Investigation of Takata Inflator Ruptures

Exponent®

Investigation of Takata Inflator Ruptures

Project Manager

Subbaiah V. Malladi, Ph.D., P.E.
Chief Technical Officer
Exponent

July 2016

Doc. no. 1600478.000 - 0471

Contents

List of Figures

Limitations

The findings presented herein are made to a reasonable degree of scientific certainty based on information possessed by Exponent as of the date of this report. In the future, Exponent may be asked to perform additional analysis. Exponent reserves the right to supplement, expand, or modify the findings in this report based on additional work or review of additional information.

The scope of this report may not be adequate for purposes other than those described in the beginning of the Executive Summary. Use of this report or the findings, conclusions, or recommendations presented herein for any other purpose is at the sole risk of the user.

Executive Summary

Exponent performed a comprehensive investigation into the cause of observed ruptures of Takata airbag inflators. This report provides a review of Exponent's findings for non-desiccated passenger side inflators manufactured by Takata ("inflators"). All inflators discussed in this report contain the same type of phase-stabilized ammonium nitrate-based (PSAN-based) propellant known as "2004".

Exponent determined that ruptures of the inflators occurred due to physical degradation of the propellant in the form of larger internal pores/channels/voids ("pores"). The degradation of the propellant arises from diurnal and seasonal temperature cycling, and it is exacerbated by higher peak cycle temperatures and increased total moisture in the inflator. Temperature fluctuations of the inflator cause moisture exchange ("movement") between the propellant and the surrounding headspace, which ultimately leads to the development of porosity.

As pore size increases beyond a certain threshold due to degradation, the rate of propellant consumption (and hence gas generation) increases significantly in comparison to propellants with minimal or no degradation. The elevated gas generation rate of the degraded propellants significantly exceeds the capabilities of the inflators to vent those gases. This results in an increased rate of pressurization and peak pressures that can exceed the mechanical strength of the inflator and cause the housing to rupture.

Degradation of 2004 propellant is progressive with time and is dependent on environmental conditions and vehicle's time in service. The primary factors that increase the rate of degradation are elevated temperatures, increased temperature fluctuations, and high propellant moisture content. Though degradation can occur in a variety of geographic locations, the most adverse conditions for inflators exist in regions of high temperature and high humidity, which is confirmed by extensive analysis of field data.

Exponent systematically investigated the cause of inflator ruptures and comprehensively considered other potential causes, such as vent hole and filter blockage, structural degradation or inadequate strength of the inflator housing, chemical sensitization of the propellant or booster materials, excessive fracturing of the inflator materials prior to deployment, and deployment at elevated temperatures. None of these potential causes were found to be viable explanations for ruptures observed either in the field or in laboratory testing of field returned inflators.

Exponent developed a numerical model that tracks moisture movement throughout the inflators based on the physical and chemical properties of the propellant and booster materials, inflator chamber geometries, moisture permeation characteristics of the inflator components, local weather data, and solar heating within vehicles. Weather data collected from over 600 weather stations around the United States was used to predict the cumulative propellant moisture movement, and by correlation the degree of degradation, in inflators for vehicles operated in different regions. The model was validated by comparing the predictions to the real-world performance of inflators, as well as to the performance of inflators and inflator materials aged and tested under controlled laboratory conditions. The model is utilized to provide characterization of the propellant degradation at different geographic locations assuming that the vehicle is continuously exposed to outdoor environmental conditions. The model results are consistent with observed geographic distribution of ruptures and with results from testing of field returned inflators. Both the modeling and testing of field returned inflators show that all designs of non-desiccated passenger side inflators are susceptible to degradation of the inflator materials. Though the model provides an estimate of propellant degradation at various geographic locations, it is not intended to provide the degradation profile of any individual vehicle. A conservative estimate of the degradation threshold for ruptures in a particular geographic region was obtained from an analysis of both the field ruptures and ruptures of field returned inflators in laboratory testing.

Note that this Executive Summary does not contain all of Exponent's technical evaluations, analyses, conclusions, and recommendations. The main body of this report is at all times the controlling document.

Background on Inflator Design

A cross-sectional view of a PSPI-L inflator, which illustrates design features common to several other Takata passenger inflator types, is shown in Figure 1. A PSPI-L inflator has two separate sides: a primary and a secondary side. Each side is comprised of a booster chamber, a propellant chamber, and an auto-ignition (AI) pouch. The booster chamber contains a small igniter (squib) triggered using an electrical signal. Deployment of the igniter initiates the burning of small tablets of booster material (known as “3110”) inside the booster chamber. The hot, high-pressure gases from the booster chamber break through a thin foil and enter the propellant chamber, igniting the propellant (known as “2004”) shaped in the form of tablets and wafers. The 2004 propellant is composed of several chemicals, of which phase-stabilized ammonium nitrate (PSAN) is a major constituent. As the 2004 material burns, it generates gases that pressurize the inflator. When the pressure exceeds a threshold value, it breaks the tape seals covering small vent holes in the inflator housing (shown in Figure 2) and the gases escape to inflate the airbag.

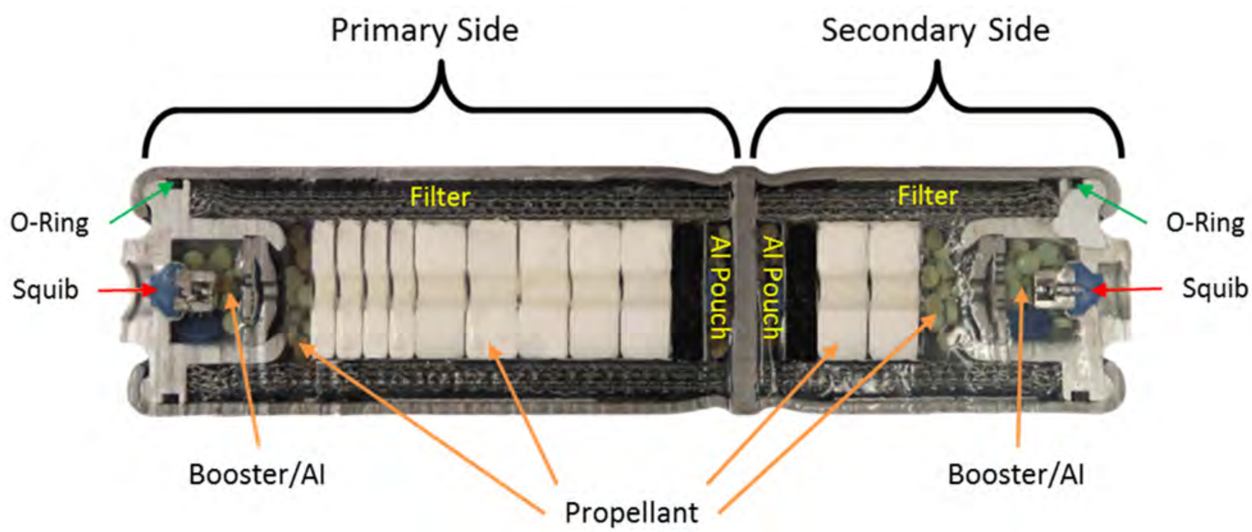

Figure 1. Cross-sectional view of a PSPI-L inflator. Other passenger inflator types characterized in this work have similar features.

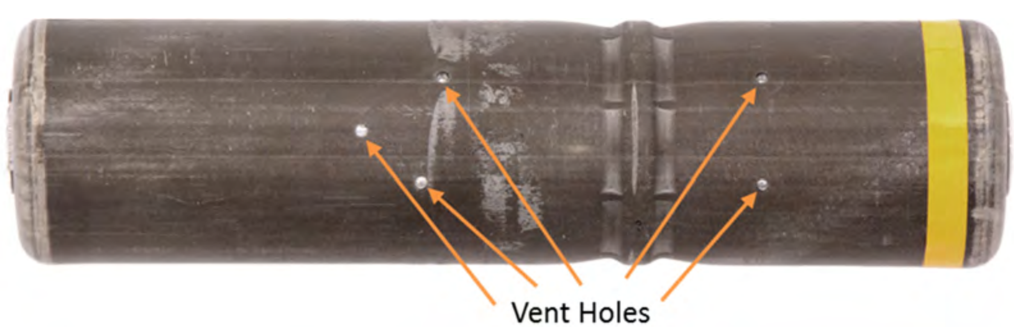

Figure 2. Exterior view of a PSPI-L inflator showing the locations of the vent holes of fixed orifice size. The inflator has a total of six vent holes in the primary chamber and four vent holes in the secondary chamber.

Potential Failure Modes

If inflator operation proceeds as designed, the peak pressure inside the inflator housing remains well below the rupture pressure of the housing and the inflator safely completes its function to activate the airbag. However, under certain circumstances, the pressure inside an inflator can exceed the mechanical limits of the housing and cause the inflator to rupture. Numerous potential failure modes were studied to identify whether they were viable causes for observed inflator ruptures, including:

1. Whether the inflator housings failed due to lower than intended mechanical strength, or had manufacturing defects, were weakened from corrosion, or otherwise had a designed rupture pressure too close to the expected range of inflator operating pressures. The evaluation was comprised of several studies, the results of which indicate that neither the as-designed strength of the inflator housings nor the degradation of the inflator housings over time are responsible for the observed field failures. These studies included:

    a. Finite element studies to determine the mechanical strength of the inflator housing. The results were compared with pressures that were safely contained by the inflators and those that resulted in ruptures.

    b. Physical measurements and metallurgical examinations of failed housings to assess whether the housing was built as designed.

    c. Pressure measurements during deployments of both virgin and degraded inflators to assess pressure levels relative to the design capabilities of the housing.

2. Evaluation of whether the vent holes were not opening or whether the vent holes and/or filter were susceptible to clogging. Clogged vent holes and/or a clogged filter can result in increased pressure inside an inflator that may exceed the capabilities of the housing. The evaluation was comprised of several studies that show that neither blockage of the vent holes nor filter clogging are responsible for the observed field failures.

3. Evaluation of whether the booster or propellant materials were chemically altered over time, possibly from environmental exposure, such that they burned too quickly and resulted in inflator overpressures. The evaluation was comprised of several studies in which sensitization of the inflator materials was not observed; thus, it is not responsible for the observed field failures. These studies included:

    a. Chemical analyses (including Fourier Transform Infrared Spectroscopy [FTIR] and gas chromatography – mass spectroscopy [GC-MS]) of virgin materials, field returned inflator materials, and laboratory tested materials performed on 2004 and 3110 to assess whether chemical degradation occurred that might result in sensitization.

    b. Thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and X-ray diffraction (XRD) to assess if the thermal properties of the degraded materials had changed or phase destabilization had occurred.

