UNITED STATES DEPARTMENT OF TRANSPORTATION

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

1200 New Jersey Avenue SE

Washington, D.C. 20590

In re:	)	
	)	**EXHIBIT A**
EA15-001	)	
Air Bag Inflator Rupture	)	
	)	
	)	

1. I have been retained by the National Highway Traffic Safety Administration (NHTSA) to consult on scientific issues related to the Agency's investigation into rupturing air bag inflators manufactured by TK Holdings Inc. (Takata), including assisting NHTSA in identification and verification of the root-cause(s) for the inflator ruptures, and assessment of technical data provided by General Motors (GM) to NHTSA in support of its Consolidated Petition[1] for inconsequential defect for inflators in certain vehicles produced by GM on the GMT900 platform.

2. The GM vehicles under Petition are equipped with defective Takata inflators that fall within two of several families of air bag inflators, the "SPI" and the "PSPI-L." Within those families, individual inflator variants are further designated by two letter codes which primarily differ by the propellant charge details required to meet individual automakers' specific air bag fill requirements. The variants tuned for the GM vehicles under Petition are "SPI YP" (YP) and "PSPI-L YD" (YD). In some instances, one inflator variant is used on more than one vehicle platform, however, neither the YP nor YD variant is used in any other vehicle platform.

3. The term "GMT900" is used by GM and in this report to refer to a range of full-size pick-up trucks and sport utility vehicles manufactured by GM and sold under the brand names Cadillac, Chevrolet, and GMC. The specific vehicle models on the GMT900 platform, all subject to the Petition, are the Avalanche, Escalade, Escalade ESV, Escalade EXT, Sierra 1500, Sierra 2500/3500, Silverado 1500, Silverado 2500/3500, Suburban, Tahoe, Yukon, and Yukon XL.

[1] GM filed a petition for inconsequential defect with NHTSA in November 2016. GM filed additional petitions for newer model years of GMT900 vehicles in January 2017, 2018, and 2019. NHTSA consolidated all four petitions and collectively I refer to them as the "Consolidated Petition" or the "Petition."

4. The frequency of inflator ruptures for defective Takata non-desiccated PSAN[2] inflators, based on field ruptures or ruptures during testing of field returned parts, is generally under 1% for many inflator variants. This makes it difficult to structure a testing program that will be able to detect rupture events in a laboratory test program that are known from sampling of field returned parts to occur in 1% of tests. In principle sample counts must be high enough to detect the failure. Testing a small numbers of inflators, relative to the frequency of occurrence in field return parts, would not be conclusive if the sample count is not representative of the 1% rupture rate.

5. As explained in more detail below, I have reviewed the materials submitted by GM in support of the Petition including supporting materials provided by Orbital-ATK (OATK)[3] and Cornerstone Research (Cornerstone)[4] on GM's behalf.

6. Since filing its Petition in November 2016, GM has met with NHTSA numerous times to discuss the testing and studies performed by GM, OATK, Takata, and other parties. During the meetings, GM discussed and explained the planning, conduct, status, and results of the various work efforts performed in support of the Petition. OATK and Takata also participated in some of those meetings. I have attended those meetings and briefings either in person or via telephone and internet-based conferencing.

7. On August 23, 2017, GM along with OATK briefed NHTSA on the work conducted in support of GM's Petition. The presentation served as a comprehensive and conclusory summary of all work conducted to that date.[5] In total, GM identified over 30 separate analyses and tests utilized in its investigation of the GMT900 inflators. The primary, and most pertinent evaluations highlighted in the briefing involved data and observations regarding consumers' use of the GMT900 inflators, testing GM and others conducted on inflators returned from the field, and a comprehensive accelerated aging study conducted by OATK. During subsequent meetings in February, April, and June 2018, GM provided additional information. I participated in these meetings and have thoroughly reviewed the materials GM relies upon in support of its Petition.

Qualifications

8. I have a Ph.D. in Chemistry and thirty-five years of industrial research and development (R&D) experience as both a staff scientist and manager/director of R&D activities. The primary focus of my industrial assignments was the design of energetic solid materials such as propellants, pyrotechnics, explosives, and gas generants (propellants) for missile systems and automotive air bag applications. (My curriculum vitae is attached hereto as Appendix 1.)

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[2] Phase stabilized ammonium nitrate, or PSAN, is an oxidizer used in some airbag propellant formulations. For convenience, Takata inflators using this oxidizer are referred to as PSAN inflators.

[3] GM contracted with Orbital-ATK (OATK) to conduct an aging program. Since this work began, OATK has become part of Northrop Grumman, but will herein be referred to as OATK.

[4] GM contracted with Cornerstone Research and Arnold Barnett, Ph.D. to provide statistical assessments of certain information related to the YD and YP inflator variants.

[5] GM Briefing: August 23, 2017. All GM and OATK briefing materials referenced through this report can be found in public Docket No. NHTSA-2016-0124, available at https://www.regulations.gov/document?D=NHTSA-2016-0124.

9. After completing my Ph.D. in Chemistry at Duke University in 1980, I began my career in the rocket industry. I led relevant propulsion R&D activities for 10 years at Aerojet Strategic Propulsion Corporation and Olin Rocket Research Corporation. I spent the next 20 years at TRW Automotive focusing on automotive air bag technologies. From 2010 to 2015, I served as Director of Research at Nammo Talley Inc. (Nammo), in Mesa, Arizona. At Nammo, my focus was on directing defense-related rocket research, specifically, unique Energetic Materials (propellants, explosives, and pyrotechnics) and the devices that utilize these materials.

10. I was employed by TRW – Vehicle Safety Systems from 1990 to 2010. I was originally hired as Manager of the Propellant and Combustion Engineering Research Laboratory before eventually being promoted to the position of North American Manager, Inflation Product Engineering Group. Based on my work during this time I hold 25 patents and received multiple awards for product innovation in air bag systems. A list of these patents and awards can be found in Appendix 1, Curriculum Vitae.

11. During my tenure at TRW Automotive I had technical management responsibilities for chemical and physical laboratory measurements, human health science as it pertains to exposure to air bag effluents (the gas used to fill the air bag), chemical process research and development, inflator design research, energetic materials (propellant, booster, autoignition) formulation R&D, and periodically had the opportunity to investigate product performance or quality. I have published select portions of this work at international conferences in the areas of air bag effluent analysis, inflator combustion performance modeling, combustion diagnostics, and product/process design. A list of these publications can be found in Appendix 1, Curriculum Vitae.

12. At the beginning of my TRW tenure, I operated TRW's Research and Development (R&D) facility at Romeo, Michigan. That facility was focused on chemical process development for azide-based pyrotechnic passenger inflators. My group finalized the functional design details for the inflator, including pyrotechnic components, and provided for design scaling to allow tailoring of inflator performance to meet customer restraint requirements. To accomplish this work, I used tools from my earlier experience in the defense community, primarily in the chemical process, composition tailoring, combustion science and performance modeling areas. These tools facilitated fundamentally sound design decisions, thereby shortening the time needed for design efforts to mature.

13. The next four years, 1991 to 1995, focused on replacing azide-based propellant technology by exploring all inflator design types, including pyrotechnic, hybrid, and stored (cold) gas inflators. Candidate designs were further developed by in-depth projects focused on both the inflator product design and the manufacturing processes required for production of the new inflators. During this time, my team brought several designs into the company portfolio, including: (i) P4.1/P4.4 smoke-free hybrid designs with low vulnerability propellant; (ii) P6.x Heated Gas Inflator, or HGI, a design that features hydrogen combustion; and (iii) DI-9 smoke-free non-azide based driver inflator featuring pressure regulation of the exit flow area.

14. The TRW DI-9 inflator is relevant to the rupturing Takata inflators because it also used PSAN oxidizer[6] in a composition with fuels and other ingredients. The TRW design embodied unique design, formulation, and chemical process approaches to mitigate life cycle characteristics unique to using PSAN. Unlike Takata's designs, the DI-9 included (1) self-regulating exit flow, (2) an allowed leak rate 100-times lower (more strict than used at Takata), (3) a hydrophobic binder polymer to suppress moisture (water) adsorption, (4) a second exothermic fuel to mitigate endothermic melt of PSAN during combustion, (5) water-free preparation of PSAN, and (6) water-free processing of the main propellant. Single-stage and dual-stage variants were shipped by TRW as early as 2000 making the oldest units currently in the field approximately 20 years old. There are no known ruptures for DI-9 PSAN-based inflators to date.

15. The unique design feature of self-regulating exit flow was accomplished by providing spring-like mechanical action which increases vent flow area in response to increased internal pressure. As used in the DI-9 this feature is beneficial because it reduces the variability in inflator operating pressure. At lower pressurization, the exit area is "small" causing internal pressure to increase, which speeds up burning. If pressure gets too high, the exit area increases, dropping internal pressure and slowing burning. This addresses production variations that can occur with propellant lot, hardware lot, and temperature at the time of deployment, all of which affect burning rate. Ammonium nitrate propellants have relatively high pressure exponents (meaning an exponential increase in propellant consumption in response to rising pressure), so a minor change in burning rate is magnified by this pressure exponent. With the DI-9, in the event the burning propellant produces pressure greater than intended, the self-regulating feature responds by opening up, providing much larger exit flow area, thus avoiding pressure runaway by venting gas (reducing pressure). Commercial pressure vessels, for example propane tanks, are required by law to have pressure relief features.

16. Over the next 15 years, 1995 to 2010, I continued my work in R&D serving in roles in engineering management and as a technical specialist, until eventually retiring from TRW as Manager for Inflator Engineering for North America.

17. While at TRW, I was also involved in international efforts involving TRW-Repa (Aldorf, Germany) and joint venture activities with Daicel Corporation (Japan). Additional international experience came with the acquisition of Temic Bayern-Chemie from Magna in 1997 which merged inflator product engineering activities in Mesa, Arizona and Aschau am Inn, Germany, thereby forming an integrated, global team where I reported to a director in Germany. Through this work I developed intimate knowledge of design and functional details of the inflator products developed by the Temic team before the merger.

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[6] Ammonium nitrate (AN) exists in different crystal forms, or phases, depending on temperature. As temperature changes, material flips from one crystal phase to the next, referred to as a phase change. AN has one such change within the temperature range vehicles experience in the field, which is accompanied by a crystal volume change of greater than 3%. Because of this, it is not possible to make pressed parts from AN alone that will not disintegrate physically due to this volumetric change during normal daily vehicle temperature changes. Including potassium (or other cations) in the AN lattice suppresses this volume change, providing (phase) stability. Hence AN with potassium is referred to as phase-stabilized ammonium nitrate, or PSAN, and does not change volume significantly within the temperature range in which vehicles operate.

18. From 2003-2006 I also served as the United States' liaison on a U.S. State Department and European Union funded project in search of custom synthesized air bag ingredients at the Institute of Problems of Chemical Physics, Moscow, within the Russian Academy of Science. The target of the work was to design numerous fuel molecules that would be suitable in compositions with PSAN.

19. In 2015, I began contract work for the United States Department of Transportation National Highway Traffic Safety Administration (NHTSA) to provide expert technical advice regarding Takata's PSAN air bag inflators. The Takata PSAN inflator recalls are the largest and most complicated automotive recalls in U.S. history. This report is being provided as part of my current role providing expert analysis to NHTSA.

20. In summary, my role as expert for NHTSA stems from: my specific experience formulating a PSAN-based propellant and compatible inflators for TRW Automotive, which led to several of my twenty-five patents related to air bags; a presentation to the energetic materials experts at Los Alamos National Laboratory; and a technical paper describing the PSAN-based propellant and corresponding inflator presented at the national meeting of the American Institute of Chemical Engineers. Fundamental work on PSAN included X-ray diffraction as a function of temperature, or T-XRD, at the University of Reno and careful measurements of the vapor pressure of ammonium nitrate at several temperatures at SRI International in Menlo Park, CA.

21. During my 20 years in automotive engineering and 15 years as a scientist and R&D manager/director for three rocket companies, I gained wide ranging experience developing energetic materials and propulsion systems. I am familiar with the automotive development process for air bag systems and have employed nearly all of the tests and analysis tools relied on by the various laboratories investigating root cause, and contributing factors, of the Takata inflator rupture, which results in the fragmentation of the metallic inflator housing after aging in consumer vehicles, as further described below. This expertise informs my conclusions with respect to the Takata PSAN air bag inflators, including, specifically, the SPI YP and PSPI-L YD variants installed in GMT900 vehicles subject to the Petition.

Overview of this Report

22. In support of its Petition claiming the defect is inconsequential to safety in the GMT900 vehicles, GM has provided NHTSA with technical data from investigations of inflators originally installed in these GMT900 vehicles, and studies using newly manufactured inflators subjected to artificial (or accelerated) aging under laboratory simulated environmental stress conditions.

23. Some background is appropriate before getting into technical details of the studies, testing, and analyses provided in support of GM's Petition. To that end, before discussing GM's Petition claims, below are brief discussions providing an **Overview of Air Bag and Inflator Operation** and **Overview of the Takata Inflator Defects**, which briefly covers the history of the Takata inflator recalls, the Takata inflator defect, and the Takata YP and YD inflator variants used in the GMT900 vehicles.

24. Following that, I discuss **GM Efforts in Support of the Petition for Inconsequentiality and the Ongoing Investigation of Takata PSAN Inflators,** which includes discussion of relevant work done by OATK and Takata as part of the ongoing investigation into Takata's PSAN inflators, industry standards for inflator performance, the comparison inflators selected by GM, the unique inflator and vehicle environment features enumerated by GM, and preliminary research[7] conducted by GM in support of the Petition. With that foundation, I discuss GM's approaches and conclusions from the technical research efforts GM undertook that focused heavily on two laboratory-based accelerated aging studies, one at GM the other at OATK. And finally, I discuss a predictive model developed by OATK (the "OATK Model").

25. Over the course of GM's Petition and investigation activities, GM has briefed NHTSA on two accelerated aging studies that carried different names over time. For clarity and simplicity, I identify the accelerated aging studies as the GM Aging Study, and the OATK Aging Study.

26. I then offer my **Analysis and Opinion** regarding key aspects of the technical work GM presented, specifically: GM's choice of comparison inflators, the uniqueness of the GMT900 inflator variant design features, the uniqueness of the GMT900 vehicle environment, the results of the aging studies, observed abnormally high pressure GMT900 inflator deployments, and the OATK Model.

27. Finally, I offer my **Conclusions** as they relate to the rupture risk posed by the SPI YP and PSPI-L YD inflator variants in the GMT900 vehicles subject to the Petition and whether GM has substantiated the technical claims made in the Petition.

Overview of Air Bag and Inflator Operation

28. Air bag systems are supplemental restraint systems (SRS) designed to work in combination with the seatbelt system. Air bags reduce the risk and severity of occupant injury in a moderate to severe impact. Vehicles can be equipped with frontal (driver and passenger) air bags, as well as other types of air bag (i.e. seat mounted or door mounted, and/or curtain). Here, the focus is on the frontal, passenger air bag installed in the dashboard in certain GM vehicles built on the GMT900 platform.

29. Supplemental restraint systems consist of three basic sub-systems:

a. a restraint system electronic control module;

b. vehicle impact (acceleration) sensors, or crash sensors; and

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[7] In the context of preliminary research, I discuss test and inspection methods used in assessing both field aged inflators returned to Takata and laboratory aged inflators, characteristics of the GMT900 inflator variants, and the characteristics of the GMT900 vehicle environment. "Field aged" means the inflator was installed in a consumer vehicle and underwent natural aging in the vehicle (in the field) as it was used by the consumer. "Returned inflators" are inflators that have been recovered from the field (i.e. removed from consumer vehicles, generally as part of a safety recall or other authorized safety action where the consumer received a new airbag or inflator) and returned to Takata. Necessarily, a field aged part that has been subjected to testing is also a returned inflator, and returned inflators are, by definition, field aged. In contrast, "lab aged" means inflators that are subjected to an artificial, accelerated, aging scheme using imposed conditions in a laboratory test chamber, whether by GM or another party.

c. an air bag module containing mounting features for attachment to the vehicle, an inflator with electrical interface, a fabric cushion that forms the part commonly referred to as the air bag, and a cover door (which may be an integrated part of the dashboard).

30. The defect in Takata's supplemental restraint systems is found in the non-desiccated PSAN inflator within the airbag module. The functional components of an inflator are:

a. an electrically activated initiator;

b. booster propellant;

c. a main charge propellant; and

d. a housing (outer casing or shell) that must be capable of withstanding the high pressure generated during the deployment process.

Main propellant, booster propellant, and the ignitor propellant are all chemical mixtures of fuel, oxidizer,[8] and supporting components, each with a separate purpose. In each case, the fuel and oxidizer levels are selected to optimize performance of the mixture.

31. *SRS Operation.* When vehicle sensors detect a crash that exceeds the pre-programmed deployment threshold, the restraint control module will deploy the air bag(s) by sending an electrical current to the inflator initiator, igniting its small pyrotechnic charge. In passenger side SRS with an "occupant classification system," air bag deployment is suppressed in certain circumstances (for example if sensors in the seat do not detect an occupant in the seat of sufficient weight to engage the air bag/SRS). *See* Federal Motor Vehicle Safety Standard No. 208.

32. Once signaled to deploy, the sequence of events within the inflator is as follows: the hot discharge from the initiator ignites the booster propellant, which in turn begins combustion of the main propellant. The burning of the main propellant causes the internal gas pressure to increase inside the inflator housing and breaks through metal foils, or "shims," covering the exit flow holes (vents). The seal created by the shim protects propellants inside the inflator from outside air, which contains oxygen and water vapor, and is referred to as a hermetic seal.[9] In addition to the shims, two other seal types are present that do not open during deployment, a gasket seal at the electrical initiator and an O-ring seal of the ignitor assembly or end plug to the cylindrical inflator body. Once the shims are broken, the seal is lost and gas flows out of the inflator through exit vents and into the folded air bag cushion,[10] which begins to unfold and inflate. The enlarging cushion pushes open the cover door on the air bag module, allowing the cushion to fully expand in front of the vehicle occupant as a protective air bag. As the occupant presses into the cushion, gas escapes through vents located on the back (windshield facing) side

[8] In the Takata non-desiccated PSAN inflators at issue, PSAN is an oxidizer.

[9] Hermetic seal means airtight, for example food packaging by canning seals out air. Realistically, most seals are not perfectly airtight, that is they leak at some very low level. One way engineers measure the leak rate is by putting Helium gas on one side of the seal and applying a vacuum on the other side. The volume of Helium passing through the seal over time is the Helium leak rate. The acceptable level of leak is set to be lower than the amount that allows "air" to damage the item being protected for the useful life of the item.

[10] The air bag cushion is the part commonly known as "the air bag."

of the cushion. This allows the occupants' forward movement to decelerate in a controlled manner, preventing or reducing the severity of occupant contact with hard structures in the vehicle and any resulting injury. This entire process occurs within 50 thousandths of a second (i.e. 50 milliseconds or 50 ms) after impact.

33. *History of Inflator Technology.* The fuel and oxidizer chemical compositions of solid main propellants have evolved since the inception of air bags in vehicles to minimize undesirable attributes (such as producing gas that is very hot or that contains high amounts of particulate or excessive amounts of potentially toxic by-product gases) and maximizes attributes that reduce system costs and/or inflator size. Historically, solid propellants evolved from propellants of sodium azide fuel plus oxidizer to those comprised of a tetrazole derivative plus oxidizer (including PSAN), and later to guanidine nitrate ("GUNI") fuel with basic copper nitrate oxidizer compositions. Other compositions have also been used, but the solid propellants in the evolutionary chain noted here represent most of the inflator designs used in the field.

