Ford Motor Company Calcium Sulfate Desiccated PSDI-5 Inflator Evaluation

November 4, 2020 Update

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

Agenda – November 4, 2020

Background: On October 26, 2018, Ford met with the Agency and reviewed the results of analysis completed on 2,242 field return parts (Takata PSDI-5 airbag inflators desiccated with CaSO4).

Information reviewed included:

- Statistical Analysis of MEAF Data
- TK Global Evaluation Results
- Northrop Grumman (OATK) Evaluation Results
- Third Party Evaluation Results

For reference, the content of the October 2018 review is included in slides three through twenty-one.

Discussion: Review and discuss new additional information related to desiccated inflator performance since the October 2018 meeting in support of Ford's petition.

Agenda – October 26, 2018

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 Evaluation 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 compared to non-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

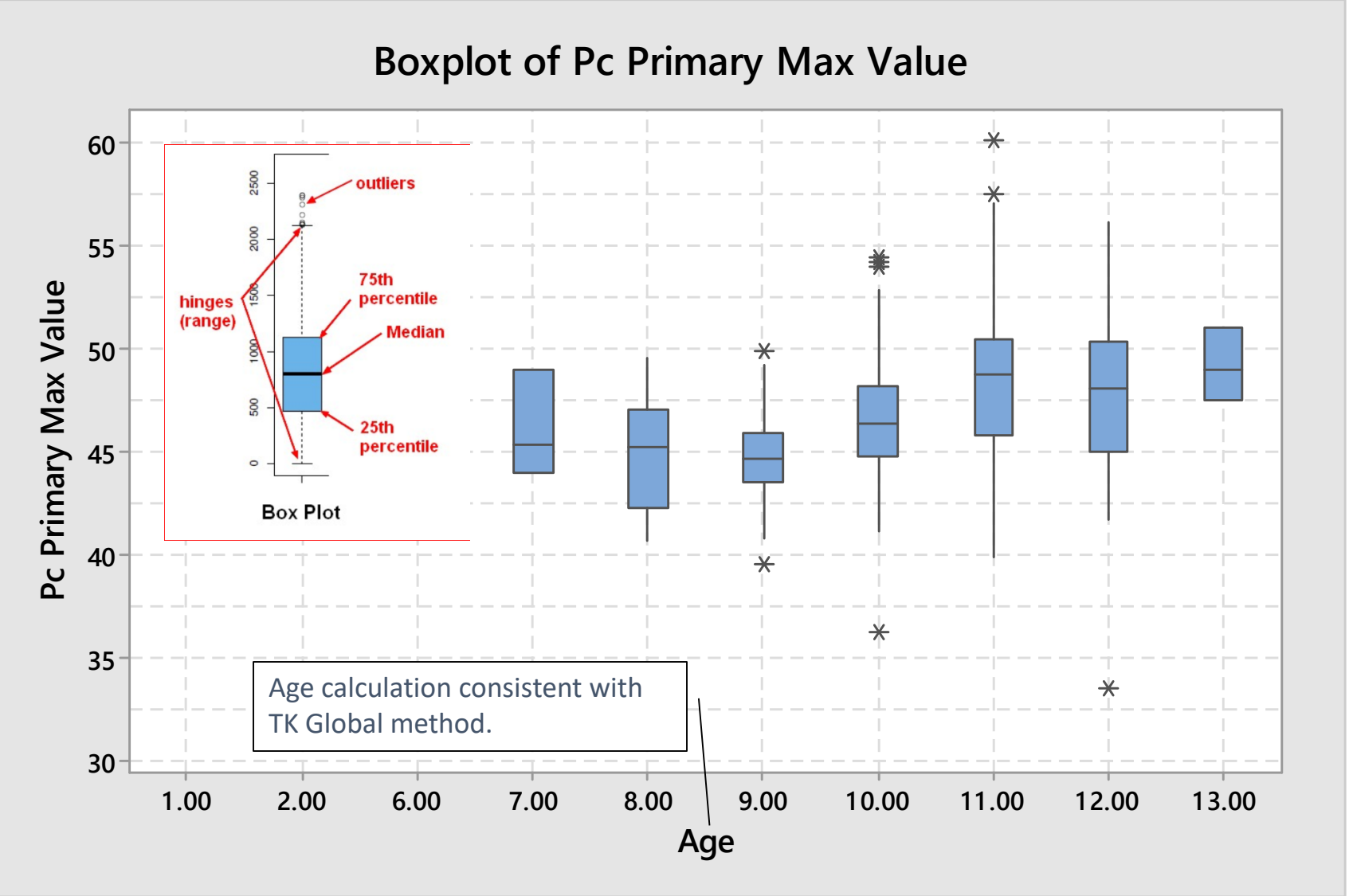
- Statistical Analysis of MEAF data

- 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

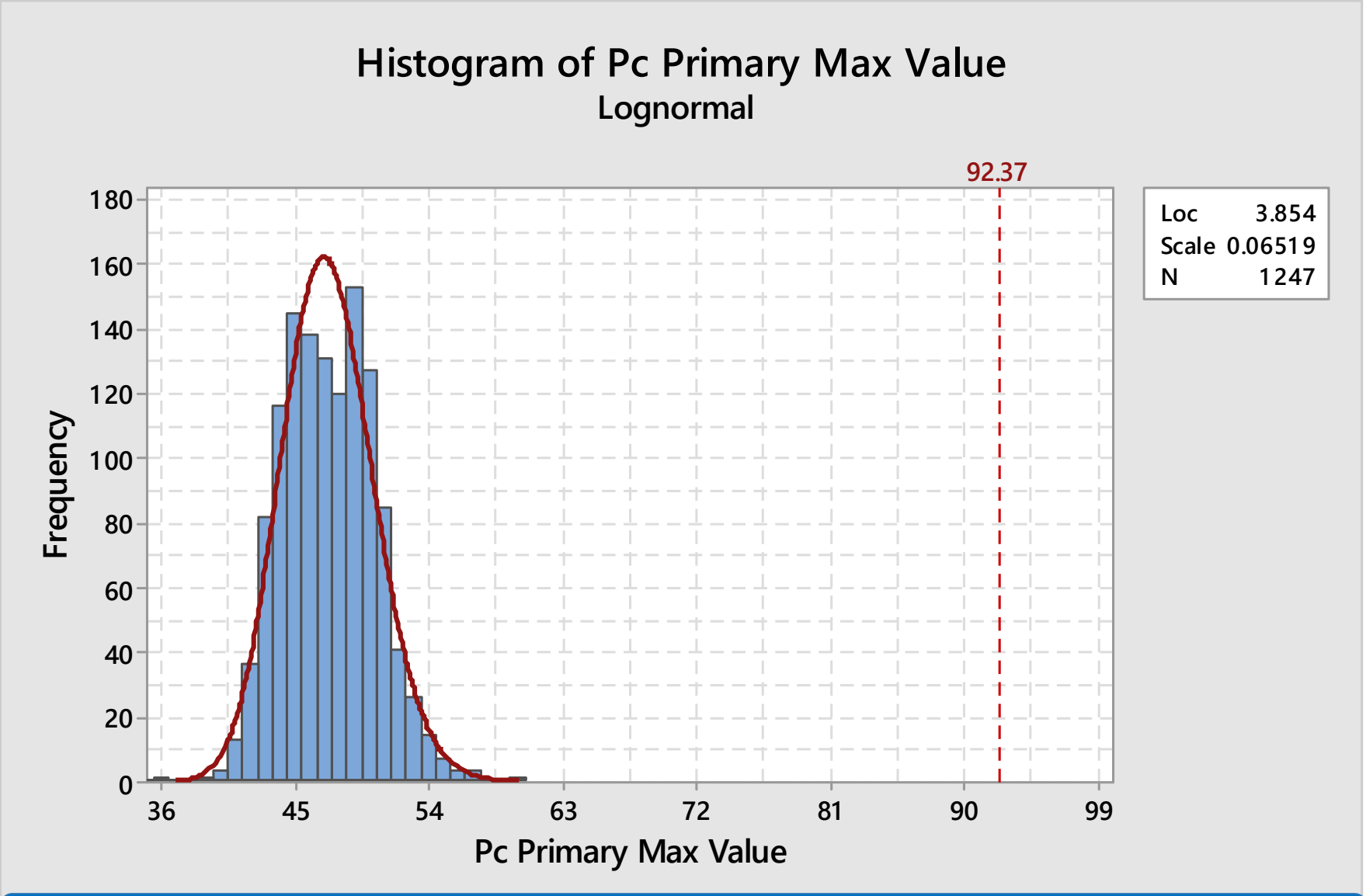
Primary Pressure by Inflator Age



FORD ANALYTICS
Global Data Insight & Analytics

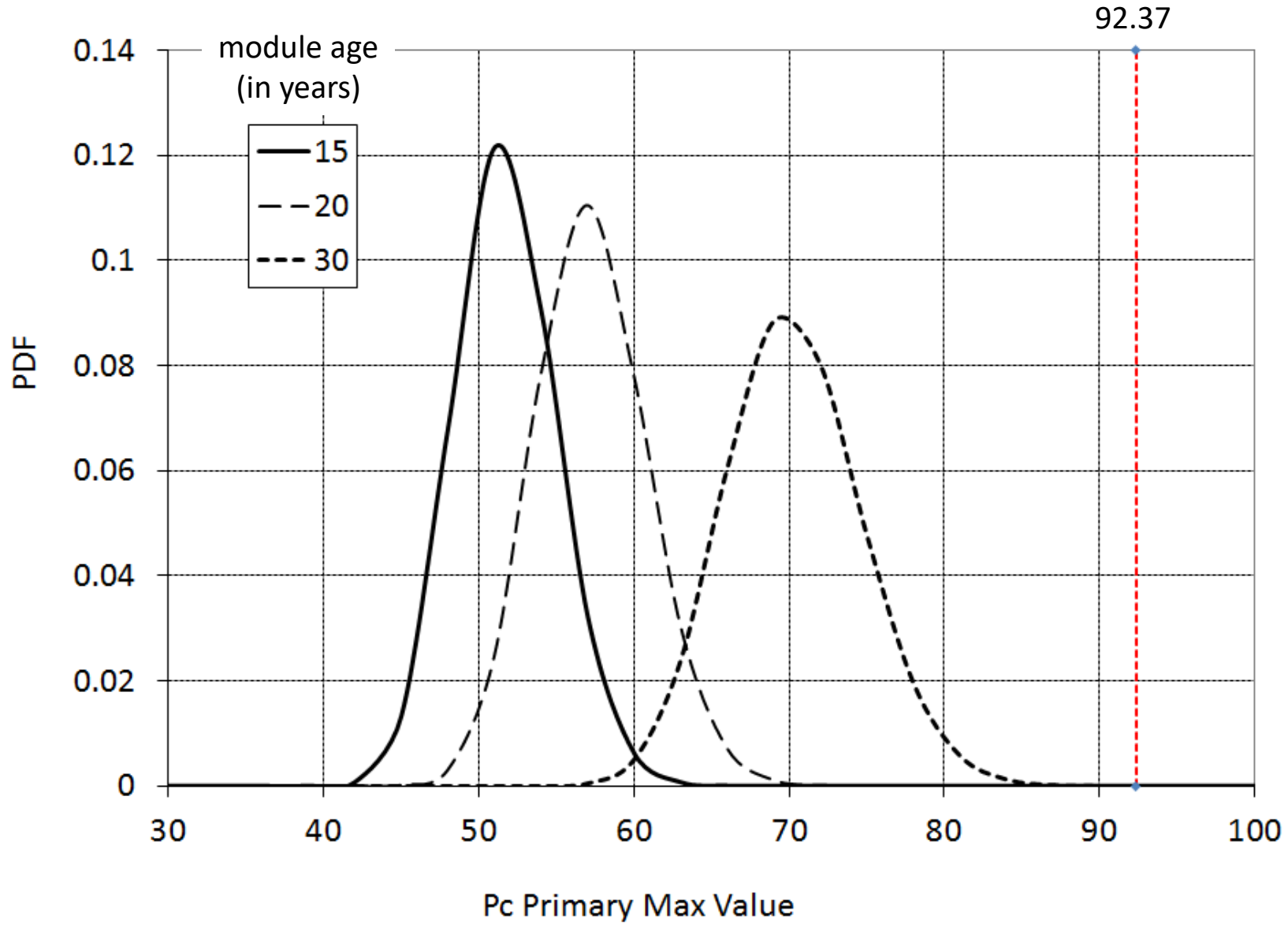
No significant trend of primary pressure increase with inflator age

Statistical Analysis of Ford MEAF Data (all ages combined)



