Takata Inflator Rupture Root Cause Summary Report

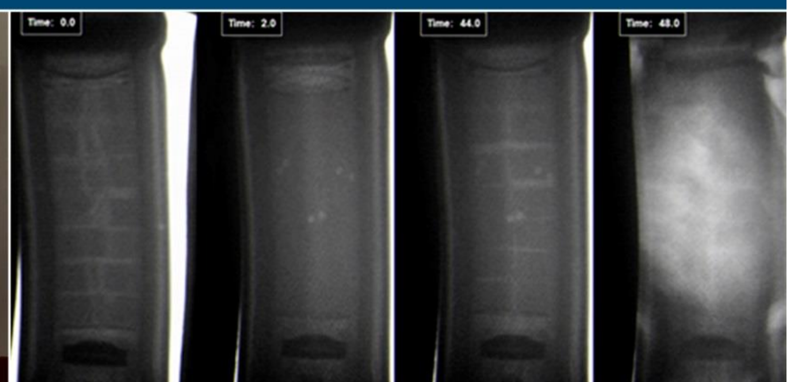
Submitted by:

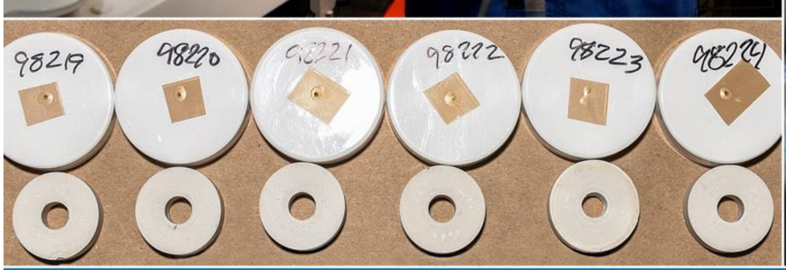
Orbital ATK for the Independent Testing Coalition

Submitted to:

National Highway Traffic Safety Administration

September 2016





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GLOSSARY OF KEY TERMS AND ACRONYMS

Burning Rate ....a measure of the rate at which propellant is combusts

Burning Rate Slope ....a measure of the change in burn rate as a function of pressure

Deliquescent...............the term for a chemical that can absorb enough water from the air to become a liquid solution

Desiccant....................the term for a chemical that can function as a drying agent

°C ....degrees Celsius

ED ....energetic disassembly

Fault Tree ....a structured, deductive approach to failure analysis

Fishbone ....a structured approach to determining cause and effect, also called Ishikawa Diagrams

g..................................gram

Gas pycnometer ....a lab instrument that uses gas displacement to measure density

HAH...........................high absolute humidity

Haystack.....................a description of the general shape in a pressure-time trace with a gentle, rounded curve typical of a regressive burn

ITC ....Independent Testing Coalition

Mdot...........................mass (gas) generation rate

MEAF ....Master Engineering Analysis File

Mm.............................millimeter

NHTSA ....National Highway Traffic Safety Administration

OD..............................outer diameter

OEM...........................original equipment manufacturer

Progressive burning surface area ....a geometry where the surface area available to burn increases over time

Regressive burning surface area ....a geometry where the surface area available to burn decreases over time

PSAN ....phase-stabilized ammonium nitrate

PSPI-L........................Takata nomenclature for a type of air bag inflator

RTR............................real time radiography, effectively an x-ray movie that allows visualization of real time events using x-rays

Executive Summary

Orbital ATK has conducted an independent investigation on behalf of the Independent Testing Coalition (ITC) and found that certain inflators made by Takata are adversely affected by three factors - all of which contribute, and are required to be present, in order to cause rupture when initiated.

These factors are:

- The presence of pressed phase-stabilized ammonium nitrate (PSAN) propellant without moisture-absorbing desiccant
- Long-term exposure to repeated high-temperature cycling in the presence of moisture, and
- An inflator assembly that does not adequately prevent moisture intrusion under conditions of high humidity

This investigation applies solely to inflators subject to National Highway Traffic Safety Administration (NHTSA) recalls 15E-040 to 15E-043. These recalls account for approximately 23 million inflators installed in vehicles in the U.S. from ten auto manufacturers.

The thirteen-month investigation involved more than 20,000 hours of testing and analysis by experienced scientists, engineers and technicians. The methodology followed a disciplined approach to investigate every potential factor, contributor or cause. It began with a detailed fishbone analysis and included detailed documentation on the adjudication of over fifty unique fault tree blocks.

It was deemed critical to thoroughly understand root cause prior to commencing aging and surveillance studies. To begin such a study without an understanding of the critical factors, and their approximate contribution to the failure, runs the risk of a result that may empirically match a limited data set or reproduce a few field results but be inaccurate for the broader application to the universe of relevant inflators and conditions. A carefully designed accelerated aging test program, based on understanding of the root cause and contributing factors, is the focus of the next phase of the Orbital ATK investigation.

Investigation Scope

The investigation focused on determining the root cause of inflator failures covered by Takata recalls 15E-040 to 15E-043. These studies were directed towards identifying long-term changes that could give a higher probability of failure based on the design of the inflators, rather than manufacturing problems. This does not mean that manufacturing problems do not play a role in failures, but these were not the emphasis of our investigation. Rather, our emphasis was on determining changes due to environmental aging, including changes influenced by inflator design differences and routine manufacturing variation. Ongoing work will examine newer inflators that contain PSAN produced by Takata, including those not under recall by NHTSA which contain desiccant.

Technical Approach Overview

Based on the complexity of this problem, we felt that a disciplined, patient and well-designed approach that would provide archival documentation of each conclusion was required. A fishbone analysis was completed to ensure complete coverage of all possible factors. The items from the fishbone then were used to generate the top-level fault tree and serve as a check for completeness (Figure 1). Next, the overall fault tree architecture was developed. In all, over 50 unique fault tree elements that went as deep as six levels on some branches were investigated and adjudicated through a formal process. Each block was assigned to one of five categories:

A. Cause – Sufficient
B. Contributor – Necessary
C. Contributor – Modifier
D. May Be a Contributor
E. Not a Contributor

No items were left simply as open at the end of the root cause analysis. One fault tree block on the driver inflator fault tree was designated as “may be a contributor” due to insufficient test data on the driver inflator failures. All other blocks were closed with detailed documentation in one of the other four categories. The fault tree was used to define technical scope of detailed investigations and reduced the amount of nonproductive or duplicative experimentation and investigation. A summary of the five top-level fault tree branches along with supporting and refuting evidence is given in Table 1.

The technical scope of the effort was designed to use three complementary technical approaches to serve as checks on each other, increasing the probability of an accurate result. This three-legged stool of statistical analysis, engineering analysis and laboratory experiments involved over 2,000 different materials, inflator parts and inflators (see summary in Figure 1).

Table 1. Summary of the Five Major Fault Tree Branches Developed and Investigated on This Study.

This disciplined approach includes documenting key supporting and refuting data for each fault tree block. This report provides interim and summary data. This table provides a brief overview of the key arguments for and against each fault tree block being a cause or contributor to the rupture event. Compare to final fault tree in Figure 19 at the end of this report.

	Case Structural Subsystem	Ballistic Subsystem	Seal Subsystem	External Environment	Vehicle Model
Description	Ruptures occur below design pressure	Higher gas flow results in higher pressure	Seal system allows moisture to find its way to the main propellant where grain growth occurs	High ambient humidity and temperature cycling from moderate to high temperature	Differences in vehicles change the environmental conditions experienced by the inflator
Key Supporting Evidence	Pressure data from Takata reports some ruptures below max operating pressure for both primary and secondary	Normal pressure traces show a rounded, “haystack” profile. We know of no ruptures with a haystack profile, even if the haystack profile exceeds maximum expected operating pressure. All rupture profiles show a steep pressure increase prior to rupture, indicating a change in ballistics. Testing in heavyweight hardware has validated higher pressures.	Passenger and driver inflators have multiple leak paths. Takata data shows inflators take on moisture over time. Original equipment manufacturer (OEM) testing showed every possible leak path did leak for aged inflators. Tolerance stack up for older passenger closure seal allows for below design O-ring compression.	Overwhelming percentages of failures both in field ED events and in field returns are from areas of high absolute humidity and high temperature. Mechanisms for wafer growth, which also correlates with ED events, require moisture and temperature cycling such as in High Absolute Humidity (HAH) areas.	Examples of the same prefix inflator show significantly different ED rates from field returns. PSPI AB shows a higher rate in one vehicle model, lower rates in three others, and a zero rate in two more models. Different vehicles reach different maximum temperatures under same test conditions.
Key Refuting Evidence	Detailed structural analysis of inflators and materials of construction showed full capability. Examination of test equipment shows possibility for low measurement. Every failure shows a distinctive "runaway" pressure trace regardless of reported pressure.	Not aware of refuting evidence. Have not reviewed every single ED pressure trace measured.	Inflators pass helium leak check. Simple ingress of moisture and moisture level necessary to cause ED are not clearly known.	There are a few specific examples of ED events that were not from vehicles in the HAH areas. Environment is within what would be predicted for these areas and system should have met expected conditions.	Failures cluster in prefixes whether there are multiple platforms or not. Even in exception examples, wafer OD correlates with ED rate suggesting another mechanism. PSPL-L FD for a sedan model shows a significant variability in ED rate by month of manufacture while still correlating with higher crimp and wafer OD.
Conclusion	**Not a contributor**	**Necessary Contributor**	**Necessary Contributor**	**Necessary Contributor**	**Contributor - Modifier**

