Ford Motor Company Calcium Sulfate Desiccated PSDI-5 Inflator Evaluation

October 26, 2018 Review

Note: The information contained in this presentation is also representative of airbag inflator performance in shared platforms with Mazda

Agenda

I. Summary of parts harvested and assessment

II. Analysis results
   A. Statistical Analysis of MEAF Data
   B. TK Global Results
   C. Northrop Grumman (OATK) Results
   D. Third Party Results

III. Discussion

Parts Harvested and Analyzed

- Summary of parts analyzed
  - TKG: 984 Fusion/Edge (ZQ) and 1,008 Ranger (ZN) return parts = 1,992 parts total
  - Northrop Grumman: 60 Fusion/Edge and 86 Ranger return parts = 146 parts total
  - Third Party: 104 Fusion/Edge and Ranger field return and virgin parts
  - 2,242 parts evaluated ranging from 8 to 11 years in the field.

Parts were retrieved and analyzed from all of the Ford vehicles using the desiccated PSDI-5 with the highest time in service in different geographic regions

Evaluation Summary and Conclusions

- Assessment through a robust variety of analytical methods, by multiple independent experts has not identified age related degradation that would signal either an imminent or developing risk to safety in the calcium sulfate desiccated PSDI-5 inflators in Ford vehicles.

- Statistical modeling and forecasting of substantial field and test data shows a clear difference in the expected performance of the PSDI-5 desiccated inflators and predicts the inflators will perform as designed for their expected design life.

- Conditions necessary to result in augmented burning using ballistic modeling of the desiccated PSDI-5 inflators were not identified in field return parts.

- Statistical analysis of the Takata MEAF data shows a clear difference in expected field performance between desiccated and non-desiccated inflators.

- The generate did not show any signs of degradation after years of exposure in the field, even though the desiccant in most inflators was saturated as early as two years in service.