34. Formulations at Takata evolved similarly to the general case above. Around 1995 Takata moved away from sodium azide plus oxidizer propellants to a non-azide formulation called propellant 3110, containing anhydrous 5-amino-tetrazole fuel with strontium nitrate oxidizer. Bentonite clay is also used in propellant 3110 as a means to immobilize solid particles from combustion. The corresponding inflator designs were trademarked Envirosure. The Envirosure products were approximately 20% more gas efficient than the previous azide products and were adopted by automakers who valued smaller, lighter inflators.

35. In 2000, Takata increased gas efficiency a further 30% with the release of Envirosure 2 products, containing a propellant formulation Takata referred to as "2004." Propellant 2004 is comprised of a tetrazole fuel oxidized by PSAN. Over time, automakers adopted this product line. Propellant 3110 was also incorporated in these designs as a booster propellant. Throughout this report I refer to Takata's non-desiccated frontal inflators containing propellant 2004 as Takata PSAN inflators.

36. When considering any inflator propellant formulation, including those based on ammonium nitrate, there are characteristic properties that must be understood and accommodated in the inflator design to avoid negative outcomes. Examples of such properties include propensity to detonate, and any sensitivity to friction, impact, or static electrical discharge. In the case of ammonium nitrate, it is well-known to have a higher sensitivity to moisture than most other propellant formulations. This characteristic property of the propellant must be thoroughly understood and addressed in any product design. Much of the study and research into the origin or root cause of Takata's defective PSAN inflators revolves around the observed degradation of the propellant driven by the combination of long-term exposure to elevated levels of moisture and normal daily temperature cycling.[11]

37. In all inflator designs, the quantity and geometric shape of main propellant, subject to break-up during ignition, defines the total propellant surface-area available to

[11] Events occurring daily are often referred to as diurnal, here being specific to changes in temperature throughout a 24-hour daily cycle.

burn after ignition. In a properly designed inflator, the rate at which gas is produced is balanced with the rate at which gas is able to exit the steel inflator housing.

38. Changes to the surface-area of main propellant in any inflator will directly alter the rate of pressurization inside the inflator. To provide reproducible, controlled combustion, and thereby consistent air bag deployment, physical properties of the propellant (such as mechanical strength, meaning the degree of resistance to when and how much it breaks apart on ignition) must also remain unchanged, since changes in the mechanical breakage can create burning area that is greater or less than the planned amount. When additional surface-area is created, burning during deployment can cause the internal inflator pressure to rise beyond what the vents can release, jeopardizing the structural integrity of the steel combustion chamber (the inflator housing).

Overview of the Takata Inflator Recalls and Defect

Brief history of the Takata inflator recalls[12]

39. The first ruptures of Takata PSAN inflators in vehicles in the field occurred in the 2007 to 2008 timeframe. The initial recalls correctly identified manufacturing process control issues, which affected the manufactured density of the 2004 propellant components, specifically, the propellant was too low in density. The inflators affected by these manufacturing issues are usually identified as the "Alpha" population.

40. Between 2007 and 2013 field inflator ruptures occurred exclusively in Alpha population driver inflators, which featured a uniquely shaped propellant part described as a "batwing." Multiple recalls were issued between 2008 and 2011 for these inflators.

41. In 2013, the first passenger inflator ruptures occurred in the field. The passenger inflators also used non-desiccated propellant 2004 pressed into both tablets and a circular ring commonly referred to as a wafer. Takata produced these wafers in three different thicknesses of approximately 5 mm, 8 mm, and 11 mm.[13] As-built, the outside and inside diameters were the same for all three wafer sizes. For each vehicle platform, the main charge propellant for passenger inflators was a combination of tablets and wafers where the specific quantities and thicknesses of wafers and tablets were selected to achieve the desired rate of gas generation.

42. Those first frontal, passenger-side PSAN inflators to experience field ruptures utilized a combination of 11 mm and 5 mm wafers, often with a small charge of propellant 2004 tablets. In later years, Takata increasingly used 8 mm wafers in place of 11 mm wafers for the main propellant charge. There are 20 Takata PSPI inflator variants[14] that primarily use the 8 mm thick wafers, including the YP and YD variants subject to GM's Petition. The degradation of propellant 2004 can be observed as reduced density as the propellant ages. Interestingly, as will be discussed further below, in the

[12] A more comprehensive and definitive history of the Takata air bag inflator recalls can be found on NHTSA's website at www.nhtsa.gov/takata.

[13] Takata makes 3 PSAN wafer sizes, thin, medium, and thick. In this report, those sizes are referred to as 5 mm, 8 mm, and 11 mm, which are rounded approximations of the actual thicknesses, and sufficient for this discussion of the GMT900 inflators and the other Takata PSAN inflators.

[14] Takata no longer manufactures inflators containing PSAN, however, these variants remain in consumer vehicles.

case of 11 mm wafers, the density change is coincident with an observed increase in diameter, though that corresponding diameter growth has not been as clearly established for the 8 mm and 5 mm wafers.

43. With additional field ruptures of passenger and driver air bag inflators in 2013 and into 2014, NHTSA and the automotive industry questioned Takata's prior root cause determination tied solely to manufacturing defects.

44. Takata (and others) conducted in-depth analysis on inflators that were rupturing, but were not affected by any identifiable Alpha population manufacturing defect, which led to new areas of study to explain the inflator ruptures. The non-Alpha passenger inflators began failing first in Puerto Rico and South Florida. Further review of Alpha failures also showed a bias to these regions. This region, and climatically similar locations, were eventually referred to as the High Absolute Humidity (HAH) region. Takata undertook what became a massive testing and analysis effort, harvesting parts from the field and deploying in the laboratory, ultimately, hundreds of thousands of inflators. Through these efforts, Takata began the process of quantifying failure rates and performed forensic analysis of other comparable field recovered inflators. In turn, this enabled Takata to gather data on propellant degradation and the moisture content inside the inflator, and to correlate propellant degradation with abnormally high internal inflator pressures during inflator deployment. It also enabled identification of inflator groupings that deploy with abnormal pressure, short of rupture, which helped to identify inflators by variant, build date, or other commonalities, that had begun demonstrating behaviors of propellant degradation.

45. Once degradation of the propellant was identified as the likely cause of inflator ruptures, Takata began recalling inflators on a larger scale, affecting more vehicle manufacturers and consumers.

<u>The Takata inflator defect</u>

46. Physical degradation of propellant 2004, via long term exposure to high heat, humidity and temperature cycling, is the root cause of the Takata inflator defect leading to inflator ruptures. Understanding of the root cause for Takata inflator ruptures stems from dedicated investigations of that issue by Takata, the High Pressure Combustion Laboratory at Pennsylvania State University, the Institute for Chemical Technology within the Fraunhofer Gesellschaft Institute (FhG – ICT, in Germany) on contract to Takata, OATK in support of the Independent Testing Coalition (ITC),[15] individual vehicle manufacturers, and failure analysis by Exponent, Inc. in support of certain vehicle manufacturers.

47. The purpose of investigating the details behind this, or any, parts failure is to gain understanding of the root cause, including the factors that contribute to the process by which failure occurs. Once understood, corrective actions can be developed that seek to avoid or correct for the deficiency. This understanding of root cause also provides a basis for assessment of the efficacy of design features that GM's Petition asserts mitigates the risk of rupture.

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[15] The ITC is a group of vehicle manufacturers who sought to study the cause of the Takata inflator ruptures independently from Takata through a combined effort in this coalition.

48. In vehicles equipped with the defective Takata PSAN inflators, the rupture of the inflator creates an otherwise non-existent hazard for injury or death by propelling shrapnel-like metal fragments into the occupant compartment of the vehicle. As discussed in my May 2016 report to NHTSA regarding the root cause of the ruptures[16] ("my May 2016 Report"), the Takata PSAN inflators, which are all built with main propellant 2004, can over-pressurize and rupture upon deployment during a vehicle crash. Inflator rupture can propel steel housing fragments, burning propellant, and other metal parts towards vehicle occupants.

49. It is not the case that any elevated pressure above the intended operating pressure will cause a rupture in the Takata PSAN inflators. Thus, it is useful to understand the gradations of pressurization and the relative hazard posed by those gradations. Operating at normal pressure, with air bag deployment as designed, internal inflator pressure is generally in the range of 35-57 megapascals,[17] or MPa. Operating at abnormal pressure, that is, intermediately elevated pressure but without risk of rupture, internal inflator pressure is generally in the range of 57-90 MPa. Operating at a pressure sufficient to rupture the inflator housing, internal inflator pressure is generally above 90 MPa.[18] Ballistic testing where the inflator's internal "chamber pressure" is measured, is described later in this report. In the context of aging, the middle "abnormal" group represents developing risk of rupture in the sense that the propellant has undergone enough degradation to begin showing changes to the combustion process, it no longer conforms to the design requirements as qualified, and continued propellant aging risks inflator rupture. It is expected that as propellant degradation progresses the peak operating pressure increases.

50. The propellant 2004 degradation process, summarized in pages 5-8 of my May 2016 Report, is facilitated by the presence of moisture with increasing degradation at higher moisture levels, up to a certain point. Moisture content changes over time and is the combination of moisture present at the time of propellant production and inflator assembly plus any change in moisture that arises from moisture movement, specifically moisture intrusion, through the seals into the inflator during each daily temperature cycle. Once moisture is inside the inflator, the degradation proceeds by a series of natural processes that are purely dependent on the response of material properties to the environmental conditions of temperature and humidity. Over time, the cycling of daily temperatures in combination with the elevated moisture levels inside the inflator degrades the propellant 2004.

51. Testing of Takata's non-desiccated PSAN-based inflators thus far has revealed challenges and complexities to understanding precisely when the PSAN degrades to the

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[16] This report is Exhibit A to NHTSA's Amended Consent Order to Takata issued on May 4, 2016, and is available at: https://www nhtsa.gov/sites/nhtsa.dot.gov/files/documents/expert_report-hrblomquist.pdf.

[17] Megapascal, MPa, is a unit of pressure equivalent to 145 pounds per square inch (psi).

[18] The specific breakpoints for the categories were selected as follows: 57 MPa is high enough to exclude inflators at the high end of normal variation based on the Maximum Expected Operating Pressure (MEOP). By definition, the MEOP is the average operating pressure plus 3 standard deviations, which mathematically leaves open the possibility that 0.1% of inflators will deploy above the MEOP. Deployment at 90 MPa is an alarmingly high pressure, more than 1.5 times the normal operating pressure, and approaching the burst pressures for the Takata PSAN inflators. Inflators operating in the 57-90 MPa range are above the MEOP and as such, are incipient failures that should not be mistaken for normally functioning inflators, though they are unlikely to rupture.

point that an inflator rupture will occur. First, the problematic moisture level in propellant 2004 is quite low, as evidenced by measurements of 0.05 to 0.3 weight percent (wt%) moisture of the total propellant 2004 weight in inflators recovered from the field. The complexities described below make it difficult to design a relevant accelerated aging test program. In essence, testing must operate in a narrow moisture range. This "Goldilocks syndrome" moisture range is bounded on the high side by levels that induce other failures (that are not observed in the field) and on the low side by levels that do not produce measurable propellant damage. Only moisture levels that are "just right" will reproduce the same propellant changes as observed in the field return inflators. Accelerated aging testing, like the studies conducted by GM and OATK, endeavors to "see into the future," prematurely aging the inflators by stressing them to a higher level for a shorter time.

52. Understanding moisture intrusion into the "sealed" inflator can be difficult. For most practical purposes, the inflator is hermetically sealed with the initiator gaskets, end assembly O-rings, and metal foil shim over the vent holes. However, at a minute level there is a very low, but measurable, leak rate. Daily temperature cycling leads to the process of moisture intrusion when, during the transition from hot to cold, a "vacuum" is created inside the inflator, which is relieved by (moist) air slowly leaking from the vehicle cabin through the various seals into the inflator headspace (i.e. the air space inside the inflator). The amount of moisture entering each day by this process is extremely small, but the cumulative amount over years is significant relative to the amount needed for degradation to occur. The detailed understanding of intrusion helps explain the observation that in geographic regions with high absolute humidity (HAH), inflator ruptures occur more often and in "younger" inflators than elsewhere.

53. The increased moisture in the propellant 2004 triggers a particle ripening process[19] by which smaller PSAN crystals relocate and merge on to surfaces of adjacent larger crystals. As ripening of the PSAN proceeds, space vacated by smaller PSAN particles form voids (unoccupied space). Over time, the ripening process enlarges the void spaces, which become pores and/or fissures visible by electron microscope, to a point that the voids contribute additional surface-area during propellant combustion thereby causing internal inflator pressure to increase significantly.

54. One added complexity to understanding the role of moisture in propellant 2004 degradation is that at the high (i.e. peak) temperature within the daily temperature cycle moisture inside the inflator shows a net migration from booster propellant 3110 to main propellant 2004. At lower temperatures, moisture is preferentially absorbed by propellant 3110, but at higher temperatures the 3110 releases moisture, increasing the moisture available in the inflator headspace for absorption by propellant 2004. The higher the inflator peak temperature during the day, the greater the extent of moisture migration from propellant 3110 to propellant 2004.

[19] Ostwald first reported this phenomenon in 1896 and, accordingly, is called "Ostwald ripening." This ripening is the process responsible for ice crystals forming on top of ice cream in the freezer (so clearly high temperature is not a requirement for this process to occur). Ice cream initially contains tiny ice particles which, over time, migrate together to form larger ones at the surface.

Takata inflators as used in the GMT900 vehicles

55. GM launched the GMT900 platform in the North American market in 2007 utilizing two variants of passenger-side Takata frontal air bag inflators, the SPI YP and the PSPI-L YD, depicted in Figure 1 using x-ray cross sections. Both of these inflator variants are part of a design family consisting of several variants, each of which is tuned to meet customer-specified requirements for a specific vehicle platform. For example, there may be five or more variants in a design family.

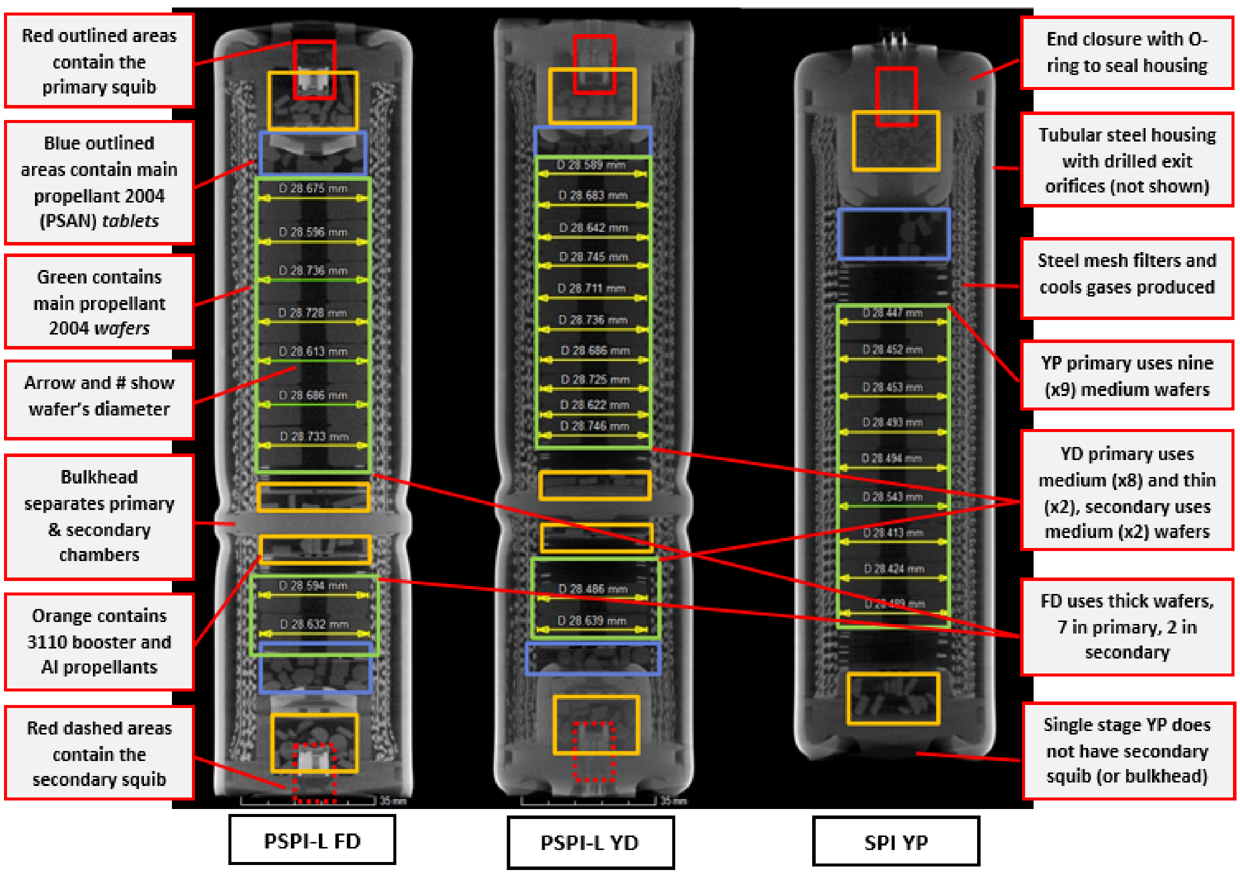

Figure 1. CT Scans of GM Inflators PSPI-L-FD, PSPI-L YD, and SPI YD [20]

[20] I annotated the x-ray image from GM August 23, 2017 presentation, page 13. The "squib" is the component that converts electrical energy to chemical energy and begins the burning process. "AI" stands for autoignition.

56. Functionally, all SPI family members are single-stage[21] cylindrical inflators with most of the PSAN propellant in wafer form with minor amounts of tablets to provide additional gas early in the deployment. Most variants used primarily 11 mm wafers though a number, including GM's SPI YP variant, used thinner 8 mm wafers.[22] Ruptures and/or abnormal pressure during testing of field aged inflators have occurred within the SPI family, including variants built with 8 mm and with 11 mm wafer thicknesses.

57. Functionally, all PSPI-L family variants are dual-stage[23] cylindrical inflators with most of the propellant in wafer form, some with minor amounts of tablets to provide additional gas early in the deployment. All other PSPI-L variants used primarily 11 mm wafers, while the YD variant used by GM uses the medium thickness 8 mm wafers.[24] Ruptures and/or abnormal pressure during testing of field aged inflators have occurred within the PSPI-L family built with 11 mm wafers. A closely related family, the PSPI-6, has variants built with 8 mm wafers, one variant of which has many observed ruptures.

58. GM's posits in the Petition that both the GMT900 vehicle environments and the inflator variants used in those vehicles are unique with the result that the inflators in the GMT900 vehicles are less affected by the processes described above, i.e. the root cause of inflator rupture. Any vehicle environment or inflator variant differences that materially alter the inflator system's behavior during deployment when using degraded propellant would be the areas of critical interest. To properly evaluate this representation, it is necessary to analyze similarities and differences between variants within a family, which is discussed below.

GM Efforts in Support of the Petition for Inconsequentiality and the Ongoing Investigation of Takata PSAN Inflators

59. GM has provided several in-person presentations to the Agency regarding GM's efforts and conclusions in support of the Petition. The next sections of this report describe the information, research, and data GM presented in its effort to support the Petition claims. These sections will cover the items below in the following order:

a. GM's selection of comparison inflators

b. GM's claims of unique GMT900 inflator and vehicle environment features

c. Preliminary research and studies as background for the GM Petition research

    i. Inflator Standard SAE-USCAR-24

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[21] Single-stage in this context means there is only one propellant chamber and the propellant combustion that generates the gas to fill the air bag cushion occurs in this chamber. These inflators were installed in the "heavy duty" (based on Gross Vehicle Weight Rating) GMT900 vehicles.

[22] Takata does use 5 mm wafers to tailor ballistic performance in some SPI inflator variants, but not in the final inflator variants used for the GMT900 vehicles.

