NORTHROP GRUMMAN FINAL REPORT ON FIELD MONITORING OF TAKATA X-SERIES INFLATORS

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Northrop Grumman for the Independent Testing Coalition

NORTHROP GRUMMAN

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GLOSSARY OF KEY TERMS AND ACRONYMS

CFD .... computational fluid dynamics
CT .... computed tomography
desiccant .... the term for a chemical that can function as a drying agent
ED .... energetic disassembly, also known as rupture
fault tree .... a structured, deductive approach to failure analysis
g .... gram
ICAM .... International Center for Automotive Medicine
ITC .... Independent Testing Coalition
LRCF .... leak rate calibration factor
MEAF .... Master Engineering Analysis File
mm .... millimeter
NGSC .... Northrop Grumman Systems Corporation
NHTSA .... National Highway Traffic Safety Administration
OD .... outer diameter
POF .... probability of failure
PSAN .... phase-stabilized ammonium nitrate
PSDI-X .... Takata nomenclature for a type of driver air bag inflator
PSPI-X .... Takata nomenclature for a type of passenger air bag inflator
T3 vehicles .... vehicles predicted have the highest cabin temperature
UF .... usage factor

Executive Summary

Northrop Grumman Systems Corporation (NGSC) conducted an independent investigation of Takata phase-stabilized ammonium nitrate (PSAN)-based inflators for the Independent Testing Coalition (ITC) whose members originally included BMW, FCA, Ford, GM, Honda, Mazda, Mitsubishi, Nissan, Subaru and Toyota. The final report of this effort was released in October of 2019.

The 2019 report included newer desiccated 2004L inflators. However, field data were available only to roughly 6 to 10 years since manufacture of these inflators. This limited the ability to validate the model for this class of inflators due to lack of field aging. Initial field data showed no reduction in density and lab studies showed reduced propensity to aging compared to 2004 propellant, especially in undesiccated inflators.

In 2019, considering the wide range of inflator designs and limited field test data, NGSC could not unequivocally say that under the most severe conditions the newer inflator designs would not eventually physically degrade. Conservative assumptions yielded predictions for the two desiccated 2004L inflators in the study of 16 to 17 years to the threshold of 1 in 10,000 chance of energetic disassembly (ED) if deployed (1% probability of failure [POF] in the worst 1% of T3 (highest cabin temperature) vehicles in the Zone 1 (Miami) climate).

The 2019 report recommended field monitoring of the desiccated 2004L (X-series) inflators to improve the fidelity and accuracy of the model through enhanced anchoring. NGSC proposed a targeted field monitoring program or accelerated aging of selected field return samples to provide added fidelity to the model.

In February 2020, ITC contracted NGSC to conduct this field monitoring program of one PSPI-X and two PSDI-X inflators. At that time, Honda resigned as an ITC member. The proposed test program was appropriately sized and focused on the highest risk categories (lower 13X desiccant to 2004L propellant ratios, Zone 1 climate, in the highest cabin temperature T3 vehicles). The program consisted of three participating ITC automaker members collecting 300 of the target inflators from its vehicles from Zone 1 and sending the collected parts to TK Global for warehousing and inventorying. Tests on the inflators included computed tomography (CT) scanning of all the collected inflators, dissecting each inflator and evaluating properties of the inflator component and propellants. These properties were used to validate and update model inputs and anchoring. The desiccated (13X desiccant) 2004 propellant inflators were not included in this study due to the younger age of these inflators (Figure 1).

POF models were created for the PSPI-X VQ, PSDI-X UD and PSDI-X SU inflators. These inflators were chosen for their oldest field age, availability in T3 vehicles in the Zone 1 location and their similarity to the PSPI-X TX and PSDI-X SV inflators from the previous investigation. The ballistic models were anchored to zero-time inflator and propellant ballistic performance and inflator enclosure hydroburst data.

The predictive aging portion of the models was anchored to the Master Engineering Analysis File (MEAF) maintained by TK Global and the latest field monitoring data including moisture transport into the inflator and 2004L density. The models were exercised and POF results were generated.

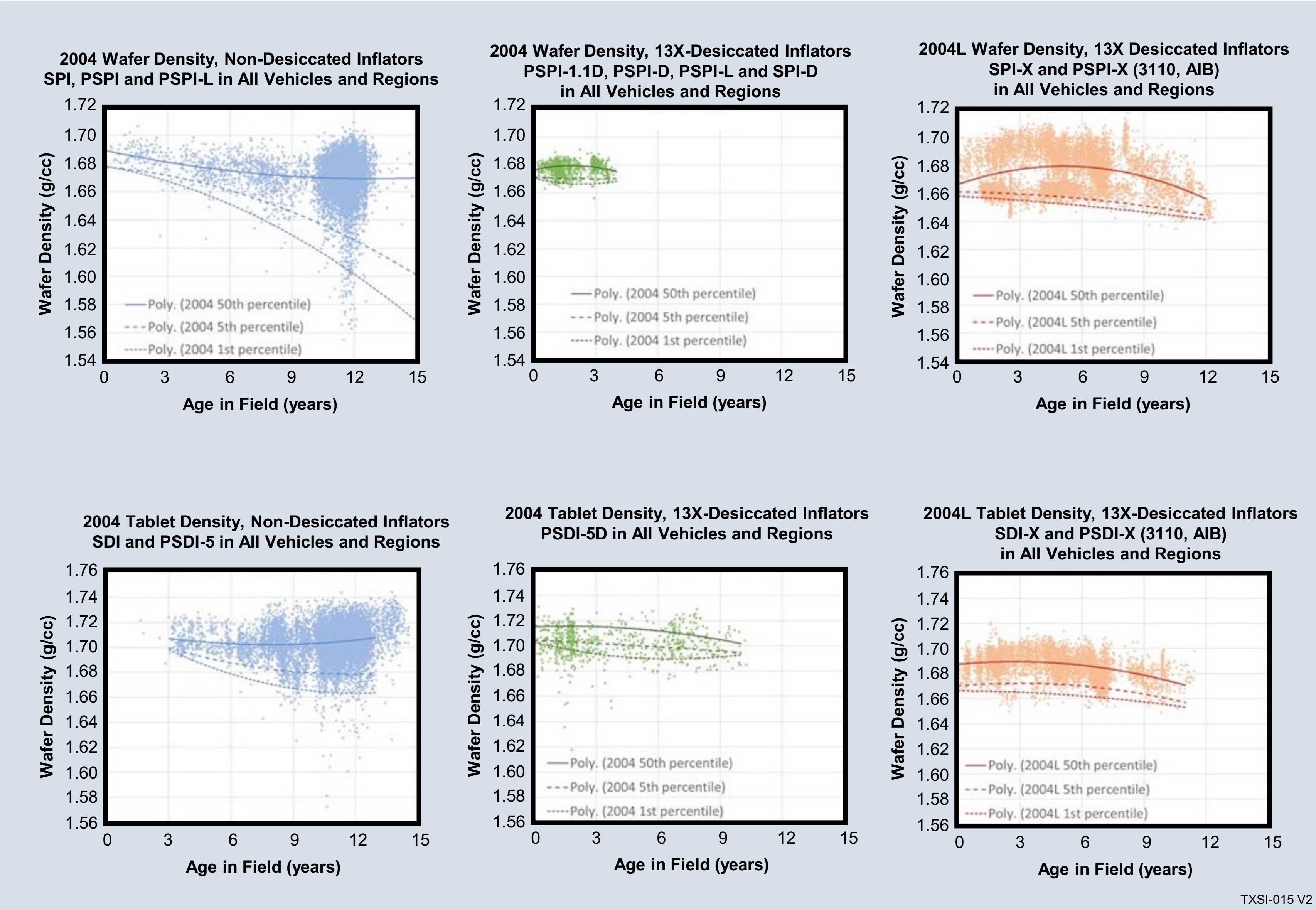

Figure 1. The Desiccated Inflators Are Not Showing the Aging That Occurs in the Undesiccated Inflators at the Same Ages.

It is worth noting that the predictive aging models in this study also retained the conservative assumption from the 2019 study that the 2004L propellant density reduction will increase in rate analogous to the 2004 propellant over time. It was deemed the correct approach at this time as there was not sufficient field data to confirm a lower rate of aging for the 2004L propellant.