Parts evaluated from Ford vehicles showed no signs of risk of inflator rupture

Analysis Performed

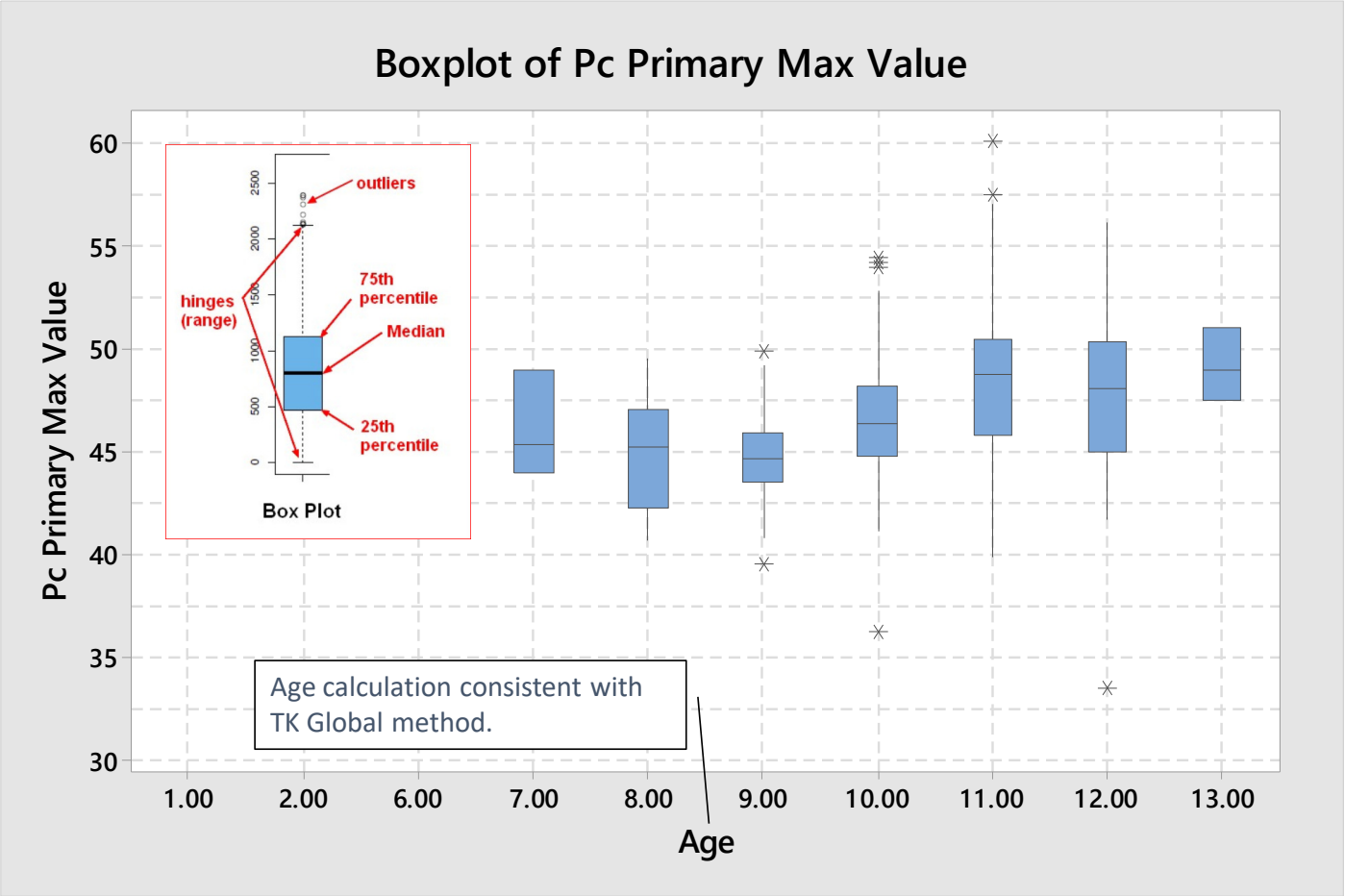
- Statistical Analysis of MEAF data

- Takata
  - Live dissection
    - Tablet density
    - IBR
    - AI-1 tablet assessment
    - Component moisture level
  - Instrumented tank deployments

- Northrop Grumman (OATK)
  - Live dissection
    - Tablet physical characteristics (weight, height, outer diameter)
    - AI-1 tablet assessment
    - Moisture content
    - Micro-CT Scan
    - SEM observations of propellant
    - Burn rate
    - O-ring/sealing assessment
  - Instrumented tank deployments
  - Comparison of virgin inflators from Ford service stock inventory to field return parts
- Third Party
  - Live dissection
    - Propellant physical characteristics
    - Moisture content
    - Mercury Intrusion Porosimetry
  - Instrumented deployments