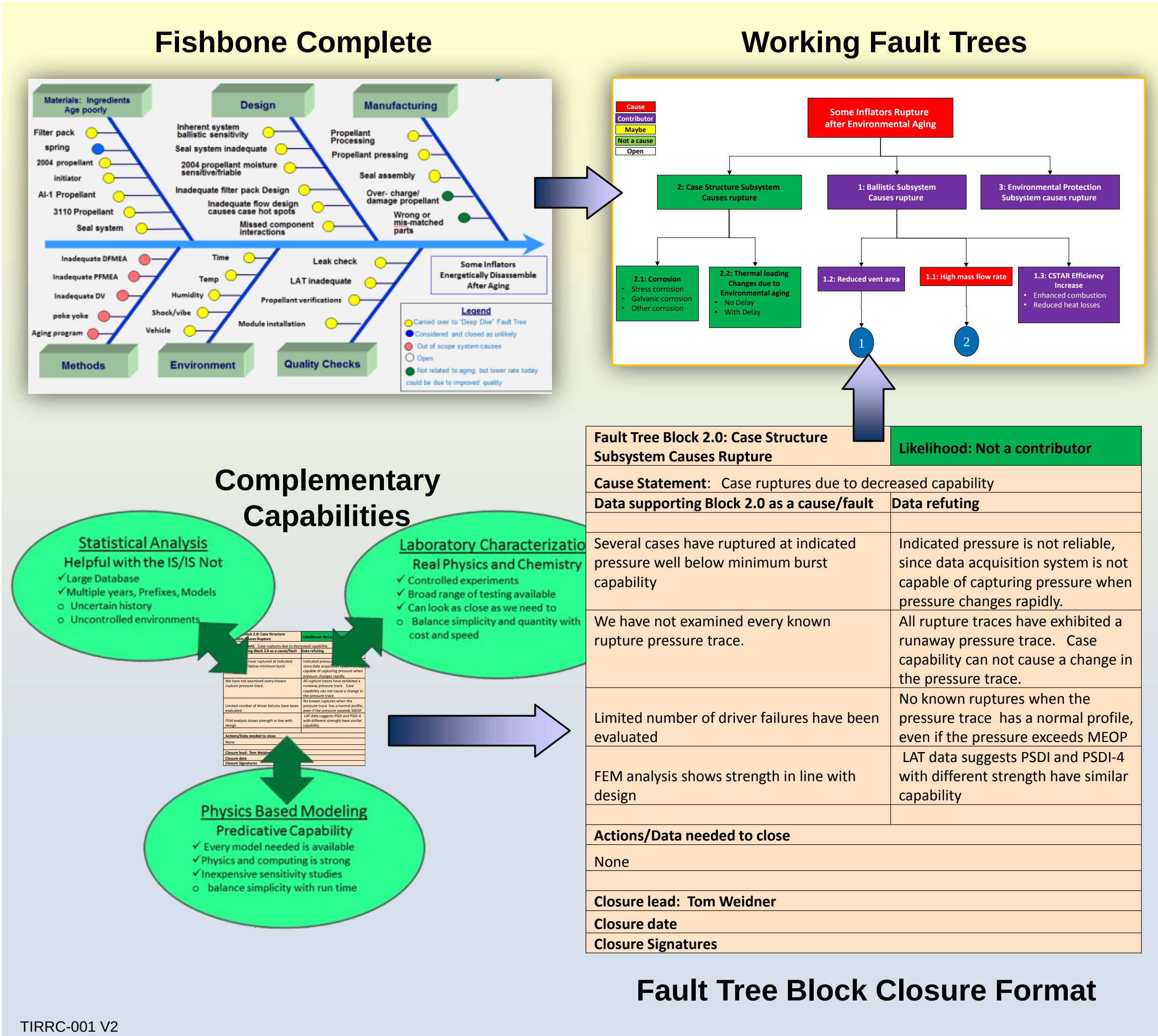

Figure 1. Overarching Project Process.

The disciplined process for root cause started with an industry-standard fishbone which was used to populate an extensive fault tree. A multi-disciplinary approach serves as checks on each other to reduce probability of errors. Full documentation of the fault tree including a formal closure process will provide a complete record for future reference.

Statistical Analysis

Statistical analysis primarily focused on the Master Engineering Analysis File (MEAF) which is the definitive set of Takata test information related to the investigation. We also reviewed databases of field failures and further information gathered by several automakers. We searched extensively for any significant correlations in the databases using standard statistical tools and techniques. As expected, the statistical conclusion reached by others regarding geographical distribution was confirmed. At a higher granularity, some of the geographical differentiations are striking, including failure rate differences between generally similar environments such as north and south Florida (Figure 2). Other items of significant interest included correlations with probability of failure based on wafer diameter and outer crimp diameter (Figure 3). Statistical analysis also shows failure rate differences across multiple vehicle platforms for the same inflator design (Table 2). The clear age-related factor should not be understated. As others have noted, none of the issues in the recalled inflator families arise immediately or in the short term[1]

Many of the correlations were found to have considerable scatter, indicating that multiple variables may affect failure probability, such as manufacturing variability, differences in the specific conditions that individual inflators experience (even between two inflators in the same vehicle platform and the same geographic area) and differences in the designs of various Takata inflators, as examples. A significant focus going forward will be to understand multiple variable

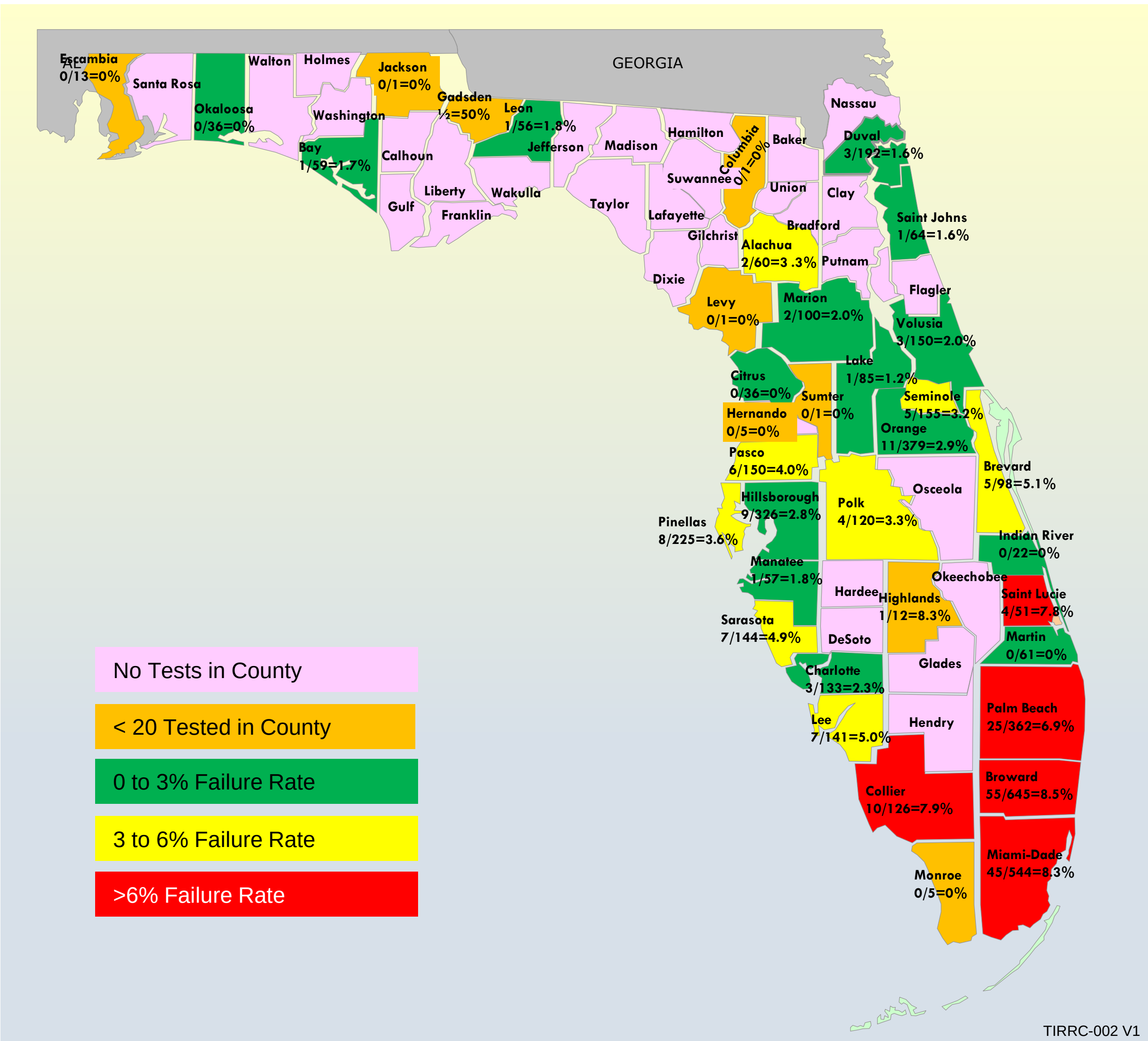

Figure 2. Failure Rates in PSPI-L for a Single Vehicle Model in Florida.

The significant difference of failure rates even within Florida is striking.

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1 *An excellent summary is available at http://www.safercar.gov/rs/takata/takata-events.html under the 22 October 2015 heading*

interactions. The statistical analysis was vital to 1) frame the problem, 2) define areas to explore in a controlled laboratory or modeling environment, and 3) provide anchoring points for investigation results. The interaction of external environment (weather and geography) with the internal vehicle environment (platform and what the actual inflator experiences) is an area where further investigation will be done in the next phase of the effort to develop aging models for non-recalled inflators.