4. Whether elevated operating temperatures (that might exist in vehicles sitting in the sun in hot climates) or breakage of the propellant wafers prior to deployment could result in overpressures sufficient to cause the inflator ruptures observed in the field. Testing confirmed that these mechanisms are not responsible for the observed field failures.

5. Whether the overpressures and ruptures occurred due to physical degradation, such as the formation of pores/channels/voids ("pores") in the inflator propellant material, causing it to burn too rapidly inside the propellant chamber. A detailed evaluation consisting of several studies determined that such physical degradation is the primary cause for the field observed inflator ruptures. These studies included:

    a. Controlled environmental cycling of inflators, inflator components, and inflator propellant materials to assess moisture movement, thermodynamic properties, and physical and chemical degradation characteristics.

    b. Pressure measurements inside inflators during deployment, including virgin inflators, inflators returned from vehicles operated in different regions of the country, and inflators subjected to controlled laboratory temperature and humidity cycling.

    c. Physical measurements of propellant dimensions both in situ and extracted from field returned and laboratory cycled inflators. Measurements included porosity characterization (mercury intrusion porosimetry [MIP]), dimensional measurements, scanning electron microscopy (SEM), elemental analysis using energy dispersive X-ray spectroscopy (EDX), computer-aided tomography (CT scans), X-ray dimensional analysis, and Karl-Fischer (KF) titration for quantifying moisture content.

    d. Pressure measurements performed during closed chamber testing of propellant materials to assess the rate of material consumption.

    e. Review of test and inflator deployment data from Takata.

The results of the studies listed in items *5a* through *5e* indicate that the cyclic moisture movement ("moisture flux") in the inflator propellant results in the development of larger pores and increased porosity. The presence of larger pores causes more rapid mass consumption of the propellant and a higher rate of gas generation. If the gas generation rate significantly exceeds the venting capability of the inflators, the internal pressure can rise and may exceed the mechanical strength of the housing, resulting in rupture.

The results also indicate that propellant moisture movement and the consequential degradation occur primarily due to daily temperature fluctuations of the inflators and are exacerbated by elevated moisture content caused by moisture intrusion. Throughout the life of the vehicles, continued exposure to fluctuations in ambient temperature and solar radiation increase the cumulative moisture movement, leading to increasing degradation over time. Higher average temperatures and higher propellant moisture content exacerbate the effect of temperature cycling on the degradation of the propellants. Inflators from vehicles operated for the longest periods in hot and humid environments and that are most exposed to direct sun are expected to experience the greatest degradation. This is consistent with the findings that the oldest inflators from vehicles operated in Florida and Puerto Rico have the greatest probability of a housing rupture during deployment.

Field Degradation of Inflators

Exponent characterized the condition of propellant and booster materials from various passenger inflators recovered from the field to determine how field exposure contributes to inflator ruptures. The characterization included pressure measurements in a closed chamber and in fully assembled inflators, testing of individual propellants to determine moisture content (measured by KF), measurements of porosity (determined by MIP), and measurements of the outer dimensions of propellants.

Moisture Content

Controlled experiments and analyses of field data indicate that the moisture content in the propellant is an important characteristic that increases moisture movement during temperature cycling and ultimately contributes to degradation. Additional experiments indicate that the total moisture in the inflators is distributed among the propellant and booster materials and that it is correlated with the moisture content of the 2004 propellant.

The moisture content of virgin and field returned inflator components were measured, examples of which are shown in Figure 3 and Figure 4. Inflators operated in humid environments generally have higher moisture content than equivalently aged inflators operated in drier environments (Figure 3), and older inflators generally have higher moisture content in the propellant than newer inflators (Figure 4). This suggests that moisture migrates through the parts of the inflator over time. Experiments were conducted to quantify the rates of moisture movement into the inflators. These rates were used in a numerical model to predict inflator moisture changes with time in different geographic locations. Inflators of a given age and region can experience a wide range in moisture content, which suggests that in addition to the ambient exposure, vehicle usage patterns, and other vehicle-specific characteristics also affect their moisture content and degradation.

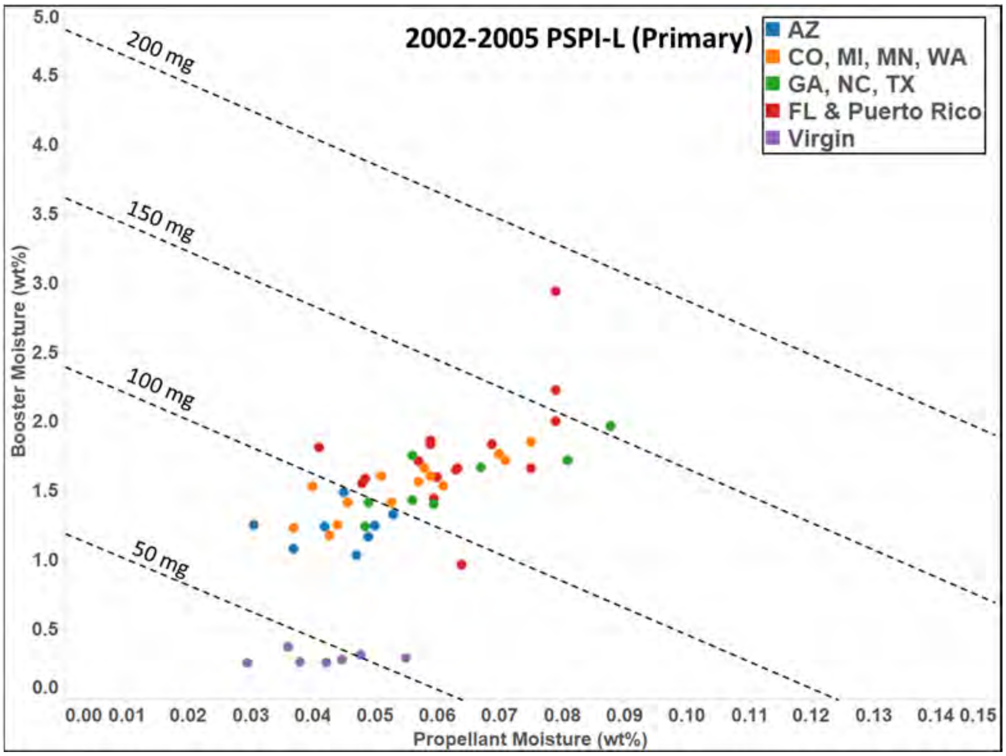

Figure 3. Moisture content in the primary chamber propellant and booster (3110 material only) in PSPI-L inflators from 2002-2005 vehicle model years. (The dotted lines indicate the total moisture in the 2004 propellant and 3110 booster materials.)

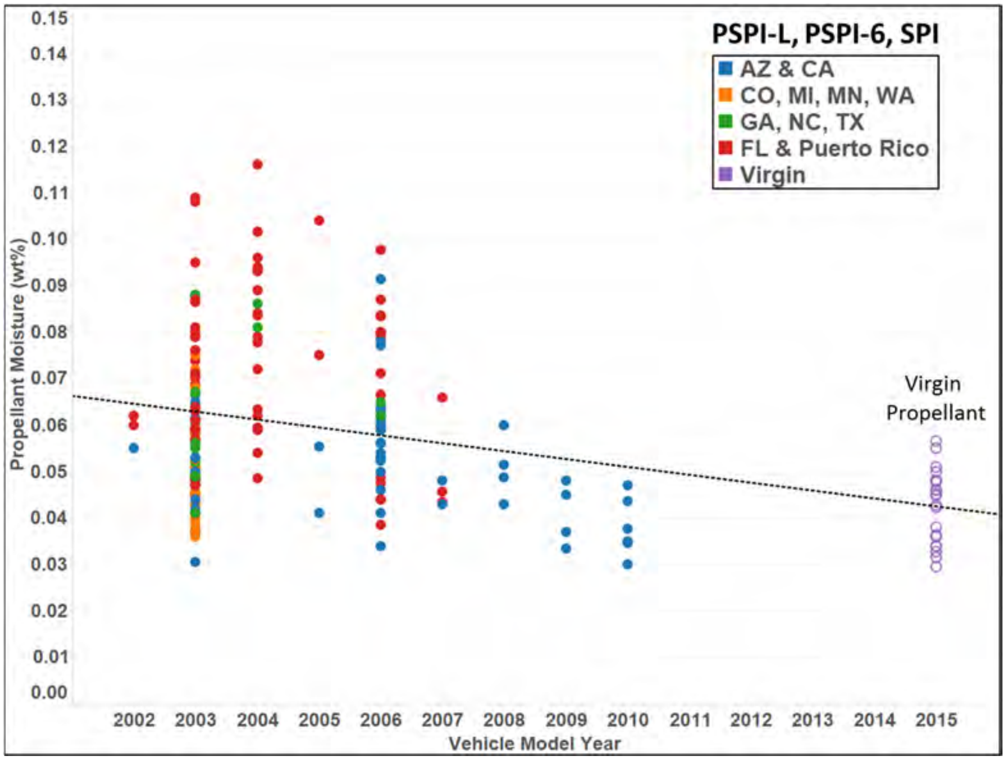

Figure 4. Moisture content in the 2004 propellant in various field returned inflators. (Data from the primary and secondary chambers are shown. The dotted line shows a linear fit through all of the presented data.)

Mercury Intrusion Porosimetry and Wafer Diameter

Mercury intrusion porosimetry (MIP) is a commonly used method for measuring the porosity and pore size distribution of materials. This technique measures the accessible void space inside a sample (i.e. porosity) based on the total volume of liquid mercury that can be intruded into the sample at increasing pressures. This technique can also be used to calculate the sample density and to estimate the size of the pores based on a theoretical relationship between pressure, mercury surface tension, and an assumed cylindrical pore diameter. When discussing MIP results in this report, "pore diameter" specifically refers to the value determined using the MIP technique. While the relationship between the MIP pore diameter and the actual shape and characteristics of the pores is complicated, the pore size distribution as calculated by MIP is a useful technique for characterizing inflator propellants. The primary MIP metrics discussed in this report are the normalized pore volume (mL/g/µm) and the porosity (%). The normalized pore volume is a measure of the porosity distribution of a sample as a function of pore diameter. Porosity is a measure of the accessible void space as a fraction of the sample volume. In Figure 5 and Figure 6, the porosity of the sample is represented by the area under the normalized pore volume curve.

The pore size distributions of virgin wafers from bulk material and a variety of inflators are shown in Figure 5. Generally, virgin materials do not show significant porosity at pore diameters greater than 0.4 µm. All virgin materials show nearly identical pore diameter distributions that are typically limited to the shaded triangular region illustrated in Figure 5. This region is used to represent the normal range of pore size distributions for virgin material as compared to field exposed materials.