Lab data strongly suggest that the second generation 2004L propellant will age less quickly than the previous 2004 propellant that was used in the first generation undesiccated PSAN inflators subject to recall. The 2004L propellant was manufactured with a processing aid / binding agent that is much less inclined to absorb moisture compared to the sodium bentonite in the 2004 propellant.

The updated modeling runs with the updated anchoring gave a modest increase in the predicted age life for X-series inflators compared to the predictions in 2019. The 2004L density data from the subject PSPI-X and PSDI-X inflators in conjunction with modeling results are shown in Figure 2, Figure 3, and Figure 4. The 2021 modeling results indicate the three evaluated X-series inflators are healthy with 19 to 21 years as the predicted time to 1% POF for the worst 1% of T3 vehicles in the Miami environment with these conservative assumptions. For the less severe environmental zones of the US, there would be a considerably longer time (larger number of years) to this same POF level consistent with the results from the 2019 NGSC study and resulting in an overall lower POF for the entire population of inflators.

There are four conclusions that can be drawn from this program and the modeling results.

1. The three evaluated X-series inflators are healthy at the time of this evaluation.
2. The model was updated for these three inflators yielding 19 to 21 years from production as the predicted time to 1% POF for the 1% T3 vehicle in the Miami environment under the most conservative assumptions.
3. Modeling and field data indicate field measures are currently not needed regarding desiccated 2004L inflators.
4. Further improvement in the fidelity of the predictive model can be achieved by a future, well designed field collection testing program for X-series inflators when enough time has passed for clear long term trends to emerge, but well before the time is reached that the most conservative application of the model predicts a 1 in 10,000 probability of failure when initiated.

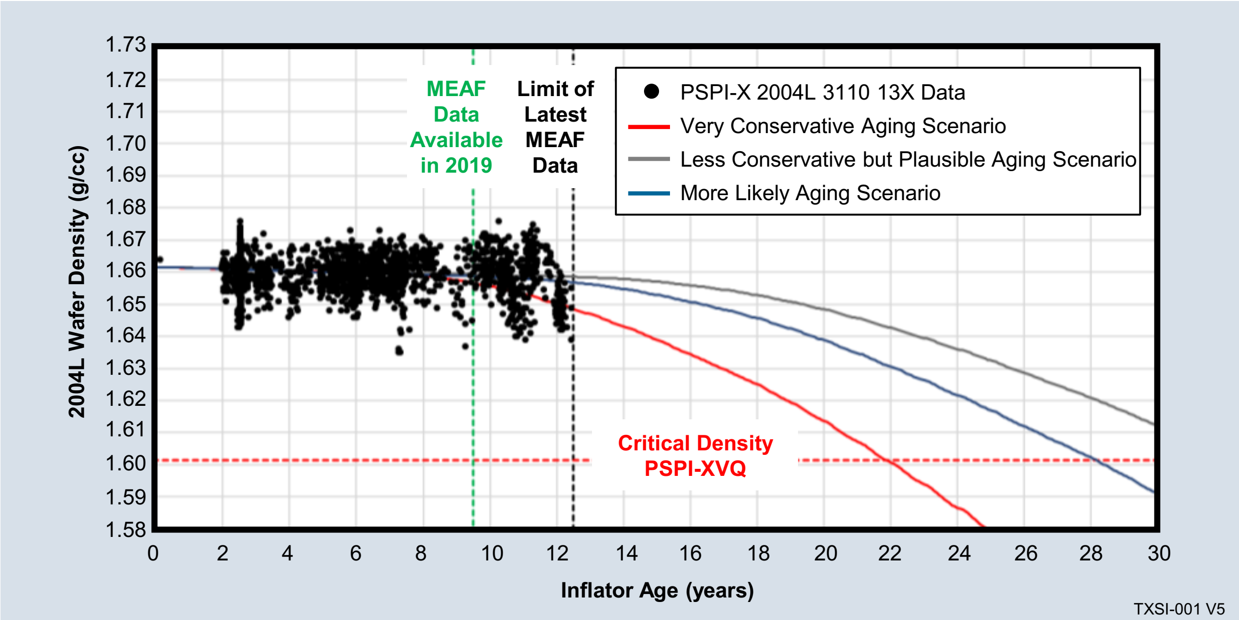

Figure 2. PSPI-X MEAF Density Data Showing Advantage of Future Testing or Surveillance Efforts in Determining the Future Aging of the 2004L Propellant-based Inflators.

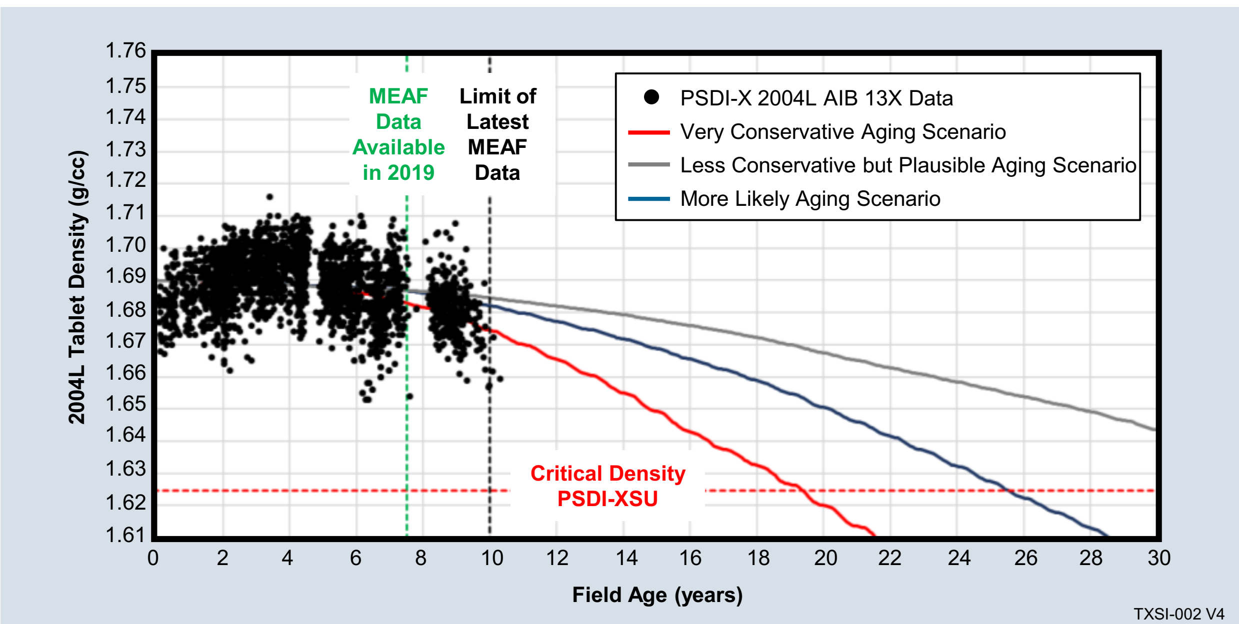

Figure 3. PSDI-X with AIB MEAF Density Data Showing Advantage of Future Testing or Surveillance Efforts in Determining the Future Aging of the 2004L Propellant-based Inflators.