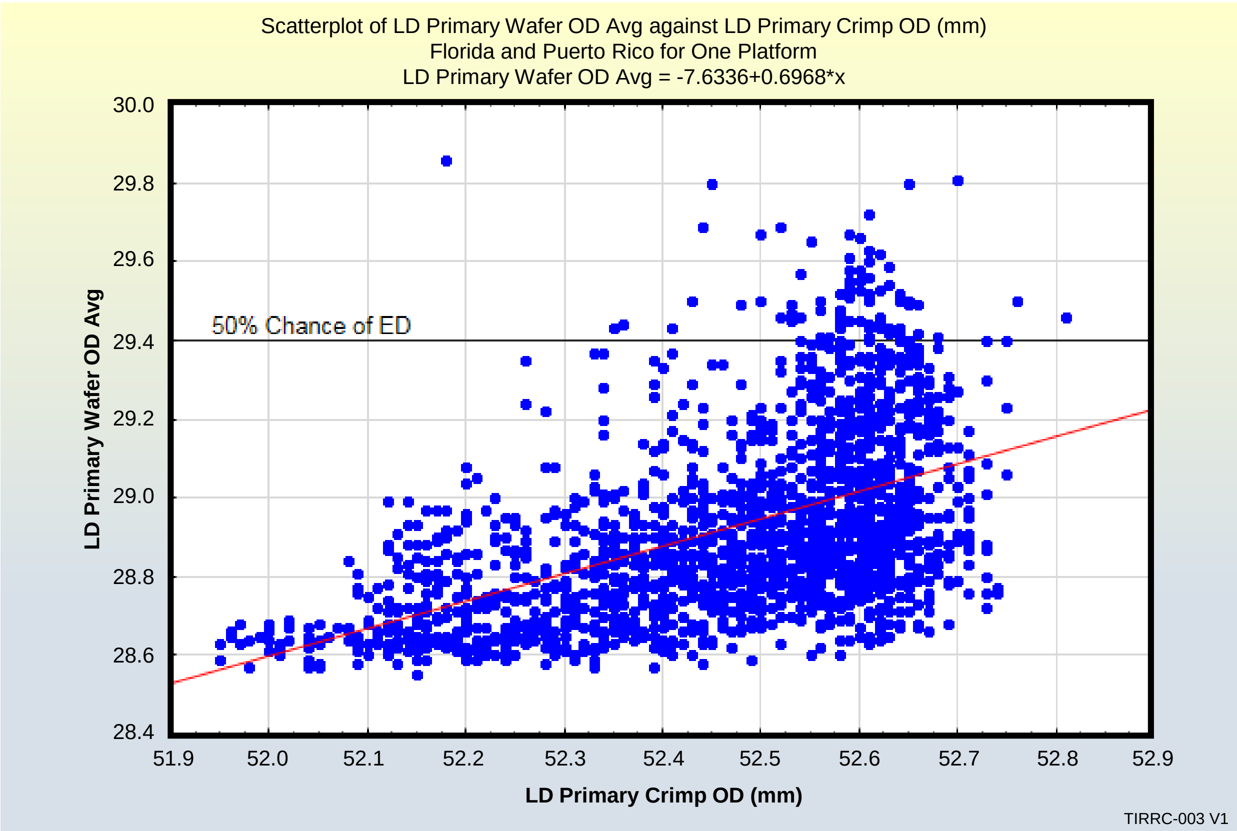


Figure 3. Wafer Outer Diameter, Crimp (case) Outer Diameter and Failure Probability for PSPI-L for a Single Vehicle Model.

The amount of data scatter seen here is typical of many of the statistical relationships but shows a trend.

Table 2. Field Return Failure Rates in PSPI-L.

Data replicated show the range of failure rates for similar or the same inflator design in different vehicles (platforms). These data are an argument for vehicle model as a contributor. It also highlights the challenge as there are convoluting and complicating factors including age of inflators.

Prefix	Platform	Number Tested That Failed	Total Tested	Failure Percentage
FD	A	188	6452	2.91%
	B	12	1698	0.71%
	C	0	9264	0.00%
	D	0	1787	0.00%
	TBD/Other	0	159	0.00%
JD	A	151	13862	1.09%
	E	2	398	0.50%
	B	10	3303	0.30%
	D	2	1611	0.12%
	F	1	1889	0.05%
	TBD	2	4125	0.05%
	G	14	30190	0.05%
	H	0	3230	0.00%
	I	0	244	0.00%
	J	0	116	0.00%
	Other	0	187	0.00%
WQ	TBD/Other	0	87	0.00%

Modeling and Simulation

Physics-based modeling and simulation is one of the three main legs of the investigation; complementing the statistical analysis and laboratory testing (Figure 1). The Takata family of inflators is complex in design, manufacture and operation. Orbital ATK employed a broad range of design and analysis capabilities to help understand normal operation and causes for abnormal operation. Our modeling and simulation efforts employed the best available ballistic, metal structures, propellant structures, seals and computational fluid dynamics/heat transfer codes and analyses to help understand these inflators.

In order to find design similarities and differences that could correlate with failure rate differences, Orbital ATK developed a family tree based on type and prefix and a part-by-part inflator comparison. Because of the large number of family members, we also looked for designs that are functionally similar and different (Figure 4).

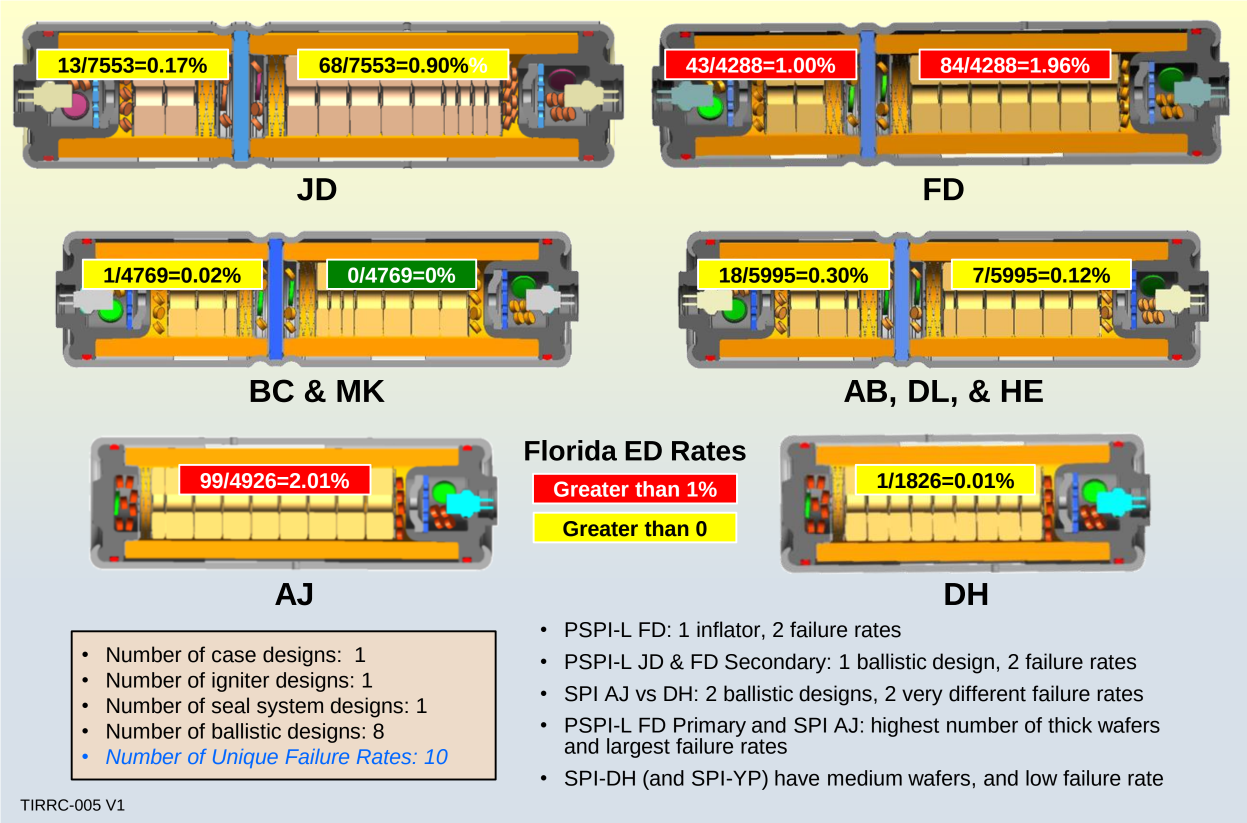


Figure 4. Summary of Similarities and Differences for Passenger Inflators.

These summaries guide where more detailed engineering analysis and testing will be most likely to identify root causes and contributors. The rupture rate on field return tests is shown for each inflator chamber superimposed on that chamber.

Analysis of the passenger branch showed a common case design, seal system design and igniter design with eight unique ballistic designs. Since the main hardware designs are the same but ballistic designs are different, this suggests a focus on ballistic differences will help to understand differences in energetic disassembly (ED), or rupture rate. This analysis shows that designs that superficially appear similar can be quite different in the ED rate. Detailed analysis is yielding insights on these differences. Each of these points is a clue in understanding the root cause.

Detailed design analysis and comparison was also done for the driver branch of inflators. This allowed us to examine the driver and passenger designs for similarities and differences (Figure 5) that could account for the order of magnitude higher passenger-branch failure rate. Key differences include: 2004 propellant geometry, igniter closure seal design, igniter design and screen pack design.

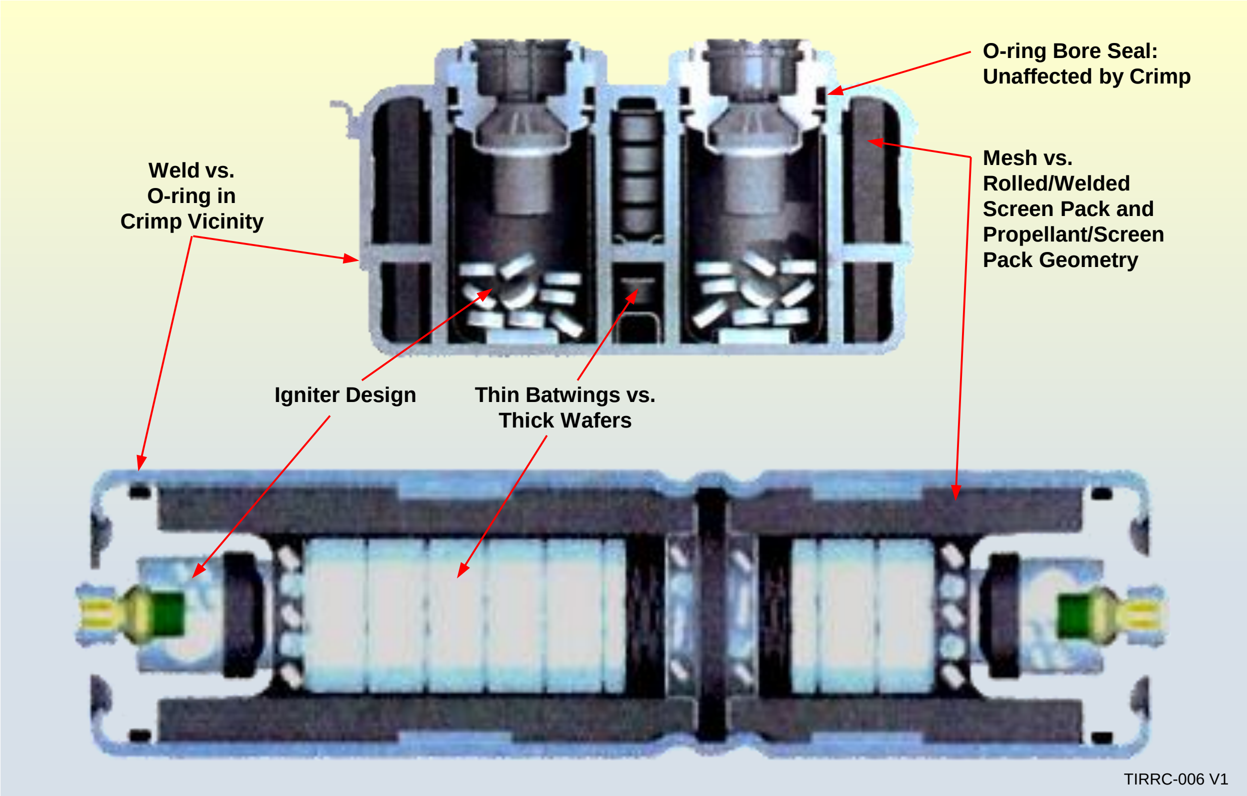


Figure 5. Comparison and Contrast of Major Design Differences in Takata Driver and Passenger Dual Chamber Inflators.