[23] Dual-stage in this context means there are two propellant chambers, a primary stage that the controller fires first and a secondary chamber that is programmed to fire a few milliseconds later. These inflators were installed in the "light duty" (based on Gross Vehicle Weight Rating) GMT900 vehicles.

[24] Similar to the SPI above, Takata does use 5 mm wafers to tailor ballistic performance in some PSPI-L inflator variants, including GM's YD variant.

ii. Stress-Strength Analysis

iii. Takata's testing, inspection, and analysis methods

iv. Inspection and ballistic testing of field returned inflators

v. Preliminary work by OATK relevant to the GMT900 inflators

vi. Preliminary investigation of GMT900 vehicle environment

d. GM Aging Study

i. GM Aging Study methodology

ii. GM Aging Study results summary

e. OATK Aging Study

i. OATK Aging Study methodology

ii. OATK Aging Study results summary

f. Observations and GM conclusions from Aging Study results

i. GM Aging Study

ii. OATK Aging Study

iii. OATK Model

iv. GM's Overall Conclusions in Support of the Petition

<u>GM's selection of comparison inflators</u>

60. GM selected two inflator variants, one each for YP and YD variants from within the respective design families (the SPI and the PSPI-L), to use as a reference or comparison against the GMT900 inflator variants.

61. GM selected the Takata PSPI-L FD (FD) variant as the comparison variant to the GMT900 PSPI-L YD variant. GM sold Pontiac Vibe platform vehicles equipped with the FD variant. The FD variant is not included in the scope of the GM Petition.[25] The FD variant represents a Takata inflator known to have a higher frequency of field rupture than most other variants (at 0.53% for all FD variant inflators, though the rate varies across vehicle platforms with one vehicle experiencing an approximately 5% rupture rate). Other researchers and experts have also studied the PSPI-L FD extensively.

62. GM selected the Takata SPI AJ (AJ) variant for comparison to the GMT900 SPI YP variant. The SPI AJ variant was used by several other vehicle manufacturers, but was not installed in GM vehicles. Examining the MEAF database[26] shows the AJ variant represents a Takata inflator known to have a higher frequency of field rupture than most

[25] GM's Petition for Inconsequentiality and supplemental filings can be found in public Docket No. NHTSA-2016-0124, at https://www.regulations.gov/docket?D=NHTSA-2016-0124.

[26] Data gathered by Takata to determine defect root cause, the expression of root cause on different vehicle platforms, the influence of age, and the influence of geographic region are compiled in a spreadsheet Master Engineering Analysis File, or MEAF.

other SPI variants. For example, when used in one non-GM vehicle manufacturer's vehicles the AJ variant experiences a 4.97% rupture rate.[27]

63. Both reference variants use primarily 11 mm wafers while the GMT900 variants use thinner 8 mm wafers. Ruptures and/or abnormally high internal inflator pressures have occurred during testing of field aged inflators for different variants within the two inflator families (PSPI-L and SPI).

GM's claims of unique GMT900 inflator and vehicle environment features

64. GM claims in the Petition that both the vehicle environment and its YP and YD inflator variants are unique with the result that the inflators in the GMT900 vehicles are unlikely to experience inflator rupture in the field for decades into the future.[28] The vehicle environment and inflator features identified as unique in GM's first petition (in November 2016) and over the course of GM's studies are listed in Table 1 with a brief description of each and the supporting data below. My assessment of these claims appears in the analysis and opinions section of this report.

Table 1. Unique inflator and vehicle environment features identified by GM in support of its Petition

I.	*Unique inflator design features (Common to PSPI-L YD and SPI YP)*	
	a.	*Vent-area to propellant-mass ratios*
	b.	*Steel endcaps (versus aluminum)*
	c.	*Thinner propellant wafers (8 mm versus 11 mm)*
II.	*Unique inflator design features (SPI YP only)*	
	a.	*Tablets in sealed cup*
	b.	*Ceramic cushions*
III.	*Unique inflator design features (PSPI-L YD only)*	
	a.	*Anvil on bulkhead disk*
IV.	*Unique vehicle environment features*	
	a.	*Solar absorbing windshield and side glass*
	b.	*Larger interior volume*

[27] GM Briefing: August 23, 2017, page 175. Rupture rates are calculated from MEAF testing database by dividing number of ruptures by the number tested.

[28] GM asserts in relation to the OATK Aging Study that the inflators are unlikely to experience rupture for at least 30 to 35 years. This claim will be addressed in the discussion of the OATK Aging Study and OATK Model.

65. GM contends that larger vent area allows for faster exit flow of gas, thereby reducing the risk of inflator rupture. The vent area is not variable in any Takata PSAN inflator. In support, GM provided results from an OATK study of what happens when 1, 2, or more vents on a GMT900 variant inflator are blocked during deployment.[29] This is, in essence, an area ratio study. The study provided pressure time events for the case of 50% blockage showing both variants FD and YD exceed 100 MPa chamber pressure, i.e. pressure high enough to expect rupture to occur. At blockages of 30%, the FD variant response is milder (meaning lower pressurization) than for the YD variant, and at 40% blockage the YD variant response is milder than the FD. From this, GM draws a general conclusion that the YD variant is less sensitive. This testing does not replicate the sudden change in pressurization several milliseconds into inflator deployment due to propellant degradation, except to the extent that a large area change is similar to a large nozzle area change. It is not known to what extent the blockage was distributed between the primary and secondary chambers.

66. Initially, GM claimed that the steel endcap body O-ring seal made the GMT900 inflator variants uniquely resistant to moisture intrusion and the associated propellant degradation that results in inflator rupture. OATK conducted engineering investigations of the O-ring seal details, discussed below. No direct comparison data was provided, however the robustness of the seal was assessed with regard to the allowed maximum crimp diameter.[30]

67. GM contends that thinner propellant wafers (8 mm vs the thicker 11 mm) and their break-up results in more efficient propellant utilization during combustion with a resulting reduction in risk of inflator rupture. Specific to wafer break-up, GM points to the more efficient burning of 8 mm wafers than 11 mm wafers during combustion under normal operating conditions.[31] No data was presented to validate extending this theory to cases where abnormal pressurization corresponding to the defect, porous propellant, that arises from degradation over time.

68. Inflator rupture has been correlated to wafer diameter in previous investigations primarily focused at variants with 11 mm wafers. GM analyzed data from the Takata Master Engineering Analysis File (MEAF) comparing the FD (11 mm wafer) variant to the YP and YD (8 mm wafer) variants returned from vehicles in Zone A[32] and concluded that, because FD inflators rupture more frequently than YD/YP, 11 mm wafers degrade faster than the 8 mm wafers.[33] That conclusion does not factor in the approximately 8 °C higher peak daily inflator temperature experienced in the vehicle for most of the FD

[29] GM Briefing: August 23, 2017, pages 81-82.
[30] GM Briefing: August 23, 2017, pages 190-204, and 301-304.
[31] Third Petition, pages 6-7. This means the mass of propellant 2004 is more efficiently consumed prior to decelerating the occupant than a corresponding design based on 11 mm wafers. GM is essentially arguing that using more propellant faster in the inflator and air bag deployment process reduces the risk of inflator rupture.
[32] Per NHTSA's Coordinated Remedy Program, NHTSA has defined three zones that separate the United States and territories based on relative risk – Zone A, Zone B, and Zone C.
[33] In the course of investigating the degradation of propellant 2004 in FD variant inflators, it emerged that when a wafer grows to 29.2 mm (and over) the probability of rupture increases, used thereafter as the threshold for rupture occurring. The initial diameter is 28.6 mm.

inflators tested versus the peak temperature for YD and YP variants in the GM vehicle platforms.

69. GM also provided data from the OATK Aging Study of as-built moisture level inflators after 1680 cycles to peak temperatures of 50 °C, 60 °C, and 70 °C, showing wafer growth for the FD (11 mm) variant, and YP and YD (8 mm) variants are very similar when temperature conditions are equal.

70. GM contends that propellant 2004 tablets in a cup (YP only) reduces access of moisture to those tablets, thereby reducing the risk of inflator rupture. GM and Takata added the cup for reasons unrelated to inflator rupture. Data was not provided indicating tablet behavior during deployment is a major or secondary factor in the root cause of the Takata inflator ruptures arising from wafer degradation. Tablet density data plotted through 1960 temperature cycles in the OATK Aging Study is nearly flat at as-built and flat at mid-level moistures at all peak temperatures for all three variants.[34] At high moisture levels in the OATK Aging Study, the YP tablets do show slower decrease in density. As to diameter, in the GM Aging Study highlighted below, wafers in YD and YP increase in diameter at the same rate.[35]

71. GM contends that use of a ceramic cushion (YP only) reduces the risk of inflator rupture. GM identified as a beneficial feature use of a ceramic cushion in combination with two springs relative to other Takata PSAN inflator variants using only one spring. The ceramic cushion, especially when combined with the additional identified benefit of tablets in a cup (both unique to the YP variant), should directionally cause wafer density reduction in the YP variant to be less than the YD variant which lacks the alleged benefits, but the results are to the contrary. At the peak cycle temperature most relevant to GMT900, 60 °C, the growth rate of YP (~28.88 mm @ 1500 cycles) is not significantly different than that for YD (~28.96 mm @ 1500 cycles), so design features uniquely favorable to YP do not provide additional resistance to aging as measured by density or diameter.[36]

72. GM contends that use of a bulkhead disk with anvil[37] (YD only) affords the booster propellant 3110 in the two autoignition (AI) canisters better access to moisture contained in the main propellant chamber headspace by disturbing the canister seal. The bulkhead steel disk is present in all PSPI dual stage inflators but only the YD variant has the added anvil intended to improve autoignition reliability. One AI canister sits on either side of the bulkhead disk (one in the primary chamber and one in the secondary chamber) in the YD variant. The anvil in YD pushes on the seal during assembly, disturbing the seal effectiveness, thereby improving access of 3110 in the canister to headspace moisture. GM theorizes that having 3110 absorb moisture reduces degradation of the main propellant 2004. In the OATK Aging Study, moisture levels in propellant 3110 in

[34] GM Briefing: August 23, 2017, page 113.
[35] E.g. GM Briefing: August 23, 2017, page 97 shows diameter growth quite similar at 1500 cycles.
[36] GM Briefing: August 23, 2017, page 97.
[37] The anvil was included to improve heat conduction to the autoignition material. In the event of external heating events, for example exposure to fire during transportation of large numbers of inflators, the autoignition material ignites itself and then lights the booster and in turn the main propellant. This avoids inflators exploding in the fire by combusting the propellant before the main propellant reaches its autoignition temperature.

YD variant AI canisters is significantly higher than for canisters in FD and YP variant inflators which have intact seals.[38] The propellant 3110 in the canister absorbed moisture early, however the moisture levels of propellant 2004 are not significantly different across the three variants (YP, YD, and FD) and three peak temperature cycles throughout the 1960 temperature cycles. Additionally, the major portion (over 65%) of propellant 3110 at the ignition assembly endcap is common to all variants, which plays a stronger role in absorbing headspace moisture in all three variants and does the most to protect propellant 2004 from moisture-induced degradation.

73. GM contends that the use of solar absorbing glass (standard on all GMT900 vehicles) reduces vehicle temperature and thereby reduces the risk of inflator rupture. GM did not provide any data specific to the role of solar absorbing glass on reducing vehicle temperature. GM did provide single point data regarding the Pontiac Vibe and two GMT900 vehicle peak temperatures at the inflator surface.[39] As discussed in greater detail below in the context of temperature bands, the GMT900 in-vehicle temperatures are relatively low, but are similar to other vehicles, that is to say the temperatures are not unusually low.

74. GM contends that the cabin volume of the GMT900 vehicles is larger than other vehicles using the Takata PSAN inflators with the result that in-vehicle temperatures are lower than the smaller vehicles, which thereby reduces the risk of inflator rupture. GM did not provide any data specific to showing that larger vehicle cabin volume per se reduces vehicle temperature. GM did observe by analysis of MEAF data, like Takata, that some correlation between vehicle cabin volume and cabin temperature is generally the case, but not universally so. It is worth noting that MEAF data also shows a vehicle with a much smaller cabin that has a lower temperature profile than the GMT900 vehicles, and has experienced inflator rupture (in the DH/MG inflator variant).

75. Figure 1 depicts an image of three CT[40] scans of the GM specific inflator variants discussed in this report (the YP, YD, and FD (Vibe) variants). The CT scans shown are sections (slices) taken through the center along the long axis of the inflator housing. The scanned section shows the internal components of the inflator assemblies, and notes have been added to highlight relevant individual components. The orientation of the section through the center of the assembly shows the wafer cross section, and software designed to work with CT data can be utilized to estimate the outer diameter of each wafer with good accuracy.

Preliminary research and studies as background for the GM Petition research

Inflator Standard SAE-USCAR-24

76. Each vehicle manufacturer has its own inflator qualification specification which lays out test methods and conformance requirements for completing Production Validation (PV). A vehicle manufacturer determines the acceptable inflator ballistic

[38] GM Briefing: June 8, 2018, page 126.

[39] GM Briefing: June 2017, page 2. Note Vibe peak temperature value of 68 °C used by GM conflicts with lower values measured in the Atlas Cabin Study.

[40] CT stands for computed tomography, which takes a series of 2-dimensional X-ray images through the subject device without changing or disassembling the device.

performance for its inflators, and testing is standardized, to a degree, in the form of industry standards published by the Society of Automotive Engineers (SAE) and voluntarily adopted by GM and some other vehicle manufacturers. U.S.-based automakers standardized inflator qualification when they released SAE/USCAR-24, which includes a matrix of testing and requirements for product reliability, ballistic performance, environmental stability and acceptable structural safety factor. A few excerpts from USCAR-24 make clear the industry expectations for inflator safety:

a. Rupture is forbidden, as described several times[41] (for any testing where the inflator is pressurized or heated) wherein the structure shall not fragment or eject any part of the structural components. The phrase "shall not" removes any discretion in accepting a non-conforming test result.

b. To confirm that inflator rupture will not occur during deployment, inflators must meet burst[42] safety requirements. The structural safety factor (SSF) is the strength of the inflator housing to withstand break-up divided by the pressure that propellant combustion imposes on that structure. Inflator housing strength is measured by pressurizing test units with water until they burst (i.e. rupture). This is directly related to combustion imposed pressure measured during chamber pressure testing. Vehicle manufacturer specifications typically require strength to be at least 50% greater than the maximum expected operating pressure (MEOP). Thus, the minimum acceptable burst safety factor (which is synonymous with SSF) would be 1.5.

c. In Sequential Test Series, propellant shall not show any loss in the measured strength or ballistic integrity of the propellant as demonstrated by ballistic performance and/or accepted break or crush strength measurement methods of live tear down inflators. In short, propellant must retain the properties demonstrated when new, even after simulated environmental stresses of the Sequential Test Series.

d. Regarding Propellant Stability, Ammonium Nitrate containing propellants shall be required to undergo added stability evaluation for propellant strength and burn rate stability as agreed to by the Responsible Vehicle Engineer.

77. The industry expectation is that the inflator will remain in conformance to this standard for the time that it remains in consumer vehicles.

Stress-Strength Analysis

78. As an integral part of assessing the risk of inflator rupture, GM evaluated the probability that propellant wafer diameters from the GMT900 inflators were as large as those measured in other inflators that later ruptured. The reliability engineering tool referred to as stress-strength analysis was used for this endeavor. Wafer diameters for the oldest GMT900 field return inflators (analysis in 2016 for inflators manufactured

41 Example tests where this language appears are (1) burst safety factor, (2) high temperature oven heating, and (3) accelerated heat aging/autoignition.

42 While SAE/USCAR-24 refers to this as burst safety testing, it is the same as structural safety factor.

between years 2006.5 to 2008) from the high absolute humidity region were used to form the stress distribution (a bell shaped curve). A threshold curve for the probability of rupture as a function of wafer diameter was derived from Takata testing of inflators from all ages of non-GM vehicles that produced ruptures, wherein a threshold value of 29.25 mm was defined and presented graphically.[43] GM represents that the population where diameters of the stress population overlap the failure threshold curve for strength is at risk of rupture. Since their plot for ~10 year old wafers from GMT900 variants shows no overlap with the threshold curve GM concluded there is no risk of rupture.

79. GM conducted this analysis for both GMT900 inflator variants. GM provided comparison of stress distributions for the wafer diameters for the SPI YP variant and non-GM SPI AJ variant and concluded there is an overlap in the distribution for the AJ variant with the threshold curve, but no overlap for the YP variant. Similarly, wafer diameter stress distributions for the GMT900 PSPI-L YD variant was compared to non-GM PSPI-L FD variant and GM concluded there is a distribution overlap of the threshold curve for the FD variant, but no overlap for the YD variant.

Takata's testing, inspection, and analysis methods

80. Takata has primarily been involved in testing returned field aged inflators, which allows for the longitudinal study of aging based on testing of different inflators given each inflators' time in the field (i.e. age).

81. Over the last several years, Takata and other researchers inspected, tested, and analyzed inflators returned from the field as a result of the various safety actions and recall campaigns being conducted by the affected vehicle manufacturers.[44] Inflator testing methods can generally be categorized as either non-destructive or destructive. As the name implies, non-destructive tests do not alter the inflator's functionality or ability to be deployed, meaning the inflator can still be actuated, or deployed after the non-destructive testing.

82. Takata conducts much of the inflator inspection and testing in-house[45] and has compiled the important data from these efforts into the MEAF. As of July 3, 2018, the MEAF contained information on the inspection and testing of over 387,000 inflators. Analyzing results for a specific property measured on multiple inflators of different ages (based on time in the field) provides an understanding of what properties are changing, and how, over time (i.e. based on inflator age). GM's comparisons to inflators from non-GM vehicles rely heavily on the extensive work at Takata compiled in the MEAF. The following are test methods used by Takata that are relevant to discussion of GM's Petition.

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[43] GM Briefing, August 23, 2017, page 95 and GM's second Petition, page 15, including Exhibits B and C.

[44] Generally, inflators recalled by the 19 affected vehicle manufacturers are returned to Takata facilities for storage, tracking, and testing and to ensure they are safely stored for future testing and/or disposal.

[45] Takata also has maintained a contract with FhG-ICT to conduct scientific studies which have contributed significantly to the understanding of root cause and factors contributing to it. The root cause work by Takata and other parties was fully address in my May 2016 Report and summarized above (section "Background on the Takata Inflator Recalls and Defect"). Some comments regarding root cause are included later in this report only to the extent it applies to the studies conducted in support of GM's Petition.

83. *X-ray imaging and CT Scans.* X-ray imaging is non-destructive and modern methods couple X-rays with computer software, referred to as Computed Tomography and abbreviated as CT (or CT scan). CT scans stitch together a series of 2-dimensional X-ray images, for example the one in Figure 1, to form a 3-dimensional likeness of the object.

84. Takata has heavily used CT scanning, primarily to estimate the dimensional characteristics (i.e. size) of a propellant wafer to within 0.01 mm inside the inflator while fully maintaining the physical integrity of the inflator. Measuring wafer outside diameter by CT scan evolved as a valid surrogate for measuring 11 mm wafer diameter by hand and computing density. Measuring diameter by hand is slow and, further, requires disassembling the inflator (a destructive method). Measuring wafer diameter by CT is non-destructive and is useful, among other things, in identifying inflators containing low density propellant that can provide interesting test samples in root cause and field aging studies.[46] A correlation of the two methods was done by Takata mathematically by plotting one against the other, and fitting a line through the data. The correlation was generally acceptable. The external geometric shape of some wafers is so badly distorted due to aging, especially in the presence of excess moisture, that the data is not useable.