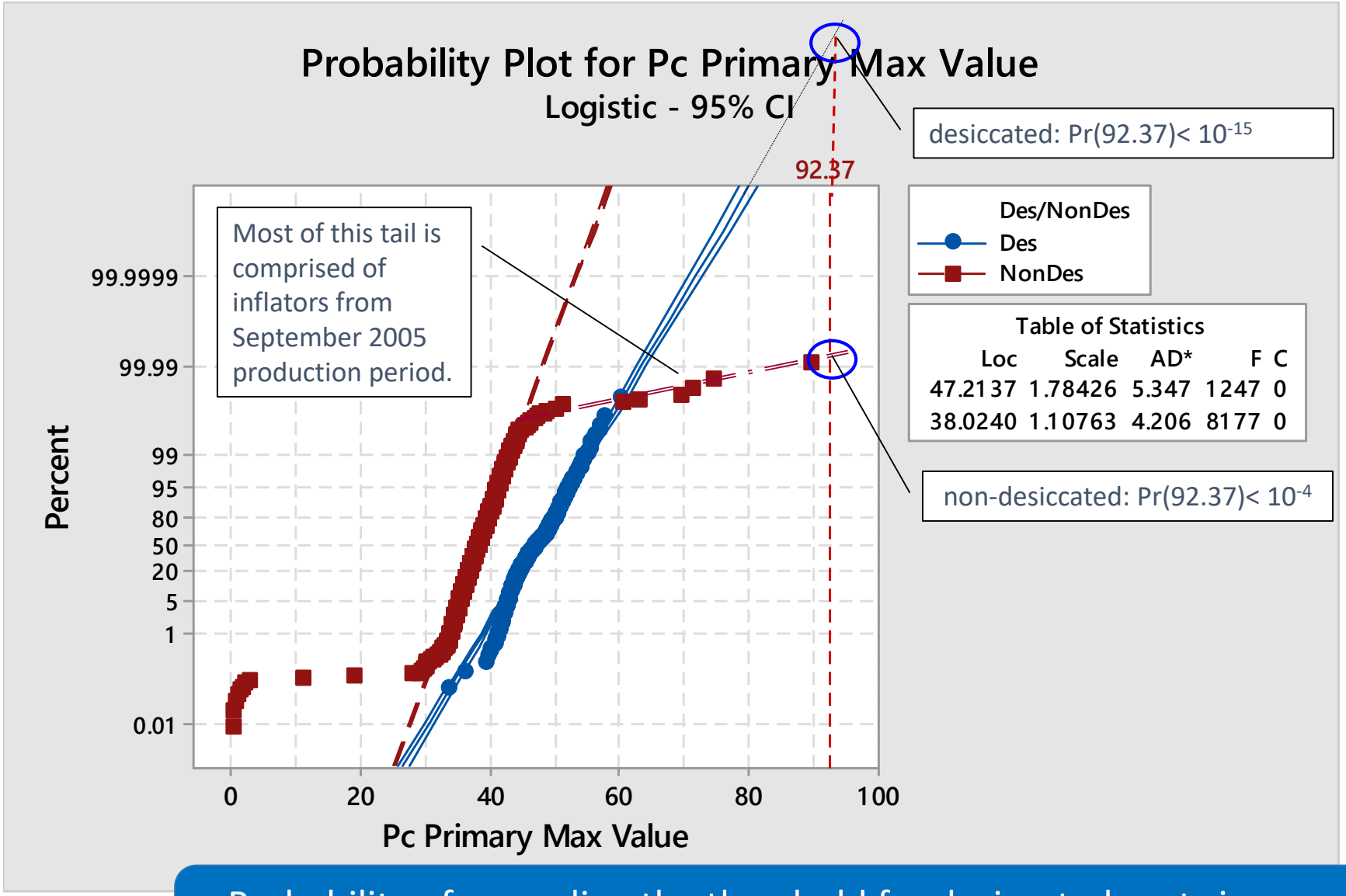
Probability of exceeding the threshold is estimated as $< 1 \times 10^{-15}$

