our cure time was about half as long as it should have been and corrected the process.
  - Increasing the cure time fixed the problem





Liner is applied to the inside surface of the tubes, and then the propellant is cast onto the liner, so the liner bonds to the metal, and the propellant bonds to the liner.

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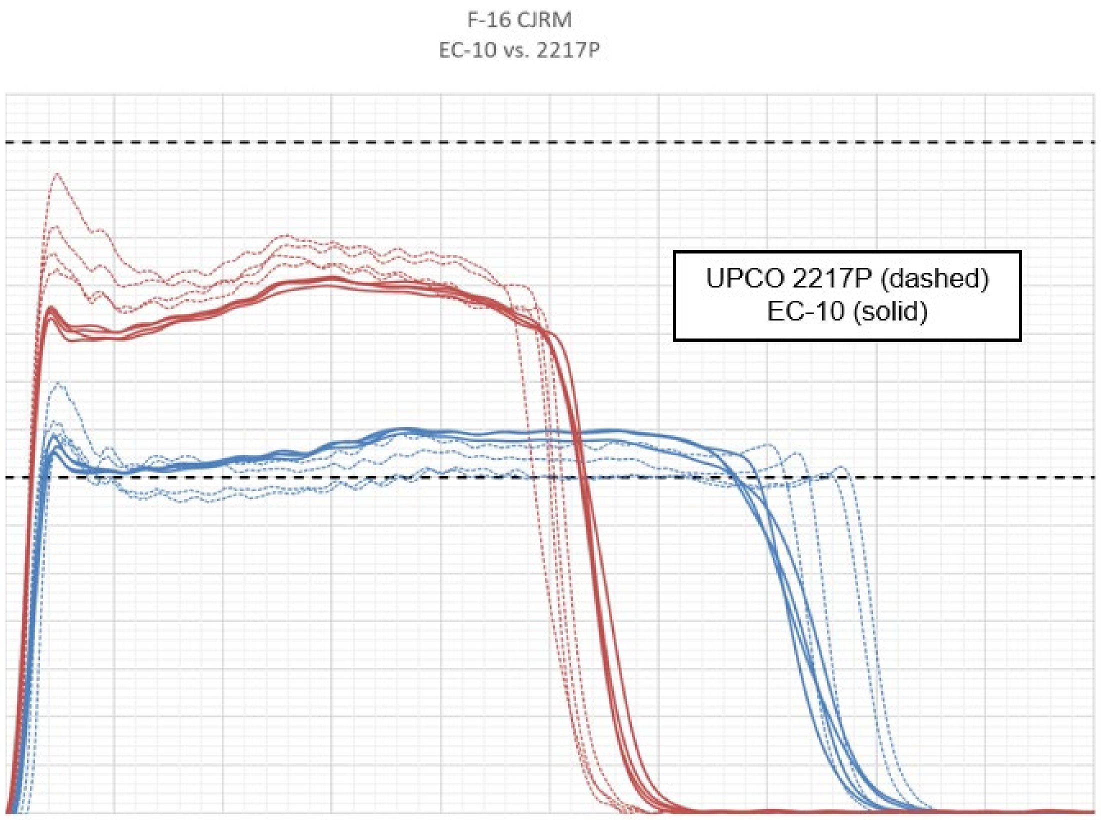
Comparison of ballistics of 1517-30 to 1517-31

- EC-10 thrust versus time has less variation
- Reduced temperature sensitivity with EC-10 propellant
- Higher peak thrust at cold, lower peak thrust at hot with EC-10 results in higher margin against performance requirements



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Conclusion

- Identified the cause of the unmixed propellant inclusions
  - The change to a bimodal oxidizer blend seems to have reduced the likelihood of occurrence of the inclusions
  - The screen makes it impossible for the inclusions to get into the motor

- Inadvertently determined that a bimodal oxidizer grind works at least as well as the trimodal.

- The ballistics of 1517-31 with EC-10 were superior to the legacy 1517-30