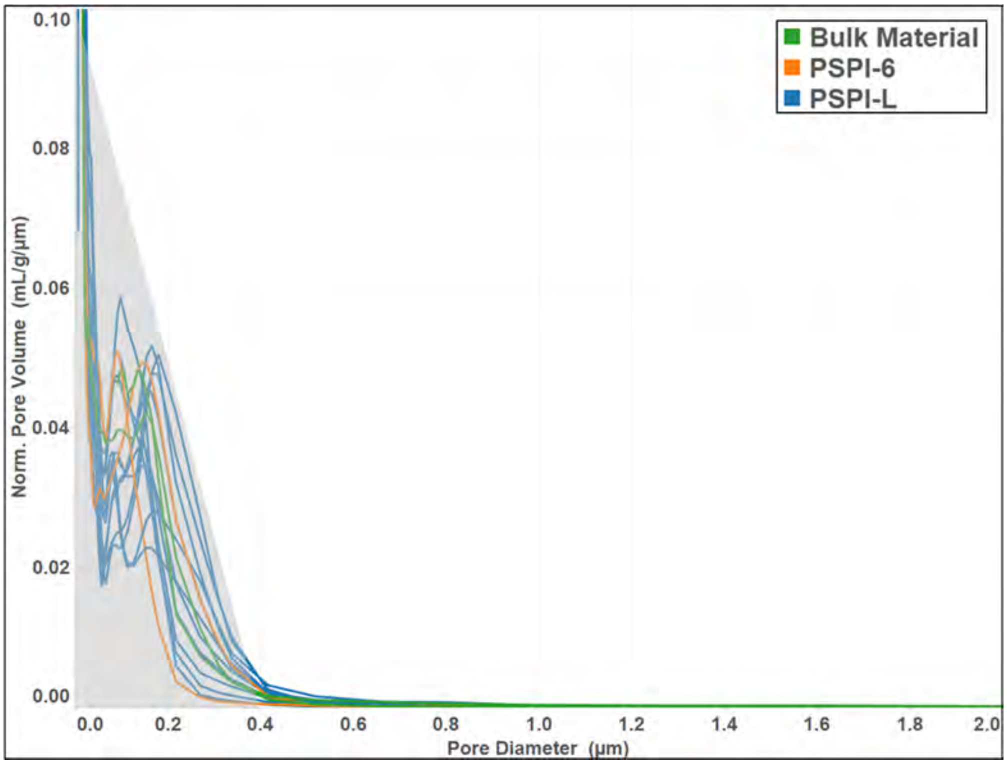

Figure 5. MIP pore size distribution for a variety of virgin 2004 propellants. (Bulk material refers to pressed 2004 propellant received directly from Takata prior to assembly into any inflators. Similarly, test material for PSPI-6 and PSPI-L was extracted from virgin inflators.)

As shown in Figure 6, passenger inflators recovered from the field exhibit increased porosity at larger pore volumes as compared to the initial porosity present in virgin inflators. This is indicated by the pore size distribution that lies outside the triangular gray region representing the porosity distribution envelope of virgin materials. Furthermore, high porosity at larger pore diameters primarily occurs in inflators that exist in regions of high temperature and humidity, such as Florida and Puerto Rico. For inflators from a given region, there is significant scatter in the porosity.

Most inflator types exhibit elevated porosity after several years of use in vehicles in comparison to virgin materials, though caution should be used when comparing the MIP data in Figure 6 for different inflator designs. For example, PSPI-6 inflators have less time in service than other designs and limited data from high humidity regions; thus, Figure 6 likely does not capture the full range of porosities of PSPI-6 inflators that can occur in regions of high absolute humidity.

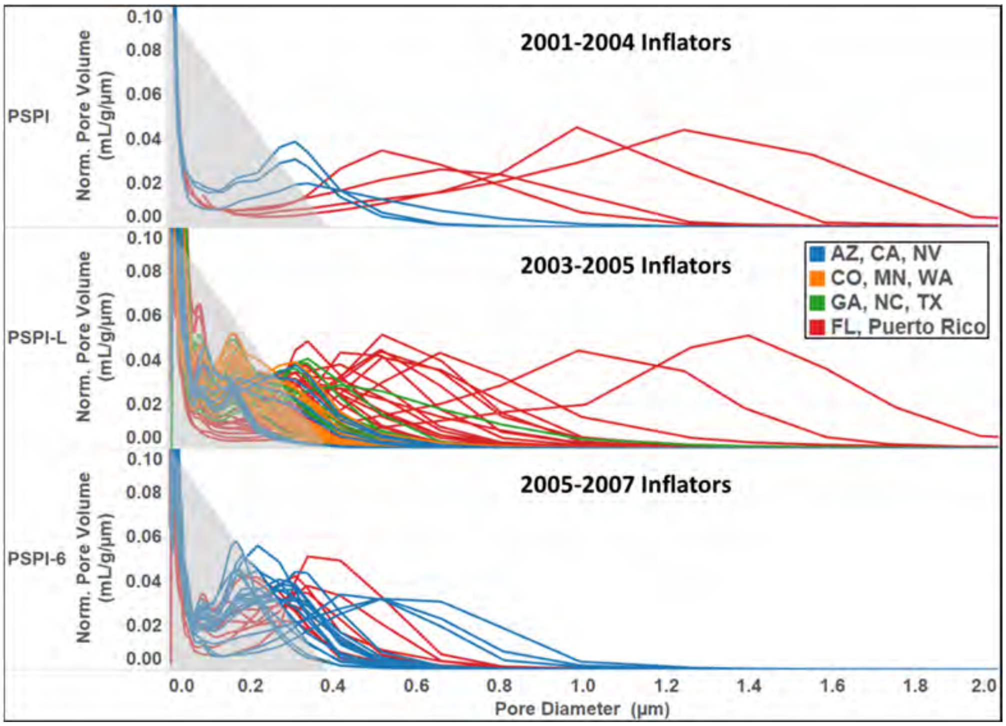

Figure 6. MIP pore size distribution for 2004 propellant wafers from field returned inflators. (Data from the primary and secondary chambers are shown. The gray region illustrates the range of typical pore size distribution in virgin materials.)

To facilitate the analysis of large amounts of MIP data, the fraction of the total porosity above 0.5 µm pore diameter was used as a metric to illustrate the porosity of materials beyond the 0 to 0.4 µm pore diameter envelope that typically contains most of the porosity in virgin materials. The choice of porosity over 0.5 µm as a metric for characterizing changes to field materials is explained further in the next section of this report (Closed Chamber Testing). As shown in Figure 7, porosities above 0.5 µm typically occur in regions with high humidity and high temperature. Available field data are predominantly from such regions. However, even in hot and dry environments like Arizona, the large daily temperature cycles in the absence of significant moisture ingress can also cause propellant degradation over a prolonged period. High moisture content alone in the absence of temperature cycling will not increase degradation.

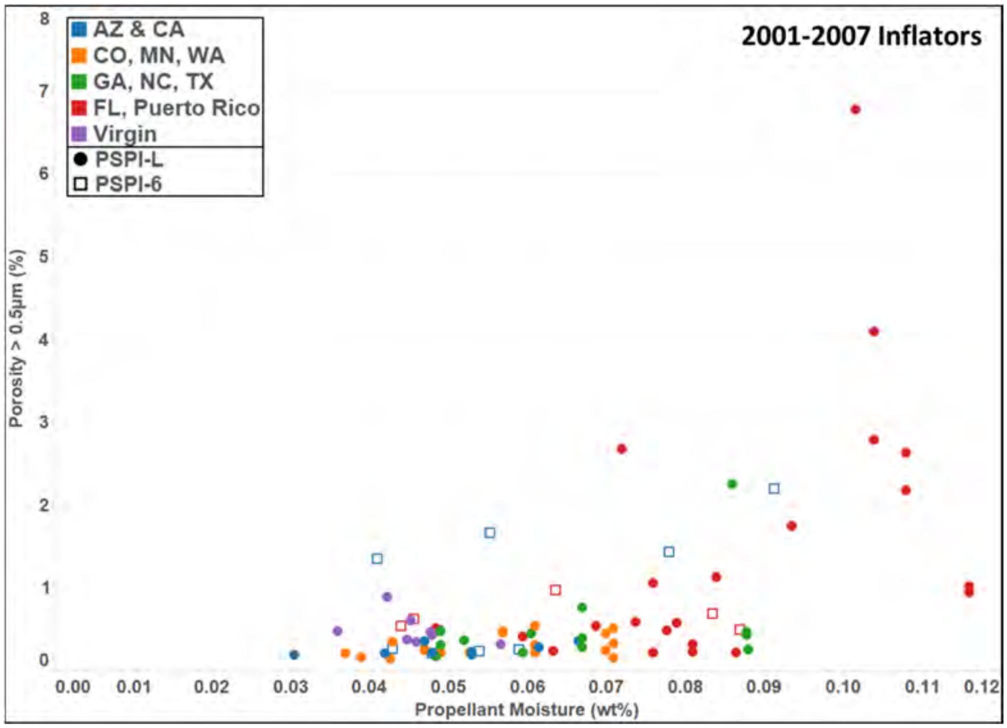

Figure 7. MIP porosity versus propellant moisture for 2001-2007 inflators from selected states.

The relationship between porosity and the time in the field follows similar trends observed for the propellant moisture content. As shown in Figure 8, porosity above 0.5 µm typically increases with time in the field, though for any given inflator age, the propellant may exhibit a wide range of porosities. Furthermore, the highest porosities are only observed for older inflator materials, which suggests that time in the field is a key factor for the development of porosity, especially above 0.5 µm. Based on the dissection of virgin inflators and undeployed field returned inflators with high moisture content and porosity, there were no apparent manufacturing defects that may have resulted in increased moisture intrusion.