85. GM points to wafer diameter average and maximum readings of more than 5,000 CT scans of YD and YP variant inflators in support of the Petition.[47] The YD variant measured average diameter of 28.77 mm and maximum diameter of 29.12 mm in inflators with average age of 8.7 years and maximum age of 12.0 years.[48] The YP variant measured average diameter of 28.77 mm also, with maximum diameter of 29.36 mm in inflators with an average age of 9.6 years and a maximum age of 10.9 years.[49]

86. Similarly, micro CT, a high-resolution form of CT scanning, is used to image smaller items like a portion of one wafer, which provides direct dimensional information about voids, fissures, channels and capillaries within the wafer on the scale of 1-5 microns (that is, 0.001 mm to 0.005 mm). This method provides the most direct evidence of the propellant 2004 degradation process. Conducting micro CT on field returned inflators of varying ages reveals the growth trend of voids over time within the wafer. CT and micro CT scanning have proven to be powerful tools used by many scientists and researchers studying the Takata inflator defect. In particular, these images unambiguously confirm conclusions previously deduced regarding the ballistic failure process, and described in my May 2016 Report, which at the time were based on other data types.

87. A third X-ray technique, high speed X-ray cinematography, has been employed to create a high-speed video of the internal processes of an inflator during deployment including: ignition, wafer break-up, wafer consumption (burning) during combustion, and any movement of structural and internal components. The high-speed video captures many frames of the image during inflator deployment, an event lasting 60 milliseconds. The video can be viewed later and at a slower frame rate (like slow motion) over a time period of seconds to minutes. Comparison of normal and abnormal inflator deployment

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46 By definition, density is mass per unit volume, so the idea in this context is that if the diameter has increased from the original controlled dimension, then the density *must* decrease since mass is constant but volume increased.

47 GM Briefing: June 8, 2018, page 37.

48 GM Briefing: June 8, 2018, page 37.

49 GM Briefing: June 8, 2018, page 37.

videos clearly shows the differences in how the inflator and propellant each behave during deployment.

88. *Ballistic (Tank) Testing.* One destructive test used industry-wide is a ballistic test wherein the inflator is deployed in an air-tight sealed tank (a canister) of a known volume (usually 60 liters) and the tank is instrumented to measure pressure inside the tank during inflator deployment. A deployment log is created by plotting pressure (P_t) in the tank versus time, which corresponds to the speed the inflator gasses will fill the air bag. It is standard practice that vehicle manufacturers qualify the suitability and performance of a supplier's inflator using this test. As part of the ongoing investigation of Takata's PSAN inflators, Takata has conducted ballistic tests of more than 4,200 field returned GMT900 inflators with no observed ruptures.[50]

89. *Chamber Pressure.* During a Ballistic Tank Test, the inflator itself can be instrumented to measure pressure inside the inflator, i.e. the combustion "chamber", during deployment. The chamber pressure (P_c) data collected during the ballistic test can be plotted versus time to create a chamber pressure curve for the test. The peak pressure measured in this test is indicative of the relative risk of rupture and is the foundation for the aforementioned pressure categories: operating normal, operating abnormal, and operating at or above the expected rupture pressure.

90. As described in statistical terms in SAE/USCAR 24-2, all inflators of the same variant should produce chamber pressure curves that are similar, with minimal variation, both when the inflator is new and over the life of the inflator in the field. Ballistic testing of field aged inflators returned to and studied by Takata vary more than is desirable; some have chamber pressure curves with very low P_c and some with very high P_c compared to the normal curve for the particular inflator variant. Inflators that rupture during ballistic testing produce chamber pressure curves with a sudden, rapidly increasing chamber pressure beginning several milliseconds into the deployment that exceeds the mechanical strength of the inflator housing. The chamber pressure data provides an excellent tool for tracking the level of degradation of propellant 2004, observable as abnormally high internal inflator pressure short of causing rupture.

91. *Live Disassembly.* One common destructive inspection method used by Takata and most other researchers is live disassembly (Live D). The un-deployed inflator is mechanically inspected then dissected to facilitate physical inspection of internal inflator components for presence and proper location, corrosion, assessment of any physical change in the propellant, and chemical analysis[51] of its contents, primarily the propellants. Live-D also affords examination for corrosion of surfaces inside the inflator. Live D is used to obtain the moisture content and physical dimensions of propellant 2004 (wafers and tablets) as well as for the other propellant materials in the inflator. Initially, wafer diameters were only obtained following Live D, by trained technicians taking physical measurements using hand calipers. However, for 11 mm wafers, the non-destructive CT scanning process yields a diameter value that correlates acceptably with

[50] GM Briefing: June 8, 2018, pages 4, 37.

[51] Previous chemical analysis of the propellants has shown no chemical change with age, and GM did not raise this, so that topic will not be covered here. Changes in color of the autoignition material have been noted, but is also not relevant to this discussion. Appendix B describes a number of tests conducted at OATK, many requiring material from Live D.

caliper measurements. Helpfully, CT scans can also make this measurement for inflators scheduled for ballistic testing, as discussed above, which is not an available option if the inflator has undergone the destructive Live D. Propellant materials collected during the Live D can be distributed for additional analysis through micro-CT and closed bomb testing of the propellant by itself.

92. *Closed Bomb Testing.* Takata and other researchers also perform a destructive test on propellant alone in a device called a closed bomb. In the closed bomb test a sample of propellant obtained through Live D is placed in a small, high-strength, closed pressure vessel and ignited. This isolates the combustion behavior of the propellant from interactions with other design features of the inflator. The pressure vessel is instrumented to measure pressure created by the burning propellant inside the pressure vessel, similar to the measurement of inflator chamber pressure discussed above. Plotting the pressure reading versus time creates a closed bomb pressure curve for the test. Comparison of the closed bomb pressure curves for new propellant versus aged propellant demonstrates the state of inflator health or extent of degradation caused by time spent in consumer vehicles (or in a laboratory aging study). If an aged wafer is healthy the closed bomb pressure curve is the same as for new parts. If pressurization is faster than new parts, the result is considered an "abnormal burn" resulting from additional surface area burning earlier in the event than designed (though rupture is not possible since the test device is much stronger than an inflator housing).

93. Computer based mathematical tools makes it easy to detect abnormal burns: at Takata and ICT they developed the integrated burn rate (what Takata calls "IBR") while OATK applied the "Vivacity" method used worldwide for qualifying gun propellant production lots.[52] In this report I am concerned with instances of abnormally high pressure, so the means of detection are not my focus and the tool used requires no analysis: both methods can identify inflators representing age driven ballistic changes producing abnormally high pressure.

94. *Compiled Inflator Data.* The Takata MEAF is an incredible information resource providing compiled and summarized results for the more than 387,000 Takata inflator inspections and/or tests. The data recorded in the MEAF can be combined and correlated to provide useful information about the current condition and health of an inflator undergoing testing, and in some cases (when enough parts have been tested and when ruptures have occurred) to predict the likelihood that an inflator will rupture if deployed. The MEAF also contains Takata inflator serial numbers for traceability, results of dissections, and key ballistic results. A serial number provides an inflator's production date, propellant lots used, manufacturing location (including the specific assembly line), and other important characteristics related to inflator production. And because inflators are traceable via the inflator serial number to the vehicle in which they were installed (via

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[52] The gun propellant metric Vivacity (liveliness) measures the rate of energy production, akin to burning rate, but integrates comparison of the test result to a reference test result. The Takata-ICT IBR is similar, in that the integral of the test result is compared to the integral of a reference test. The integral is the area under the pressure time curve and reflects the energy output. In both methods, new propellant lots reproduce the reference test. As it relates to Takata's PSAN inflators, a significant increase in vivacity due to aging requires additional burning surface area to cause the increase, which can put the inflator housing at risk of rupture. On GM's behalf, OATK produced and analyzed vivacity plots during the OATK Accelerated Aging Study.

the VIN), information about field age and geographic location(s) of the vehicle while in service can be obtained and analyzed for each inflator returned from the field.

95. The MEAF file is extremely valuable and is the most relevant source of data for assessing inflator health and the risk that inflators will rupture. The combination and analysis of Takata's inflator test data in the MEAF and the vehicle related data forms the basis for much of today's understanding of the Takata PSAN inflators defect, as well as the understanding of the relative performance for various inflator families and variants in different vehicles. This information is also useful in defining the geographic zones for recall activities, including the HAH and Non-HAH regions used in some earlier recalls, and Zones A, B and C used in later recall actions.

Inspection and ballistic testing of field aged GMT900 inflators

96. GM reported that Takata had conducted ballistic testing on over 4,200 GMT900 field-returned inflators[53] with most of the tested SPI YP and PSPI-L YD inflators returned from the HAH or Zone A areas of the United States. About 60% of those tests were conducted on the SPI YP variant. The average field age of the PSPI-L YD and SPI YP inflators was 8.6 and 9.5 years, respectively. In August 2017, GM reported that no ruptures or abnormal pressure results were observed on either of these two inflator variants.[54] Takata continued to conduct testing on GMT900 inflators.

97. In the February 2018 briefing to NHTSA, GM provided information on a high-pressure deployment during a January 2018 test of an SPI YP variant inflator recovered from Texas with approximately 10 years of field exposure.[55] The peak pressure for that test was 91 MPa, which is within 10% of the burst pressure for this inflator variant. The shape of the chamber pressure curve was characteristic of curves for Takata passenger inflators experiencing a rupture. GM suggested treating this high-pressure occurrence as being irrelevant to the Petitioned inflator population by placing this unit into a newly identified sub-group of first generation SPI YP inflators (dubbed by GM as "Gen1"). According to GM, the differences between "Gen1" and "Gen2" YP variant inflators[56] are a shift from propellant 3110 booster in the form of tablets to propellant 3110 in the form of granules in the initiator assembly, a minor decrease in the amount of propellant 2004 tablet weight, the use of a cup instead of a sleeve with orifice plate to hold the propellant tablets, and the addition of ceramic cushions with springs in place of spring alone. The so-called "Gen1" YP inflators are already completely under recall, which is why the

53 GM conducted a pair of field-returned recovery efforts to obtain SPI YP and PSPI-L YD inflators from certain MY 2007 and 2008 GMT900 vehicles. First, GM conducted a field recovery effort, prior to any recall, in the HAH region to obtain a sufficient quantity of the oldest field aged PSPI-L YD inflators, which were then returned to Takata for inspection and measurement to begin to understand the aging process specific to GMT900 and, as needed, to identify large diameter wafer samples suitable for GM's proposed test plan. Later, GM recovered additional field aged SPI YP variant inflators, per NHTSA Recall No. 15V-324, and returned those parts to Takata for inspection, analysis and testing.

54 Records as of July 24, 2020 indicate that three SPI YP inflators and one PSPI-L YD inflator have abnormally high chamber pressures (over 57 MPa), which are all addressed later in this report.

55 GM Briefing: February 12, 2018, pages 5-18.

56 GM Briefing: February 12, 2018, page 7.

inflator was available for testing. The inflator that reached 91 MPa, and three that measured above 57 MPa discussed later in this report, are all YP and YD inflators that embody all of the unique features GM presented in its Petition as protecting against the risk of inflator rupture. A more thorough discussion of this test and its significance is presented in the analysis section.

98. Identifying peak pressures above 57 MPa as abnormal is relative to a typical pressure of 44 MPa,[57] that is 13 MPa (1,885 psi) above 44 MPa. The two YP inflators and one YD inflator that also experienced abnormally high pressures were between 9.5 and 10.5 years in the field and measured peak pressures above 57 MPa when deployed at ambient temperature. Specifically, the YP variant inflators were returned from MY 2007 GMT900 vehicles located in Texas and experienced 61.7 MPa and 57.7 MPa (abnormally high) pressure deployments during ballistic testing on April 27, 2017 and July 27, 2017, respectively. A YD variant inflator returned from a MY 2007 GMT900 vehicle located in Alabama experienced a 57.03 MPa (abnormally high) pressure deployment during ballistic testing on July 27, 2017. GM has not commented on the MEAF data showing these abnormally high pressures for YP and YD variant inflators manufactured in 2007.

99. GM later briefed NHTSA on a second field return YP inflator that showed unusually high pressures in closed bomb testing wherein individual wafers are tested.[58] Three wafers from a "Gen2" YP variant inflator obtained through Live D and subjected to closed bomb testing measured peak pressure was between 69 and 90 MPa. Per the working standard at OATK, "good" medium (8 mm) wafers are consistently below 64 MPa, so these values are abnormally high.[59] Other data indicated that the wafers from this inflator were high in moisture and low in density, based on which GM suggests the result may be due to a manufacturing related issue leading in some fashion to high moisture and thereby failing for reasons other than the known failure process for PSAN inflators. This suggestion does not reconcile how an inflator that passed Helium leak testing is, after time in a consumer vehicle, showing higher than typical moisture levels. It is equally likely that these characteristics are consistent with the expectation from MEAF data that wafers with nominal "as-built" can degrade to this degree via the known PSAN failure process and during deployment or lab test exhibit high pressure and/or cause inflator rupture during deployment.

Preliminary work by OATK relevant to the GMT900 inflators

100. An understanding of the GMT900 inflator variant properties is critical to assessing how inflator behavior is impacted by those properties. As used here, properties is a broad term intended to include measurable physical characteristics of the variant design features as they impact both dynamic changes during deployment and changes relevant to the propellant degradation that leads to inflator rupture.

101. Prior to and separate from GM's Petition, OATK conducted an independent assessment for the ITC of the design and functionality (how the inflator works during

[57] GM Briefing: June 8, 2018, page 51.
[58] GM Briefing: February 12, 2018, pages 5-18.
[59] GM Briefing: June 8, 2018, pages 115, 120, and 121.

deployment) of all the design families within the population of the recalled Takata PSAN inflators. OATK also independently made findings of root cause of propellant degradation for the ITC. OATK's conclusions regarding the inflator design and functionality were consistent with work conducted by others. Regarding root cause OATK found the structural failure (i.e. rupture) is due to abnormal propellant combustion caused by physical changes in propellant 2004 facilitated by increased moisture in the inflator, which results from moisture intrusion through the seal system and is also consistent with the description in my May 2016 Report.

102. The independent design assessment for the ITC included chemical and physical engineering analysis of the chemical components and other functional mechanical components of the various inflator families and variants. OATK confirmed prior findings by other organizations that chemical properties of propellant mixtures in aged inflators are present and located as intended, i.e. not chemically changed, and that all hardware components are present, properly installed and properly functioning. OATK also confirmed prior findings that physical changes in propellant 2004 had taken place and proceeded to quantify pore formation, wafer break-up on ignition, gas diffusion rates, and conducted closed bomb ballistic tests, the many tests as summarized in the attached Appendix 2. Further, OATK also reviewed the ballistic and Live D results contained in the MEAF.

103. OATK likewise performed these assessments for the GMT900 inflator variants. Since GM initially claimed the endcap body O-ring seal supported its theory that inflators in GMT900 are uniquely resistant to aging,[60] the OATK assessments also included tests to validate and quantify moisture ingress properties through the inflator seals including o-rings.[61]

104. Finally, OATK replicated subsystem level tests previously conducted at FhG-ICT that characterized the pressure equalization rate in response to the pressure difference caused by daily temperature change. This gas movement and pressure equilibration are largely complete in 2 hours and contributed to GM's establishing that the length of temperature cycles used in the GM and OATK Aging Studies and there was an assumption that it was also sufficient to allow moisture to fully equilibrate between the headspace and chemical components (propellants) during each cycle.[62]

Preliminary investigation of GMT900 vehicle environment

105. Early Takata testing showed vehicle environment plays a role in the rate of propellant aging (which was observed as density loss or diameter growth), including the fact that the same inflator in different vehicles will age at different rates (meaning the propellant will degrade at different rates). In both the GM and OATK Aging Studies the intent is to replicate real-world inflator aging, so an accurate picture of the vehicle environment is essential.

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[60] GM First Petition, page 16, Second Petition, page 17, and Third Petition, pages 10-11, 16.

[61] OATK studied crimp diameter (o-ring gap might be too large), o-ring degradation, and leak rate, summarized at August 23, 2017, pages 190-191, 192-201, and 202-204, respectively.

[62] GM Briefing: August 23, 2017, page 303.

106. GM conducted a vehicle temperature study (GM Temperature Study) regarding the GMT900 vehicles internal cabin temperature including Pontiac Vibe as a reference vehicle. The details GM provided are not precise or extensive. In various NHTSA updates, GM reports on 1, 2, or 3 vehicles subjected to testing in the field for lengths of time that are either not revealed or only vaguely described, ultimately arriving at a peak temperature of 55.0 C and 59.5 C in Miami for Suburban and Silverado Pickup truck, respectively.[63] This is a small data set considering the critical use of this information later in the work. GM also reported peak inflator surface temperatures in Miami, FL for the Pontiac Vibe (as a reference system) of 68.0 °C. Nevertheless for sake of discussion I accept this temperature information at face value.

107. Trim level can influence temperature and humidity. GM did not provide temperature data for any of the other several GMT900 vehicle models (cabin style or length) or different trim levels covered by the Petition. Truly comparable data would include evaluation of vehicle usage factors such as the influence of air conditioning and circulation vent position on temperature and humidity conditions within the vehicle. From this limited data set, GM concluded that the peak temperature for all GMT900 vehicles in the most severe environmental conditions (Zone A) with solar loading present is 60 °C or lower.

108. GM also had access to a report prepared for Takata by Atlas Material Testing Solutions (Atlas Cabin Temperature Study).[64] This study provided simulated peak temperature, solar load and humidity including that which is typical of vehicles in "Miami, Florida" measured under controlled and identical laboratory conditions outside the test vehicles. Inside the test vehicles temperature and humidity were measured in the cabin and at the inflator surface.[65] The Atlas Cabin Temperature Study involved twelve vehicles, including the Pontiac Vibe and assorted non-GM vehicles, but did not report on GMT900 vehicles. The peak temperature at the inflator surface or in the vehicle cabin span approximately 13 °C.[66] Pontiac Vibe peak temperature was recorded to peak at 63 °C, well below the 68 °C field value cited by GM.

109. GM's Temperature Study[67] results were generally consistent with the Atlas Cabin Temperature Study results. Solar load is evident in the plotted vehicle temperatures by noting exterior temperatures averaging 34 °C results in cabin temperatures differing by vehicle, overall ranging from 62 to 75 °C. The corresponding passenger air bag surface temperatures is 5-8 degrees lower, ranging overall from 54 to 70 °C. In support of the Petition, GM provided NHTSA a chart showing plots of data for two GMT900 vehicles which appear to be superimposed on top of the Atlas Cabin Temperature Study plots.

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[63] GM Briefing: December 2016, page 3. Since these data points are critical input, a clearer presentation of the information would have been prudent. Precise descriptions of conditions are required when comparing GMT900 vehicles with vague supporting data to non-GM vehicles for which precise details of temperature and humidity data gathering are more complete.

[64] GM Briefing: August 23, 2017, page 171.

[65] GM Briefing: August 23, 2017, pages 8, 171, and 172. Inflator temperature is marked AB OB in chart headers, page 172.

[66] GM Briefing: August 23, 2017, page 8, upper curves are inflator surface temp, lower curves are cabin temp.

[67] GM Briefing: August 23, 2017, page 8, histograms on left side.

110. Solar radiation and the resulting solar loading have a strong influence on vehicle cabin temperature and inflator temperature. The temperature studies above both include solar effects on the temperatures that are measured. Solar loading is used here to describe the heating of the vehicle cabin interior by solar radiation entering through the windows and was present when inflator surface temperatures described herein were collected. The radiation is absorbed by interior surfaces, which vary with trim level, raising the cabin temperature. This in turn increases inflator surface temperature so the effect of solar loading can be accounted for when studying inflators without actually imposing solar loading by programming the test chambers to cycle to the peak passenger air bag surface temperature found for the inflators when the cabin is exposed to solar loading.