Predicted Primary Chamber Pressure with Age for Ford MEAF data



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

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

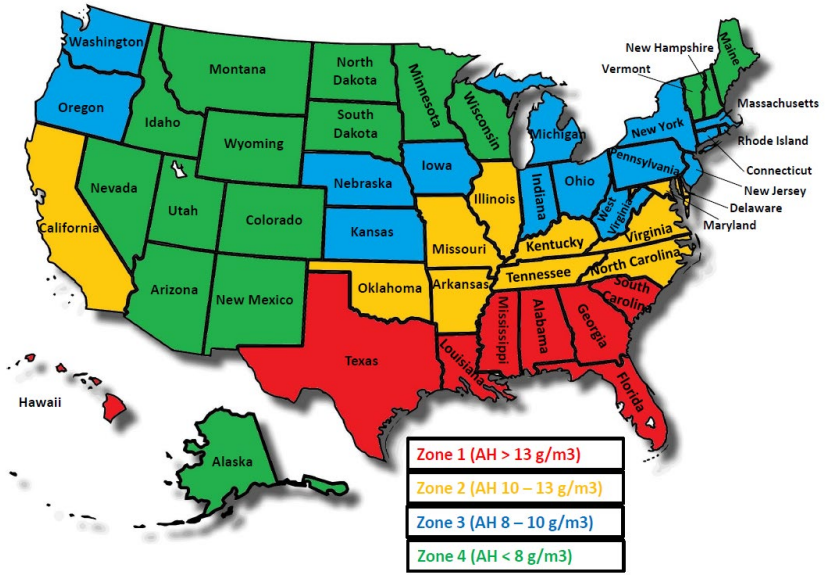
- Analysis results
  - The analyses conducted on nearly 2,000 returned inflators, from across the U.S. did not identify any trends that suggest the inflators present a risk to safety through degradation.
  - There were no inflator ruptures during any of the testing and there were no pressures observed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

- 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 compared to non-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

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

Additional Information Since Ford's October 2018 Submission

Since Ford's October 2018 review with the Agency:

- Northrop Grumman completed their inflator aging model and provided projections for the ITC
- Northrop Grumman completed projections for the Ford/Mazda inflators under petition
- Ford considered Northrop Grumman's Probability of Failure (PoF) projections in addition to typical vehicle attrition and probability of experiencing a crash with airbag deployment

Northrop Grumman Final Report

Probability of 1 in 10,000 Failure for an Inflator when Deployed from the Scientific Aging Model

NORTHROP GRUMMAN

Inflator Type	Prefix	Main ID	Booster ID	Desiccant ID	Desiccant as % of Main in Primary	Platform Temp Band**	Miami	Atlanta	Phoenix	Detroit	Seattle
PSPI-L	LT	2004	3110	NA	NA	T3	9	15	16	21	
						T2	12	21	18	30	>30
						T1	21	>30	23		
PSDI-5	ZA	2004	3110	NA	NA	T3	10	17		25	
						T2	14	26	>30		
						T1	22				
PSDI-5D 13X	GE	2004	3110	13X	4.4	T3	24				
						T2	>30				
						T1					
PSDI-5D CaSO4	YT	2004	3110	CaSO4	5.1	T3	24				
						T2	>30				
						T1					
PSPI-LD	DU	2004	AIB	13X	1.7	T3	23				
						T2	>30				
						T1					
PSPI-X	TX	2004L	AIB	13X	0.9	T3	16 to >30	27 to >30			
						T2	23 to >30		>30		
						T1					
PSDI-X	SV	2004L	AIB	13X	1.3	T3	17 to >30	29 to >30			
						T2	24 to >30		>30		
						T1					

*Note that the values in this table are shown as single value integers outside of the last two entries but should be considered to have +/- 5%-15% ranges. The values can be compared with each other directly.

**The Platform temperature bands are described in detail on charts 49-51. This is the vehicle model with T3 being those that exhibit the highest temperature and T1 those that are lowest under direct thermal exposure

- The data here report the model predictions for time in years to a 1 in 10,000 chance of an ED for:
- Inflator identified in the left two columns,
- Climate identified
- Vehicle temperature band (T1 is coolest, T3 is hottest)
- All cases are for the most severe aging (1% vehicle)
- Next four columns identify:
- PSAN main grain propellant as the older 2004 or newer generation 2004L,
- Booster formulation,
- Whether there is a desiccant present
- Amount of desiccant present relative to the propellant.
- The improvement for newer designs is determined by comparison to baseline PSPI-L LD and PSDI-5 ZA for the years to 1/10,000 failure
- The ranges shown on the 2004L propellants reflect the limited field data for anchoring
- Baseline value for PSPI-X TX Miami T3 is 25 years

YT Family is utilized by another OEM

"X" Families in ITC/TKG Surveillance Program

Completion of the ITC surveillance program is expected to affirm the current model or increase the fidelity with more mature field data and potentially extend the service life projections (currently ~26 years for the Ford variant)

Northrop Grumman's Final Report Indicated that for the YT PSDI-5/CaS04 inflator only a T3 Vehicle in Miami may Reach a 1 in 10,000 PoF in less than 30 years

Vehicle and Environmental Parameters that Affect Inflator Aging

- Northrop Grumman's Probability of Failure (PoF) predictive model considered inflator aging for various passenger compartment temperature cycle ranges (related to the passenger compartment volume and other variables) and various climates as well as customer usage

  - The size of the vehicle affects the maximum passenger compartment temperature that a vehicle may experience with smallest vehicles typically experiencing the highest passenger compartment temperatures (T1, T2, and T3 in the model).