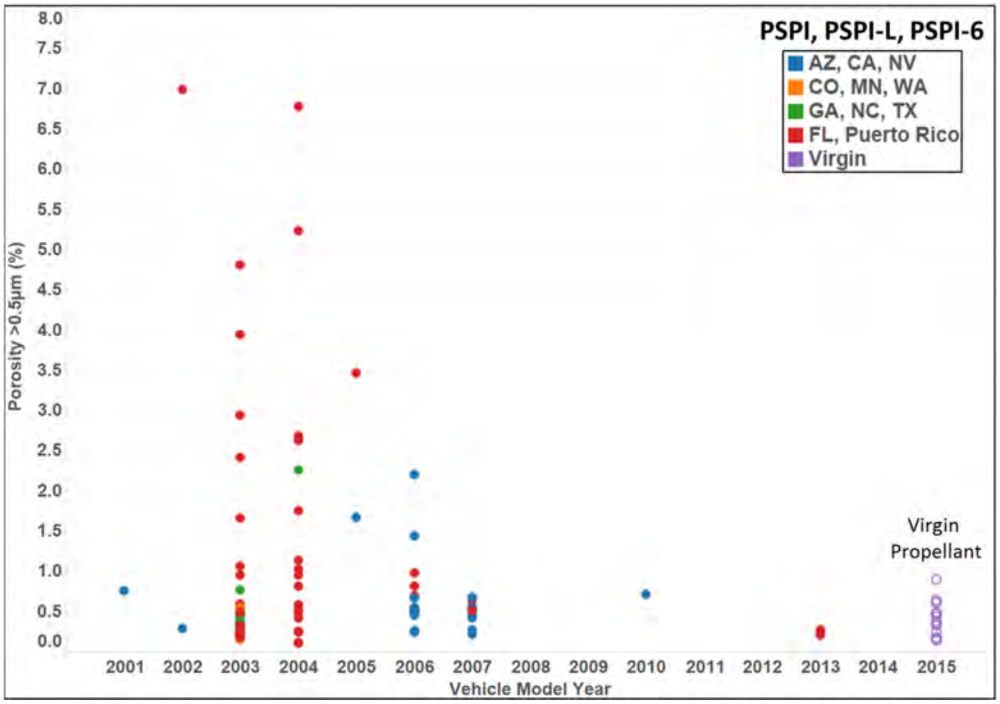

Figure 8. MIP porosity (for pore size above 0.5 μm) in 2004 wafers from inflators of different model year and location of operation.

Exponent's analysis of field returned inflators indicates that the outer diameters (OD) of 2004 propellant wafers increase for degraded wafers and are associated with a reduction of the propellant density. Wafer OD is a useful metric for assessing the condition of field returned inflators because it is one of the few characteristics of 2004 propellant that can be readily measured using non-destructive techniques, such as X-Ray or CT. Figure 9 shows that porosity above 0.5 µm increases with larger ODs. All inflator types exhibit a similar relationship between OD and porosity. The largest ODs are observed in inflators from high humidity, high temperature regions such as Florida and Puerto Rico.

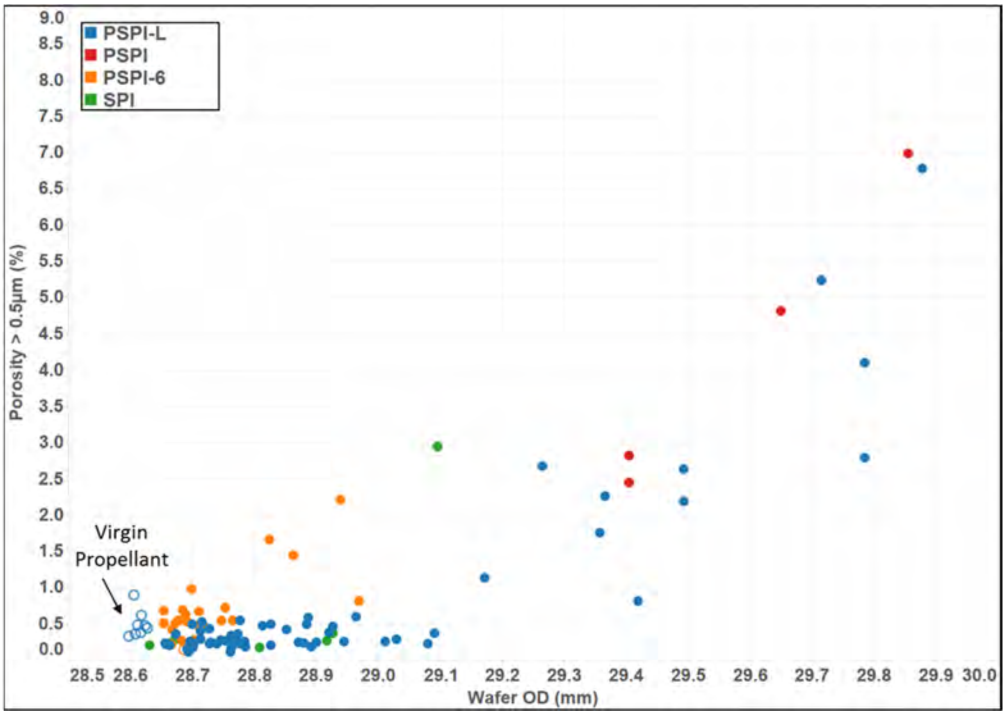

Figure 9. MIP porosity above 0.5 μm pore diameter versus OD for propellant wafers from different inflator designs. (The nominal OD for virgin wafers is 28.6 mm, as denoted by the hollow circles.)

Closed Chamber Testing

To characterize the burning behavior of 2004 propellant, Exponent performed pressure-time history measurements during propellant ignition in a closed 57 mL chamber. The measured pressure-time history is primarily sensitive to the mass consumption rate of the propellant.

The relationship between the wafer OD, porosity, and pressure-time history for selected 2004 wafers is shown in Figure 10. Wafers with larger ODs (corresponding to high porosity and lower density) exhibit significantly higher propellant mass consumption rates, as indicated by the increase in the slope of the pressure-time history. The pressure at which the mass consumption rate deviates from the nearly linear pressure increase (referred to as the excursion pressure) is typically lower for materials with larger pores. While some increase in porosity in comparison to virgin material (shown in blue in Figure 10) has no effect on the mass consumption rate in closed chamber tests, once significant porosity is generated at pore diameters larger than approximately 0.5 μm, excursions of the mass consumption rate relative to virgin propellants begin to occur. Simulations of inflator pressure using the accelerated mass consumption rates observed in closed chamber tests indicate that the increase in propellant mass consumption and gas generation is sufficient to cause significant inflator overpressure and/or ruptures. Exponent's analysis and testing also demonstrate that the characteristics (moisture content, pore size distribution, and OD) of different wafers within a given inflator are very similar. As a result, repeat closed chamber tests using materials from the same inflator produce consistent results.

The peak pressure, which in closed chamber tests is primarily dependent on the chemical properties of the propellant, does not change significantly for degraded and virgin propellants. This observation—in addition to other material characterization methods such as FTIR, DSC, GS-MS, and XRD—indicate that chemical sensitization is not the cause of the accelerated burning observed during testing. Exponent's closed chamber tests indicate that accelerated burning of degraded propellants occurs even in the absence of any other intervening factor, including degraded or altered booster material.

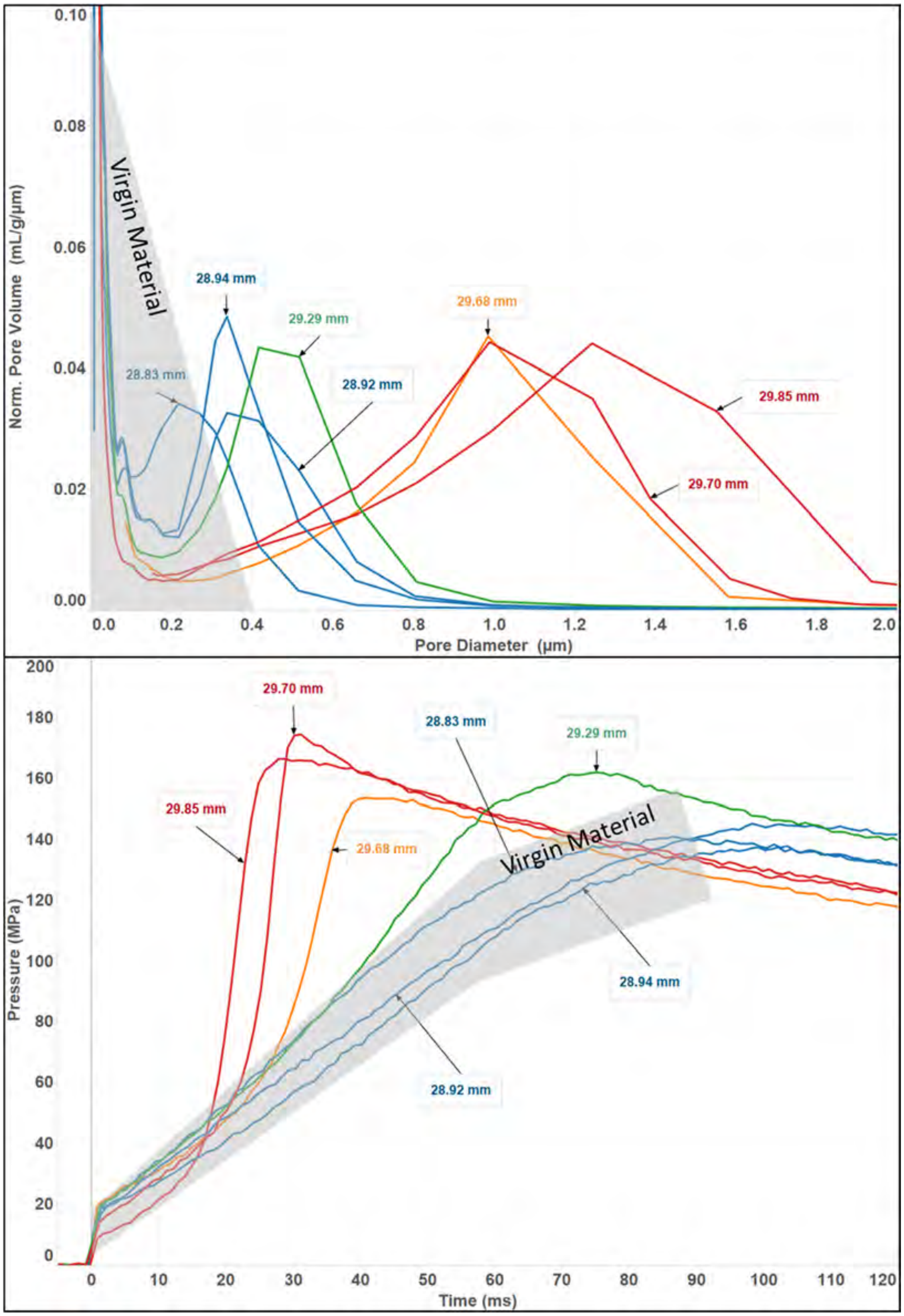

Figure 10. Pore size distribution (top) and corresponding closed chamber pressure-time histories (bottom) for selected 2004 10.8 g wafers. (Curves with the same color in each plot represent materials from the same inflator identified by OD of the MIP tested wafer. The gray area represents the typical range of behavior of virgin materials.)