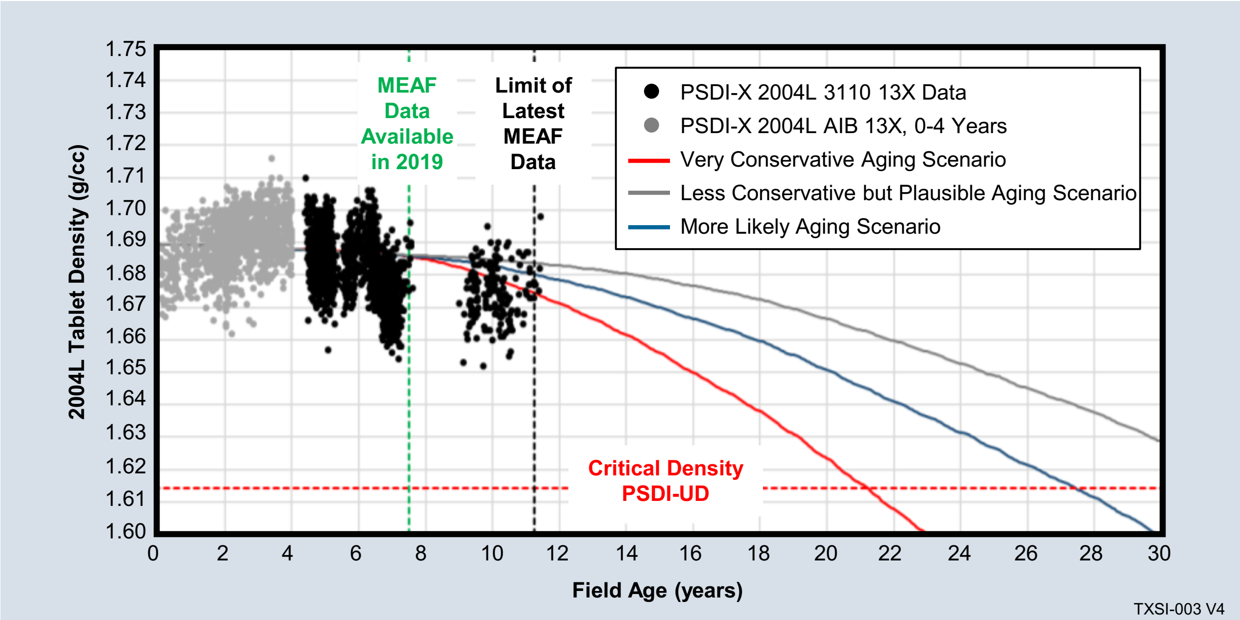

Figure 4. PSDI-X with 3110 MEAF Density Data Showing Advantage of Future Testing or Surveillance Efforts in Determining the Future Aging of the 2004L Propellant-based Inflators.

Investigation Scope

The scope documented in the 2019 report included three passenger and four driver inflator designs. The 2019 report stated, "*With the newer PSAN propellants, designated 2004L, the fidelity of the models will benefit from further data to anchor*."

In February 2020, the ITC contracted NGSC to conduct a field monitoring program of PSPI-X VQ, PSDI-X SU, and PSDI-X UD inflator designs as shown in Figure 5. These ten inflator designs (including the seven from the original study) cover six combinations of propellant, booster and desiccant as shown in Table 1.

The 2021 field monitoring test program was designed to be sufficient in size to generate data with confidence that it is representative. It was focused on the highest risk categories (low 13X to 2004L ratio, Zone 1 climate, in vehicles with the highest cabin temperatures and longest available field exposure). The focus on the highest risk areas provides an extra degree of conservatism by not diluting the testing with inflators that would be expected to not show any signs of aging due to milder environments or vehicle influence.

The distribution of zone of origin for all inflators in Figure 2 through Figure 4 is shown in Table 2 and illustrates the focus of the data on Zone 1. The percentage of Zone 1 origin for this collection study was higher than these values.

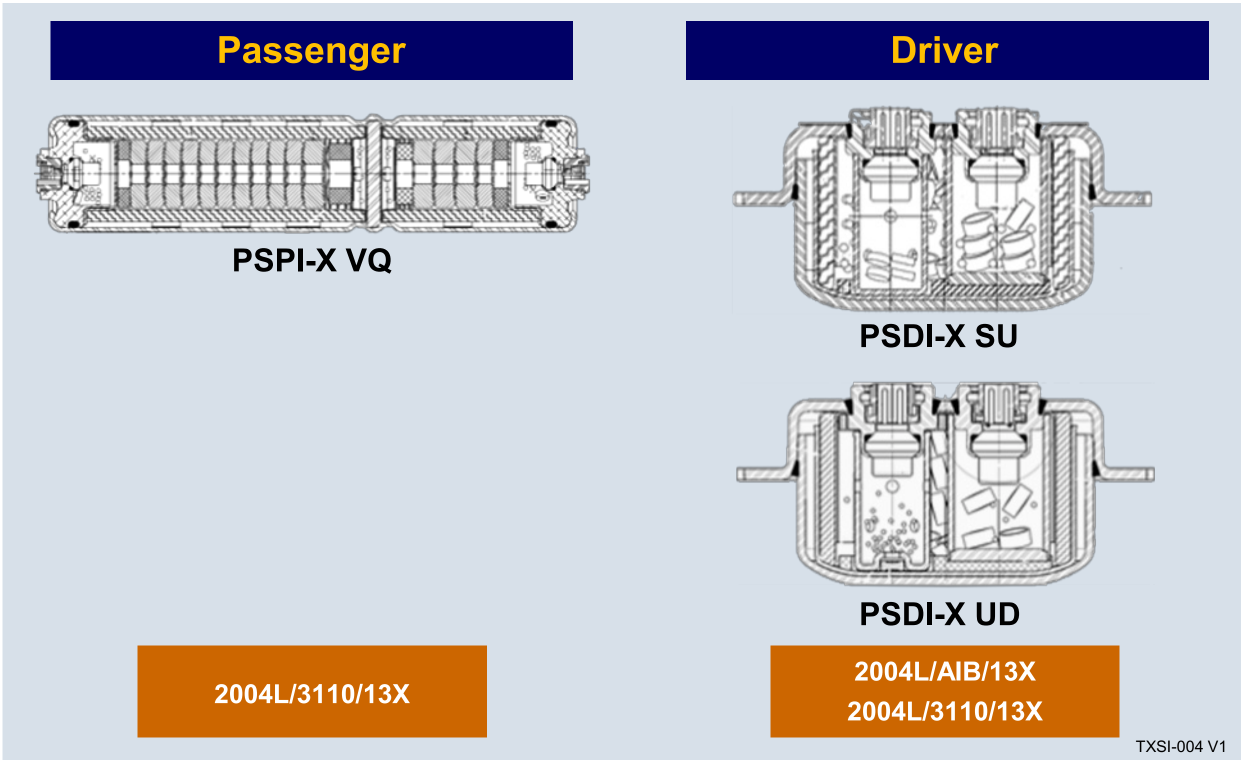

Figure 5. Field Monitoring Inflators Investigated.

Table 1. Propellant Systems Reported in 2019 Report and Field Monitoring Program in 2021

Study	Inflator	Type / Propellant Form	PSAN Formulation	Booster Formulation	Desiccant
2019 Series Inflators	PSPI-L FD	Passenger / Wafer	2004	3110	None
	PSPI-LD DU	Passenger / Wafer	2004	AIB	13X
	PSPI-X TX	Passenger / Wafer	2004L	AIB	13X
	PSDI-5 ZA	Driver / Tablet	2004	3110	None
	PSDI-5D YT	Driver / Tablet	2004	3110	CaS04
	PSDI-5D GE	Driver / Tablet	2004	3110	13X
	PSDI-X SV	Driver / Tablet	2004L	AIB	13X
2021 Series Inflators	PSDI-X SU	Driver / Tablet	2004L	AIB	13X
	PSDI-X UD	Driver / Tablet	2004L	3110	13X
	PSPI-X VQ	Passenger / Wafer	2004L	3110	13X

Table 2. Environmental Zone for Inflators Collected in this Study

Zone	Figure 1 (Like PSPI-X VQ)	Figure 2 (Like PSDI-X SU)	Figure 3 (Like PSDI-X UD)
Zone 4	4%	7%	8%
Zone 3	8%	14%	18%
Zone 2	4%	27%	17%
Zone 1	84%	52%	57%

The program consisted of the automaker collecting 300 of each inflator design, obtaining CT data on every one, then NGSC would dissect a subset of each inflator spanning the range of 2004L density observed with focus on the lowest densities observed in the CT scans and evaluate key properties of the inflators' components and propellants. TK Global would dissect and test the remaining inflators as shown in Figure 6.

This modest-sized surveillance program was not intended to provide the data needed to empirically determine the probability of inflator rupture from testing and statistical analysis alone. Since the predictive aging model is largely deterministic, this surveillance program was intended to provide data for enhanced anchoring of the model and its subroutines, thus increasing the fidelity of the model projections. The data obtained from this surveillance program also originated from inflators that are several years older than what was available in 2019. These data answers some of the questions related to how the X-series inflators age in the most extreme environments.

The testing performed on the collected inflators provided updates to key parameters versus time such as 2004L density, inflator moisture and propellant burn rate versus pressure. These test data were specifically selected based on being, first, the data that showed consistent changes in the aging of the undesiccated 2004 propellant inflators that have exhibited failures in field events and in testing recalled inflators. Secondly, these are the data that would support an update of the NGSC predictive aging model and reduction of the uncertainty in the previous results. These data are able to identify possible aging trends that are known to be leading indicators of inflator health.