111. GM also acknowledged potential contributions of vehicle volume, vehicle weight, air-conditioning cycles, and interior trim to the observed differences in peak temperature between vehicle platforms. Air conditioning has two contributions, reducing temperature and removal of humidity. Trim level includes differences in interior surface materials that can absorb and retain moisture and heat differently, contributing to differences in actual moisture and temperature levels in the cabin and thereby the area surrounding the airbag. The value of these considerations is an understanding of their collective net effect, described as vehicle utilization, on the humidity and temperature surrounding the airbag inflator as it affects propellant degradation during field aging. Unfortunately vehicle utilization is not known for any field return inflator tested.

112. The vehicle temperature data from the GM Temperature Study and the Atlas Cabin Temperature Study informed the temperature cycles used in the GM Aging Study and OATK Aging Study, and the temperature bands used in summarizing the outputs of the OATK Model, all discussed in greater detail below. GM and OATK each used three peak temperatures, 50 °C, 60 °C and 70 °C, in testing, which encompasses the span of peak temperatures observed in all vehicles for Zone A climate conditions when solar loading is also present.

GM Aging Study

113. The GM Aging Study was a preliminary investigation of 31 YP and YD inflators[68] divided into two groups: one group of field aged inflators were to be analyzed by Takata including ballistic deployment testing after about 340 cycles of laboratory aging, and a second group of field aged inflators that were further aged by GM in the laboratory. GM sought to induce aging by temperature cycling the inflators in laboratory test chambers with imposed conditions of temperature and high humidity in an effort to create test units representing inflators with a total of 15 years of aging comprised of the field age when received plus some number of years derived from the about 340 laboratory cycles.

[68] GM provided inconsistent data as to how many inflators were actually used in the GM Aging Study. As discussed in detail below, the GM Aging Study involved 13 YP inflators returned from the field, 13 YD inflators returned from the field, and newly manufactured YD inflators. GM's submissions alternate between stating 5 or 6 newly manufactured YD inflators were used. However, my impression is that 5 is the correct number of newly manufactured YP inflators studied, for a total of 31 inflators in the GM Aging Study.

114. GM conducted its Aging Study to demonstrate the safety of GMT900 inflators in the short-term, which would then allow GM time for a more thorough evaluation of the inflators by OATK, including continuation of the OATK Aging Study. This effort subjected inflators to lab aging in commercially available test chambers that could be programmed to control temperature and humidity, including the ability to schedule changes to those variables.

115. GM settled on specific environmental test conditions intended to induce propellant degradation under conditions representative of real-world vehicle environments representative of the worst case, or harshest geographic regions. These include selecting test temperature conditions consistent with details described above and imposing high absolute humidity during the laboratory aging study.

116. Gm briefed NHTSA on their strategy to replicate real-world propellant degradation. For the GM Aging Study desires to accelerate degradation was constrained by certain practical limitations on both moisture and temperature cycle parameters. For example, increasing temperature is a common means to accelerate chemical degradation, but in this case increasing temperature beyond 70 °C is known to drive moisture out of the propellant, which would undermine the intent to replicate the moisture driven degradation process which the study intends to accelerate. Likewise, introducing too much moisture in propellant 2004 can produce artificial changes, i.e. changes that do not correspond to real world aging. One technique that remained available as a means to accelerate lab aging was to decrease the elapsed time for the effect of the stressors to accumulate in the propellant by shortening the daily cycle, which GM did by reducing a 24-hour day of temperature cycling to 4 hours. Temperature and humidity were cycled through real-world levels to avoid producing the artificial effects just described.

GM Aging Study methodology

117. The GM Aging Study is structured around 31 GMT900 inflators for inclusion in the GM Aging Study.[69] First, GM CT scanned field returned inflators and selected 26 inflators for additional aging and testing based on larger wafer diameter, with the rationale that inflators with larger wafer diameters would be more likely to rupture during deployment than inflators with smaller diameter propellant. Specifically, GM selected 13 PSPI-L YD inflators and 13 SPI YP inflators for additional lab aging and testing. In addition, 5 newly manufactured YD inflators were also lab aged, bringing the total to 31.

118. GM's acceleration strategy was based on two critical assumptions. First, the strategy assumes that most propellant degradation occurs only on days with the highest peak temperatures. GM reported analysis of weather information from Miami, Florida for approximately 2 months and concluded there are approximately 56 days per year when the air temperature is above 90 ºF (32.2 °C).[70] GM also recorded inflator surface temperatures for at least 13 days of field tests of vehicles in Miami, Florida, Milford,

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[69] GM Briefing: August 23, 2017, page 95-97. Here I state 31 inflators, actual count may have been 32.

[70] GM Briefing: August 23, 2017, page 14, and GM Petition, November 2016, Exhibit D, for example page 32shows 560 lab temperature/humidity cycles is taken to equal 10 years.

Michigan, and Yuma, Arizona[71] and reported a peak inflator surface temperature in Miami for the Pontiac Vibe (FD variant) of 68 °C and for the Silverado pick-up truck (vehicle class not specified[72]) of 59.5 °C. Using the 56 days to represent the entire year, GM estimates that 448 laboratory temperature cycles would simulate 8 years of environmental stress due to exposure to daily temperature cycles.[73]

119. Second, the strategy assumes that reaching the equilibrium point for environmental moisture (in the air) to enter or leave the inflator follows the time for pressure to equalize (which is less than 2 hours), and therefore GM assumes this will adequately represent the effect of moisture on propellant degradation.[74] This may not be so since GM's data also showed that the time for moisture to transfer between the booster propellant 3110 and main propellant 2004 is much longer than 2 hours, on the order of 24 hours, following a change from, for example, 60 ºC to 20 ºC for moisture in propellants 2004 and 3110 to re-equilibrate.[75] Based primarily on pressure equilibration times, GM concluded that a 4-hour cycle time was sufficient to reach the necessary equilibrium. The use of 4-hour cycles enabled GM to perform 6 temperature cycles per day. By combining these two assumptions, GM conducted 6-cycle/day for 74.66 days of testing that it contends simulates 8 years of aging, assuming 56 cycles equal one year's stress on the propellant.

120. In addition to the thermal stress, GM also designed its Aging Study to simulate humid environment moisture intrusion by imposing a controlled level of humidity in the test chambers. During the downward temperature change during the 4-hour cycle the inflator is at lower pressure than outside the inflator. This "vacuum" gradually equalizes by drawing in humid air from outside the inflator. This difference in internal inflator pressure and external pressure during the temperature cycling is a driving force of moisture intrusion in customer vehicles aging in normal used.

121. GM utilized two Thermotron brand environmental test chambers for this testing, one representing GMT900 vehicle conditions (i.e. low peak temperature, later referred to as Temperature Band 1) and one representing Pontiac Vibe vehicle conditions (i.e. high peak temperature, later referred to as Temperature Band 3). The low temperature for the GMT900 Thermotron cycling was 23 ºC for all cycles and the high temperature varied in a 4-cycle sequence of 60 ºC, 55 ºC, 60 ºC, and 50 ºC. GM also cycled the humidity with 80% relative humidity (RH) at the low temperature and 20% RH at the high temperature of the cycle.

122. The low temperature for the Vibe Thermotron cycling was 23 ºC for all cycles and the high temperature varied in a 4-cycle sequence of 70 ºC, 65 ºC, 70 ºC, and 60 ºC.

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71 Miami, Florida, along with Puerto Rico, represent the harshest environmental conditions, most likely to lead to propellant degradation in Takata's PSAN inflators, in the United States.

72 Silverado and Suburban both have configurations that are heavy duty, which use SPI YP variant inflators, and light duty, which use PSPI-L YD variant inflators.

73 GM Briefing: August 23, 2017, page 14. Note: at various times GM indicated in the body of charts and petitions that 49.7 or 58 cycles is the number of cycles that represent one year of aging. However, after some early work GM most often represents 56 cycles as estimating one year of aging.

74 GM Briefing: August 23, 2017, page 303.

75 GM Briefing: August 23, 2017, page 189.

Again, GM also cycled the humidity, with 90% RH at the low temperature and 20% RH at the high temperature of the cycle.[76]

123. The GMT900 Thermotron was loaded with 7 PSPI-L YD inflators and 6 SPI YP inflators. Conversely, the Vibe Thermotron was loaded with 6 PSPI-L YD inflators and 7 SPI YP inflators. Two or three newly manufactured PSPI-L YD inflators were added to each Thermotron during the testing for a total of 31 inflators subjected to lab aging.

124. GM cycled all of the inflators using the temperature and humidity conditions stated above. In order to analyze the data and provide an interim update to the Petition, GM halted cycling between 340 and 350 cycles for both Thermotron chambers. The 340-plus cycles calculates to an estimated 6.9 years of accelerated aging using GM's strategy at the time of 49 cycles equals one year (later used 56). GM CT scanned all 31 of the inflators to measure wafer diameter, and three of each field recovered inflator variant from each Thermotron were selected, based on possessing the largest wafer diameters, and subjected to ballistic testing. The remaining 20 inflators were subjected to additional temperature and humidity cycles to reach over 1600 total cycles and were periodically CT scanned to measure wafer diameter.[77]

GM Aging Study results summary

125. In the GM Aging Study, all of the inflators subjected to lab aging (i.e. temperature and humidity cycling) showed wafer diameter growth after just over 340 cycles, and 12 of those inflators were deployed in the laboratory at Takata. The 12 inflators subjected to ballistic testing all produced unremarkable chamber pressure curves consistent with normal inflator deployment. One chamber pressure curve was slightly lower than the other 11 curves. This interim data was incorporated in GM's estimates of service life in the Petition, by adding an estimated number of years that GM believes is represented by 340 cycles.[78]

126. The balance of the field aged inflators in the study have continued aging and are periodically checked by CT scan for changes in wafer diameter. After 600 cycles, inflators cycling in the "GMT900 Thermotron" experience an average diameter increase of 0.38 mm/1000 cycles, which should take 1474 cycles to reach a diameter of 29.2 mm (taken as the threshold for "rupture risk" derived from prior studies of the FD variant, starting at 28.6 mm). As of 600 cycles, inflators cycling in the "Vibe Thermotron" experience an average diameter increase of 0.62 mm/1000 cycles, which should take 903 cycles to reach 29.2 mm.[79] As of August 10, 2017, 1600 cycles had been completed.

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[76] GM Briefing: August 23, 2017, pages 95-97.
[77] GM Briefing: August 23, 2017, pages 96-97.
[78] GM's First Petition, page 15. GM compared the wafer growth rate observed from parts aged in the two Thermotron studies to the growth rate calculated from MEAF data over several years. GM mathematically converted the lab aged wafer growth rate to the equivalent growth in the field to derive the number of lab aging cycles corresponding to one year. From this, GM determined that 340 cycles is equivalent to approximately 7 years of field aging in this study.
[79] GM Briefing: December 2016, page 14.

While wafers in YD and YP inflators age faster in the Vibe Thermotron conditions, they are just reaching 29.08 and 29.23 mm, respectively, after 1600 cycles.[80]

OATK Aging Study

127. On behalf of GM, OATK conducted a study wherein newly-built GM inflators were assembled by Takata containing main propellant 2004 that was modified to contain added moisture prior to inflator assembly. In this way, the inflators were intended to represent field parts in a later stage of moisture increase in the propellant 2004 (i.e. older inflators). The test units were then lab aged by temperature cycling without imposed humidity (since the desired moisture level was already present). Tested units were analyzed at intervals of 280 cycles, with the last planned interval being 1680 cycles. Near the conclusion of the planned study, GM and OATK added an additional 280 cycles, for a total of 1960 cycles. The study addressed the main contributing factors influencing propellant 2004 degradation and are discussed in greater detail in this report. In briefings and presentation materials, GM has also described this work as the Long Term Aging Study or the Scientific Aging Study with GM.[81]

128. OATK's Aging Study on behalf of GM was a broader and more comprehensive study than the GM Aging Study described above. In 2016, Takata specially manufactured a total of approximately 1036 new inflators, with approximately equal quantities of PSPI-L YD, SPI YP, and PSPI-L FD variant inflators, to the same manufacturing control standards in use by 2016, specifically for use in OATK's Aging Study. These test inflators may differ from older production inflators, now field aged in consumer vehicles, to the extent they incorporate any manufacturing process improvements Takata implemented in the intervening years.

OATK Aging Study methodology

129. The OATK Aging Study employed largely the same acceleration strategies used for the GM Aging Study. The real-world daily cycle was replaced with the 4-hour cycle, and 56 cycles were used to represent, according to GM, 365 days of real-world cycling. Figure 2 depicts the overall test strategy. The plan called for periodic testing of some inflators at intervals of 280 cycles, which GM contends represents 5 years of field aging.[82]

130. However, to address the moisture level inside the field aged inflators, OATK's Aging Study used a different approach from the GM Aging Study. In OATK's Aging Study, Takata built new test inflators preloaded with specific moisture amounts intended to represent different advanced stages of moisture intrusion into the inflator and a corresponding variety of field aging conditions. As such, OATK did not impose high humidity as part of the temperature conditioning (to facilitate moisture intrusion), since the target level of moisture was already present in the propellant. OATK utilized three pre-set moisture levels to represent different field conditions in the primary stage based

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80 GM Briefing: August 23, 2017, pages 96-97.
81 GM's First Petition, scope of OATK work, Exhibit D.
82 GM Briefing: August 23, 2017, page 14, and GM's 1st Petition, Exhibit D. It is GM's contention that 56 cycles is equivalent to one year of field aging, based on GM's assertion that there are 56 days over 90 °F in Miami, FL annually.

on MEAF data. The lowest pre-set moisture level added no moisture beyond the "as-built" level present in normal inflator production in 2016. The "mid-moisture" level added moisture intended to represent the average moisture levels commonly found in field recovered inflators primary stage. The "high-moisture" level added moisture representing the maximum level found in field recovered inflators primary stage, but not unusual in a secondary stage. This strategy assumes that the propellant 2004 degradation process is not meaningfully affected by the slowly increasing moisture levels over years or the actual passage of time.

131. The baseline or "as-built" propellant moisture level for all three inflator variants was between 0.06 wt% and 0.09 wt%, which was typical of production at the time these study parts were assembled.[83] For the SPI YP variant, and the primary chambers of the PSPI-L YD and FD variants, the pre-set target for mid-moisture and high-moisture levels were 0.15 wt% and 0.30 wt% moisture respectively, as shown in Figure 2.[84] The actual moisture level achieved fell below those targets at 0.14 wt% and 0.24 wt%, respectively. Nevertheless, resulting data is referred to by the intended target value.

132. The secondary chamber for both PSPI-L variants (YD and FD) were also prepared for the OATK Aging Study with higher moisture levels than the corresponding primary chambers of the mid-moisture and high-moisture levels. In general, the MEAF data shows higher secondary chamber moisture levels for all variants of the PSPI-L inflator family. The secondary chamber mid- and high-moisture target levels were 0.45 wt% and 0.70 wt%, respectively. However, on average, the actual moisture levels achieved were 0.31 wt% and 0.54 wt%, respectively.[85]

133. Unlike GM, as noted above, OATK did not control the chamber humidity as a variable in the OATK Aging Study. With no environmental moisture during the laboratory temperature cycling, the only moisture available to the propellant was the pre-loaded moisture in the inflator and the nominal ambient humidity in the Northern Utah lab, which was anticipated to have minimal impact on the moisture level in the inflators during the study. As planned OATK monitored the moisture content of the propellant at temperature cycling intervals, which indicated that the moisture in the inflators remained in many cases nearly constant for the duration of the study.[86]

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83 GM Briefing: August 23, 2017, pages 179-183. Note moisture level on plots for nominal inflators at zero cycles, representing the as-built moisture level. Nominal moisture level data is generally the blue points and lines. Similarly, actual level for added moisture test inflators is found on the zero cycles point for respective lines.

84 GM's First Petition, Exhibit D – Scope of Work.

85 GM Briefing: August 23, 2017, pages 179-183. Secondary chamber results are generally the lower plots on these pages.

86 GM Briefing: August 23, 2017, pages 179-183. Changes are present in some results.

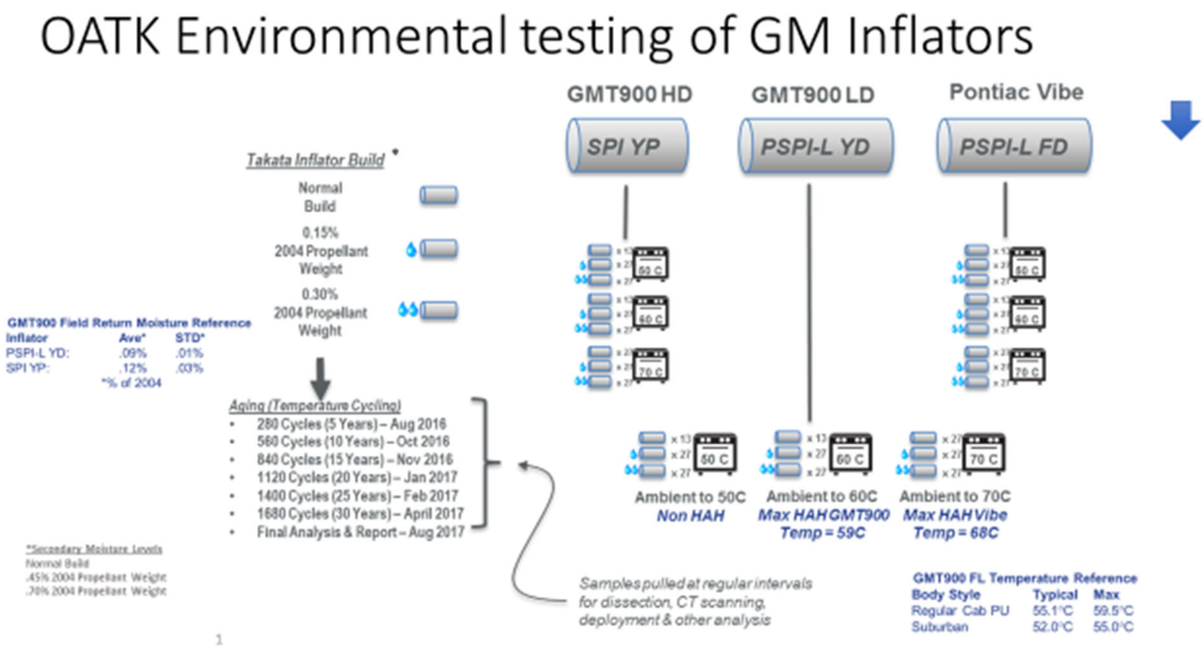

Figure 2: Test design for OATK Accelerated Aging Study (provided by GM)[87]

134. Inflators within each variant (YP, YD, and FD) were also separated into three peak temperature cycling groups. The inflators were cycled between laboratory ambient temperature (approximately 23 ºC) and either 50 ºC, 60 ºC, or 70 ºC. The 50 ºC cycle represents inflators in the field that are not in the high absolute humidity region. As illustrated in Figure 2, the 60 ºC cycle represents GMT900 inflators and 70 ºC cycle represents Vibe inflators exposed to the maximum temperature measured in vehicles in Miami, Florida. This also is representative of the 13 C° range of peak inflator surface temperatures measured while various vehicles were exposed to Zone A (e.g. Miami, FL) environmental conditions with solar radiation imposed, as measured in the Atlas Cabin Temperature Study.[88]

135. Within the OATK Aging Study, the measurement and testing plan for cycled inflators involved CT scanning, Live D, closed bomb testing, and ballistic tank testing.[89] These techniques were performed first on uncycled units of each of the three inflator variants at each preloaded moisture level to establish baseline values for future measurements. In an effort to understand how the inflators were aging and when to expect inflator ruptures to begin occurring in the field, at each interval of 280 temperature cycles, OATK performed measurements and testing on an average of approximately 70

[87] GM Briefing: March 15, 2017, page 3.
[88] The span of 13 C° would cover the GM vehicles as they note Pontiac Vibe peak temperature of 68 ºC and the GMT900 vehicles with peak temperatures between 55 ºC (Suburban) to 59.5 ºC (regular cab Silverado) as noted in Figure 2.
[89] GM Briefing: December 2016, page 2.

of the cycled parts at the early intervals with 330 parts available at 1680 cycles. The original test plan specified a total of 1680 test cycles, which GM contends represents 30 years of real-world aging in the field. Late in the study, having not yet observed any inflator ruptures in testing, GM and OATK decided to reassign approximately 90 remaining inflators after completion of 1680 cycles for an additional 280 cycles for a total of 1960 cycles, or, according to GM, the equivalent of 35 years of field aging.