2,242 Inflators Evaluated Both Quantitatively and Qualitatively

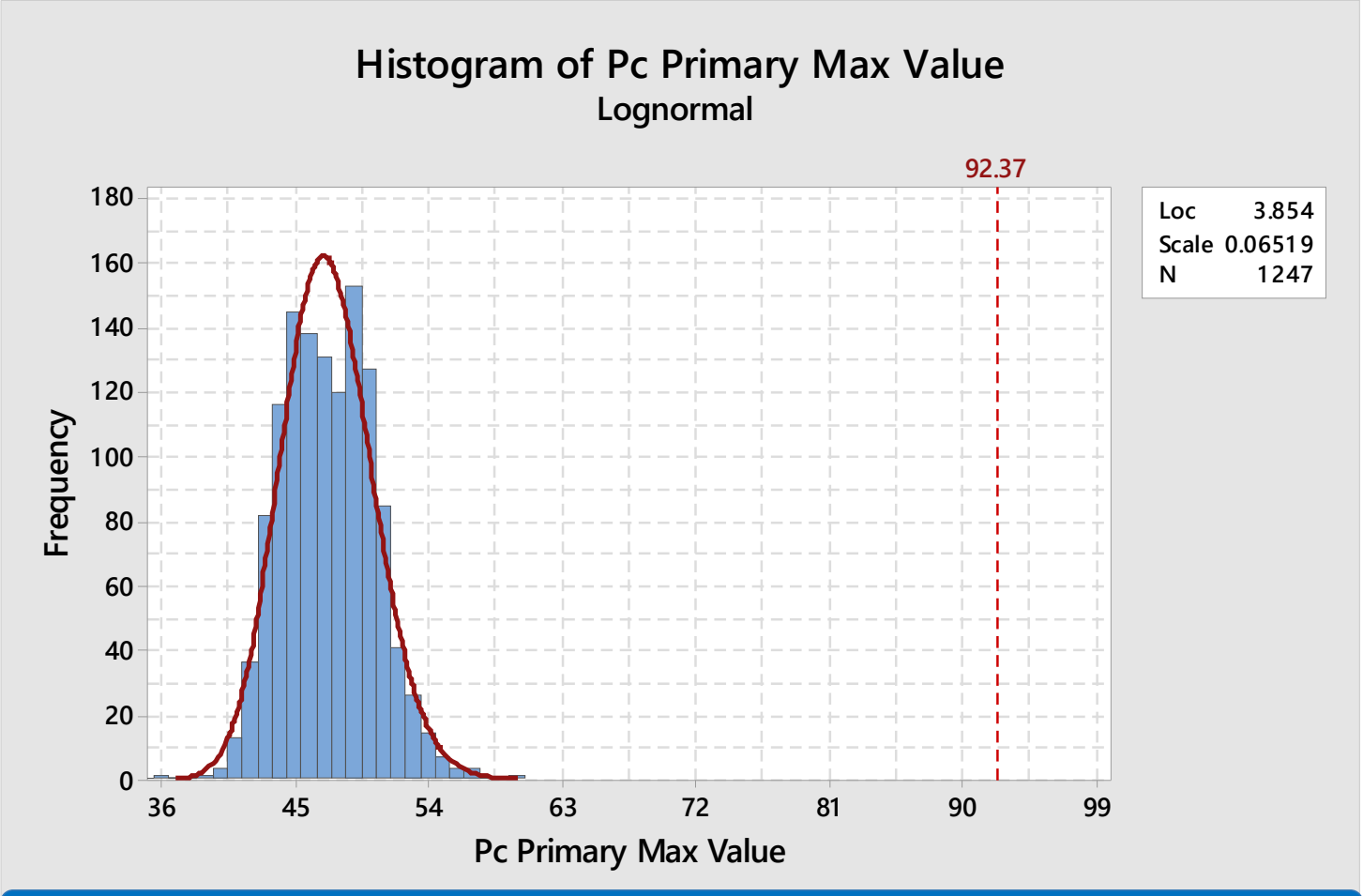
Primary Pressure by Inflator Age



FORD ANALYTICS
Global Data Insight & Analytics