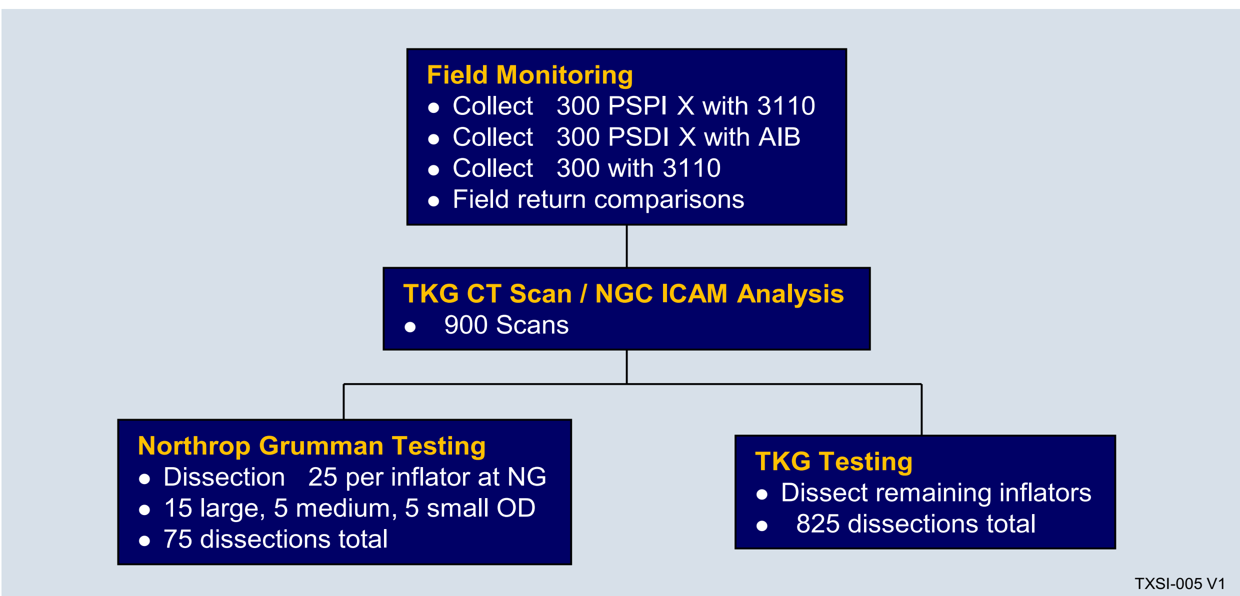

Figure 6. Field Monitoring Program Flow.

Technical Approach

The Takata airbag inflator investigation documented in NGSC's 2019 report described the three-part approach to aging and surveillance that has been used in the rocket motor industry for decades. This approach is diagrammed in Figure 7.

Part I of this approach is related to the identification and ranking of failure modes. The Phase I investigation into the root cause of the failures of inflators subject to National Highway Traffic Safety Administration (NHTSA) recalls 15E-040 to 15E-043 as submitted by Takata falls into this part. Phase I efforts included: 1) inflator design reviews, 2) identifying and verifying existing critical data, and 3) determining what was needed in Phase II.

Part II of the NGSC approach to aging and surveillance dealt with identifying and developing the best analysis tools, determining appropriate tests and test specimens, acquiring aging data, quantifying aging mechanisms and verifying and validating prediction tools. The scope of the Phase II effort was expanded to include desiccated 2004 and desiccated 2004L propellant-based inflator designs not subject to the original recalls noted above[1] to provide prognostic data and inform key decisions regarding these inflators. Phase II of the investigation belongs in Part II of the process shown in Figure 7. The predictive aging program in Phase II was comprehensive, covering the complete sequence of aging changes.

Phase II investigated three passenger and four driver inflator designs. At the time these inflator designs were selected, they were directly representative of the design of roughly 60% of the inflators in the field and were closely related to over 90% of all Takata manufactured inflators. From each of these inflator design families, NGSC selected a single specific model (or prefix) for detailed evaluation.

As discussed in the 2019 report, NGSC utilized many standard "rocket motor analysis tools," but the unique characteristics of Takata inflators demanded the development of a new predictive aging model. The output of the predictive aging model is the probability that an inflator will fail structurally (ED) if deployed. It is the output of this aging model that comprises Part III of the NGSC approach to the POF / service life prediction. The recommendation from the 2019 report for added anchoring is consistent with the bottom of Figure 7 recommending field surveillance.

A detailed description of the predictive aging model was included in the 2019 report and is not included here. In summary, the predictive aging model begins with the environment from a given geographic location and finishes with a prediction of the probability that an inflator will ED if deployed. The model was developed using the foundation provided by the NGSC investigations performed in Phases I and II, including inflator design, propellant behavior in the presence of moisture and temperature cycling and ballistic performance of the inflator. The model employs a modular architecture so each module could be tested, parameterized and calibrated with test data.

[1] Some desiccated PSDI-5D (2004 propellant) inflator designs subsequently became the subject of later recalls.

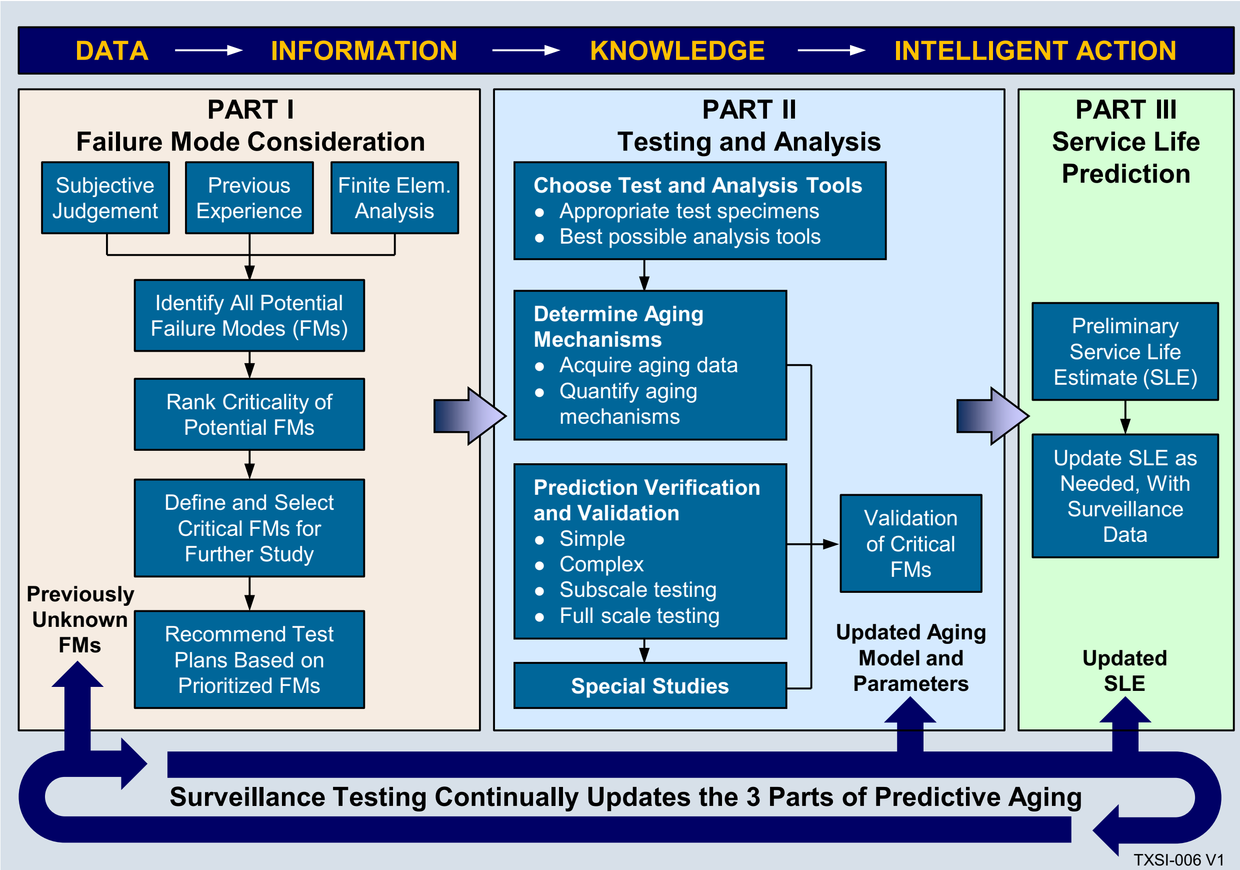

Figure 7. Three-part Approach to Aging and Surveillance Used in the Rocket Motor Industry.