While functionally similar (see Figure 7), understanding these differences is relevant to understanding differences in ED rates.

Detailed structural analysis was done for both driver and passenger inflators. In general, we found the design minimum capability to be in line with reported values from Takata lot acceptance testing. In the driver design, we searched for stress concentrations, particularly those that align with bends and joint welds. We examined the possibility of locations where ingested water could collect and cause corrosion, especially when coupled with propellant dust. We performed thermal analysis looking for the potential for strength reduction of the secondary chamber due to heat soak. In no case were the contributions deemed large enough to reduce the pressure capability sufficiently to be a contributor to increased ED probability.

Although we have no evidence of structural failure at normal pressure, there is data showing ED events are associated with runaway ballistics (Figure 6). While some of the failure traces indicate failure below design capability, a separate analysis showed this is likely due to the capability of the data acquisition system.

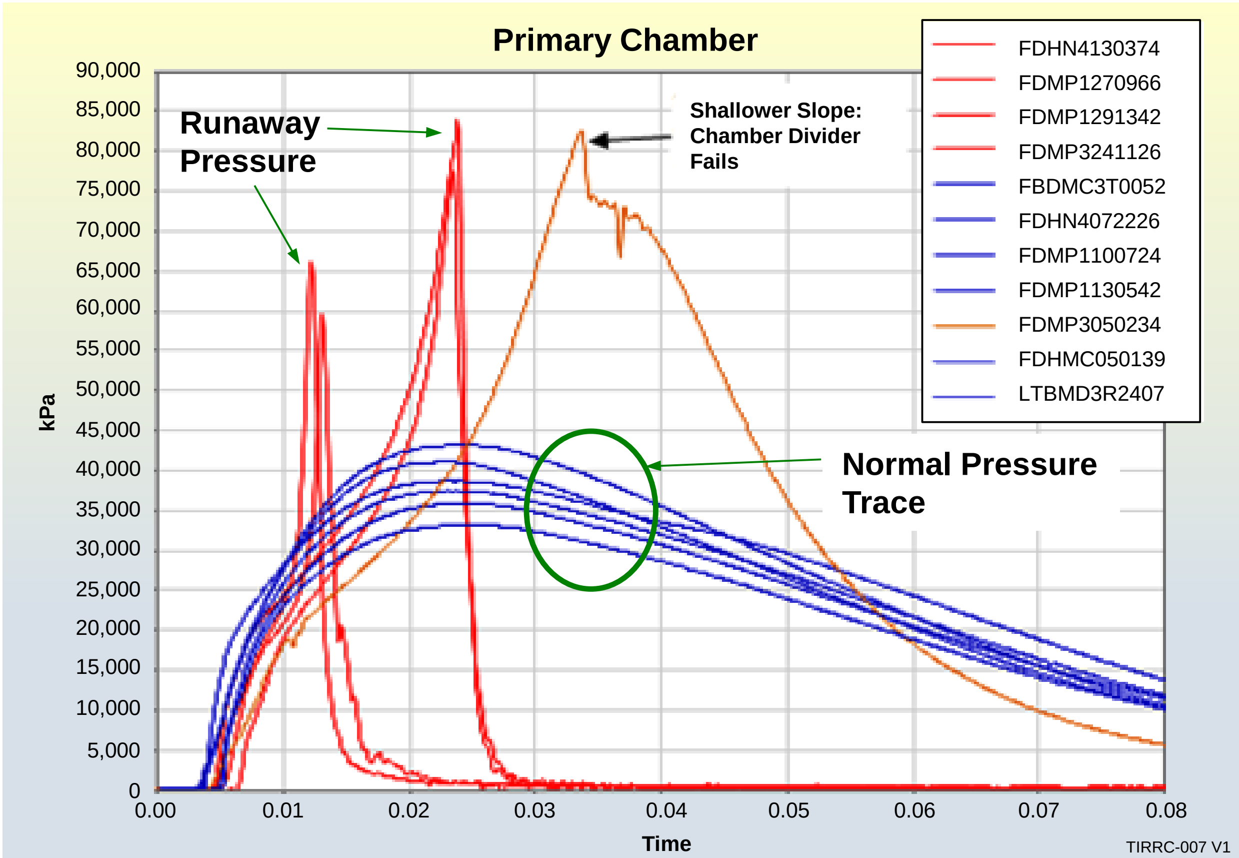


Figure 6. Typical Ballistic Traces.

Shown here are typical pressure-time traces for nominal operation and runaway pressure of an ED. The rounded, "haystack" of the nominal operation is indicative of regression normal to the propellant surfaces. The unique shape of the ED trace provides information regarding what ballistic effects could lead to this shape of trace.

We conducted a wide range of ballistic modeling to help understand potential causes for ED. We modeled both driver and passenger inflators, but studied the passenger inflators in greatest depth. We chose this approach because 1) driver and passenger inflators are functionally similar (Figure 7), and 2) the PSPI-L primary chamber has a wealth of ED data. First, we conducted ballistic analysis to gain an understanding of normal operation for these complex inflators. We then looked at deviations from normal operation that could result in the pressure trace associated with ED. This pressure trace typically shows an initial pressure rise followed by a short "pause" where the pressure rise rate slows followed by a rapidly increasing rate of pressure rise to a pressure that causes a rupture of the inflator housing. This sort of rapid pressure increase is often associated with a progressive burning surface or one that is increasing in the amount of available surface area to burn. This is consistently and strikingly different from the rounded or "haystack" pressure trace associated with normal operation (Figure 6). This kind of "haystack" trace is typical of what would be expected in a normal burn of wafers or tablets of the kind in these inflators. This "haystack" is referred to as a regressive surface area trace due to the wafers or tablets having the highest surface area at the time of ignition followed by a consistent reduction of the available burning surface area as they get smaller burning from the outside in.

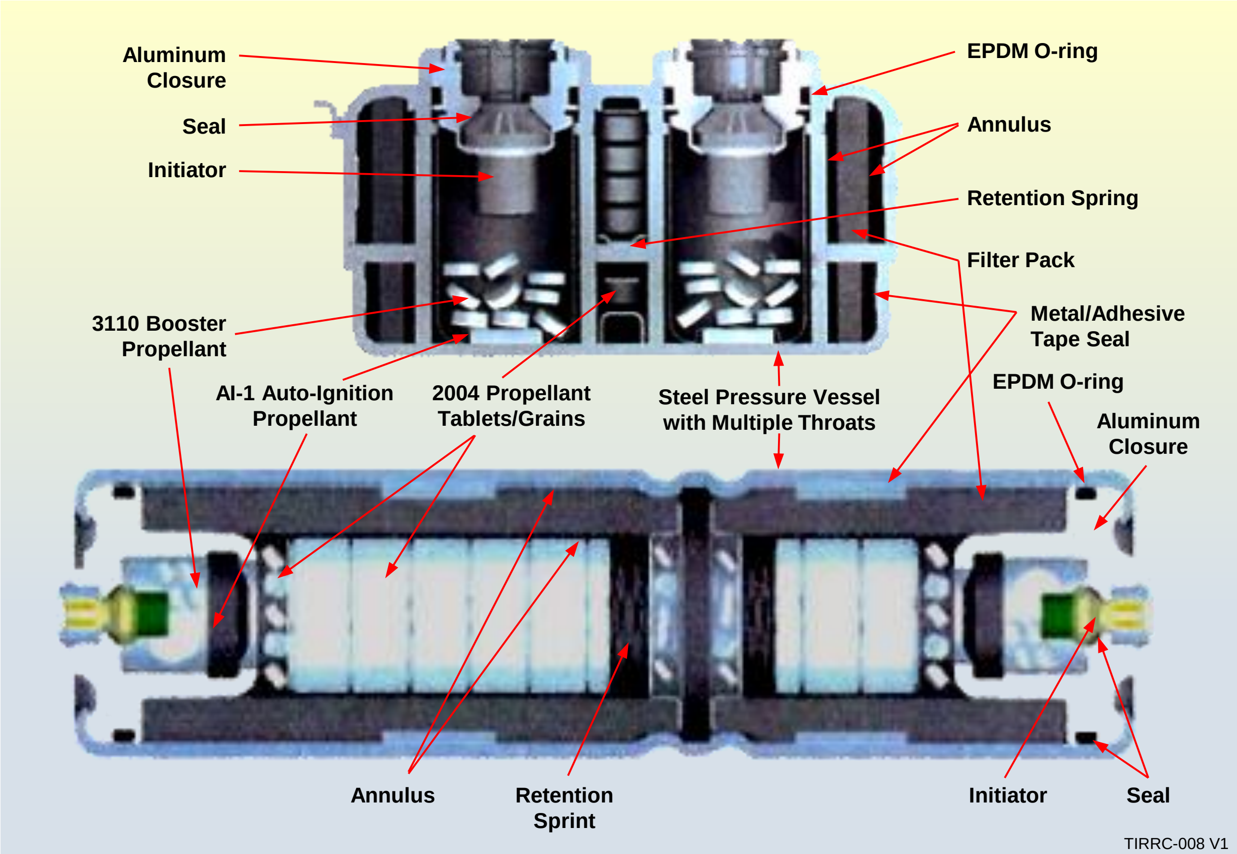


Figure 7. Similarities in Operating Features of Takata Driver and Passenger Inflators.

While there are certain differences (Figure 5), there are many similarities in propellants, materials and designs for the inflators under recall. These similarities allow conclusions regarding both designs to be reached on several key parameters.