No significant trend of primary pressure increase with inflator age

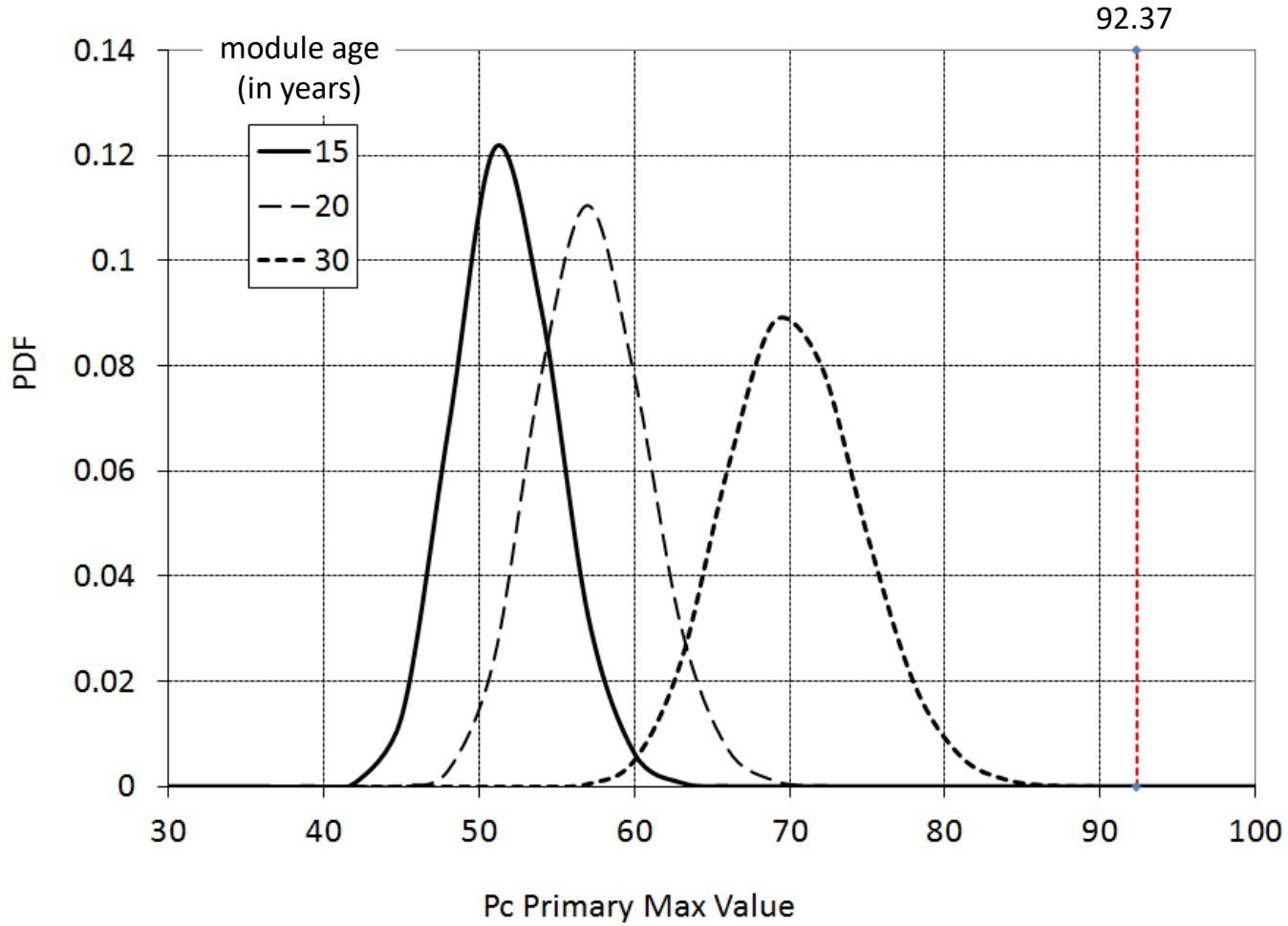
Statistical Analysis of Ford MEAF Data (all ages combined)