Field Return Testing Results

The testing performed on the collected inflators in the 2021 study provided updates to key parameters that, in the 2019 study, had shown consistent changes in the aging of the undesiccated 2004 propellant inflators that have exhibited failures in field events and in testing of recalled inflators.

The first is 2004L density, which was plotted in Figure 2, Figure 3, and Figure 4. The second is propellant burn rate versus pressure, which is shown in Figure 8, Figure 9, and Figure 10. These data are able to identify possible aging trends that are expected to be leading indicators of inflator health. Both the density and burn rate show the inflators are healthy with no significant signs of aging.

The burn rate versus pressure data depicted by the dotted blue and red lines shown in Figure 8 through Figure 10 are from specially fabricated low-density tablets and wafers produced by TK Global built to determine the potential impact of lower density wafers on burn rate. The dotted line data is not from field aged production inflators with 2004L propellant where such low density has not been observed. It is shown here to illustrate the current unaltered, stable burn rate of field aged inflators compared to the nominal density (as manufactured) wafers or tablets and to contrast to what would be expected to be observed for burn rate if there had been significant density reduction (aging) in the field inflators. This is further evidence of the health of these inflators.

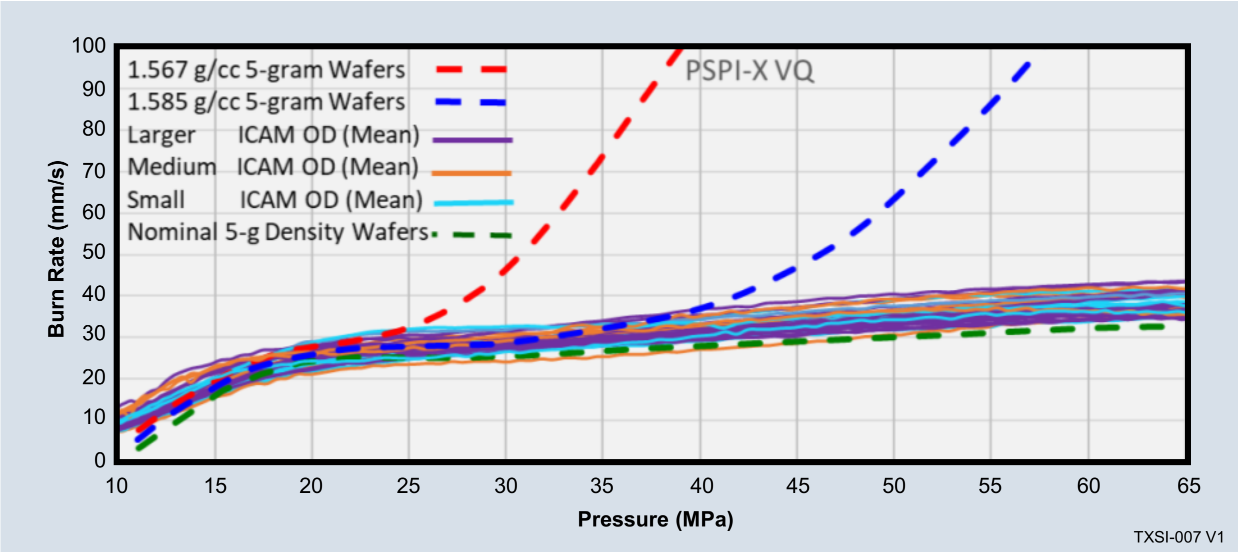

Figure 8. PSPI-X VQ 2004L Burn Rate vs. Pressure. No deviation from the baseline burn rate was observed in this or any of the inflators in this study**.**

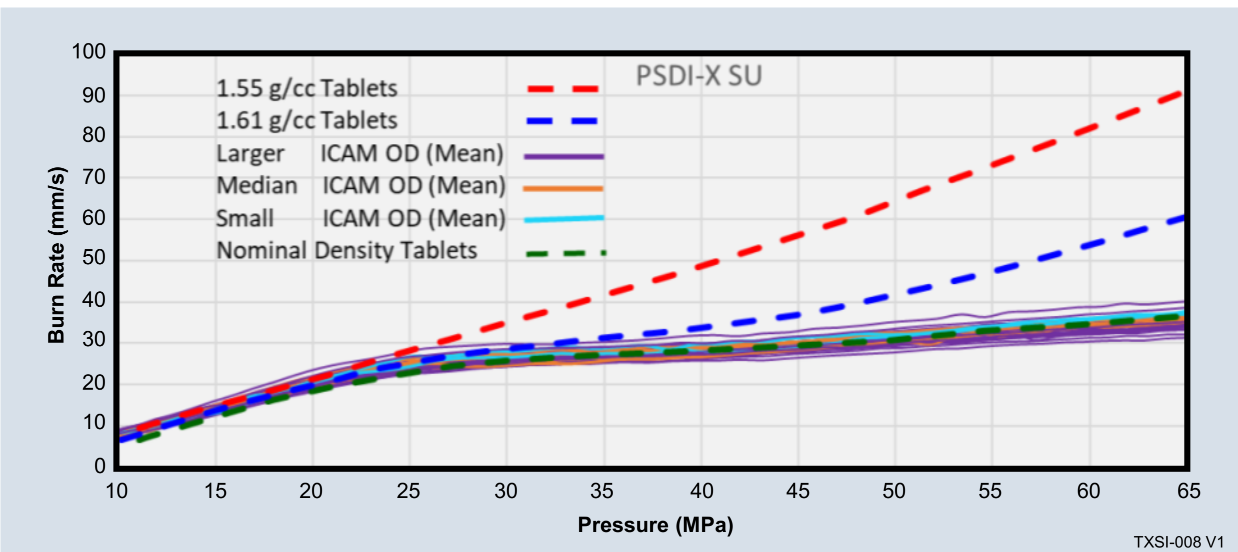

Figure 9. PSDI-X SU 2004L Burn Rate vs. Pressure. No deviation from the baseline burn rate was observed in this or any of the inflators in this study.

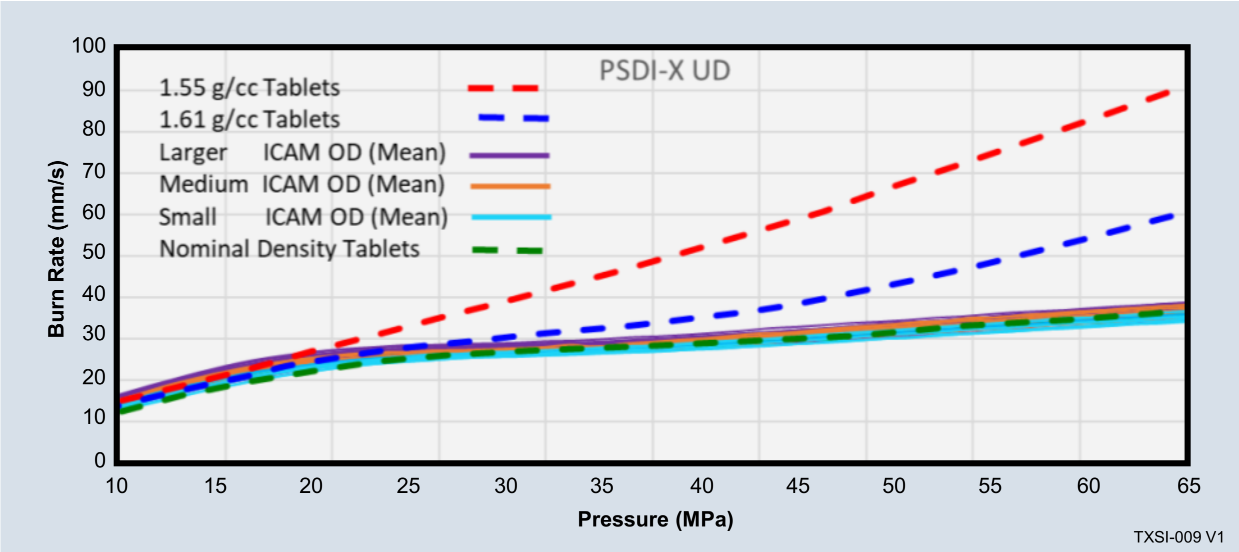

Figure 10. PSDI-X UD 2004L Burn Rate vs. Pressure. No deviation from the baseline burn rate was observed in this or any of the inflators in this study.