  - Geographic climate affects inflator aging with climates experiencing the highest daily temperature cycles coupled with high humidity resulting in the highest degradation rates.

  - The "1% usage" vehicle was identified as having inflators displaying the most degradation as described in Northrop Grumman's final report shared with the Agency.
    - The "usage" factor incorporates variability in how sun, temperature and humidity transmit to the vehicle based on actual customer usage
    - The majority of vehicles are not parked outside in the sun for their entire lifetime, so an empirical usage factor (*UF*) is used that captures the effects of parking the vehicle in the shade, "cracking" the windows, or parking in a garage.

Northrop Grumman Modeling of Ford/Mazda Parts

The results of the predictive modeling by Northrop Grumman for the Ford/Mazda desiccated PSDI-5 parts is shown below.

	Inflator	Prop/Boost/Des	Time to .01% P.O.F. (Years)
Ranger →	PSDI-5D ZN	2004/3110/CaSO4	25.7
Fusion/Edge →	PSDI-5D ZQ	2004/3110/CaSO4	25.6

Ford Inflators Require an Additional Two Years for a T3 Vehicle in a Miami Climate to Reach a .01% PoF (1% probability of rupture in the 1% usage vehicle) Compared to the YT Version

Assessment

The earliest Fusion/Milan/MKZ vehicles equipped with desiccated PSDI-5 inflators were built in calendar year 2005
If the vehicle performs as a T3 vehicle the earliest 1 in 10,000 PoF is in CY 2031 for a “1% Usage Vehicle”

The earliest Ranger, Edge/MKX vehicles equipped with desiccated PSDI-5 inflators was built in calendar year 2006
If the vehicle performs as a T3 vehicle the earliest 1 in 10,000 PoF is in CY 2032 for a “1% Usage Vehicle”

For a vehicle to reach the probability of failure indicated in the model it would require cumulative exposure of approximately 26 years. Additionally, for a rupture to occur the vehicle must be in service and experience a crash resulting in airbag deployment. Based on typical vehicle attrition and crash statistics, there are no expected field events projected at 26 years in service.

Vehicle	MY	Combined Volumes (FL)	Probability of inflator rupture* at 26YIS	Expected Cum. Events at 26YIS*
Fusion	2006-2012	75,232	5.08E-07	0.038
MKZ	2006-2012			
Milan	2006-2011			
Edge	2007-2010	39,161	6.34E-07	0.025
MKX	2007-2010			
Ranger	2007-2011			

* Adjusted for the population attrition & accident probabilities using vehicles currently registered in Florida (not all of which have always been registered in Florida)