We performed significant ballistic modeling to understand normal operation to develop a foundation for understanding higher pressure and ED events. We started with the basics: burn rate and surface area of the main 2004 propellant. Burning rate in propellants is described by the equation here, referred to as St. Robert's Law:

$$r = aP^n$$

In this equation, r is the burn rate, a is a constant, P is the pressure and n is the pressure exponent often referred to as the burn rate slope. Since it is an exponential equation, typical plots are done as log of the burn rate versus log of the pressure which results in a straight line (Figure 8) for a typical combustion process. Changes in the exponent, or slope, have a profound effect on the burn rate. Burn rate combined with available surface area determines the rate that gas is produced. An ED occurs when gas is generated faster than it can move through the screens and out the vents built in the inflator.

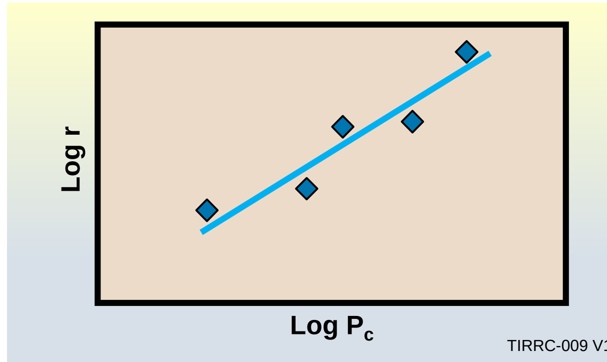


Figure 8. Schematic Representation of Burn Rate and Pressure Plot.

Propellants combust following an exponential relationship of pressure and burn rate. With a high slope of the line, burn rate rises rapidly with increasing pressure. Such propellants exhibit larger changes in burn rate and gas production than those with lower slopes.

Burn rate data for virgin wafers showed a high burn rate slope (~0.8) at low pressure. In the pressure range near the maximum achieved in normal operation, a lower slope (~0.5) is observed. This is discussed in further detail below. These properties are critical to normal operation of these inflators and relevant to understanding the reasons for ruptures. At low pressures, this propellant burns very slowly and can extinguish. At a higher pressure, the burning rate is sufficient to generate gas at the right rate to inflate the air bag. If the pressure increases significantly beyond design, the burning rate also increases resulting in more gas, more pressure and an eventual ED. This iterative pressure/burn rate building results in the typical shape of the pressure-time curve for an ED (Figure 6). These measured burn rate and slope data are the input used for modeling the behavior of this system. We used the lower slope in our baseline modeling because it is the pressure exponent near the maximum pressure.

Wafers break into smaller pieces on ignition. We conducted multiple studies on this breakup. All breakup models resulted in regressive surface area versus distance burned. Variation in breakup strongly influenced peak pressure, but did not change the basic haystack profile. More breakup resulted in higher peak pressure and lower tail-off pressure. Sufficiently high break-up (essentially pulverizing wafers at the extreme) results in an overpressure event.

We examined the potential of the ignition propellants to cause ED. Specifically, we looked at the PSPI-L secondary chamber because of the relatively high ratio of ignition propellant weight to 2004 wafer weight (Figure 9a). We found that 1) we could double the ignition propellant mass flow rate without a significant change in peak pressure, and 2) if we added all the auto ignition propellant at peak pressure we could not increase pressure enough to cause ED (Figure 9b). This important finding helped focus our propellant investigation on the 2004 main propellant.

We examined four theoretical potential causes for ED: 1) increasing burning surface area, 2) increasing burn rate, 3) throat blockage, and 4) increasing combustion efficiency. Mechanisms for increasing burning surface are: a) continued breakup after ignition, and b) burning of interior fractures, cracks and pores. Continued breakup remains a possible cause, but we were able to rule out interior (closed) pore burning (Figure 10) as a primary contributor.

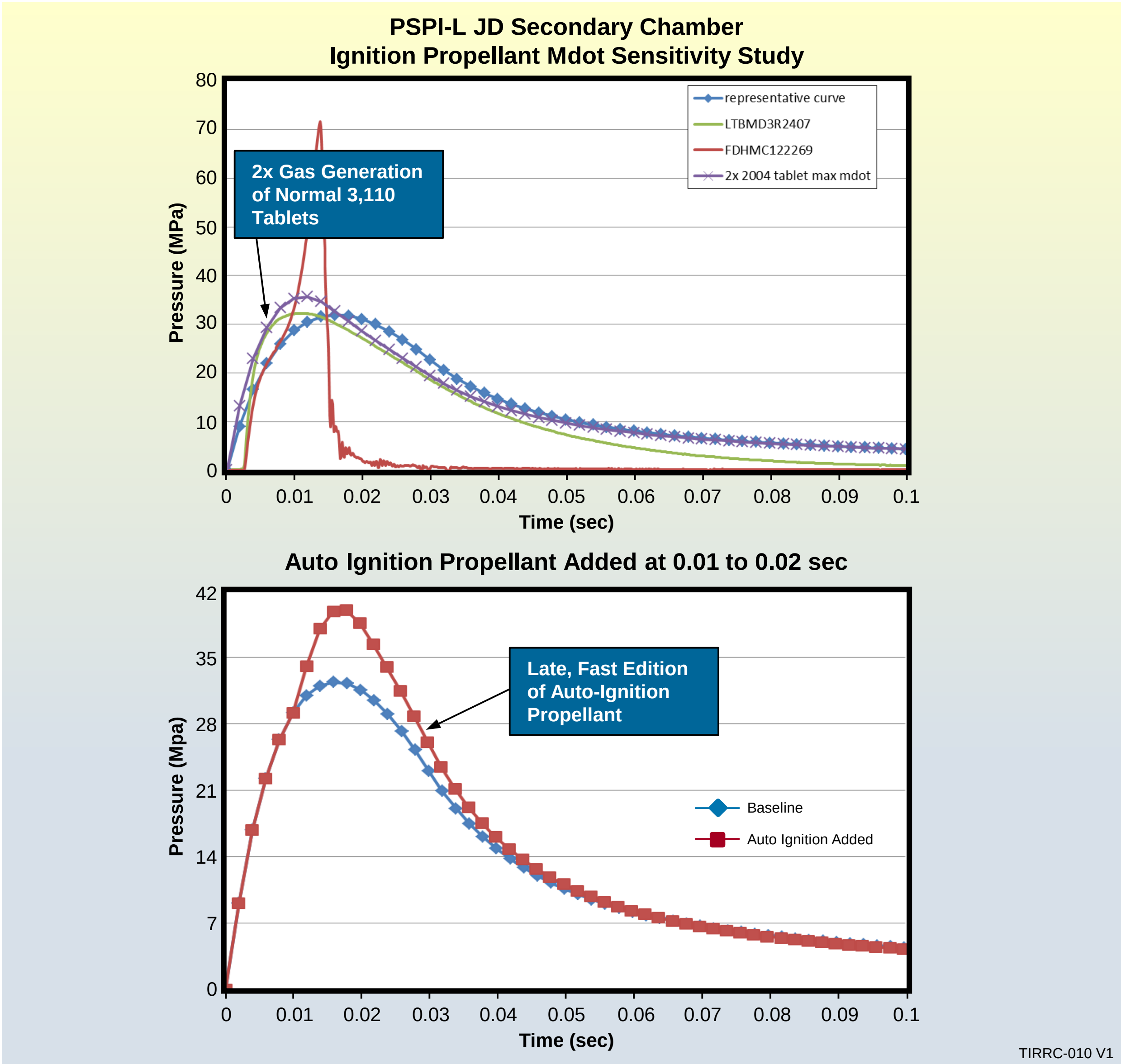


Figure 9. Potential of Ignition and Auto Ignition Propellants to Cause an ED.

These two figures show data from gas or pressure generation studies (Mdot, gas generation rate) on the potential of the igniter closure 3110 propellant (top) or the auto ignition propellant (bottom) to cause an ED. Even under extreme cases, these propellants cannot of themselves cause an ED. This focused our studies on the main 2004 propellant.

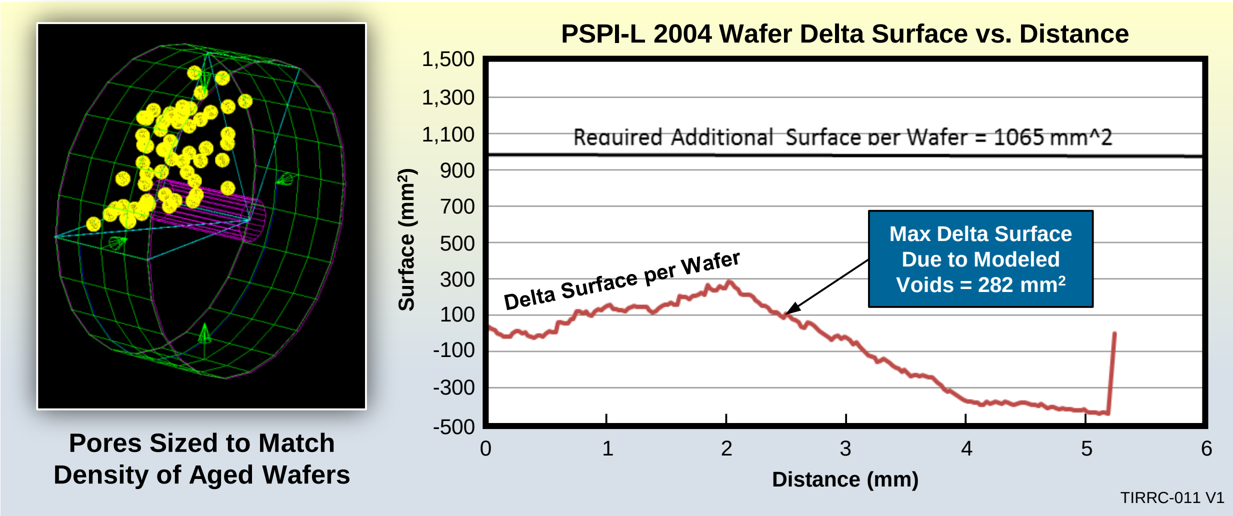


Figure 10. Closed Pore Impact on Burning Surface.

Calculations were done matching the lowest wafer density from field returns by adding closed pores to otherwise nominal wafers. With this matched density, closed pores are insufficient to explain the surface area increase needed to result in an ED event. It may contribute, however. This analysis does not apply to connected pores where there are potential gas paths as discussed below.