Full Inflator Pressure Tests

In order to better understand the pressurization and gas dynamics of the inflators, Exponent measured the pressure inside the propellant chamber in a variety of inflators. As shown in Figure 11, the majority of tested field returned inflators exhibit pressure profiles comparable to their virgin counterparts. Similar observations can be made from a review of the Master Engineering Analysis File (MEAF) data Takata compiled from their tests of field returned inflators. Two of the Exponent tests shown in Figure 11 exhibit degradation and pressure increases that resulted in inflator ruptures. Both ruptures occurred in Florida inflators and exhibited similar characteristics to ruptures observed in field returned inflators that were cycled in a laboratory between 2-80°C in a 4-hour cycle, as shown in Figure 12.

For the inflator ruptures to occur, a threshold of increased porosity is needed to result in the increased propellant consumption rate by mechanisms such as porous burning and micro bursts of degraded propellant that can rapidly increase the propellant surface area. This is consistent with observations made during the closed chamber tests discussed in the previous section.

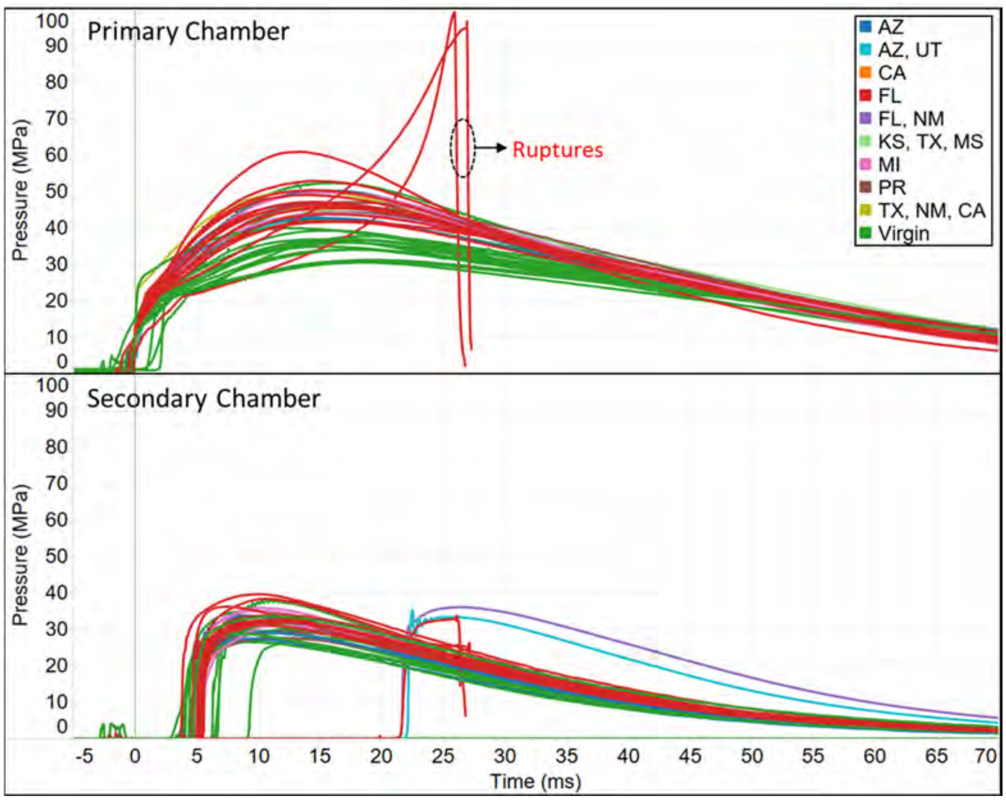

Figure 11. Measured pressure-time histories for virgin and field returned PSPI-L inflators. Data were acquired with various time delays between the deployment of the primary and secondary chambers.

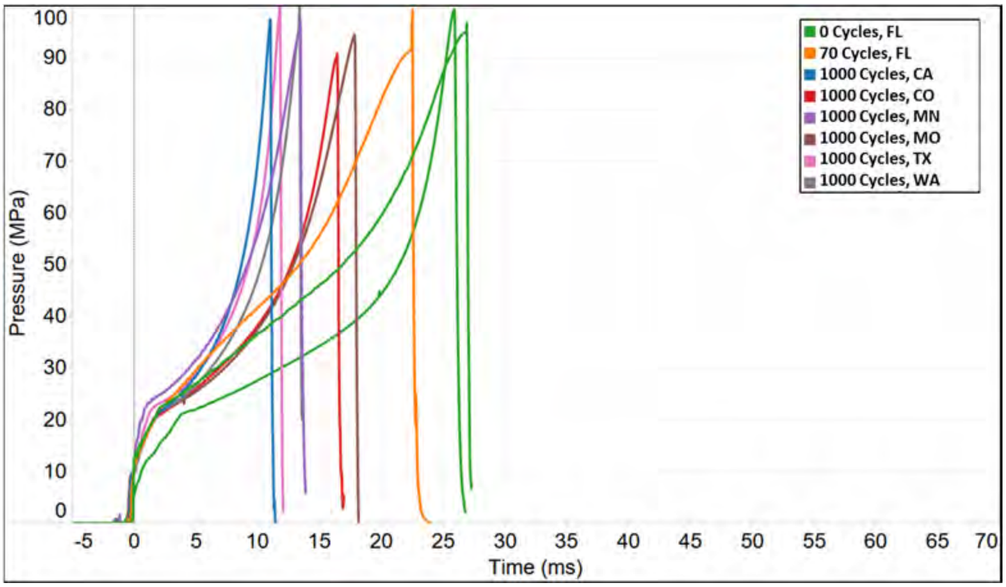

Figure 12. Measured pressure-time histories for ruptured field returned PSPI-L inflators. (All ruptures occurred in the primary chamber. Cycling conditions were 2-80°C, 4 hours/cycle.)

Temperature Cycling of Passenger Inflators

Exponent performed temperature cycling of inflators and their constituent materials to study porosity development of the propellants in a controlled environment. Whole inflators were cycled without modification. Additionally, materials extracted from inflators were cycled in custom-designed closed chambers to characterize the effect of temperature cycling in the absence of other factors that might contribute to the degradation of the propellant.

Cycling of Whole Inflators

Both virgin and field returned inflators were cycled under a range of temperature and humidity environments. For example, virgin passenger inflators were temperature cycled (2-80°C, 4 hours/cycle) in an environmental chamber. Propellant material cycled 800 times developed significant porosity, as shown in Figure 13, and exhibited elevated mass consumption rates in closed chamber tests, as shown in Figure 14. Figure 15 shows the results of pressure tests of these inflators during which one unit ruptured. These tests demonstrate that cycling of virgin inflator materials without added moisture can cause increased porosity in the propellants that can lead to inflator rupture. CT scans of propellant from cycled virgin inflators shows that degradation is concentrated nearer to the surface of the material in comparison to degradation observed in field returned samples where porosity appears to be more uniformly distributed.

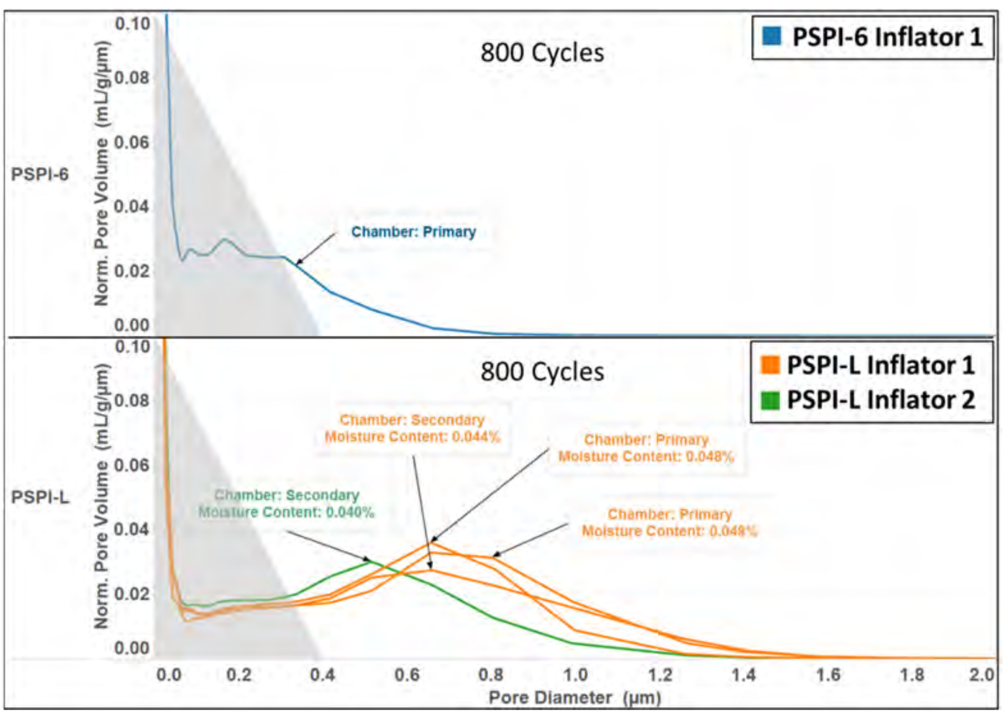

Figure 13. MIP pore size distribution of virgin inflators cycled 800 times (2-80°C, 4 hours/cycle).

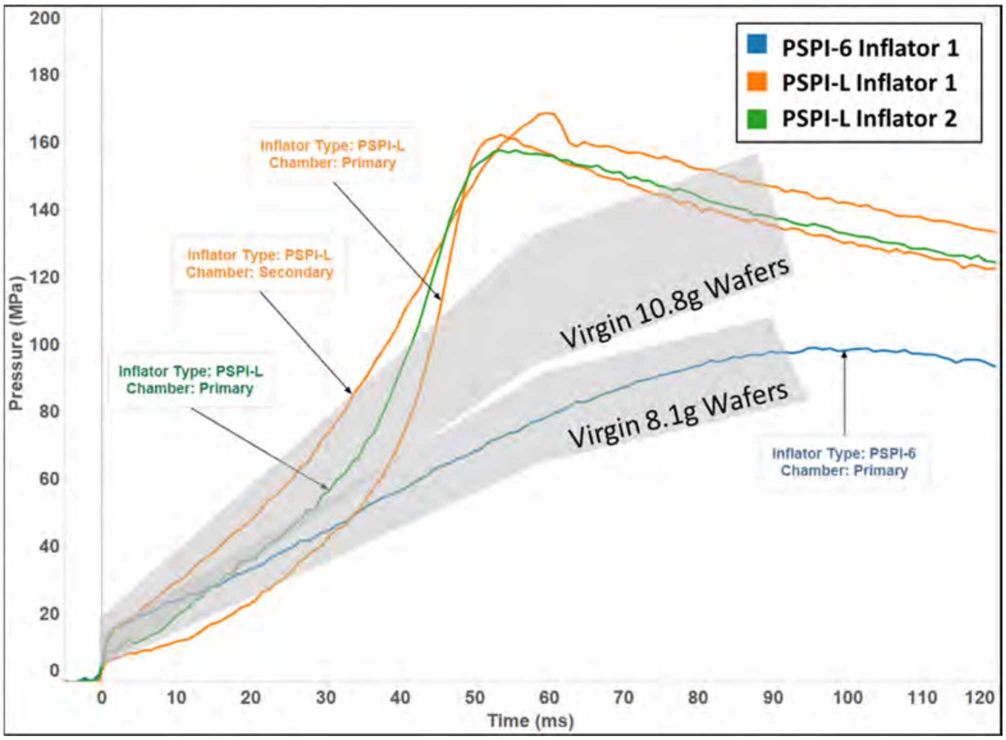

Figure 14. Closed 57 mL chamber pressure-time history of virgin inflators cycled 800 times (2-80°C, 4 hours/cycle). (10.8 g wafers are present in PSPI-L inflators and 8.1 g wafers are present in PSPI-6 inflators.)