136. The OATK Aging Study work plan included multiple samples of each unique inflator configuration (meaning variant pre-loaded propellant moisture level, and peak temperature) at each cycling interval to bolster the usefulness of the data for analytical evaluation. This was important to provide an average data-point for each interval and to test replicate units to guard against occasional test anomalies.

OATK Aging Study results summary

137. Key results are shown in Table 2 below, and summary highlights are described in the following paragraphs. For reasons explained in the analysis section, only the primary chamber results are summarized in this section. All temperature references in this section refer to the peak temperature in a given cycle.

138. These results are also used to set parameters for OATK's predictive model, discussed later in this report.

139. In July 2017, the original aging work plan was complete but, as noted above, GM and OATK decided to test only 69 inflators at the 1680 cycle interval and continue aging 90 inflators for an additional 280 cycles (to 1960 cycles). That work was largely completed by the February 12, 2018 briefing to NHTSA. Among all the YD and YP inflators tested at the 1960 cycle interval, only YD inflators from the as-built moisture level and cycled to a peak temperature of 70 °C, exhibited abnormal burn behavior in the closed bomb test.[90]

140. The FD (Vibe) variant produced ruptures and/or abnormal pressures at several temperature and cycle conditions, mainly at 70 °C and at the 1680 and 1960 intervals encompassing all moisture levels. At 50 °C there were no ruptures or outlier pressures for any inflator variant tested at any moisture or interval.

As-built Moisture Level Key Observations

141. As summarized in Table 2, overall at the as-built moisture level all three inflator variants (YP, YD, and FD) produced similar wafer diameter growth under the same test conditions (temperature cycle) and number of cycles, regardless of wafer thickness.

[90] GM Briefing: February 12, 2018, summarized on page 20-21. It is curious that the mildest moisture condition produces a negative outcome, but not so higher moisture units. This may call moisture pre-load approach in to question.

Table 2. Summary of Key Test Results after 1960 Test Cycles[91]

Inflator Variant	Peak Temp °C	Moisture Level	Wafer Growth (mm)	Density Loss (g/cc)	Earliest Rupture (Cycle Interval)	Earliest High Pressure (Cycle Interval)
PSPI-L FD	50	As-Built	0.10	0.03	-	-
		Mid	0.20	0.03	-	-
		High	0.30	0.04	-	-
	60	As-Built	0.25	0.08	-	-
		Mid	0.40	0.06	**1680**	**1120**
		High	0.40	0.07	-	-
	70	As-Built	0.50	0.11	**1680**	**1400***
		Mid	0.50	0.07	**1120**	**560**
		High	0.45	0.07	**1960**	**1120**
PSPI-L YD	50	As-Built	0.10	0.00	-	-
		Mid	0.05	0.00	-	-
		High	0.45	0.01	-	-
	60	As-Built	0.25	0.06	-	-
		Mid	0.20	0.04	-	-
		High	0.45	0.03	-	-
	70	As-Built	0.40	0.06	-	**1680***
		Mid	0.40	0.03	-	**1680***
		High	0.45	0.04	-	**1680***

91 GM briefings: August 23, 2017, page 48 and February 12, 2018, page 21.

SPI YP	50	As-Built	0.05	0.00	-	-
		Mid	0.25	0.02	-	-
		High	0.50	0.03	-	-
	60	As-Built	0.10	0.01	-	-
		Mid	0.30	0.03	-	-
		High	0.65	0.03	-	-
	70	As-Built	0.45	0.07	-	-
		Mid	0.45	0.05	-	-
		High	0.70	0.06	-	-
* Abnormal burn behavior on vivacity plots from closed bomb tests						

142. All density losses were 0.11 g/cc or less, for all temperatures. Density loss and diameter growth did not correlate with each other as closely as expected given the acceptable correlation found for the 11 mm wafers from MEAF data. Density of tablets drifts very slightly lower with age across variants and peak temperatures after 1960 cycles.

143. The only rupture in an as-built moisture level inflator occurred after 1680 cycles in a PSPI-L FD inflator cycled to 70 °C. The ruptured inflator contained low density propellant, which is consistent with field and test data. Separately, an abnormally high pressure deployment was measured for another 70 °C FD inflator at the 1400 cycle interval. Additionally, during closed bomb testing, the propellant from a 70 °C YD variant inflator experienced an abnormal burn at the 1680 cycle interval.

Mid-Moisture Level Key Observations

144. As summarized in Table 2, and similar to the as-built moisture level, at the mid-moisture level all three inflator variants produced similar wafer diameter growth under the same test conditions and number of cycles, regardless of wafer thickness. Again, similar to the as-built moisture level inflators wafer growth roughly doubles for each 10 °C increase in peak temperature.

145. Density loss and diameter growth did not show the expected correlation with each other as moisture level increases. In several instances the as-built moisture level

produced the highest density loss within the moisture series for a variant-peak cycle temperature group. Density loss is minimal at 50 °C, but for the FD variant is significant at peak temperatures of 60 °C and 70 ºC. Density loss generally doubles for all variants between 50 °C and 70 °C. Density loss for the YP variant is only significant at 70 ºC, while the change in the YD variant was not significant at any temperature. Tablet density is essentially flat across variants and peak temperatures.

146. The FD variant was the only mid-moisture level variant to rupture. Ruptures occurred in both peak 60 °C and 70 °C samples at the 1680 and 1120 cycle intervals, respectively. In both instances, rupture occurred in inflators where low density propellant was measured prior to the ballistic test, consistent with field return testing experience.

147. An abnormal burn was observed in closed bomb testing for the FD variant cycled to a peak temperature of 60 °C at the 560 cycle interval. Abnormal burn behavior was observed in closed bomb testing for the YD variant cycled to a peak temperature of 70 °C at the 1680 cycle interval.

148. The moisture content in the propellant at the mid-moisture level is double the as-built moisture content and within the range of moisture levels observed in returned field aged inflators. Thus, for all three inflator variants the mid-moisture inflators were expected to show earlier and greater wafer diameter growth with corresponding density loss, leading to earlier and more frequent ballistic test abnormalities. Results did not confirm that expectation.

High-Moisture Observations

149. At the high-moisture level (0.24 wt% actual), diameter growth was the same, at 0.45 mm or above, for most temperatures and variants. It was highest (at 0.70) for YP at 70 °C and lower, 0.30 to 0.40 mm, for FD at 50 and 60°C.

150. At the high-moisture level, density loss stopped (leveled off) for all three inflator variants around 1120 cycles regardless of whether the inflator was conditioned to a peak temperature of 50 °C, 60 °C, or 70 °C. After 1960 cycles density loss is high for FD variant when cycled to 60 and 70 °C and for the YD variant when cycled to 70 °C.

151. Ruptures in ballistic testing occurred only for the FD variant at the 1960 cycle interval at 70 °C. Two high pressure events were noted for cycling to 70 °C, one for the FD variant inflator in ballistic testing at the 1120 cycle interval and one for a YD variant inflator in closed bomb testing at the 1680 cycle interval (described by OATK as abnormal burn behavior).

152. One unexplained result for the study is that ballistic tank testing for all high-moisture inflators shows a trend towards lower performance, that is, lower pressure outputs, with temperature cycling even at larger wafer diameters. As such, larger wafer diameters expected to produce abnormal burning or ruptures did not. This is not consistent with the generally expected pattern observed in field return testing and prior work on 11 mm wafers.

Observations and GM conclusions from Aging Study results

GM Aging Study

153. The GM Aging Study data provided some support for GM's short-term request for time to complete the more comprehensive OATK Aging Study, but the preliminary GM data results were not a major factor in GM's final conclusions. Accordingly, they are only briefly addressed further in this discussion.

154. The GMT900 inflators used in the GM Aging Study were evaluated using CT scans to measure wafer diameter throughout the study. The initial group of inflators evaluated in August of 2016 after approximately 340 test cycles (which GM equates to 6 years of simulated aging on top of the years of field aging) were selected for ballistic testing based on the wafer diameter as measured by CT scan.[92] Inflators with the large wafer diameters were selected since it was expected these inflators would be most likely to rupture during deployment. No ruptures or abnormal pressure events were noted from testing at this interval.

155. The GM Aging Study continued to over 600 cycles and revealed that lab aging of 8 mm wafers in both the GMT900 Thermotron and Vibe Thermotron conditions produced additional increased wafer diameter: 0.38 mm/1000 cycles and 0.62 mm/1000 cycles, respectively.[93] No wafers increased to the expected diameter required for an inflator to rupture when deployed, estimated to be 29.25 mm. These growth rates are consistent with field aged inflators where exposure to lower peak temperatures results in slower wafer diameter growth and density reduction. GM continued to check diameter periodically, with steadily continuing growth over 1,600 cycles.[94]

156. The GM Aging Study was not designed to quantify how GM's alleged design advantages of the YD and YP inflator variants affect the propellant aging process. It does examine the advantage of exposure to lower temperatures in slowing wafer growth as shown above. Assuming that the accelerated aging strategy accurately replicated field aging, the favorable results for the GMT900 Thermotron schedule inflators supported GM's contention that in the near-term, even after artificial aging using the more aggressive (higher temperature) Vibe Thermotron aging conditions, GMT900 inflators were not likely to rupture in consumer vehicles.

OATK Aging Study

157. The OATK Aging Study, in contrast, was designed to quantify certain of GM's alleged advantages; specifically, the advantages of wafer thickness and lower peak temperature of GMT900 inflator variants compared to other variants, including the PSPI-L FD (Vibe) inflator variant which was included in the test program.

158. During the planned 1680 cycles and subsequent extension to 1960 cycles, the following dimensional and ballistic observations includes some anomalies relative to

[92] GM Briefing: August 23, 2017, pages 95-96. Horizontal axis is in 1000 cycles, so 0.34 is 340 cycles.
[93] GM Briefing: January 2017, page 20.
[94] GM Briefing: August 23, 2017, pages 96-97.

field return part testing results. Field return parts have consistently shown more extensive degradation when exposed to elevated moisture and/or higher peak cycling temperature.

159. Ballistic anomalies. In this aging study, ballistic anomalies for PSPI-L FD (Vibe) inflator variant occurred earlier and at lower temperatures. The earliest rupture occurred after 1120 cycles to 70 °C (Vibe cycle) for a mid-moisture FD inflator. The earliest FD high pressure anomalies were noted after 560 cycles to 70 °C and 1120 cycles to 60 °C. For the YD GMT900 variant, no high pressure anomalies occurred prior to the 1680 cycle interval where it occurred at all moisture levels for YD inflators cycled to 70 °C. For the YP variant inflator only a single abnormal curve shape in high pressure testing was noted.[95] Ballistic anomalies did not increase with moisture level, a known contributing factor in field return results. Sibling units for the above noted anomalies, tested to the same conditions, were free of ballistic anomalies.

160. Density loss and wafer diameter increases. Density loss and wafer diameter increases after 1960 cycles in Table 2 are difficult to analyze since they do not correlate well with each other and there are some inconsistencies in damage indicators relative to expected trends for increasing heat and moisture stress levels. Damage did increase with cycle temperature at all moisture levels for all variants, but higher damage proportional to moisture increases was not observed. A few broad observations: (1) diameter growth is high for GMT900 variants YP and YD at high moisture (0.24 wt% actual) at all cycle temperatures; (2) diameter growth when cycling to 70 °C is relatively high and similar in actual growth (in mm) regardless of variant and moisture level, except for the YP variant at high moisture, which showed diameter growth nearly 1/3 greater than all other values; (3) diameter roughly doubles between 50 °C and 60 °C regardless of variant and moisture; (4) density loss in the FD variant at many test conditions are above any observed for YP and YD variants, with as-built being highest; and (5) significant density loss in FD did not correspond to trends in diameter growth.

161. When evaluating cycle temperature results, 50 °C cycle peak results are less confounding than other temperature cycle levels. Density and wafer changes are minimal for all three variants and moisture levels, with the exception of high diameter growth for the two GMT900 inflator variants at high moisture (diameter growth of 0.45-0.5 mm, at 0.24 wt% actual moisture, but minor density change). The minor density change is consistent with observing normal ballistic results for inflator deployments and closed bomb wafer tests wherein the high diameter (without corresponding low density) did not cause abnormal pressures.

162. For cycling to 60 °C results vary from expected trends from field return results. For all variants, diameter growth is larger than for cycling to 50 °C as expected. Growth is particularly high for YP at high moisture cycled to 60 °C, +0.65 mm, but did not correspond to density change. Density loss does not respond to increased moisture level: it is highest for as-built moisture level in FD and YD variants, despite diameter generally increasing with moisture. For the YP variant, density loss is very low for all moisture levels despite diameter increasing with peak cycle temperature.

[95] GM Briefing: February 12, 2018, page 21.

163. For cycling to 70 °C, conflicting conclusions can be drawn from the results, depending on what is being compared. All three variants show wafer diameter increase compared to cycling to 60 °C for most moisture conditions, but for some change is not significant. Wafer diameter growth did not consistently increase with increased moisture level: for moisture increase from as-built to mid moisture level all variants observed essentially no increase in diameter. From mid to high moisture level variant FD diameter growth actually decreased 10% (compared to lower moisture levels), while variant YP increased 12.5%, and variant YD increased 55%.

164. The expected pattern regarding density is for density to decrease, a density loss, with increase in peak cycle temperature, and also for density to decrease with increase in moisture content. As a baseline, cycling to 50 °C density loss is found to be very low for all variants and density loss minimally responds to increasing moisture level.

165. Cycling to 60 °C relative to 50°C generally resulted in density loss increase at comparable moisture levels in FD and YD variants. Cycling to 60 °C produced density loss in the range where ballistic anomalies occur for FD and YD variants. Unexpectedly the as-built moisture for FD and YD had the greatest density loss of the three moisture conditions. YP variant density loss for cycling to 60 °C remained very low and any increase for comparable moisture levels was very low, between 0.0 and 0.1. For cycling to 50 °C and 60 °C density loss in YP variant were not in the range associated with ballistic anomalies.

166. For density loss cycling to 70 °C relative to 60 °C results also do not consistently follow the expected pattern. YP variant increased density loss at all moisture levels, some in the range associated with ballistic anomalies yet none occurred. Unexpectedly as-built moisture levels shows the greatest density loss of the three moisture levels at both test conditions. At the two higher moisture levels FD and YD variants density loss is essentially not increasing as cycling temperature increased, with FD variant density loss in the range associated with ballistic anomalies where some did occur. The density loss as-built is relatively high and for both cycling to 70 °C and 60 °C levels are in the range associated with ballistic anomalies, but was only observed for cycling to 70 °C.

167. For all variants, diameter growth 0.40 mm and above essentially occurs for high moisture condition cycling to 60 °C and all moisture conditions cycling to 70 °C. The expected corresponding and significant density loss did not occur, so diameter is not a reliable indicator of degradation. Since density change is predictive of ballistic anomaly, lack of significant density loss is consistent with the low level of ballistic anomalies in the study.

168. Diameter increase and density loss behavior of wafers from the FD variant was expected to be consistently higher than the YD and YP. For the FD variant density loss at or above 0.06 g/cc occurred in 6 of 9 conditions and 4 of the 6 high loss conditions produced ballistic anomalies. Diameter increase was somewhat predictive in FD.

169. Density loss behavior of wafers from both the YD and YP variants produced density loss at or above 0.06 g/cc in 2 of 9 conditions for each variant. Although ballistic anomalies were observed in FD at that density loss level, no wafers from the two high density loss YP variant conditions produced ballistic anomalies. Unexpectedly, ballistic anomalies did occur in the YD variant at significantly lower density loss levels: 2 of 7

conditions with density loss of under 0.06 mm produced ballistic anomalies. YP produced no ballistic anomalies regardless of density loss as high as 0.07 mm.

170. At the as-built and mid-moisture levels, which were designed to reflect moisture levels for many returned field aged parts, wafer diameter growth is relatively low for all variants. GM's conclusion that FD ages more quickly than YD and YP is also contradicted by the high-moisture level results, where the YP and YD variants have relatively higher diameter growth and both experienced diameter growth greater than the FD variant.

171. GM concluded from the GM and OATK Aging Studies that the YP and YD inflator variants are more resilient to heat/humidity induced rupture risk compared to other Takata PSAN inflators in other vehicles, and points to alleged unique design and environmental features to explain this. GM views the OATK Aging Study as supporting its conclusion of higher resilience regarding rupture because no ruptures were observed in YP or YD variant inflators within 1960 cycles of lab aging. GM believes that 1960 cycles of environmental conditioning accurately simulates 35 years of inflator exposure to extreme temperatures and moisture levels.

172. GM also views these conclusions to be consistent with the absence of rupture during field deployments (in what GM estimates as approximately 66,000 crashes involving GMT900 vehicles to date) and during more than 4,200 ballistic tests[96] of field returned GMT900 inflator parts.[97] The latter population was biased towards the oldest GMT900 vehicle model years (MY 2007-2008) and over-represented the highest risk regions of the country (collectively referred to as Zone A).

173. GM's conclusions predated the occurrence of a high-pressure deployment nearing the capability to rupture the inflator and recorded during ballistic testing of a SPI YP inflator in January 2018. The inflator's peak pressure reached 91 MPa during ballistic testing. [98] A number of Takata inflators have ruptured at that pressure. That inflator had been returned to Takata for testing after being removed from a MY 2007 GMT900 Crew Cab pickup registered in Texas.

174. A review of wafer diameter in the MEAF file for field returned GMT900 inflators reveals the wafer diameters are creeping up after 10 years.[99] For SPI YP variant inflators with approximately 10 years of field aging, approximately 64 inflators subjected to CT scan show propellant wafer diameter over 29.1 mm and 12 are over 29.2 mm. It can be noted that the correlation of diameter to abnormally high pressures is good for 11 mm

[96] GM's Fourth Petition at 12. For comparison, as of May 2019, field returned FD variant inflators (Vibe) ruptured in ballistic tests at a rate of 0.1% (or 1-in-992). However, in contrast, when the FD variant is installed in a large (non-GM) vehicle, similar in size to GMT900 vehicles, and used in the field as long as 11 years, field returned inflators experienced zero ruptures or high pressure events in testing. GM briefing: August 23, 2017, page 173.

[97] GM Briefing: June 8, 2018, page 4.

[98] GM Briefing: February 12, 2018, page 12.

[99] GM Briefing: August 23, 2017, page 14, and GM Response September 29, 2017 to NHTSA September 15, 2017 Information Request, pages 23-27 Exhibit F. For example compare mean and width of distribution at year 5 versus year 10 on page 25.

wafers, but is not well established for the case of 8 mm wafers, which are becoming less dense, though this is not significantly reflected in increasing diameter measurements.