Our investigation identified throat blockage as a potential contributor, but not a cause. Several inflators showed abnormal flame plumes at the throats prior to ED and several filter packs showed buckling under the throats in post-test inspection; these observations are consistent with the thermal-structural analysis that showed concentrated heating under the throats. However, the filter packs show little pressure drop even when pressed against the case inner wall. In order to block a throat, the filter pack would have to get hot enough and weak enough to compress into a throat, without being weak enough to blow through the throat under the high pressure associated with ED.

Combustion efficiency is associated with the actual pressure level achieved compared to the theoretical pressure level reached from burning the propellant completely in the absence of heat losses. Heat losses to the filter pack are significant and result in lower combustion efficiency. Closed bomb testing indicates combustion efficiency may increase with pressure. If the inflator is on the way to ED, then increasing combustion efficiency will aggravate the pressure increase by producing more gas for a given amount of 2004 propellant burned. Going forward, we intend to examine combustion efficiency changes with pressure using our heavyweight test hardware.

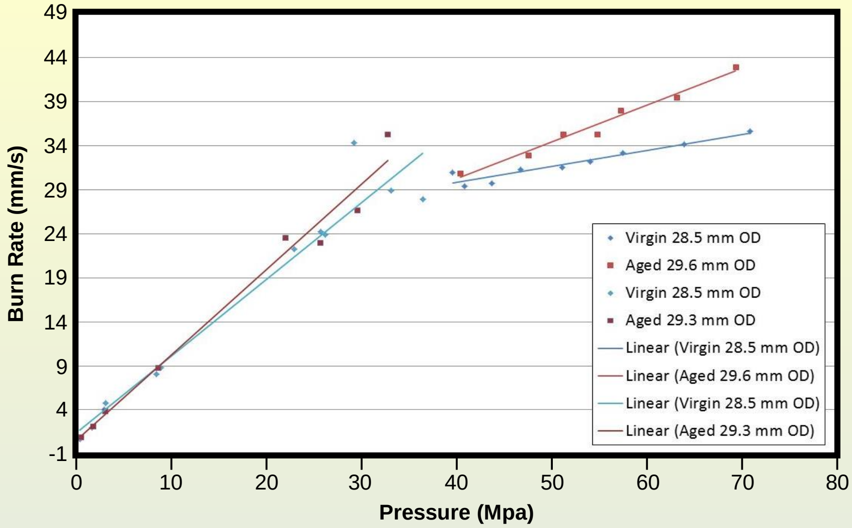
We examined multiple potential causes for the apparent increase in 2004 burn rate. We looked at a number of phenomena known to the ballistics technical community including: oscillatory burning, high base burn rate, erosive burning, burning due to preheating the propellant and permeable burning. Of these causes examined, permeable burning showed potential to contribute to ED.

Orbital ATK and Penn State data[2] showed the potential for low-density 2004 propellant to have a slope increase at high pressure compared to the normal slope at high pressure (Figure 11). Modeling the effect of slope change shows that increasing slope from the baseline value of 0.5 to 0.8 is enough to reach ED pressure levels. This ballistic change most likely is caused by the permeable and porous burning noted below.

Permeable burning is a mechanism that can increase burn rate by preheating the propellant. 2004 propellant burn rate increases with temperature until the auto-ignition temperature is reached. If the propellant is porous (volume is available for hot gas to fill) and permeable (hot gases can flow to the free volume), then hot gas has the potential to preheat the propellant to the depth the permeability extends (Figure 12). This can express itself in what appears to be “in-depth” burning as the hot gases ignite more surface area of the propellant below the normal advancing surface. In a parametric studies completed to test this phenomenon, 2% porosity is typical of virgin propellant, and 10% porosity is similar to aged propellant. For the study, three values for the permeability constant, Gamma, were chosen that span the range likely for this material and to model the potential impact from a change in permeability. This example showed the potential for a 50% burn rate increase due to changes in porosity and permeability. This theoretical underpinning may serve to explain the empirically measured “Integrated Burning Rate” data reported by Takata. Understanding the mechanism will allow validation of appropriate aging models.

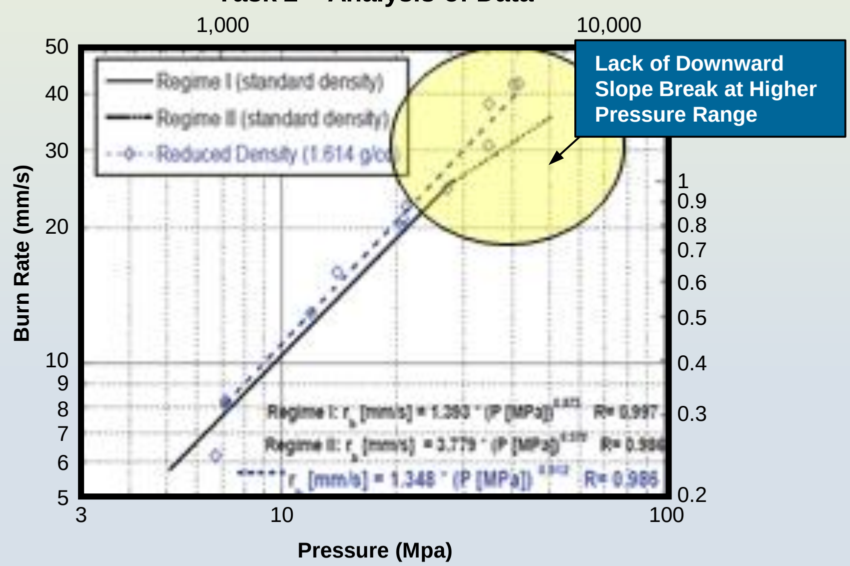
[2] *Essel, J.T., Boyer, E., Kuo, K.K., and Zhang, B., “Transient Burning Behavior of Phase-stabilized Ammonium Nitrate Based Airbag Propellant”, Int. J. of Energetic Materials and Chem. Propellants, Vol. 11, pp. 473-486, 2012*

Comparison of Burnrates Between Aged and Virgin Quarter Wafers



Task 2 – Analysis of Data

Penn State data for static burning rate at normal and low density



Applying their curve fits, and calculating the burning rate at 40 Mpa (typical of PSDI and many other 2004 containing inflators), we obtain the following:

Pressure, Mpa	Burning Rate for 1.71 g/cc	Burning Rate for 1.61 g/cc	Increase, %
40	30.94	38.97	26.0
50	35.14	47.77	35.9

TIRRC-012 V1

Figure 11. Change in High Pressure Regime Slope.

Data at several locations have shown similar data as depicted here from Orbital ATK (top) and Penn State (bottom). This change in apparent slope at higher pressure is consistent although graphically represented several different ways. Several phenomena can result in this apparent slope change as noted below.

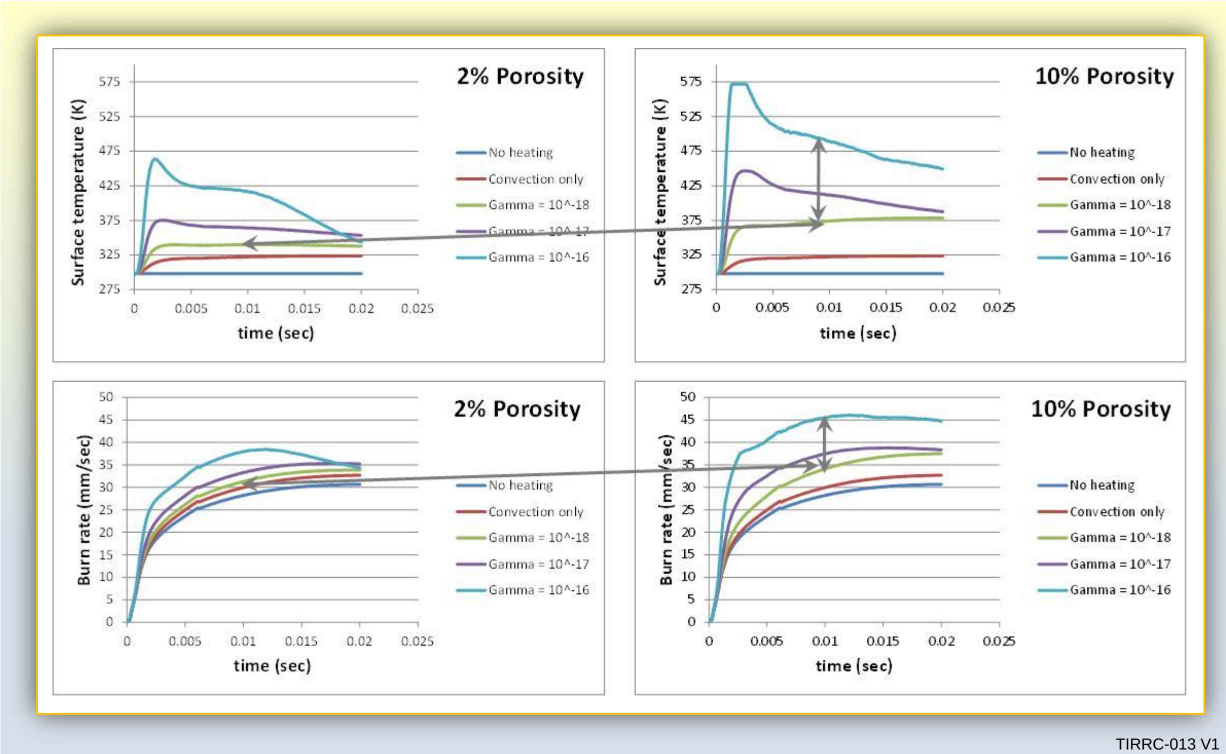
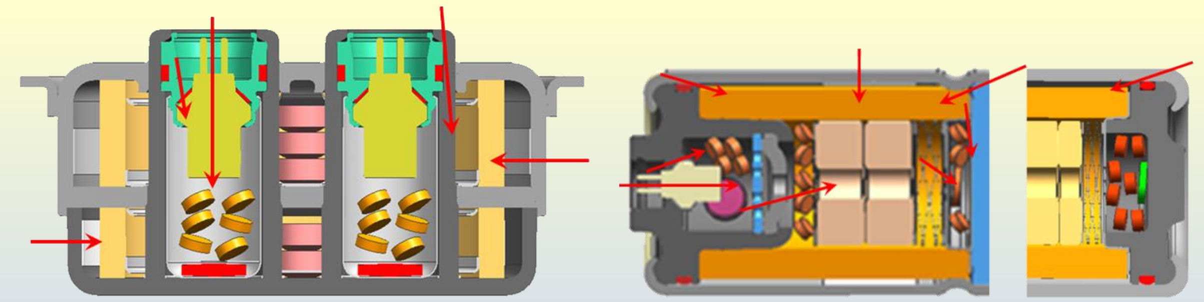


Figure 12. Impact of Porosity and Permeability.