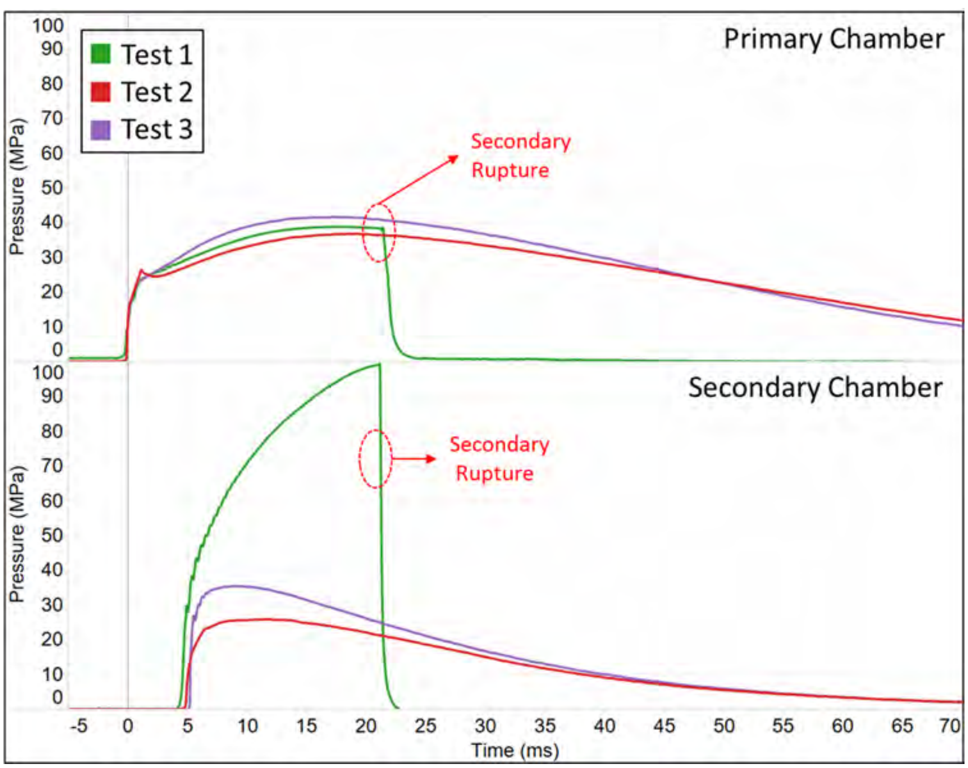

Figure 15. Inflator pressure-time history of virgin PSPI-L inflators cycled 800 times (2-80°C, 4 hours/cycle).

Cycling of 2004 Propellant

Exponent undertook a series of temperature and humidity cycling tests with individual 2004 propellant samples. These tests were done with materials extracted from both virgin and field returned inflators, bulk 2004 wafers, and custom-formulated propellant wafers. For example, Exponent performed temperature cycling (2-95°C, 3 hours/cycle) of 2004 propellant materials from field returned inflators in custom-designed 77 mL sealed chambers. Field propellant used in the testing was characterized extensively prior to cycling to distinguish the existing degradation that occurred in the field from subsequent degradation that occurred during cycling. The purpose of this testing was to isolate the effect of moisture movement between 2004 propellant and its surrounding headspace, and to eliminate any contribution to 2004 porosity development from any other source; for instance, communication with the booster or interaction with components inside the inflator, such as the spring or filter.

As shown in Figure 16, the porosity of the 2004 propellant increases with the number of cycles, and the MIP pore size distribution is similar to that observed in propellant from field degraded inflators. These data indicate that propellant degradation can occur solely due to the temperature cycling of the propellants in a closed headspace. Closed chamber tests for the most degraded samples exposed to 500 cycles (shown in Figure 17) exhibit pressure excursions similar to those observed in degraded field samples, as shown in Figure 10.

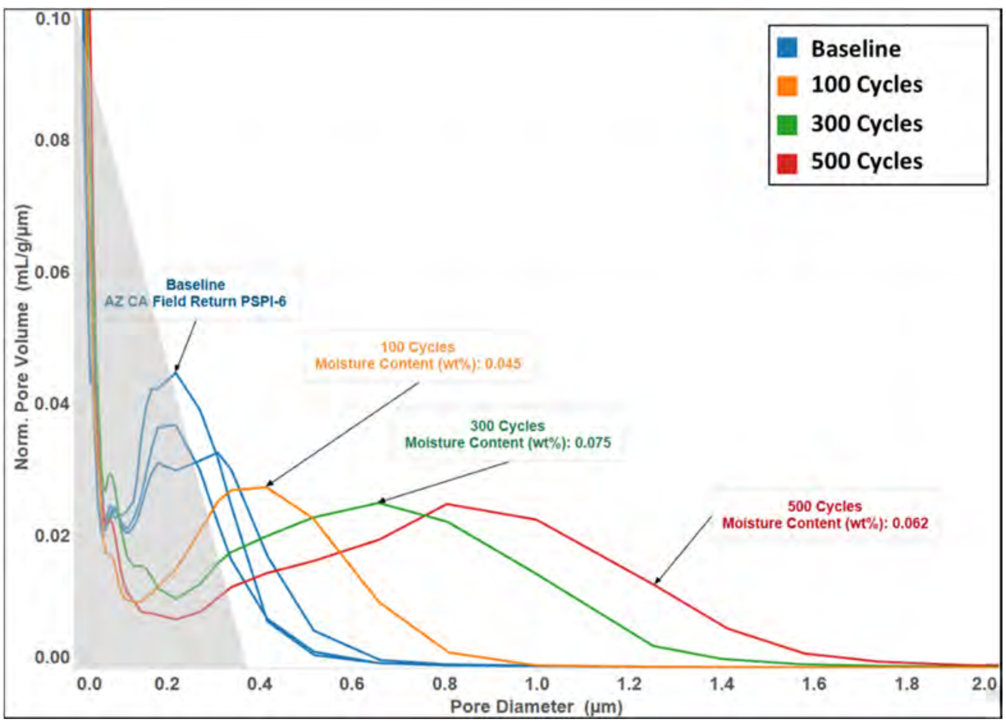

Figure 16. MIP pore size distribution of field returned 2004 propellant cycled (2-95°C, 3 hours/cycle) in 77 mL chambers. (The baseline data were obtained from the population of 2007 model year Arizona and California field samples that were used in the subsequent cycling.)

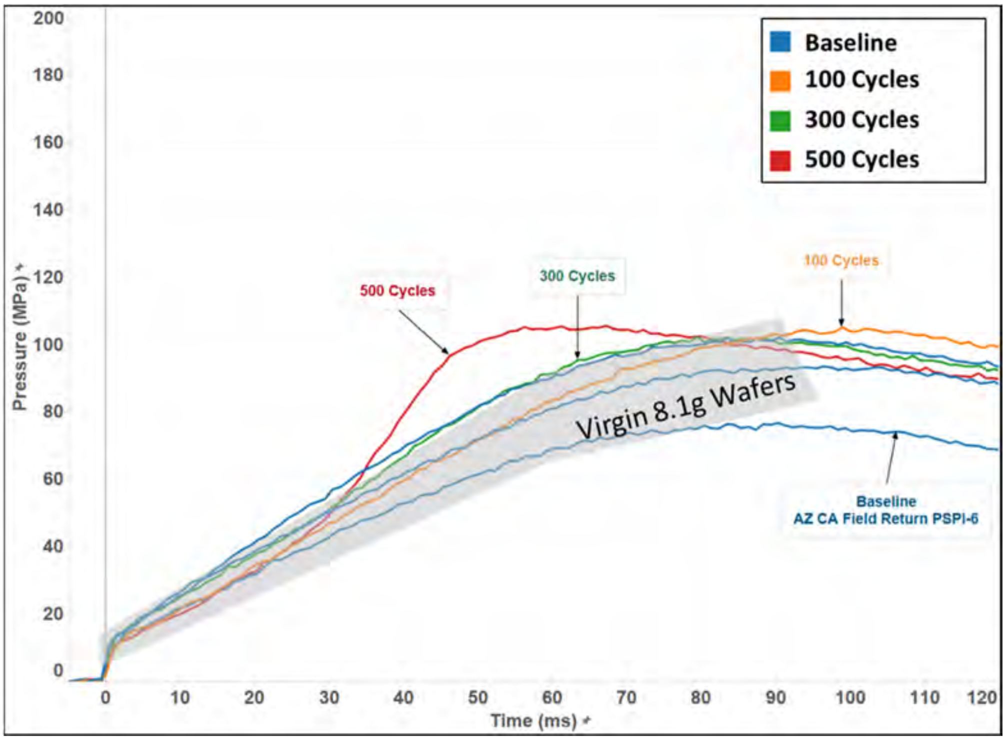

Figure 17. Closed chamber test pressure-time histories for field returned 2004 propellant cycled (2-95°C, 3 hours/cycle) in 77 mL chambers. (The baseline data were obtained from the population of PSPI-6 field samples [8.1 g wafers] that were used in the subsequent cycling.)

Modeling

A numerical model was developed to assess the relative degradation of 2004 propellant in passenger inflators for different geographic areas throughout the United States as a function of time in service. The cumulative moisture flux—defined as the total cumulative movement[1] of moisture in the 2004 wafers as a percentage of the total weight of 2004—was selected as a surrogate measure of degradation. This metric was chosen because it correlates well with the field observations and laboratory testing of propellant degradation and is highly dependent on variables like time in service, temperature oscillations, propellant moisture content, and overall temperature. Prior to any moisture movement into and out of the propellant, the moisture flux is defined as 0%.