Probability of exceeding the threshold is estimated as $< 1 \times 10^{-15}$

FORD ANALYTICS
Global Data Insight & Analytics

Predicted Primary Chamber Pressure with Age for Ford MEAF data



Probability of exceeding the threshold @30YIS: 6.56 x 10^{-6}

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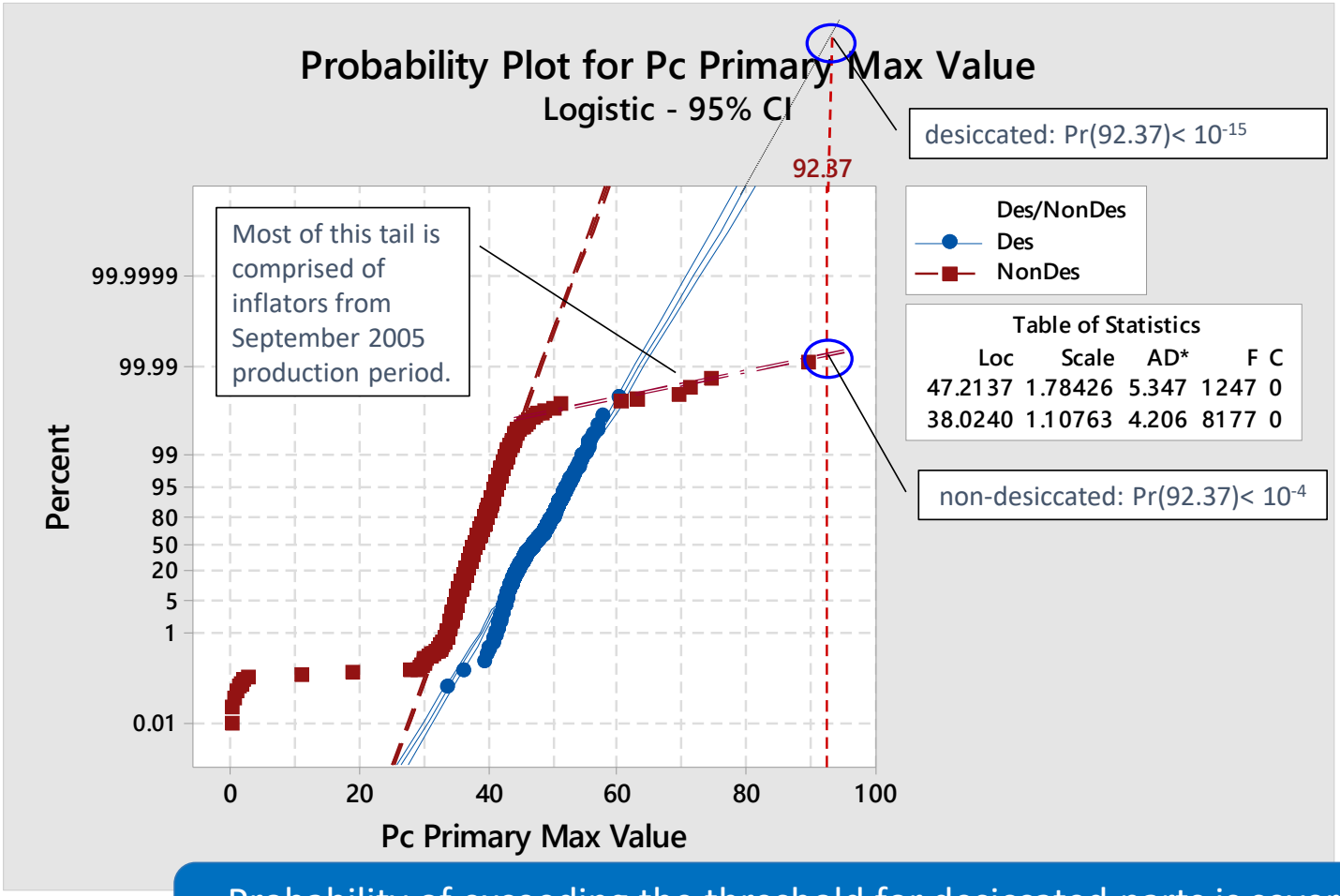
Takata Ford Modules: Desiccated vs. non-Desiccated



Probability of exceeding the threshold for desiccated parts is several orders of magnitude lower than that of the non-desiccated parts

MEAF Data Statistical Analysis Conclusions

Statistical analysis of the Takata MEAF data shows a clear difference in expected field performance between desiccated and non-desiccated inflators.

The statistical analysis also suggests that the factors causing degradation in the non-desiccated population of inflators are not currently affecting the calcium sulfate desiccated ammonium nitrate inflators

Takata Analysis and Conclusions

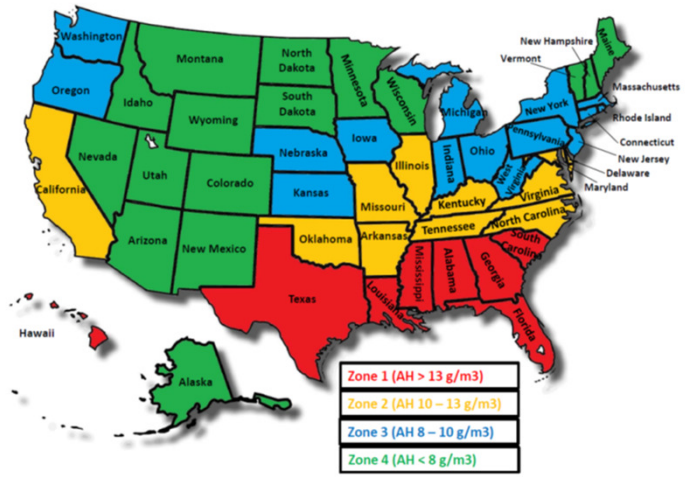
- Analysis results
  - The analyses conducted on nearly 2,000 returned inflators, from across the U.S. did not identify any trends that suggest the inflators present a risk to safety through degradation.
  - There were no inflator ruptures during any of the testing and there were no pressures observed during the evaluations near the rupture pressure for the inflator.

- Conclusion
  - Analysis identified signs of aging but no indication of degradation that could lead to a rupture and no imminent risk to safety has been identified.