These four figures graphically depict the dramatic effect on in-depth heating and burning rate with increasing porosity and permeability to hot gases. Each graph shows data for no heating and for increasing levels of permeability (gamma). This in-depth heating along gas paths is consistent with the real time radiography, pycnometry data and ED event ballistic traces.

Analysis of the seal systems showed that each driver and passenger inflator has multiple potential leak paths (Figure 13). The leak path of greatest concern is the passenger closure O-ring seal (Figure 14). Based on nominal dimensions for the closure, O-ring and case (away from the crimp zone), O-ring squeeze is excellent. Unfortunately, the closure crimp footprint overlays the O-ring sealing footprint. This design/manufacturing feature allows the possibility of no O-ring squeeze at the maximum engineering-allowed crimp outer diameter (OD) of 52.65 mm. In addition, many inflators were built with crimp ODs that exceed the allowed value. These paths result in greater moisture movement in and out of inflators than what would be calculated based on diffusion through a rubber O-ring and is consistent with reports from Takata, Fraunhofer ICT and original equipment manufacturers (OEM) of higher moisture levels in field return inflators. This moisture movement is critical to generate the observed growth in wafer diameter.



Total	Throats	Closures	Squibs	Squib Gaskets
12-14	6-8	2	2	2

	Total	Throats	Closures	Squibs	Squib Gaskets
PSPI-L	16	10	2	2	2
PSPI	16	10	2	2	2
SPI	10	6	2	1	1

TIRRC-014 V2

Figure 13. Potential Leak Paths in Takata Inflators.

Several different seals are present in both passenger and driver inflators (marked by red arrows). While a great deal of emphasis has been placed on the passenger crimp and O-ring, every seal is a potential path for moisture to enter the inflator and must be considered in any valid moisture transport model.

Passenger Side – Inflator O-ring Squeeze

Parameter	Nominal	Tolerance Stack Up		
Concentric	Yes	No	Yes	No
Crimp	No	No	Yes	Yes
Max Squeeze (%)	28.7	29.3	15.5	29.3
Minimum Squeeze (%)	17.4	16.8	0.9	0

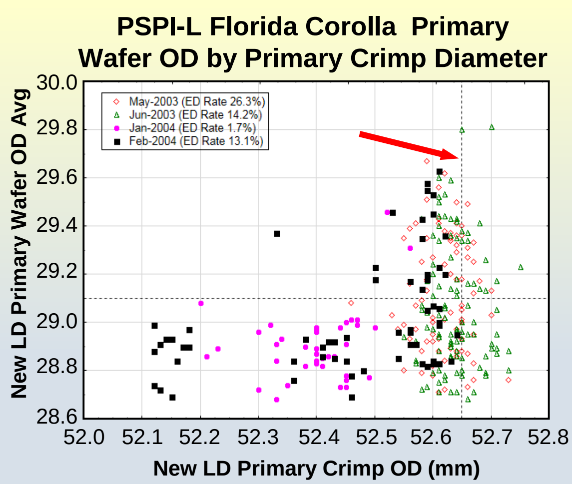


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Figure 14. Passenger Inflator Primary Crimp Data.

The table on the left presents results from analysis using a proprietary tool developed by Orbital ATK to be a more accurate measure of O-ring squeeze. The tool was developed due to the criticality of O-ring seals in rocket motors. The data on the right show that manufacturing in the time frame of interest for these recalls (2003 and 2004 shown here), that a measurable percentage of all primary crimp diameters exceeded the engineering allowed maximum of 52.65 mm (marked by the red arrow).

Laboratory Experiments

There was a wide range of activities that we broadly grouped under laboratory experiments. The range is from detailed chemical analysis of raw materials to metallurgical investigations of inflator hardware to heavyweight ballistic analysis to static and dynamic x-ray analyses. The specific work performed was driven by the needs derived from the fault tree closure efforts.

Several noteworthy conclusions can be drawn from our laboratory experiments:

1. There is no significant chemical degradation or chemical composition change occurring to a sufficient degree in the 2004 propellant or in the 3110 propellant after field exposure which could contribute significantly to the failure rate. That is, PSAN is still the same chemical when aged under the conditions typical in the subject inflators. While the chemical constituents do not change, in contrast, changes in the shape and size and growth in pores, cracks or fissures in pressed wafers, tablets or batwings are observed.
2. Moisture transport inside an inflator follows expected behavior of the hydroscopic, desiccating and deliquescing behaviors that would be expected for these materials based on general principles of chemistry. That is, sodium bentonite, which is a component of both the 2004 and 3110 propellants, can function as a drying agent and PSAN can absorb significant amounts of moisture if available. There are not dramatic cliffs but rather gradual changes as a function of temperature, as shown in the experiments conducted by Fraunhofer ITC and confirmed by our efforts. However, these cumulative changes over the temperature range to which the inflator is exposed appear to be significant. Figure 15 and Table 3 report critical lab data describing moisture transport.
3. The 2004 propellant wafers in passenger inflators grow after repeated temperature cycling with moisture present (transitioning in and out of propellant grains). This effect was observed in both wafers and tablets in primary and secondary chambers of passenger inflators (Figure 16). The growth results in reduced envelope density but very little change in pycnometry density, suggesting that the increased volume is void spaces that are connected (Figure 17). These connected pores, flaws or fissures allow hot gas penetration resulting in increased mass flow when ignited (porous and permeable burning).

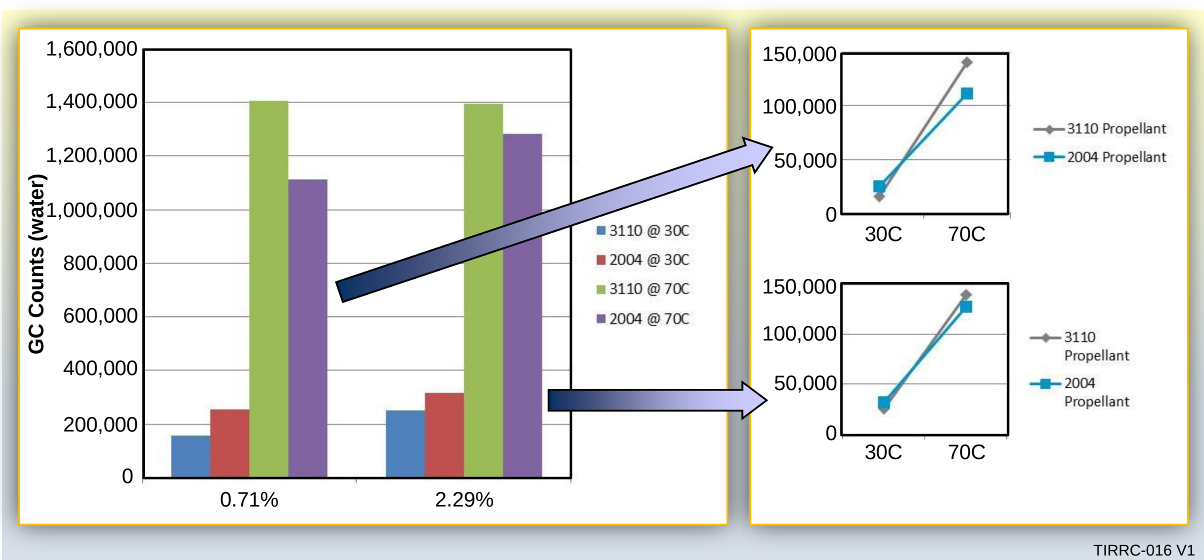

Figure 15. Headspace Moisture Above 2004 and 3110 Propellants with Moisture Added as a Function of Temperature.

In each case, the change in the amount of water that is available is dramatic when transitioning from 30°C to 70°C. This suggests transport is much more likely at the higher end of the range. The 3110 propellant shows a modest increase in propensity to give up moisture compared to 2004. This variability gives rise to the "x-graph" when suitably drawn although the effect is not as dramatic as suggested in some depictions.

Table 3. Moisture Competition Experiment for 2004 and 3110 Propellants in a Closed System.
Data reported here are percent moisture in the propellant. The initial conditions were six open vials containing dried 3110 propellant and 2004 with a known percentage (2%) of moisture. They were first allowed to equilibrate for 5 days at ambient. A significant amount of moisture moved from the moist 2004 propellant to the dry 3110. Cycles at higher temperature with two additions of small amounts of water mimicking HAH conditions followed by simple heating showed slow movement back towards the 2004 from the 3110. This matches the data in Figure 15 and quantifies the mobility under these relevant conditions. Further experiments at 50°C and 60°C along with smaller amounts of water are planned.

Mass Propellant	1.14 g 2004	1.90 g 2004	3.08 g 2004	0.18 g 3110	0.32 g 3110	0.2 g 3110
Start	2.0	2.0	2.0	0.0	0.0	0.0
5 days ambient	1.4	1.7	1.6	3.1	2.4	2.6
Add 0.1 g water, heat to 70°C and let cool over night	3.6	2.7	2.3	8.5	6.2	5.2
Add 0.07 g water, heat to 70°C and let cool over night	5.6	3.7	2.6	12.1	8.5	6.7
Heat to 70°C and let cool over night	6.2	4.0	2.5	9.5	7.6	6.5
Heat to 70°C and let cool for 6 hours	6.3	4.1	2.5	8.8	5.9	5.9

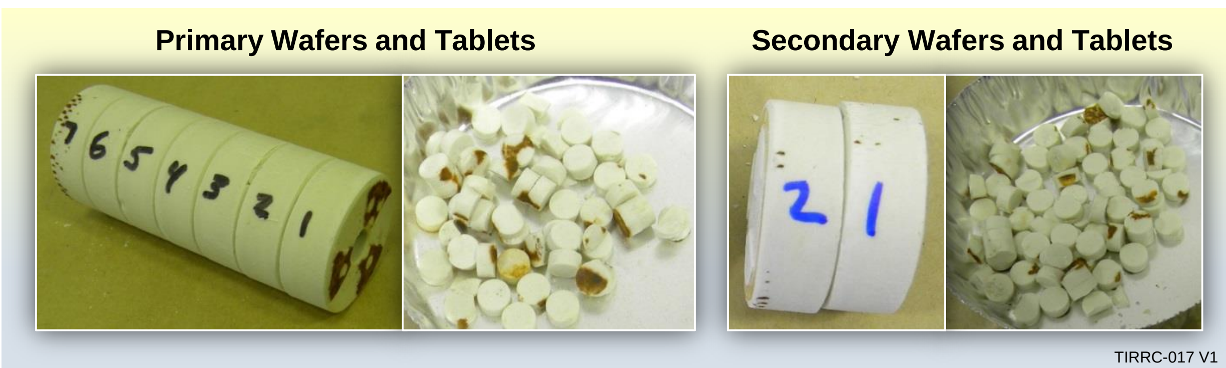

Figure 16. Examples of Fused Wafers and Tablets.