The model relies on characterization studies of several phenomena, including historical environmental conditions (ambient temperature, humidity levels, and solar radiation) for various geographic locations, rates of ingress of moisture as a function of external humidity, impact of solar heating on vehicle temperature, 2004 and 3110 moisture content, moisture exchange of 2004 and 3110 with their respective headspaces, and moisture exchange between the booster and propellant chambers. For each of these factors, tests and analyses were performed to develop input parameters for the numerical model. The simulations developed in the model use continuous exposure of the vehicle to outdoor environmental conditions at the location under consideration.

The effect of moisture infiltration through seals from ambient humidity was studied theoretically and experimentally. Experiments using environmental chambers to control the temperature and humidity of the tested parts generated data used in the modeling to quantify moisture ingress. Additional studies were performed to assess moisture movement between the booster compartment and the inflator compartment. These studies provided fundamental data that were used to quantify moisture movement through various seals in the inflators.

The model fundamentally operates on the principle that moisture movement within the inflators occurs based on a difference in the partial pressure of water vapor between the various inflator chambers. Furthermore, moisture movement in and out of the propellants occurs based on the difference between the headspace humidity surrounding the propellants and the equilibrium relative humidity (ERH) of the propellants at a particular moisture content and temperature. The ERH values are important properties of the propellant and the booster material. They were obtained by measuring the headspace humidity sustained by propellant and booster materials of different moisture contents across a range of temperatures. Other factors include the times needed to reach equilibrium for the different materials, which were also studied by measuring the moisture uptake and release rates of the propellants at various conditions. Generally, the time to reach equilibrium conditions for 2004 and 3110 was on a comparable time scale to diurnal cycling, so kinetic factors were included in the model.

[1] Both the movement into and out of the material positively contributes to moisture flux.

A summary of the inputs, assumptions, and calculation procedure in the numerical model are shown in Figure 18

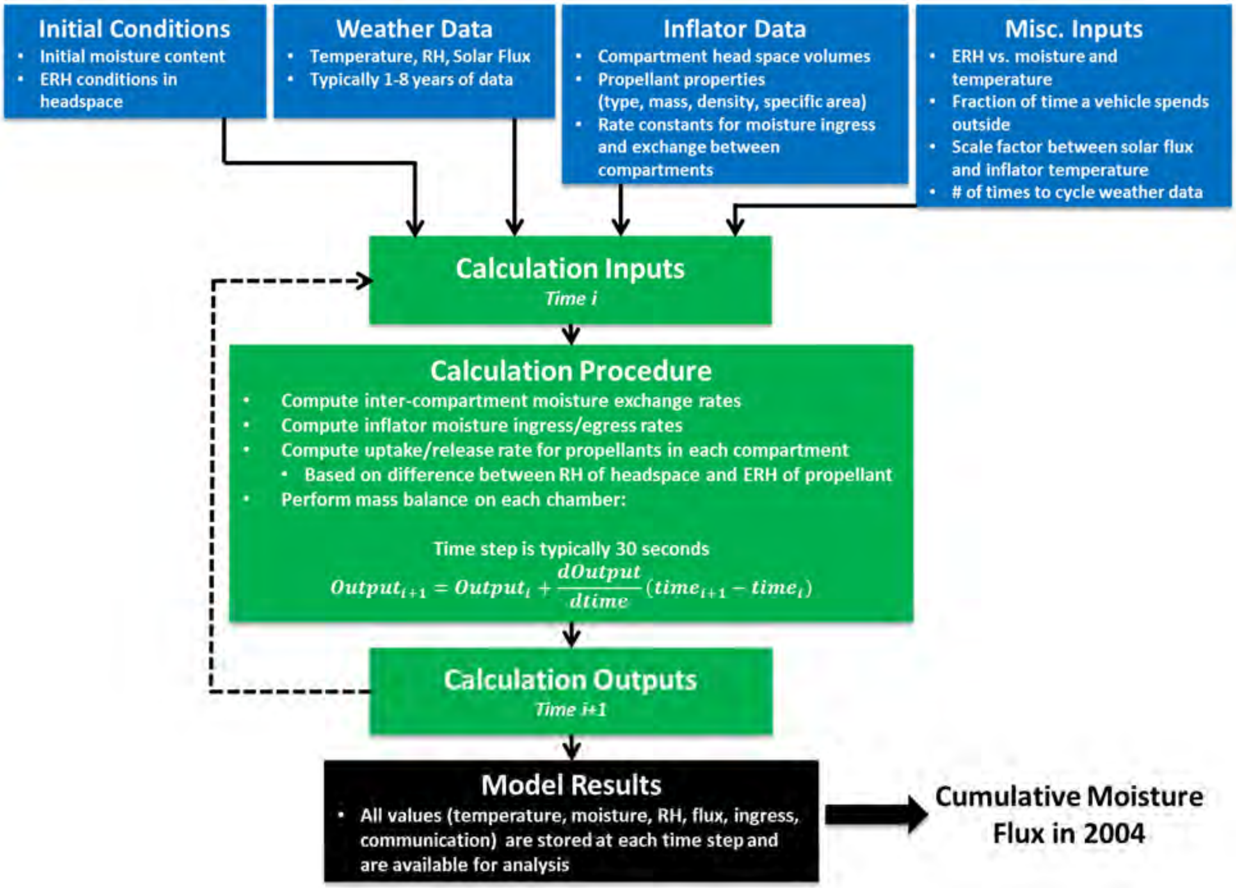

Figure 18. Summary of the inputs, assumptions, and calculation procedure in the Exponent numerical model for tracking moisture movement in the inflator.

The calculated moisture contents of the propellant and booster materials were compared with measurements from various field returned inflators for different periods in service. There was good agreement between the calculated and measured moisture content. The level of observed degradation of the propellant was found to be better correlated with the calculated moisture flux than the measured moisture content at a given time. This is confirmed by the rates of inflator ruptures presented in Takata MEAF data for field returned inflators returned from different geographic locations.

Sensitivity analyses were also performed to assess how degradation and the potential for rupture would be affected by changes in inflator geometry or the assumptions and values used in the analyses. While various assumptions and geometries affect the time until cumulative moisture flux reaches levels where inflator ruptures might start to occur, all of the inflator geometries studied have the potential to reach these levels. Analysis shows that the calculated moisture flux is sensitive to heating of the vehicle, initial moisture content in the propellant, and permeation rates of moisture into the inflator. For example, a 22% increase in the magnitude of the temperature fluctuations caused by solar radiation increased the moisture flux by 24% relative to the nominal value. Parameters such as booster-to-main-chamber communication and initial moisture content in the booster material do not significantly affect the calculated moisture flux.

Results for Selected Locations

The model results for selected locations representing different environmental conditions within the United States are shown in Figure 19. This plot describes the calculated response of the primary chamber of a PSPI-L inflator installed in the same vehicle in various locations across the United States over 22 years of outdoor exposure. During this period, moisture ingress occurs in the inflator at varying rates depending on the geographic location. There is significant variation in 2004 moisture flux depending on the location; for example, the 2004 moisture flux in Seattle, Washington is 80% less than in San Juan, Puerto Rico over the same period of time. The model also indicates that even though inflators installed in vehicles in dry regions may not contain high moisture content in the propellant, the moisture flux can still be significant due to large daily temperature fluctuations.

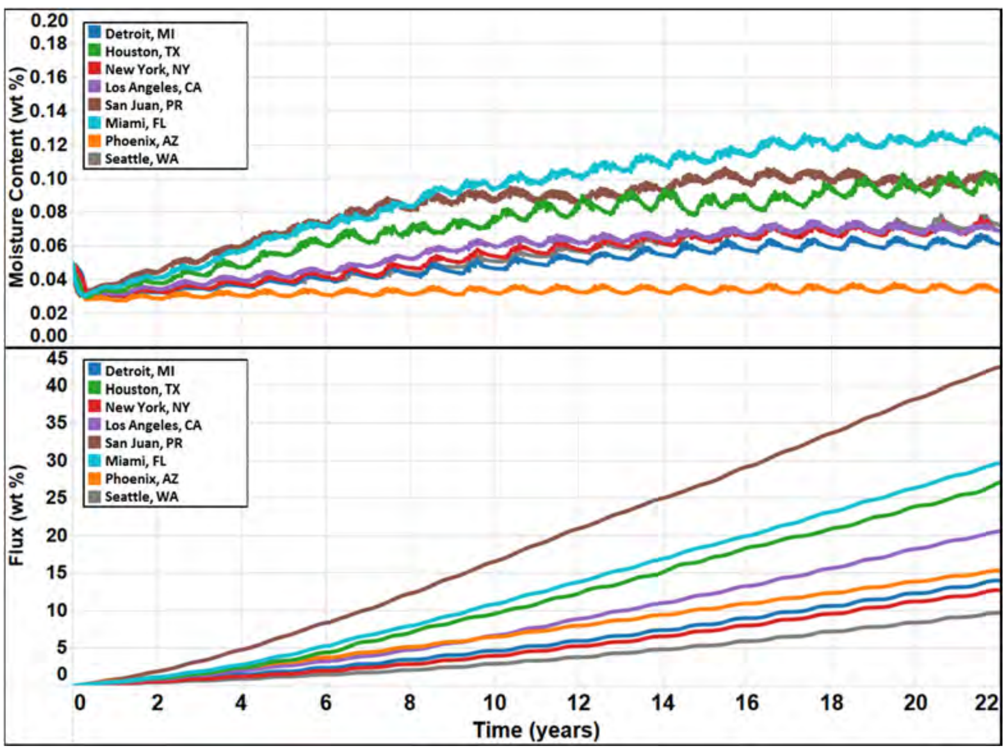

Figure 19. Moisture content and moisture flux in the 2004 propellant material over time in a PSPI-L primary chamber with outdoor exposure in different cities across the United States.

Model Results Summary

The model was run for the environmental conditions present in over 600 cities in the United States. The data were plotted on maps as the number of years it would take for the cumulative moisture flux to reach a value of 8%. The 8% moisture flux value was determined empirically by comparing the predicted cumulative moisture fluxes for inflators from different regions with the data available to Exponent to date regarding the real-world inflator rupture observations, as well as the available data from pressure tests on field returned inflators. The correlation of the available pressure test data to the 8% flux value is described in more detail in the next section of this report. Both datasets indicate that inflators in hot and humid regions have the shortest time in service to reach the 8% threshold and that the opposite is true for colder and drier climates.