175. GM's conclusions from the OATK Aging Study do not consider the three additional abnormal high pressure deployments (61.7, 57.7 MPa for two YP inflators, and 57.03 MPa for a YD inflator) in the population of 4,200 ballistic tests conducted by Takata of GMT900 inflators. Normally YD and YP inflators operate at a peak pressure of 44 MPa.[100]

OATK Model

176. OATK has recently completed a predictive model, the OATK Model, for future performance of the YP and YD inflators in the GMT900 vehicles, a subset of ongoing work to build a more comprehensive model regarding certain Takata inflators. The primary use of the OATK Model output is to estimate the age at which an inflator variant in a specific location reaches internal pressure sufficient to rupture. Information and functional details within the model were only provided at a high level when briefed to NHTSA in June 2018, so the description below represents my current preliminary understanding of the functional pieces within the model.[101]

177. In overview there are two main sections to the Model: (1) the propellant Aging section and (2) the Ballistic section, which assess potential for rupture for inflators containing propellant aged according to the first section.

178. In developing the Aging section of the Model OATK reviewed known data and factors regarding the Takata PSAN inflator defect. For the Aging section OATK built deterministic sub-models which, when combined, represent a comprehensive model of propellant response within the inflator to local environmental stress inputs. The response of main propellant 2004 is expressed as a range of densities, which corresponds to the state of propellant degradation.

179. To predict Ballistic response and the probability of rupture in the vehicle OATK used Monte Carlo simulation methodology. Monte Carlo is employed where variation is known to exist in parameter(s) that influence the probability of interest, in this case probability of rupture within the output for the given inputs.

180. The density range of interest from the Aging section is input to the Ballistic section. That input is coupled with two aspects of the Ballistic section: a randomly selected pressure-time output (derived from data sets for equivalent inflators) and a randomly selected structural strength (derived from burst test data sets). When an individual case results in force from gas pressure exceeding strength of the housing rupture is the expected outcome. The computer repeats this process thousands of times to yield a set of results that can then be assessed for the probability of rupture occurring for the selected vehicle in the selected location.

181. For each inflator variant and location of interest the OATK Model was run 32,000 times producing a population of results, some portion of which may represent likely

[100] GM Briefing: June 8, 2018, page 51.
[101] GM Briefing: June 8, 2018, results summarized pages 7-14.

rupture. For discussion sake, a low but non-zero proportion was selected to represent the threshold level for acceptable risk of rupture.

182. As inflators age in customer vehicles density decreases and consequently the portion of the population of results that exceed the acceptable threshold level increases. When the portion of the population of results that rupture exceeds the acceptable threshold the safe life for use of the inflator has been reached.

183. The OATK Model output is communicated as the age (end of safe life) at which the probability of failure (POF) exceeds the selected acceptable threshold, here chosen to be 1% of the cases run. This age where the POF exceeds the threshold is specific to an inflator variant in a specific location, so it is at that age 1% of the 32,000 case runs resulted in a pressure sufficient to rupture the inflator.

184. Vehicle usage affects the results. To address this the OATK Model initially calculates the worst case usage, then modifies results by applying a usage factor, described later.

185. The aging section links factors (1a) climate outside the inflator to (1b) moisture details inside the inflator, and in turn to (1c) OATK's understanding of cumulative propellant damage. Factors outside the inflator (1a) include inputs for weather, vehicle-specific environment, and vehicle usage. Factors on moisture details inside the inflator (1b) include the total moisture present, the increase (or decrease) in moisture inside the inflator during aging time, and the equilibration of moisture in each of the propellant components and inflator headspace. "C-integral" is the output, which is an internal parameter that connects moisture movement with propellant density change which decreases with the age of the inflator. OATK's understanding of cumulative propellant damage (1c) converts the C-integral into propellant 2004 density according to empirical data from the OATK Aging Study. The output density changes with age and is specific to the inflator variant's response to specific vehicle environment being modeled.

186. The ballistics section contains (2a) ballistic output, which has known variation, as a function of propellant damage which imparts internal inflator pressure onto (2b) the inflator structural strength, which has known variation, of the housing for the specific variant. Ballistic output (2a) is adjusted according to the propellant density, which changes with age. This adjustment is made by applying an OATK-derived burning rate acceleration factor calculated from ballistic tests of propellant wafers of various densities. Inflator structural strength (2b) is based on the burst pressure and its standard deviation as measured for each variant by Takata.

187. To more generally assess risk for the wide variety of vehicles that used Takata PSAN inflators the Model results can be aggregated according to key inputs. For example, peak inflator surface temperature is a key variable affecting rate of propellant density decrease, so segmenting vehicle specific data into groups within a few narrow bands of peak inflator temperature is helpful. Model results grouped by peak temperature bands can be compared to the OATK Aging Study results that were also organized by bands of peak temperature.

188. In the presentations to NHTSA, OATK grouped Model results for vehicles grouped by three peak temperature bands (derived from measured values from closed

vehicles in the Atlas Study replication of Miami, FL conditions): T1 (vehicles that normally do not achieve 60 °C), T2 (vehicles that achieve 60 but do not typically reach 65 °C), and T3 (vehicles that achieve temperatures above 65 °C).[102] These temperature bands represent relative response to Zone A conditions represented by Miami, FL a climate zone known to induce short inflator safe life. At the upper end of this span of temperatures, T3, moisture movement within the inflator between booster propellant 3110 and the PSAN main propellant 2004 is known to be greater.

189. A modifying input to the aging section is vehicle usage profile, meaning how the vehicle is driven, where it is parked, how often and how high the air conditioning is run, and any other factors that affect the moisture and temperature environment of the inflator, for example, solar load. During development of the Model, OATK added vehicle usage profile to its understanding of the root cause, as laid out in its fault tree analysis.[103] The vehicle usage profile for return inflators that were tested (summarized in the MEAF data) can only be guessed, so OATK used a generalized parameter for usage expressed in the Model as a value between 1% and 99% where 1% infers worst case usage and 99% infers best case usage. GM and OATK did not provide analysis or practical implications of the extremes of vehicle usage profiles, however, the general assumption is that rupture risk is highest for the worst usage (1% in the Model). However, the probability of failure, POF, of most interest is for 1% ruptures within the population (of aggregated model runs) representing the 1% worst vehicle usage[104] which represents shortest inflator safe life.

190. GM concludes that the OATK Model shows that the "GMT900 Takata inflators do not reach a threshold risk level within 30 years of worst case environmental field exposure in Miami, Florida."[105]

GM's Overall Conclusions in Support of the Petition

191. GM concludes that the YD and YP inflator variants used in the GMT900 vehicles "utilize a unique design with features that, along with the GMT900 vehicle environment, make them more resilient to heat/humidity induced rupture risk compared to other Takata [PSAN] inflators in other vehicles" and that "all available data supports the conclusion that the GMT900 inflators are uniquely resilient against heat/humidity induced rupture risk."[106]

192. In support of this conclusion, GM specifically points to: (1) field crash data, with no known ruptures in GM's estimated 66,000 field deployments; (2) ballistic testing of field returns, with no observed ruptures in over 4,270 ballistic tests conducted by Takata; (3) the OATK Aging Study, with no observed ruptures in the YP or YD test inflators; (4) the OATK Model; and (5) a statistical risk assessment conducted by Cornerstone and Arnold Barnett, Ph.D.[107] Regarding the OATK Aging Study, GM asserts that the 1960 cycles of accelerated aging simulates 35 years of environmental exposure at extreme

102 GM Briefing: June 8, 2018, page 14.
103 GM Briefing: June 8, 2018, page 9, right column.
104 GM Briefing: June 8, 2018, page 8.
105 GM Briefing: June 8, 2018, page 4. Showing 1% POF at 1% vehicle usage.
106 GM Briefing: August 23, 2017, page 33.
107 GM Briefing: August 23, 2017, page 4.

temperatures and moisture levels and, further, that while the study induced ruptures and abnormal deployments in FD variant inflators (albeit much later than field results) used in the Pontiac Vibe, that none of the GMT900 inflators ruptured, abnormally deployed, or displayed the warning signs associated with a possible future rupture, despite identical study aging conditions.

Analysis and Expert Opinion Regarding Data Presented by GM and the GMT900 Inflators

193. As a preliminary matter, in my expert opinion, the scientific methodologies used in the studies GM presented to NHTSA are sound, and the laboratory analysis methods are both well established and well suited to the challenge. This is an extremely challenging problem wherein variables interact in complex ways and, because the overall failure rate is relatively low, test sample counts must be high enough to detect the failure.[108] Analysis of GM's statistical conclusions as presented by Cornerstone is outside the scope of my expertise and I do not offer an opinion of that work.

194. Conclusions drawn by GM from the GM Aging Study and OATK Aging Study results are curiously selective. In reviewing the data provided by GM in support of the Petition and otherwise available to GM and NHTSA through the ongoing investigation of Takata's PSAN inflators, I do not agree with GM's conclusions and, further, do not agree with certain of its underlying assumptions and assessments. The SPI YP and PSPI-L YD inflator variants are nearly identical to certain other Takata PSAN inflator variants that share many of the attributes claimed as "unique" to the GMT900 variants and logically are equally susceptible to ruptures and/or abnormally high internal pressure deployments as those variants, some of which have ruptured. The attributes GM identified do not mitigate moisture intrusion or the poor stability of propellant 2004 in the presence of moisture and temperature cycling which leads to density reduction.

195. Based on the studies conducted, at best, GM can conclude that the YP and YD variant inflators in the GMT900 vehicles age slower than the worst performing variants, for example those selected by GM as comparison inflators. In my opinion density reduction for all non-desiccated Takata PSAN inflators is a continuum and every inflator sits somewhere on the continuum wherein a complex set of details influences the state of density at any time and the time when rupture will occur. In concluding that (GMT900) PSPI-L YD variant inflators age slower than (Vibe) PSPI-L FD variant inflators, GM chose not to comment on the performance of PSPI-L FD inflators installed in a large non-GM vehicle with zero ruptures or high chamber pressure test results after 6,064 tests, wherein 4,297 inflators were returned to Takata from Zone A. In concluding YD and YP age slower, GM also did not consider the very similar diameters for 11 mm and 8 mm wafers measured after 1680 cycles in the OATK aging study. That result implies the two age the same under identical conditions.[109]

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108 Studies testing small numbers of inflators can be misleading if that number is not representative of the overall rupture rate. For example, a rupture rate of 0.015% of units tested implies several thousand units may pass before one ruptures. Since rupture rates are often much less than 1%, any conclusions drawn from several inflators cannot be definitive, because sample counts are too small relative to the failure frequency.

109 GM Briefing: June 8, 2018, page 63.

Choice of Comparison Inflators.

196. In the research to support its petition, GM selected comparison inflator variants, the SPI AJ and PSPI-L FD (comparison variants), with two important differences from the GMT900 inflator variants under the Petition, the SPI YP and PSPI-L YD. The comparison variants use primarily 11 mm wafers and are commonly installed in vehicle platforms with peak temperatures 10 °C higher when all are subjected to solar loading and under High Absolute Humidity environmental conditions. The selected comparison variants have been shown in Takata test and field data, contained in the Takata MEAF, to age faster and/or show ruptures and abnormal pressures more often than many other variants.[110] In considering comparisons of the YP and YD variants to the comparison variants, the conclusion that GMT900 variants age slower than these inflator variants with relatively high rates of rupture or high-pressure deployment appears valid; but it does little to quantifying the rupture risk of the GMT900 inflators.

197. GM concludes there is a unique benefit of 8 mm wafers used in its YD and YP variants. This cannot be evaluated from the GM data, however, since the contribution of peak daily temperature is also present in comparisons to the FD and AJ variants. Alternatively, comparison of the GMT900 variants to non-GM inflator variants that share the claimed inflator design and vehicle environment advantages, i.e. nearly equivalent variants and comparable peak daily vehicle temperature, would better complete the picture as to whether the GMT900 variants are unique in their response to environmental stressors.

Comparison inflators for SPI YP

198. The SPI AJ variant, used as the comparison inflator for the GMT900's SPI YP, is known to have an above average failure rate, as high as 0.34% (or approximately 1-in-300) in one platform.[111]

199. Using GM and OATK's own analyses of configuration details,[112] a better comparative variant for the YP is the nearly identical non-GM DH/MG variant of the SPI inflator since it, like the YP, shares use of both 8 mm wafers and, like the GMT900 vehicles for which temperatures are known, enjoys a low peak inflator surface temperature in tests replicating heat, humidity, and solar load conditions of Miami, FL (Zone A). A comparison of diameters in the MEAF for approximately 10 year old field return inflators shows the average (mean), maximum, standard deviation, and 95th percentile of the 8 mm wafers in the DH/MG and YP are not different.[113] The fact that the

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110 There are 30 variants of passenger inflators within 7 design families and some variants are used in several vehicle platforms. Not all variants and vehicle platforms have been tested to the same degree, Test inflators are selected for many reasons, but to a significant degree those from high risk Zone A have been most heavily tested.

111 Rupture rates vary widely, which has been puzzling for some time since the same variant can have, for example, 0 rupture in one vehicle platform and 1.88% in another. Some variants go thousands of tests before rupture. Of the 50 vehicle platforms, as a matter of rupture rate as a percentage, the selection of FD and AJ represents comparison to the worst case inflators; only 1 inflator variant ruptures more often than the AJ variant and only 2 rupture more often than the FD variant.

112 GM Briefing: August 23, 2017, design comparisons at page 45.

113 MEAF file sorted for locations Florida and Texas. Values found in millimeters were as follows:

average age 9 years YP: mean 28.776, max 29.36, std dev 0.1035, 95th percentile 28.98;
average age 10 years DH/MG: mean 28.785, max 29.15, std dev 0.1107, 95th percentile 29.05.

DH/MG and YP variants are both aging at exactly the same rate reinforces the similarity of these two variants and the associated risk of rupture.

200. Ballistic tests performed on field returned DH/MG variant inflators have experienced 1 test rupture out of 6,771 tested units; a rupture rate of 0.015%. The remarkably similar inflator design and environment details, evidence by the same diameter growth rate in field aged inflators, implies the SPI YP variant is essentially at the same level of rupture risk as the DH/MG variant. GM speculated that the DH/MG inflator that ruptured may have been part of an Alpha inflator population, but did not provide any information to support that. To the contrary, a simple examination of the timeline of Takata PSAN inflator production and recalls clearly shows that the rupturing DH/MG inflator was manufactured outside the date range for the Alpha inflators as identified by Takata to NHTSA and automakers.

Comparison inflator for PSPI-L YD

201. For comparison to the PSPI-L YD variant, GM selected the "FD" variant which is installed in the Pontiac Vibe and two related vehicles sold by another vehicle manufacturer. As previously noted, the FD variant represents a PSPI-L variant with both a different wafer size (11 mm) and a high peak inflator surface temperature in response to solar loaded Zone A conditions. As noted for SPI above, since two alleged advantages are present their separate contribution to risk/benefit cannot be derived from a comparison of YD to FD.

202. In order to establish a unique resistance to inflator rupture, a better comparison inflator for the YD variant inflators would be one using 8 mm wafers and installed in a vehicle with a Zone A temperature and solar loading response similar to the YD variant. Such a comparison would enable assessment of the features that are not shared between the YD variant and this better hypothetical comparison PSPI-L variant. The 20 PSPI variants using 8 mm wafers fall into the families PSPI, PSPI-L, PSPI-1.1, and PSPI-6, which represent a progression of the PSPI design over time. However, the GMT900 variant is unique in that it uses primarily 8 mm wafers in the PSPI-L family, which no other PSPI-L variant does. Thus, a comparison within that specific family with 8 mm wafer and low peak temperature cannot be made.

203. However, relevant insight can be gained from two vehicle platforms from a different vehicle manufacturer that use the PSPI-6 "YB" variant. Like the GMT900's YD variant, the PSPI-6 YB variant uses primarily 8 mm wafers. Comparing the two non-GM vehicle platforms to the GMT900 vehicles, one responds to Zone A conditioning with a peak temperature slightly lower than the GMT900 (both in band T1), affording good comparison of YD to YB variant performance. For this low temperature platform using the YB variant, no ruptures have been recorded.

204. The other non-GM vehicle platform using the PSPI-6 YB variant responds to Zone A conditioning with peak temperature in band T3. For 11- to 12-year old YB inflators residing in Zone A there is one field rupture (on September 11, 2017 from Hawaii), three inflator ruptures during field-return ballistic testing, and one abnormally high pressure, at 79.61 MPa, with the last four of these events occurring during testing in

June and July 2018. These results indicate that an 8 mm wafer inflator variant experiencing high peak inflator temperature in Zone A can rupture at a similar age to the Vibe PSPI-L FD (with an 11 mm wafer) that GM used for comparison. As with the YD variant described above, the PSPI-L FD in the Vibe, which has ruptured, can be compared with a large vehicle PSPI-L FD with no known ruptures. Whether wafers are 8 mm or 11 mm, the peak temperature of the daily cycle contributes more significantly to the risk of inflator rupture than does wafer diameter.

205. Another non-GM vehicle platform uses a PSPI-6 inflator, the “XG” variant, which uses primarily 8 mm wafers. The MEAF data shows ruptures/abnormal pressures for the XG variant at a high rate, 1.06% of inflators tested, with all ruptures coming from inflators installed in MY 2006-2007 vehicles and thus field aged 9.4 to 10.3 years. Peak temperature at the inflator surface is not known for that vehicle platform, but even assuming the temperature response to Zone A conditioning results in a relatively high peak inflator temperature (in band T3), it is another example that, as shown for the YB variant, the 8 mm wafers still degrade by the same process as the 11 mm wafers and GM’s claim of slower degradation in the 8 mm wafer appear weak in field aged inflators. This degradation does lead to a relatively high rate of rupture and/or abnormally high pressure deployments in Zone A after only 10 years of field aging suggesting the influence of other factors.

206. *Unique inflator design features.* GM claims 6 inflator design features (see Table 1 above) are unique to its YD and YP variant inflators that “make them more resilient to heat/humidity induced rupture risk compared to other Takata inflators in other vehicles.”[114] Three of those features apply to both the YD and YP variants, specifically (1) thinner wafers, (2) steel endcaps, and (3) vent-area to propellant-mass ratio. Two features apply only to the YP variant, specifically (4) tablets in a sealed cup and (5) a ceramic cushion. The sixth “unique” feature applies only to YD and is (6) the use of a bulkhead anvil.

207. GM does not claim any of the features were designed to mitigate any contributing factors to the now known failure process. It is critical to point out that the work GM has done since filing the Petition was focused on the rate of propellant aging, and not on quantifying the claimed benefits arising from the unique inflator variant and vehicle environment features. Useful data for some features was gathered during various efforts undertaken by OATK efforts, but was not specifically presented by GM as foundation for how the alleged unique features make the YP and YD variants more resilient to environmentally induced rupture risk.

208. GM’s data confirms its “unique” design claims do not limit moisture intrusion into the inflator, a known contributing factor to the root cause of propellant 2004 degradation. That is the logical expectation since the GM variants share the system of seals that is common throughout the Takata PSAN inflator product line under recall. Specifically, all Takata passenger air bag inflators contain a gasket seal for each ignitor, and O-ring body seal for each endcap, and contact adhesive metal foil seals for the vent holes.

[114] GM Briefing: August 23, 2017, page 33.

209. *Thinner wafers*. The Takata variants used in the GMT900 vehicles use primarily 8 mm wafers of propellant 2004. GM became a relatively early user of 8 mm wafers as a result of Takata's ballistic tailoring efforts to improve gas production efficiency for larger volume air bags used in large platform vehicles like the GMT900. Subsequently, 20 PSPI inflator variants with 8 mm wafers were adopted for vehicle platforms covering a variety of vehicle sizes. As such, use of 8 mm wafers is not unique.