Similarly, moisture data was collected for each major composition in the inflators. These data are reported in Figure 11, Figure 12, and Figure 13. Figure 11 shows the data for the PSPI-X family of inflators with 2004L main propellant, 3110 booster propellant and 13X desiccant (which includes the PSPI-X VQ inflator of this study). Figure 12 shows the data for the PSDI-X family of inflators with that same mix of compositions (which includes the PSDI-X UD inflator of this study). Figure 13 shows the PSDI-X family of inflators with 2004L main propellant, AIB booster and 13X desiccant (which includes the PSDI-X SU inflator of this study).

The progression of moisture gain over time matches well with previous data and model predictions. The 13X desiccant collects the overwhelming majority of moisture until saturated. The time to complete 13X saturation for all three of these inflators is similar at near 8 to 9 years. Once the 13X is saturated, environmental moisture seeks other materials within the inflator, raising their moisture contents.

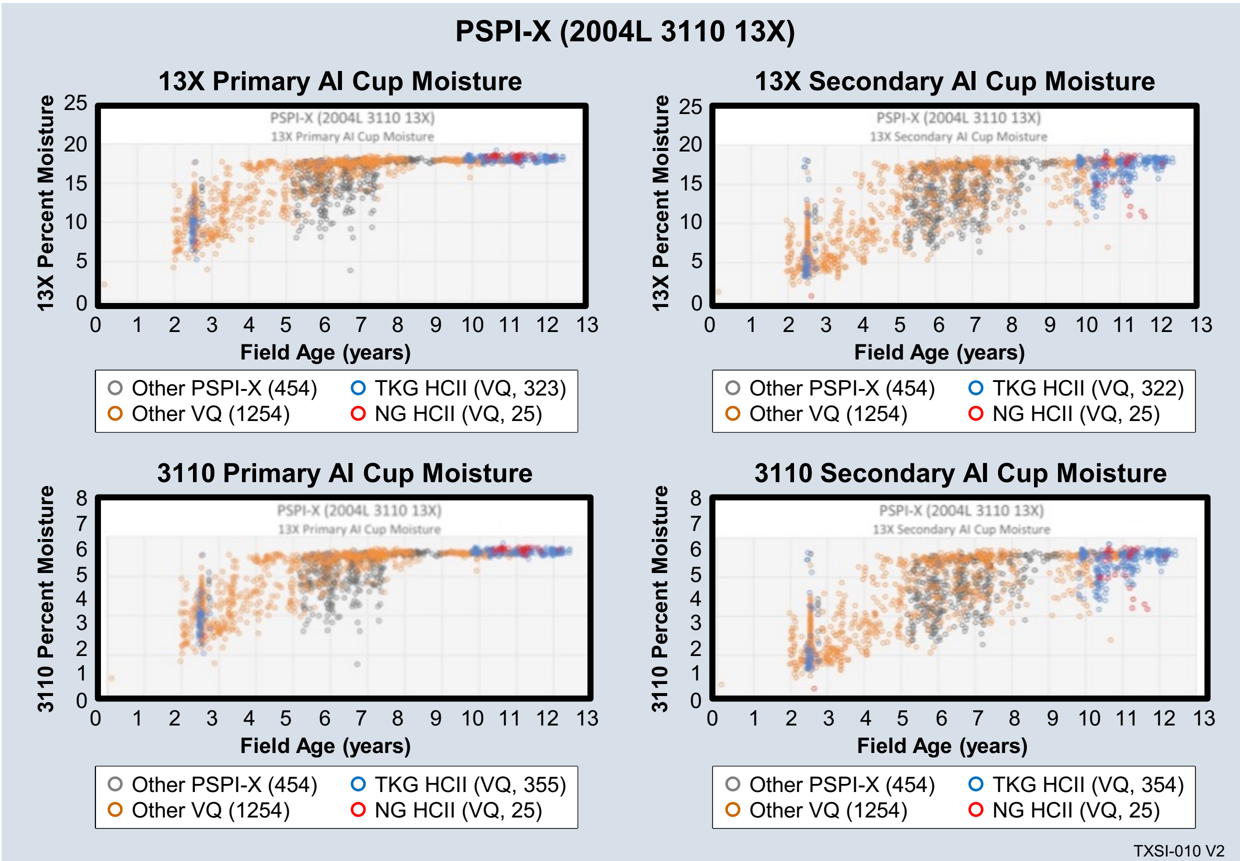

Figure 11. PSPI-X Inflator Family Moisture Data. The four charts here contain data from field returns including the PSPI-X VQ of this study. Patterns and values are as expected and consistent with model predictions.

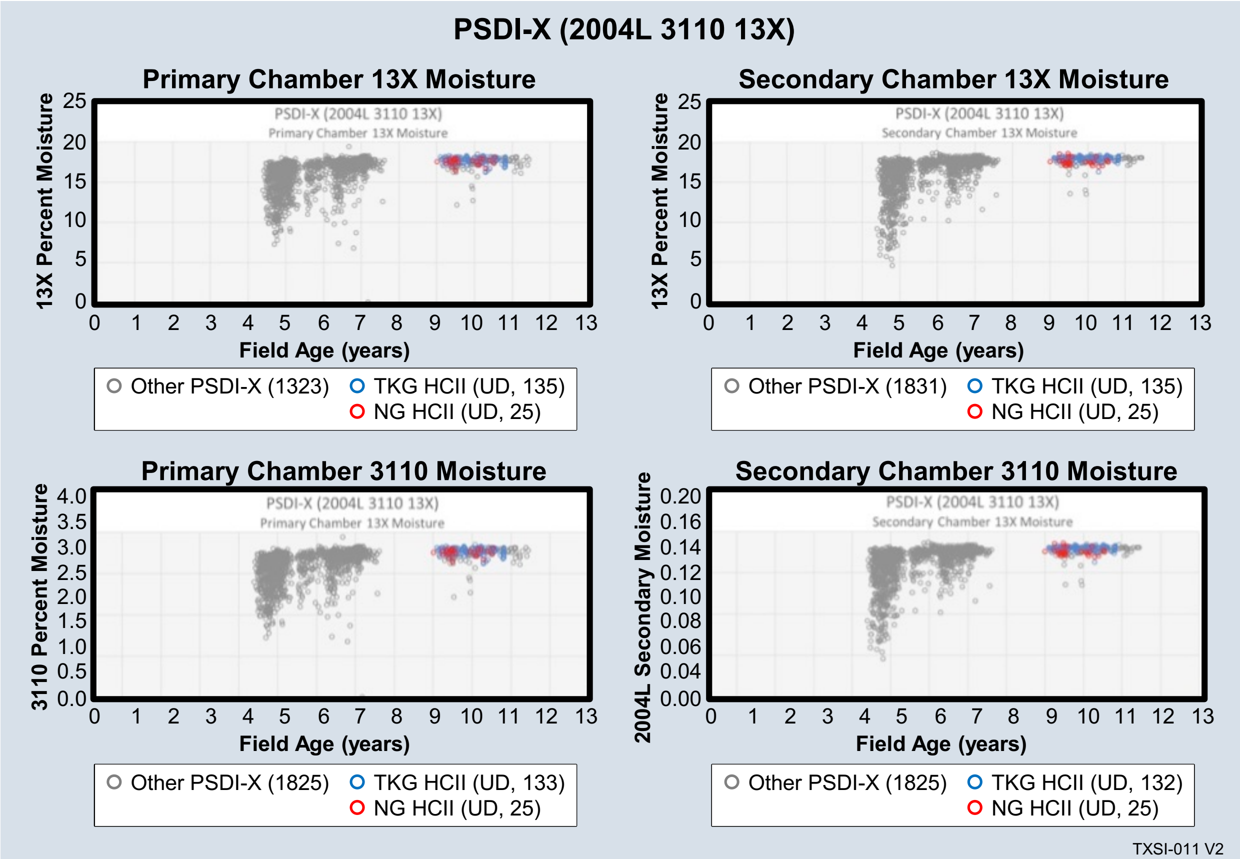

Figure 12. PSDI-X Inflator Family (3110 booster) Moisture Data. The four charts here contain data from field returns including the PSPI-X UD of this study. Patterns and values are as expected and consistent with model predictions.