Figure 20 shows the number of years it takes for a PSPI-L inflator to reach 8% moisture flux in different parts of the United States. A smaller number indicates a faster buildup of moisture flux (greater degradation rate) in the 2004 propellant. The vehicle model year that will reach 8% moisture flux at January 1, 2016 is shown in parenthesis. Of the locations considered in the analysis, the shortest time to achieve 8% moisture flux (or fastest degradation) is about 6 years, which occurs in San Juan, Puerto Rico. In general, the areas of highest degradation are in hot and humid climates of the southeastern United States, which include Puerto Rico, southern Florida, and the coastal areas around the Gulf of Mexico. Areas with the lowest degradation are typically in the north and in the areas around the Rocky Mountains.

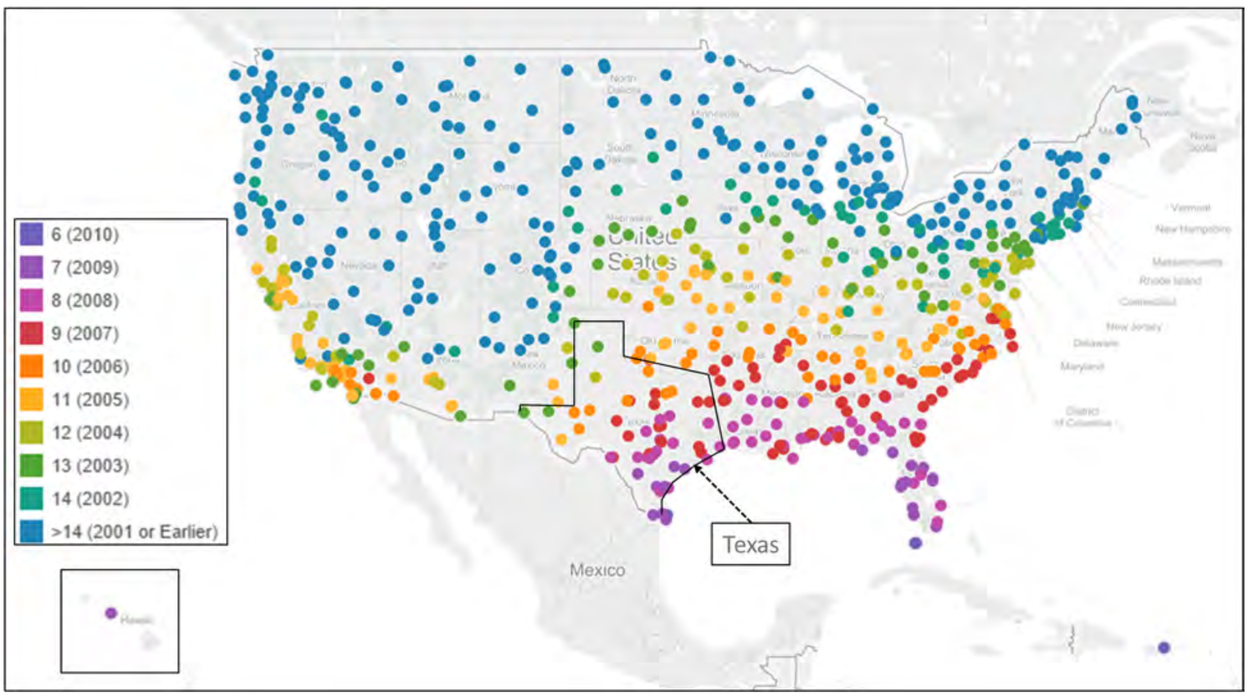

Figure 20. Map of number of years to get to 8% moisture flux in 2004 propellant (and vehicle model years reaching 8% moisture flux on January 1, 2016). Texas is outlined to illustrate the variations within a given state.

For many geographic locations with diverse climates, the time to reach a target moisture flux can vary substantially from one location to another. Time to reach target moisture flux can also be substantially different than those shown in Figure 20 for vehicles crossing over to different climate zones. These include vehicles that are used for extended visits to areas with substantially different climates. As shown in Figure 20, the 51 weather stations analyzed within the state of Texas show large variation in the time it takes to reach 8% moisture flux, ranging anywhere between 6.5 to 12.7 years (vehicle model years of 2003 to 2010).

Calculated Moisture Flux Compared to Rupture Rates in Takata Testing

Takata provided data from pressure testing of approximately 40,000 PSPI-L inflators that were collected from the field as part of the recall. Of these, 336 inflators ruptured during the tests performed by Takata. The tested inflators represent many geographic regions and inflator ages. Over 600 locations were analyzed, and a moisture flux was calculated for each of the tested inflators. For these calculations, we assumed that the vehicle remained at the last reported location for the entirety of its life and was continuously exposed to outdoor environmental conditions. Figure 21 shows that the calculated moisture flux and the rate of rupture from Takata’s tests are correlated such that an increase in maximum moisture flux results in an increased rate of rupture, confirming that 2004 moisture flux can be used as a measure to assess propensity of degradation or rupture. No inflator rupture occurred in over 8,000 tests that were performed on inflators with flux below 7.6%. Only three ruptures occurred for flux values calculated to be between 7.6% and 8%. Of these three, two are from vehicles that have a higher solar coefficient than that used in the calculations. A moisture flux of 8% is thus chosen as a conservative threshold for defining the onset of increased rupture potential for the primary chamber in PSPI-L inflators based on test data available to date.

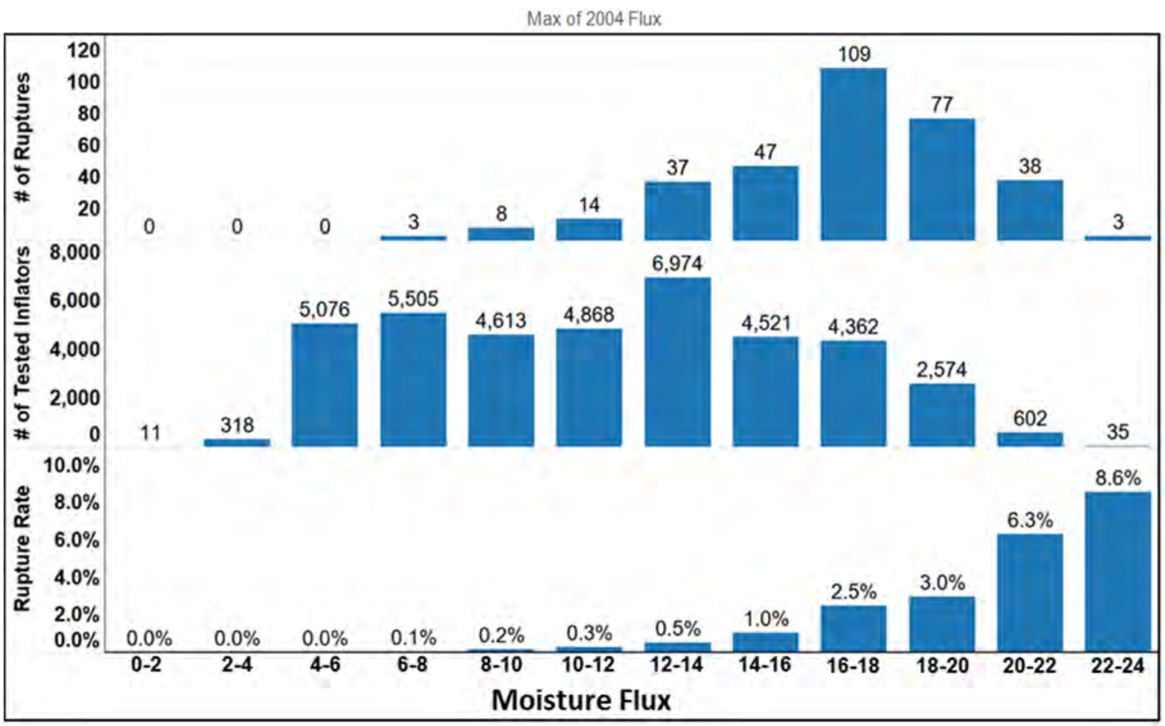

Figure 21. Rate of PSPI-L inflator rupture in Takata testing as compared to the calculated 2004 propellant moisture flux. No ruptures occurred below 7.6% moisture flux as calculated using the parameters specified in the model.

Conclusions

Exponent determined that the ruptures of Takata PSAN-based inflators occurred due to physical degradation of the propellant in the form of larger internal pores, resulting in elevated pressures that exceed the mechanical strength of the inflator housing. The degradation of the propellant arises from diurnal and seasonal temperature cycling, and it is exacerbated by higher peak cycle temperatures and increased moisture content in the inflator. Temperature fluctuations of the inflator cause moisture exchange between the propellant and the surrounding headspace, which ultimately leads to the development of porosity. As pore size increases beyond a certain threshold due to degradation, the rate of propellant consumption (and hence gas generation) increases significantly in comparison to propellants with minimal or no degradation. The elevated gas generation rate of the degraded propellants significantly exceeds the capabilities of the inflators to vent those gases. This results in an increased rate of pressurization and peak pressures that can exceed the mechanical strength of the inflators and cause the housing to rupture.

The propensity for rupture depends on several factors, including: time in service, temperature fluctuations, high environmental temperature, humidity, and solar radiation. Consequently, the areas of highest degradation are in hot and humid climates typical of the southeastern United States, including Puerto Rico, southern Florida, and the coastal areas around the Gulf of Mexico. Even within a particular geographic location, propellant degradation can vary due to individual vehicle differences and differences in their environmental exposure. In addition, the type of degradation that leads to rupture can occur in most geographic locations over a sufficient period of time.

Exponent's investigation also considered other potential causes of inflator ruptures, such as vent hole and filter blockage, structural degradation or inadequate strength of the inflator housing, and chemical sensitization of the propellant and booster materials. None of these potential causes were found to be viable explanations for the ruptures observed in field returned inflators.

As part of this investigation, a numerical model was developed to predict moisture movement in the inflators over time for different inflator types, geographic locations (including local weather and solar conditions), and initial moisture content of the propellant and booster materials. Characterization of the moisture ingress into the inflator, moisture movement within the inflator, and the kinetics of the moisture exchange between the propellants and the inflator headspace are based on extensive experimental testing. Weather data from over 600 weather stations around the United States were collected and used in the model to predict the cumulative propellant moisture movement, and by correlation the degree of degradation, for vehicles operated in different regions. The model was validated by comparing model predictions to real-world performance of inflators. Though the model provides an estimate of propellant degradation at various geographic locations, it is not intended to provide the degradation profile of any individual vehicle. A conservative estimate of the degradation threshold for ruptures in a particular geographic region is obtained from an analysis of currently available data on both the field ruptures and ruptures of field returned inflators in laboratory testing.