- Number and type of tests

	Ballistic	Live Dissection	Total
Zone 1	991	448	1,439
Zone 2	174	13	187
Zone 3	38	136	174
Zone 4	46	131	177
Unknown	8	7	15
Total	1,257	735	1,992

TKG: 984 Fusion/Edge (ZQ) and 1,008 Ranger (ZN) return parts = 1,992 parts total



Northrop Grumman Conclusions

- Conclusion
  - The assessment of field return parts along with the modeling identified expected signs of aging but no indication of degradation that could lead to a rupture.
  - The assessment identified clear and significant differences between desiccated and non-desiccated inflators of similar age and design.

Northrop Grumman Analysis and Results

- Summary of Grumman's analysis
  - 58 PSDI-5 Dissections
  - 138 Tank Tests
  - MEAF Analysis
  - Design Comparisons
  - CT Scans
  - Ballistic Modeling

Inflators Procurement Summary			Testing	
Inflator Type / Platform	Location	Inflators	Dissections	Tank Tests
Ranger ZN South Florida (06' – 07')	South Florida	31	10	21
Fusion ZQ South Florida (06' – 08')	South Florida	31	10	21
Edge ZQ South Fl / Ga (06' – 08')	South Florida	29	10	19
Ranger ZN Arizona (06' – 07')	Arizona	24	8	16
Ranger ZN Michigan (06' – 08')	Michigan	31	10	21
Virgin ZN	N/A	25	5	20
Virgin ZQ	N/A	25	5	20
	Total	196		

Northrop Grumman Live Dissection Summary

- **2004 Propellant Health Analysis**
  - Densities of tablets from the returned PSDI-5D ZN and ZQ inflators are well above 1.63-1.64 g/cc. PSDI-5 inflators containing 2004 tablets with densities of 1.64g/cc or lower are susceptible to energetic disassembly.
- **AI-1 Analysis**
  - AI-1 tablets were removed, measured for outer diameter, weight, and color. The outer diameter and weight of field returned samples were similar to virgin samples. In older undesiccated inflators, the AI-1 tablet color is an indicator of age based on humidity and temperature exposure in the field. The field returned Ford inflators retained a 0-2 color (10 the darkest) similar to virgin samples. Thermogravimetric analysis indicated similar weight loss to virgin samples.
- **Moisture Content**
  - The propellants from the Ford inflators were lower in moisture than non-desiccated PSDI-5 ZA and the desiccated PSDI-5 YT inflators.
- **X-ray Micro Computed Tomography (Micro-CT Scan)**
  - Typically, 20,000 voids were identified ranging in size from 1×10^{-5} to 0.3 cubic mm. No definitive trend was observed with void count, void size or total void volume and tablet density.
- **Scanning Electron Microscope (SEM) of Propellant**
  - 2004 tablets from non-desiccated ZA inflators processed through the accelerated ITC aging study cycled 1920 times have higher surface roughness than tablets from Ford desiccated inflators. The desiccated 1920 cycled PSDI-5 GE and YT inflators had higher surface roughness than the Ford field returned PSDI-5 ZN and ZQ inflators. Tablets from ZN and ZQ returns have surface roughness similar to virgin ZN inflators.

Northrop Grumman Live Dissection Summary - continued

- **Burn Rate (Closed Bomb, 2004 Tablet)**
  - No significant differences were observed between 2004 propellant from virgin and returned inflators. No anomalous pressure traces were observed.
- **O-Ring**
  - Older O-rings have compression set / loss of resiliency as determined by a decrease in the O-ring horizontal diameter with increasing O-ring age. O-ring squeeze was determined by comparing this O-ring horizontal diameter to the corresponding height of the notch in which the O-ring was housed. Although a significant decrease in O-ring squeeze is observed in the 2006-8 PSDI-5D inflator igniter assembly sealing system, the remaining squeeze is deemed acceptable to prevent moisture leakage around the O-ring.
- **Inflator Tank Testing**
  - Test results from PSDI-5 ZN inflators showed one inflator chamber pressure was ~20% higher than the average of the other inflators tested. All other PSDI-5 ZN curves were grouped tightly with the virgin inflators. The PSDI-5 ZQ inflators were grouped tightly with the virgin inflators. The inflator with the higher than average pressure was from a vehicle located in Michigan, and the pressure was well below any expected inflator rupture pressure.