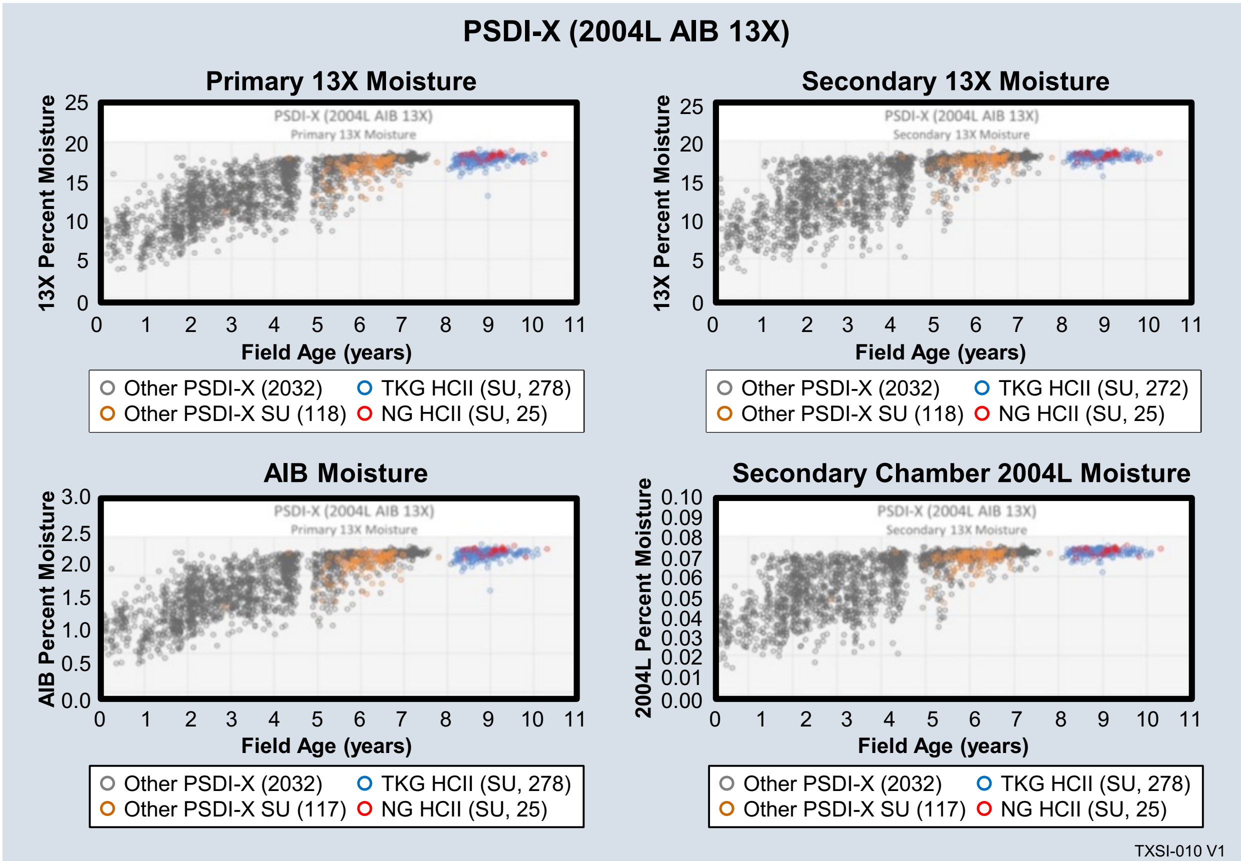

Figure 13. PSDI-X Inflator Family (AIB booster) Moisture Data. The four charts here contain data from field returns including the PSPI-X UD of this study. Patterns and values are as expected and consistent with model predictions.

The data for these desiccated 2004L propellant inflators differs, in expected and predictable fashion, from the data for undesiccated inflators. At a very high level, there is further reinforcement of these differences in the complete MEAF data, depicted graphically by propellant and desiccant. This is shown in Figure 1. That the desiccated systems are markedly different than the undesiccated 2004 system, in aggregate, is apparent. The most obvious difference is the significant number of the undesiccated 2004 propellant inflators with wafer or tablet density that had decreased significantly from the as-manufactured values.

This is indicative of the kind of aging that could result in high pressure events including failures if the density reduces sufficiently. This divergence of the first and fifth percentile from the fiftieth percentile (median) for the undesiccated inflator designs, stands in marked contrast to the tighter pattern of the three percentages in the desiccated systems to this age of the inflators.

This lack of divergence is firm evidence of the lack of significant aging in these families of inflators with 13X desiccant. More detailed examination of the MEAF data will probably reveal other significant differences based on platform, usage and design specifics as discussed in earlier reports.

Just as in the previous efforts, NGSC exercised the multi-disciplinary core team of senior investigators. The team included experts in propellant chemistry, combustion, ballistics, design, manufacturing, predictive aging, and failure analysis. Specialists in structures, heat transfer, computational fluid dynamics (CFD), and testing were utilized from across the company.

Summary Model Results and Conclusions

POF models were updated to include PSPI-X VQ, PSDI-X UD and PSDI-X SU inflators. The ballistic models were anchored to zero-time propellant ballistic performance and hydroburst data for the inflator enclosure. The predictive aging portion of the models was anchored to the MEAF and the latest field monitoring data.

Comparisons were made for each parameter where data were available. As an example, the total moisture versus model parameters is shown in Figure 14. In this example, the parameters on usage factor and moisture gain via enclosure leakage were compared against field data. The entire range of usage and leakage reasonably fits the data. The intermediate values (Leak Rate Calibration Factor [LRCF] 2 through 4, usage of 0.5 or 0.6) are the best fit to the data. These same parameters were carried forward in a limited trade study to determine impact on the POF.

The range of parameters were carried forward into a limited Sensitivity Study of the effect of these parameters on the POF outcomes. Figure 15 shows these data. Also shown is the difference in values of usage showing limited impact. When the more likely values for the moisture gain (LRCF of 3) are applied, values shown in Figure 2, Figure 3, and Figure 4 as “more likely” are obtained.

For the conclusions of this report, the more conservative, highest moisture gain rates are applied. This level of extra conservatism adds confidence that the inflators are healthy for several years into the future. A further conservatism is added in that the density reduction acceleration observed in the 2004 propellant is assumed here while lab experiments suggest that the density loss may be more linear, as illustrated by the dotted blue line in Figure 15.

An additional conservatism, consistent through all of the model studies, is that a short 5 ms delay is always applied between primary and secondary chamber firings when applicable. Longer delays are common in lower velocity collisions involving inflators that have a variable delay as a design feature and would result in lower pressures compared to the short delay and a longer time to reach the threshold of a 1 in 10,000 POF.