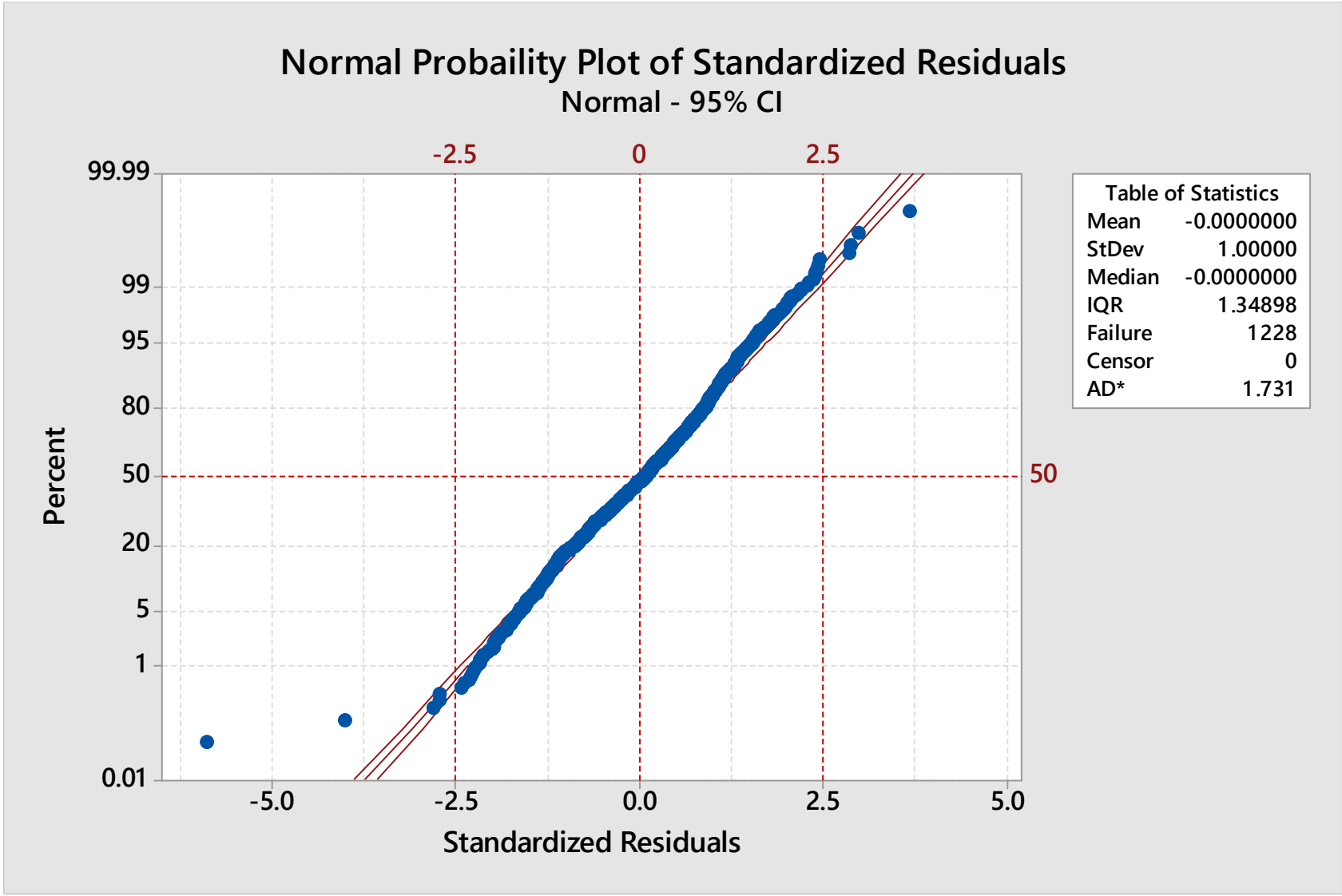
The Earliest that a Ford Vehicle in a Miami Type of Environment May Reach a .01% PoF is over a Decade in the Future for a T3 Vehicle with a “1% Usage” Profile

Discussion

- The predictive model suggests that no inflator ruptures are expected to occur for at least 26 years of cumulative exposure in the worst case environment, worst case vehicle configuration, and worst case customer usage. (CY 2031 for the oldest vehicles)
- Studying parts prior to approximately 16 - 18 years in service would not identify meaningful inflator aging information. (CY 2023 for the oldest vehicles)
- As the Agency is aware, the ITC in coordination with Northrop Grumman is conducting a surveillance program for other desiccated inflators and with data gathered from the surveillance program the Northrop Grumman PoF models can be validated and the most conservative scenarios either verified or reduced in severity.
- With newer inflators that have not yet shown signs of aging, there is a significant opportunity for improving the fidelity and accuracy of the model with enhanced anchoring data.
- Results of the surveillance program are expected in CY2021, well before any potential risk is projected to exist in the PSDI-5 desiccated parts and allow time for a separate surveillance program for those parts should it be considered necessary.
- Ford believes that the current data indicates that the subject inflators do not present an unreasonable risk to safety and that it supports granting the petition.

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

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

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

```
Response Variable: Pc Primary Max Value

Censoring Information  Count
Uncensored value        1228

Estimation Method: Maximum Likelihood
Distribution:   Lognormal

Regression Table
```

Predictor	Coef	Standard Error	Z	P	95.0% Normal CI 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
```

$$F(p,t) = 1 - \Phi\left(\frac{\log(p) - (\gamma_0 + \gamma_1 t)}{\sigma_p}\right)$$

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)