Northrop Grumman Analysis and Modeling

- **Ballistic Modeling**
  - Ballistic modeling was conducted using Northrop Grumman propellant grain design and internal ballistics software. Ballistic models were developed to investigate the observed performance behavior of Ford PSDI-5 ZN and ZQ inflators and to evaluate the potential sensitivity of the inflators to certain design deviations. This study developed representative inflator performance models, which were anchored to measured pressure data for virgin inflators. The models simulated inflator ignition, chamber volumetric filling, burst tape rupture, ignition delay between chambers and steady state combustion. To achieve failure pressures, the PSDI-5 design requires significant degradation of the 2004 propellant tablets. An equivalent low press tablet density below 1.631 g/cc was required to produce sufficient augmented burning. This degradation was not observed in the PSDI-5 ZN or ZQ field return inflators that were evaluated.
- **MEAF Assessment**
  - Data analysis of the latest (February 2018) MEAF was conducted to determine if PSDI-5 ZN and ZQ ED rates are dependent upon platform, inflator age, climatic zone or other factors. The key findings of the analysis are:
  - Undesiccated PSDI-5 inflators begin experiencing abnormal deployments after 10.5 years and ED's after 11.5 years
  - Calcium Sulfate desiccated variants experienced normal deployments up to 12.5 years (the oldest inflators contained in the MEAF to date)
  - The Calcium Sulfate desiccant appears to be largely saturated after 8 years
  - ZN and ZQ inflators contain less moisture in the 3110 booster propellant than undesiccated inflators

Third Party Conclusions

- No pressure excursions were detected in the Ford PSDI-5 w/$CaSO_4$ field inflators analyzed to-date.

- Porosity growth greater than virgin 2004 has occurred in propellant from some field inflators, but not to a level sufficient to cause pressure excursions in bomb testing (normal aging characteristic).

- No significant increase in tablet ODs was observed for field populations of PSDI-5 w/$CaSO_4$ inflators.

Inflators with the highest field age had no significant OD growth

Third Party Evaluation

- Evaluation Summary
  - Live dissections performed on 39 inflators
  - Deployment tests performed on 65 inflators
  - Field return parts were from FL, MI, and OH