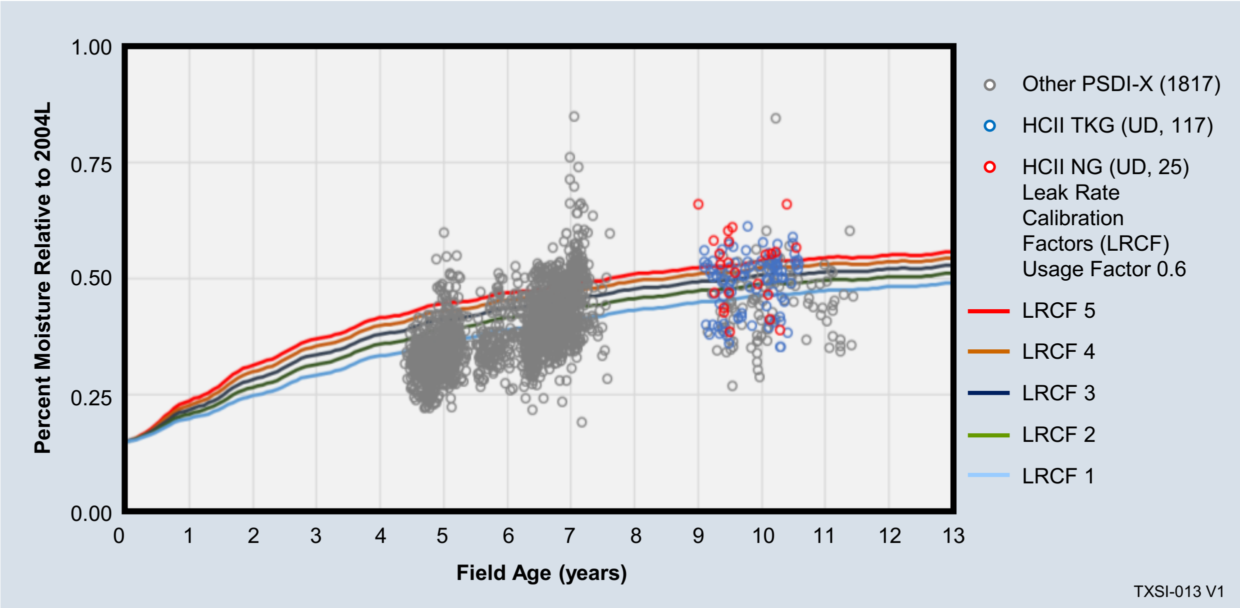

Figure 14. Model Predictions for Total Moisture in PSDI-X Inflators. The good correlation between field return data and predictive models is shown in this figure. A parametric study was done on usage factor (U factor above) and moisture intrusion via leakage (LRCF leak rate calibration factor above). All are a good fit to the data with the middle values more closely matching.

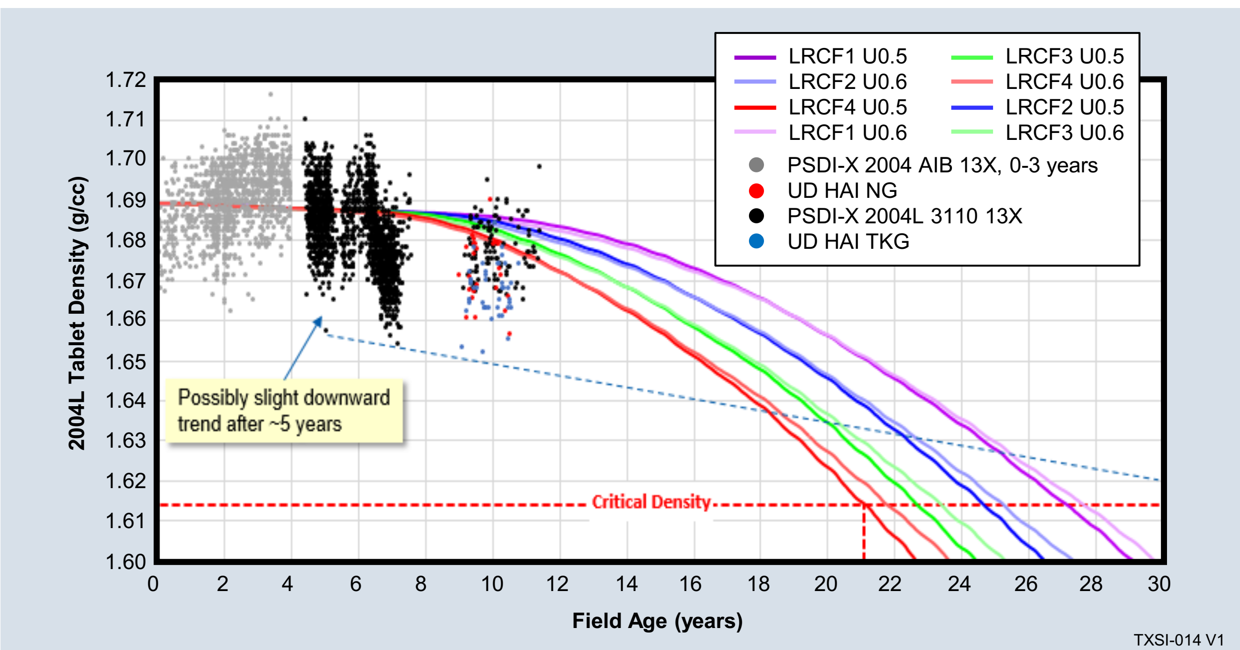

Figure 15. Sensitivity Study for POF for Usage Factor (U) and Moisture Intrusion Rate (LRCF). Also shown here is the curvature to more rapid density reduction assumed to match 2004 propellant. Conservative values were selected for the time to threshold POF reported in this document.

The models were fully exercised and POF results were generated (see results in Table 3). To determine the POF results, the predictive aging model was run to 30 years, simulating approximately 25 inflators (of each inflator type) in the worst-case vehicle platform (T3) experiencing the most severe usage, in an extreme Miami environment using model parameters for that inflator that yield the fastest aging of 2004L propellant.

The extensive work done previously on the PSPI-L inflators provided the information needed to target the most severe aging scenarios. For each of these 30-year simulations, 10 years of hourly Miami, FL weather data were repeated three times. The moisture movement was calculated at ~1 second time intervals, and the POF was calculated every four weeks using a Monte Carlo algorithm with 32,000 iterations. The POF results, for each inflator type, represent the results of over 300,000,000 Monte Carlo iterations.

There are four conclusions that can be drawn from this program and the modeling results.

1. The three evaluated X-series inflators are healthy at the time of this evaluation.
2. The model was updated for these three inflators yielding 19 to 21 years from production as the predicted time to 1% POF for the 1% T3 vehicle in the Miami environment under the most conservative assumptions.
3. Modeling and field data indicate field measures are currently not needed regarding desiccated 2004L inflators.
4. Further improvement in the fidelity of the predictive model can be achieved by a future, well designed field collection testing program for X-series inflators when enough time has passed for clear long term trends to emerge, but well before the time is reached that the most conservative application of the model predicts for a 1 in 10,000 probability of failure when initiated.

Table 3. Model Output as Years Until a Predicted Probability of 1 in 10,000 Chance of a Failure for an Inflator when Deployed after Aging in a T3 vehicle in the Zone 1 (Miami) environment

Inflator Type	Main ID	Booster ID	Desiccant ID	Desiccant as % of Main in Primary	Platform Temp Band	Time to 1 in 10,000 POF (years)*	
PSPI-X	2004L	3110	13X	1.1	T3	19 to >30	VQ
PSDI-X	2004L	3110	13X	1.4	T3	21 to >30	UD
PSDI-X	2004L	AIB	13X	1.3	T3	21 to >30	SU

**The time to 1/10,000 POF that is stated here assumes that the inflator is in a T3 vehicle in a Miami-like environment. That same inflator in a T2 or T3 vehicle, or in a Zone > 1 environment (or that inflator in all vehicle types and locations throughout the U.S.) will have a POF much, much less than 1/10,000 at that same time.*

Field Monitoring to Validate / Increase Model Fidelity

Further improvement in the fidelity of the model through additional monitoring is consistent with NGSC's standard approach shown in Figure 7. Future collections should again be focused on the desiccated 2004L propellant designs with a low ratio of 13X to 2004L (<1.5%), from the highest risk categories of climate and vehicle temperature, with the longest field exposure to improve the fidelity and accuracy of the model. The timing for this next field collection is suggested by examining Figure 2 through Figure 4.

Two factors are relevant. First, considering the most conservative predictions (red lines), a study would not be of value if not enough time had passed between the studies such that the predicted density was still close to the existing test data presented in this report. Second, the study needs to be completed before the time that the most conservative application of the model predicts a 1 in 10,000 chance of an ED if the inflator is deployed such that there would be sufficient time available to take action, if warranted. This logic suggests a time interval near the midpoint between this study and the most conservative predicted density crossing the critical density threshold (reported in Table 3).

With more time passed, consideration should also be made for the timing of a field monitoring study of the inflator designs with 2004 propellant desiccated by 13X, which today are too young to have shown the potential for any indication of potential first indications of aging.

Possible X-series Field Monitoring Program (ongoing)

- PSPI-X and PSDI-X with 2004L/AIB and/or 3110/13X
- Target inflators with low ratio of 13X to 2004L propellant (<1.5%)
- Focus on Zone 1, temperature band 3 vehicles
- Repeat testing if needed to validate trend and impact to model prediction