Both tablets and wafers are often fused in inflators where there has been significant diameter growth in the wafer consistent with a process similar to Ostwald ripening. The kinetics of such processes are relevant to any aging models.

Real time radiography (RTR) provided remarkable insight into the processes involved in both a nominal burn and during over-pressure events. This technique showed the typical fracture of wafers during ignition. In a nominal deployment, the regular burning normal to all surfaces is apparent. However, in an ED, the initial state shows less distinct wafers, consistent with wafers expanding into direct contact with each other. Fracture occurs on ignition, although perhaps less pronounced than in a nominal deployment. Initial burning is followed by a transition to a much higher mass consumption, consistent with ballistic traces and penetration of combustion gases through void spaces resulting in increased surface area (Figure 18).

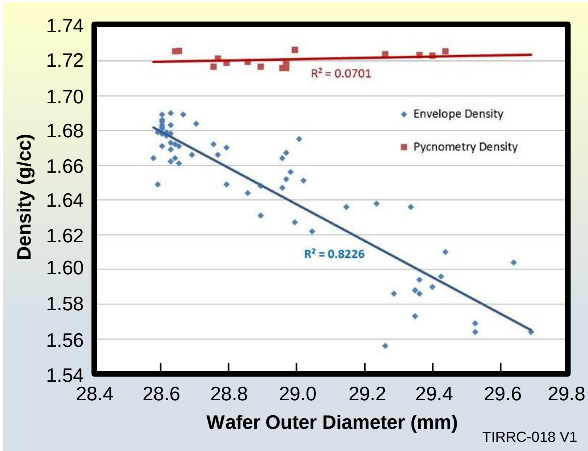

Figure 17. Density Measurements for 2004 Propellant Wafers.

Shown here are measurements of a large number of propellant wafers with increasing OD. Outer diameter has been correlated with likelihood of an overpressure event. These data show two different density measurement techniques. The envelope density method gives an overall geometrical density while the pycnometry density method allows gas penetration, yielding a result that remains constant due to accessibility to gas to the majority of low-density spaces or voids in the propellant. These data show that the low-density voids generally allow gas to pass from one to the next, suggesting connected or communicating voids.

Root Cause

The root cause statement is summarized in Figure 19. When all three necessary, mutually synergistic conditions are present, they combine to result in a single sufficient failure condition. The case, or enclosure, structural integrity was not found to be a contributor. The particular vehicle model or platform was found to be a contributing modifier. The magnitude of that effect will be examined in the next phase of the program as part of the aging and surveillance testing effort.

Figure 18. Real Time Radiography Still Images.

Shown above are individual frames from two RTR experiments with PSPI-L FD inflators showing the primary chamber. Stills 1-3 are from test #98553, which was a nominal firing. Stills 4-6 are from test #95179, which was an ED. The time sequence is from left to right. In the first pictures (1 and 4), differences can be seen with the distinct individual wafers with space between wafers in #1 and less distinct boundaries in #4 reflecting the wafer growth in #4. In pictures 2 and 5, the ignition has occurred and flame spread has begun. The typical fracturing of wafers is visible. Space between wafers from flame intrusion is now clear, which is not seen in the baseline (picture 4) for test #95179. In #3 and #6, radical differences are clear. In #3, regression of the surfaces, reducing wafer size but maintaining integrity, is observed. In #6, combustion at a much higher rate and in depth in the wafers is visible although some integrity remains as would be expected. Rupture occurred shortly thereafter attributed to excessive chamber pressure.

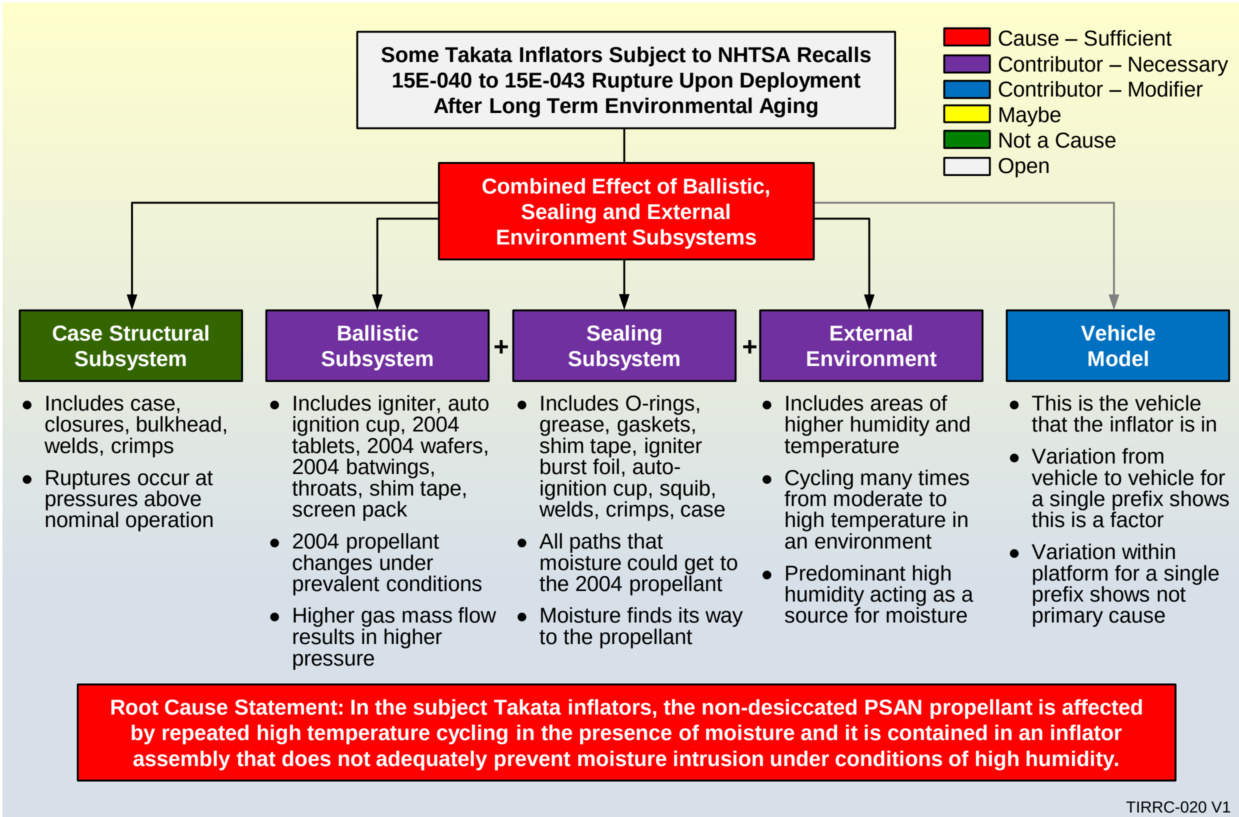

Figure 19. Summary Fault Tree.

The first level fault tree with the summary of the root cause is shown here. Please note the color key in the upper left. Compare to the summary of the supporting and refuting evidence shown in Table 1.

Continuing Efforts

Our activities are moving into the next phase of the investigation, namely to focus on the performance of all inflators that are being used as replacement parts for current recalls, as well as desiccated inflators being used in existing vehicles. A primary question is whether the newer inflator designs are susceptible to failure under conditions that have resulted in ED events with inflators currently under recall.

Addenda

A. Sources of Information and Acknowledgements

The scope of the project as presented to Orbital ATK by The Independent Testing Coalition (ITC) was to pursue root cause and ramifications using all available information. The investigation was not limited in focus or scope. There was not any direction given by the ITC. No limitations were imposed on avenues of the investigation or scope of questions asked. We received consistently strong support from each member of the ITC. Each ITC member willingly shared relevant data they had.

We received critical support from Takata. They supplied proprietary engineering drawings to support our modeling. Takata provided aged and new inflators as well as inflator hardware, raw materials and access to their engineering and manufacturing facilities. Takata met with us on several occasions to respond to our questions. Takata also provided access to their Master Engineering Analysis File (MEAF).

We also met with individuals from Fraunhofer ICT as arranged by Takata and with faculty from Penn State to discuss their studies. National Highway Traffic Safety Administration (NHTSA) personnel provided relevant information regarding their in-house investigations and from their review of efforts by all other parties.

We considered all the data we gathered as relevant to the investigation and sought to include every possible source in our work. We independently verified data from all sources to ensure that we could stand by all the critical data we cite as relevant to our investigation.

B. ITC Membership and Purpose

Formed in December 2014, the ITC has as its sole purpose to conduct an independent and comprehensive investigation of the technical issues associated with Takata airbag inflators. The ITC comprises ten automakers that have Takata airbags subject to the noted recalls in their passenger and light truck vehicles: BMW, Fiat Chrysler Automotive, Honda, Ford, GM, Mitsubishi, Mazda, Nissan, Subaru and Toyota.

C. Orbital ATK Relevant Qualifications and Background

The Orbital ATK team was primarily located within our Propulsion Systems Group in Utah. We called on expertise relevant to the project from across the company and outside of our company for specific technical capabilities and for real time radiography and computed tomography image analysis. The core team has extensive experience in the design, research and development, testing and manufacture of propellants, explosives and pyrotechnics including many years of experience with automotive inflators. Orbital ATK is not involved in the inflator business today and, as such, is well positioned to serve as an objective investigator on this project. We were and are fully committed to providing the best technical personnel and using the best of the tools at our disposal to provide an accurate and objective assessment.