Evaluation Summary and Conclusions

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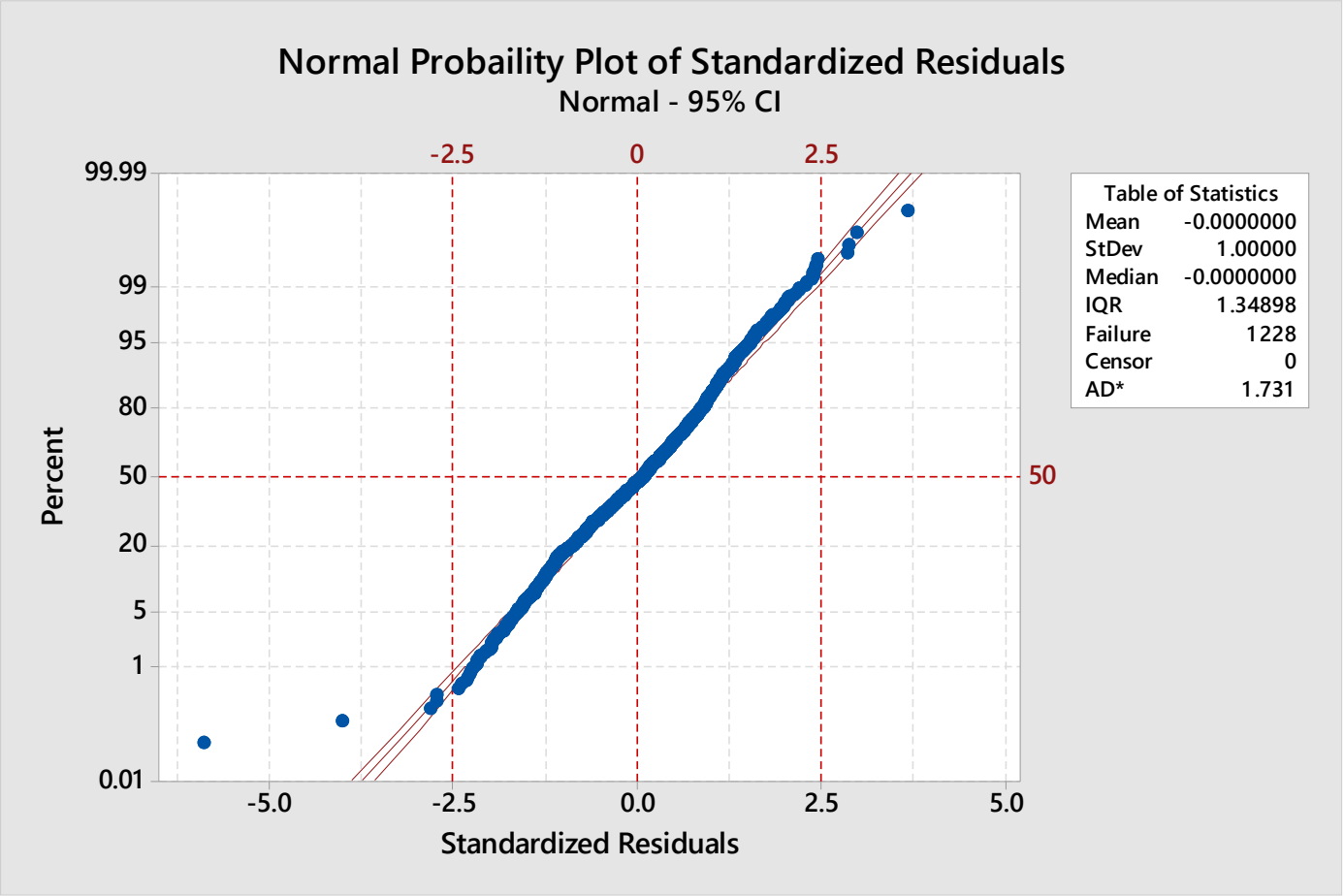
Next Steps

- Ford is sharing the information developed by Northrop Grumman for use in the larger ITC project
- Collaborate with the Agency on any additional information that may be helpful in assessing desiccated inflators

Discussion

Back-up Information

Primary Pressure with Age as a predictor (cont'd)



Symmetry of the residuals around zero indicate a good model fit

Primary Pressure with Age as a predictor

$$F(p,t) = \Phi\left(\frac{\log(p) - \mu_p(t)}{\sigma_p}\right) = \Phi\left(\frac{\log(p) - (\gamma_0 + \gamma_1 t)}{\sigma_p}\right)$$

$$\mu_p(t) = \gamma_0 + \gamma_1 t$$

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Response Variable: Pc Primary Max Value

Censoring Information  Count
Uncensored value        1228

Estimation Method: Maximum Likelihood
Distribution:   Lognormal

Regression Table

                          Standard                                  95.0% Normal CI
Predictor       Coef         Error        Z      P       Lower       Upper
Intercept    3.63750     0.0254657   142.84  0.000     3.58759     3.68741
Age        0.0204186     0.0023943     8.53  0.000  0.0157258   0.0251113
Scale      0.0632742     0.0012768           0.0608206   0.0658268

Log-Likelihood = -3085.699

Anderson-Darling (adjusted) Goodness-of-Fit:
Standardized Residuals = 1.731
Cox-Snell Residuals = 1.874
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$$F(p,t) = 1 - \Phi\left(\frac{\log(p) - (\gamma_0 + \gamma_1 t)}{\sigma_p}\right)$$

Ford vs. Non-Ford PSDI-5D Design Parameters

Component	YT PSDI-5 CaSO4	Ford PSDI-5 CaSO4
Secondary Al Cup Al-1	Yes (3 Al-1 total)	No (2 Al01 total)
Secondary Al Cup Al Seal	No	Yes
Primary Cusion	Ceramic	EPDM (until 2008) Ceramic (after 2008)
Secondary Cusion	Ceramic	EPDM
Divider Disk Tape Foil	No	Optional (after 2009)

Cross Section Schematic of Ford PSDI-5 w/ $CaSO_4$