210. GM also believes one aspect of thin wafer advantage is 8 mm wafers are pressed to a higher density than 11 mm wafers, which, if true, should slow moisture intrusion into the wafer. However, the difference in pressed density are relatively small with both having void volumes of between 2.1 to 3.1 vol%[115] corresponding to small differences in density, 1.69 versus 1.67, as noted by the unaged densities that anchor the density versus cIntegral plot for the OATK Model.[116] These void volume values are in the normal range expected for tablets pressed from powders. While it is a fact that 8 mm wafers are slightly more dense than 11 mm, relying on this point overemphasizes the role of the slight difference. In my opinion, the density difference between 8 mm and 11 mm wafer thicknesses only incrementally affects moisture intrusion affording only a minor advantage, if any. Any difference in density at similar points of field aging are likewise not significant.[117]

211. This is further borne out by considering tablets, with void content of 0.52 vol%, much less than either wafer diameter. If density differences between 8- and 11- mm wafers significantly affect the rate of degradation, systems entirely comprised of tablets should show exceptionally low rate of degradation, avoiding catastrophic ruptures. While this expectation is interesting, tablets do degrade as noted by several ruptures (non-GMT900) for inflators using Propellant 2004 exclusively in the form of compressed tablet.[118] Furthermore, neither GM nor other investigators have established a major or secondary role for tablet degradation in the inflator rupture and/or over-pressurization process in Takata SPI or PSPI passenger inflators where wafers predominate. This applies to original or degraded tablets.

212. GM's claim of 8 mm wafers aging slower than 11 mm wafers is not supported by results of the OATK Aging Study wherein there is no significant difference in wafer growth over time for the as-built moisture inflators. After 1680 cycles to 70 °C the FD variant (11 mm wafers) and YP variant (8 mm wafers) inflators both measure 29.2 mm in diameter; and similarly, cycling to 60 °C for the FD and YD (8 mm wafer) variants both measure 28.95 mm. While GM did provide some MEAF-based diameter data supporting the claim that thinner wafers age slower, comparisons of the FD variant family to the YP and YD variants in the MEAF data are not simply diameter differences, but are comingled with a difference in peak daily inflator temperature, with the bulk of FD inflators tested reaching higher peak temperatures. That being true, the as-built moisture

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115 The maximum theoretical density for Takata propellant 2004 is 1.73. The void volume as volume percent is the air space within the geometric volume of the tablet or wafer.

116 GM Briefing June 8, 2018, page 12.

117 GM Briefing: August 23, 2017, page 184-186. The small difference shown can be attributed to the FD inflators being in the field 25% longer.

118 Some Takata inflators such as SDI (single stage) use exclusively tablets, that is, there are no wafers or batwings shaped propellant. A number of ruptures and/or high pressure events are on record for field aged SDI.

level results in the OATK Aging Study teach that at comparable moisture and temperature conditions growth rates are essentially the same.

213. *Steel endcaps.* GM initially claimed that the endcap fabricated from steel used in the YD and YP variants offers a distinct advantage in reducing moisture intrusion through the endcap O-ring seal. GM presumed a more consistent O-ring seal of the endcap to the tubular body when compared to the O-ring seal between the baseline aluminum endcap and the inflator body used in most Takata inflator variants.

214. OATK conducted an engineering investigation of leak rate past the O-ring that found both steel and aluminum endcaps sealed sufficiently to pass the leak test requirements for all dimensions within the allowed tolerance.[119] Testing included at least two points representing o-ring groove (gap to be sealed) greater than allowed by the upper specification limit. Therefore, the steel endcap design feature offers no measurable advantage over other Takata variants regarding moisture intrusion. All inflators shipped by Takata use the same seal system, pass the same helium leak test, regardless of endcap material used, and all are equally subject to moisture intrusion.

215. *Vent-area to propellant-mass ratio*. The vent-area to propellant-mass ratio is a peculiar description somewhat related to a fundamental principle for balancing solid propellant combustion, referred to as the vent-area to propellant burning surface-area ratio. The ratio to area, and not mass, controls the operating pressure for the normal function of the inflator. The ratio to mass is not fundamental and ignores the critical role of burning surface-area.

216. The actual burning surface-area includes surface-area generated on ignition by wafer breakup, a common feature in all the recalled Takata PSAN inflators. The fundamental principle described above applies equally to venting an 8 mm variant or venting an 11 mm variant. For any wafer thickness, the total vent-area (the sum of all vent-areas together) is sized to achieve balance between gas generation by the actual burning surface of the chosen wafer size and gas exiting through the vents.

217. During the occupant restraint event, most of the propellant 2004 is burned to fill the expanding air bag cushion while decelerating the vehicle occupant, with the remainder of the propellant burning after occupant contact with the air bag cushion. GM is correct when it indicates that to fill a specific size air bag, normal and balanced combustion of an 8 mm wafer variant uses a larger portion of the propellant prior to the period when the passenger occupant makes contact and is restrained. That constitutes a design improvement in the 8 mm wafer inflator variants during normal combustion over a corresponding 11 mm inflator variant. While true, this more timely and efficient use of propellant does not translate into the inflator being more resilient to the failure process.

218. Instead, this GM claim ignores well established principles of gas dynamics. Systems operating at high pressure, which includes all Takata inflators, will increase internal pressure in response to sudden increase in burning surface-area because the exit flow cannot increase proportionately (it is already in a state referred to as choked flow). GM's inflator variants cannot increase vent flow area so, like all other recalled Takata PSAN inflator variants, they are not immune to the expected ruptures and/or abnormally

[119] GM Briefing: August 23, 2017, page 204.

high internal pressure readings that result from a steep pressure increase that is caused by a sudden increase in the burning surface-area due to the uncontrolled burning of degraded propellant 2004.

219. Early in the investigation of the field rupture of a PSDI driver inflator, Takata experimentally demonstrated the foundation for excess propellant surface area causing ruptures and/or abnormally high internal pressure readings. Structural failure identical to field evidence was recreated by loading inflators with extra propellant (all un-degraded) constituting 10% additional surface-area. The experiment verified that extra surface-area was all that was needed to cause inflator rupture. The experiment did not replicate the delay (approximately 10 milliseconds after ignition) aspect observed for ruptures or over-pressurization of field return inflators.

220. Once the surface-area to vent-area ratio is established to balance an inflator for GM or any other vehicle manufacturer, a sudden increase in burning surface-area will overwhelm the exit flow area causing pressure to rise and increase the risk of structural failure for any inflator.

221. Helpfully, there is now visual evidence of what occurs during combustion, including the delay that leads to inflator rupture. OATK shared X-ray cinematography videos[120] of normal deployments and deployments that rupture. Videos of normal combustion deployments show wafers breaking on ignition and those broken segments steadily decreasing in size over time as they burn. In contrast, videos of deployments that rupture show wafers breaking on ignition and those broken segments beginning to decrease in size until several milliseconds into the burn a bright flash is observed on screen indicating burning *en masse* coincident with the catastrophic failure (i.e. rupture) of the inflator housing.

222. GM claims the GMT900 inflator variants feature a larger vent-area that lessens potential for over-pressurization. The vent-area GM and Takata selected to achieve air bag cushion fill in the necessary time to provide occupant protection is, nevertheless, operating under choked flow conditions and will respond to a sudden increase in burning surface-area by over-pressurizing the structure. A non-GM variant that uses 8 mm wafers and has a comparable vent-area (the SPI DH/MG)[121] has ruptured during ballistic testing of field returned inflators aged approximately 11.6 years. There are also ballistic test ruptures and abnormally high pressure events on record for other variants using 8 mm wafers, all of which were balanced to achieve the air bag fill desired by the corresponding automobile manufacturer and all operate under choked flow.

223. *Tablets in a cup*[122] *(SPI YP only).* Neither GM nor other investigators have established a major or secondary role for tablet degradation in the inflator rupture and/or over-pressurization process. This applies to original or degraded tablets. The presence of

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120 These videos were incorporated, with OATK's permission, into a keynote speech I gave in 2018 (*Investigations of Takata Airbag Propellant Degradation*, slide 40). The same sequence of events holds true whether rupture occurs in the primary or secondary stage.

121 GM Briefing: August 23, 2017, page 45.

122 Placing a propellant in a cup is most often done to simplify assembly operations or to constrain the location of tablets for ballistic control reasons. The reason in this case has not been provided.

the cup is unique to the YP variant, but did not influence wafer moisture increase in field aged SPI YP and PSPI-L YD (no cup) variant inflators, and when further aged in the GM Aging Study growth for the 60 °C cycle (GMT900) is very similar.[123] Tablets in the YP variant inflators can only have a limited effect since they only constitute 6% of the total main propellant 2004 charge weight. GM claims that the inflator design feature of "tablets in a cup" is beneficial, reasoning that this limits exposure of those tablets of propellant 2004 to moisture present inside the inflator, but this would be important only if tablet degradation is a factor in the risk of inflator rupture. OATK found that tablet density after 1960 cycles is essentially not different for the three variants at as-built and mid-moisture levels (all drift slightly down, if anything, YP is worse).[124] GM also concluded that wafers in the YD variant, and not the YP variant, saw the least density reduction. This feature has no effect on propellant wafer degradation because the tablet densities between the 3 inflator variants are indistinguishable and wafer growth rates for filed return inflators in the GM Aging Study are the same for YD and YP.

224. *Ceramic cushion (SPI YP Only).* GM identified a second YP only feature, the use of a ceramic cushion, as a unique feature of the YP inflator variant. This change was implemented to reduce damage that can occur to the propellant if the inflator is dropped, as in the drop test required in qualification test.[125] As described for tablets in a cup, YP does not age superior to YD. Furthermore, GM did not provide any information supporting the relevance of this feature to mitigating ruptures and/or abnormally high internal pressure deployments. Cushion in place of springs may influence dust in inflator due to vibration, but dust has not been identified as a factor in occurrence of rupture, regardless of whether the variant has a ceramic cushion (and springs) or springs only. Even combined with tablets in a cup as outlined above, the wafer density reduction in the YP variant inflators is greater than in the YD variant inflators, so there is no advantage accruing from the combined features unique to the YP variant.

225. *Bulkhead anvil (PSPI-L YD only).* In all PSPI-L variants, a metal disk bulkhead separates the primary and secondary combustion chambers, as can be seen in Figure 1 for both FD and YD variants. GM's YD variant has a feature, referred to as an anvil, added to the bulkhead disk that protrudes into the combustion chamber. GM claims that during assembly the anvil contacts the autoignition-booster cup so as to disrupt the seal of that cup, thereby allowing the moisture in the inflator headspace greater access to the booster propellant 3110 within the cup.

226. GM provided data from the OATK Aging Study demonstrating that moisture increases in propellant 3110 in YD inflators with a disrupted autoignition-booster cup. In contrast, in the YP and FD variants (without an anvil) propellant 3110 in the canister picks up essentially zero moisture. If moisture gain in propellant 3110 in the YD variant is beneficial, a drop in propellant 2004 would be expected. Since the data also shows propellant 2004 moisture varying in the same small range across all three variants throughout 1960 cycles, the benefit of moisture increase in propellant 3110 in the YD variant AI canisters cannot be detected as reduced moisture in propellant 2004. In my

123 GM Briefing: August 23, 2017, page 97. This page shows diameters on the line fitted to the data after approximately 1,600 cycles the YP variant is at 28.95 mm and the YD variant is at 28.96 mm.
124 GM Briefing: June 8, 2018, page 108.
125 GM Briefing: February 12, 2018, page 6.

opinion, moisture going into the canister is verified, but it does not have the theorized beneficial effect of reducing moisture in propellant 2004. That being true this design feature has no influence on risk of inflator rupture.

227. *Unique vehicle environment features.* GM asserts two features of the GMT900 vehicle environment contribute to reduced probability of rupture in Takata inflators when installed in the GMT900 vehicles: (1) solar absorbing windows and (2) large vehicle volume. The potential benefit from either of these is a reduction in peak temperature experienced by GMT900 vehicles to Zone A climate while solar loaded.

228. *Solar Absorbing Windows.* GM indicates that solar absorbing windows are present in 100% of the GMT900 vehicles. GM logically asserts that solar absorbing windows affect temperatures inside the vehicle but did not provide any data specific to prove this (e.g. comparing two vehicles differing only as to the glass in windows). However, GM provided peak inflator surface temperature data from the Pontiac Vibe (68 °C) and 2 of the GMT900 vehicle models (59.5 and 55 °C) when exposed to Zone A temperature and humidity conditions (in Miami, FL) with solar loading also imposed. This led to the two Thermotron schedules in the GM Aging Study, one cycling to 10 C° hotter peak temperature corresponding to Vibe and one corresponding to GMT900. Growth rates of 8 mm wafers was 59% higher for the Vibe schedule, demonstrating a strong influence for peak temperature. Overall, vehicles tested were later bracketed by OATK according to peak temperature values into three temperature bands (T1, T2, and T3) with the GMT900 vehicles fitting generally in the lowest temperature band, T1.

229. As discussed above, vehicles in temperature band T1 share a relative advantage over inflators on vehicle platforms that register in the higher temperature bands, T2 and T3 (including GM's Vibe vehicle that reaches 68 °C when solar loaded). The GMT900 vehicles generally being in this lower temperature band (T1) does not impart an advantage over other vehicle platforms also in band T1. Vehicles in temperature band T1 have experienced inflator ruptures (e.g. variant DH/MG) and abnormally high internal pressure deployments, including the GMT900 variant events largely ignored, and not explained, by GM during the Petition process.

230. *Vehicle volume.* Takata observed that, overall, generally, it appears smaller vehicles have a rupture rate that is higher than larger vehicles. In general, smaller vehicles have higher inflator surface temperatures (and are therefore more often categorized in temperature band T3) than larger vehicles, which have generally lower inflator surface temperatures (and are categorized in temperature band T1). Unfortunately, isolating the influence of vehicle volume independent of temperature band on many other large vehicle platforms cannot easily be done because the inflator surface temperature for these vehicles was not provided. At this point, despite the interesting observation that most smaller vehicles experience poor ballistic performance relative to most larger vehicles, the influence of vehicle volume separate from temperature band cannot be determined from the data available from GM.

231. In reality, peak temperature is the relevant fact, so it is sufficient to consider the combined effect of vehicle volume and solar absorbing windows since it is reasonable to believe that together they influence the peak temperature and temperature band, where

the peak temperature in turn determines moisture movement between propellant 3110 and propellant 2004 inside the inflator (i.e. a significant factor in the root cause of the defect).

<u>Summary Opinion Regarding "Unique" Vehicle and Inflator Variant Features</u>

232. As just discussed in detail, GM identified certain design differences as "unique" for its YP and YD inflator variants coupled with a vehicle environment it considers unique, i.e. the GMT900 platform. GM posits this combination of allegedly "unique" features justifies considering this platform and the YP and YD inflator variants as safe in comparison to other vehicles under recall. In my opinion, the beneficial effects GM claims are not of significant importance except for peak inflator surface temperature in response to Zone A conditions which itself is not unique.

233. Generally, GM did not provide data that serves to support its claimed benefits for the design features of steel endcap, vent-area, tablets in a cup, ceramic cushion, and bulkhead anvil. Even if factually unique, some of the claims are refuted by the data, and none were shown to have a significant mitigating effect on moisture level in propellant 2004 or its density during the 1960 cycles of the OATK Aging Study. Thus, there is no evidence that these features lead to a reduced risk of inflator rupture. Since certain non-GM vehicles which share most of the alleged advantageous features, such as 8 mm wafer size, larger vent area, and lower peak temperature vehicle environment, have shown high pressure events and/or ruptures in testing at Takata, it is my opinion that the GMT900 platform vehicles are on the same continuum with all non-desiccated Takata inflators and they share the risk of ruptures and abnormally high internal pressure deployments for all inflators that are aged approximately 10 years or more.

<u>Analysis and Opinion of the Stress-Strength Analysis</u>

234. GM conducted a stress-strength analysis of the probability that the distribution of propellant wafer diameters overlap the threshold curve in wafer diameter sometimes associated with inflator rupture (particularly for 11 mm wafers). The work was based on wafers from SPI YP inflators with an average age of 8.3 years and likewise for PSPI-L YD inflators with an average age of 8.9 years.[126] However, since essentially all passenger side inflator variants are free of rupture before 10 years of aging, it is not particularly useful in assessing the actual risk of inflator rupture.

235. The analysis also does not address the rupture of a SPI DH/MG variant inflator that was field aged 11.6 years in Florida, which is indistinguishable as to wafer diameter growth rate from the GMT900 YP variant.[127] The DH/MG variant is the most similar variant to the GMT900 YP variant[128] including sharing many design attributes and similarly low peak inflator temperature as integrated into its respective vehicle. The correlation of wafer diameter to high pressure events is generally acceptable, but not an absolute predictor of events that occur at low frequency.

[126] Note that the average ages stated here are not to be confused with those associated with the 26 field return inflators used in the GM Aging Study.
[127] See results in footnote 112.
[128] GM Briefing: August 23, 2017, page 45.

Analysis and Opinion of the GM and OATK Aging Studies

236. Laboratory efforts to accelerate aging of the Takata PSAN inflators are extremely difficult due to the characteristics and complexity of the process that leads to rupture and/or abnormally high internal pressure deployments. Because the GM Aging Study was intended to show only the short-term safety of the inflators during the pendency of the Petition, the following assessment focuses instead on the more in-depth OATK Aging Study.

237. Takata prepared some PSPI-L inflators with very high moisture in the secondary chamber for the OATK Aging Study. The density changes observed for inflators prepared with very high moisture in the secondary chamber, targeting 0.45 wt% and 0.70 wt%, appear to be unrelated to the failure process relevant to inflator rupture. Unexpectedly, total moisture in the very high-moisture inflators increased with temperature cycling in the OATK Aging Study,[129] though this moisture increase was not observed for inflators prepared with lower moisture and exposed to the same temperature conditioning. In my opinion, the physical changes behind low density for the inflators at 0.45 wt% and 0.70 wt% moisture levels do not replicate the density changes in field aged inflators, and test results from aging these inflators will not be assessed. Observed diameter changes were large enough that high pressure events were expected, however, in testing, peak chamber pressure values drifted lower. This is strong evidence of the challenge in attempting to accelerate the degradation process of the Takata PSAN inflators in the laboratory by increasing the moisture (stress) level at the time of assembly.

238. In the OATK Aging Study the as-built moisture level showed degradation. This is very concerning, since it is one more indicator that the Takata airbag defect is inherent in the design even when properly manufactured, hence constitutes a defect which is common to all variants as evidenced by degradation in lab aging of these newly made GMT900 inflator variants. That degradation level was higher than for mid-moisture level for some parameters, which is not consistent with returned field aged inflators.[130]

239. Propellant degradation occurred in the OATK Aging Study, however, pore formation and growth did not appear to recreate the extent of pores observed in field aged wafers. The limited micro-CT testing conducted by GM and OATK indicated far fewer voids (pores or fissures) in propellant samples from the respective Aging Studies than from corresponding propellant wafer samples removed from vehicles after ten or more years of field aging.[131] If the aging studies had effectively replicated reality, the voids (pores or fissures) should be similar in number, size and distribution for both the field aged and lab aged samples. What the OATK Aging Study showed is that density and diameter did change with age with the expectation this correlates, at some point after 10 years, to apparent burning rate increases and abnormally high pressures and/or ruptures. Unexpectedly, in the OATK Aging Study when wafers were above the diameter where burning rate acceleration is expected, both YD and YP inflators showed no tendency to increase in pressure[132] (despite this result being well-documented in many variants of

[129] GM Briefing: August 23, 2017, page 183.
[130] GM Briefing: June 8, 2018, page 109. Cycling results for 60 °C.
[131] GM Briefing: Aug 23, 2017, page 293.
[132] GM Briefing: August 23, 2017, pages 16-18.

Takata inflators) and instead seems to plateau with additional aging. This suggests the physical changes to propellant 2004 responsible for the observed density and diameter changes are not the same in the OATK Aging Study as that documented for changes in propellant 2004 from field aged inflators responsible for high pressure. The absence of pressure changes adds to my concerns for the far fewer number of voids observed, which may have been influenced by the means by which the moisture was introduced (preloaded to elevated levels, rather than through gradual moisture intrusion). While porosimetry techniques are commonly used to characterize pores (including number, size, and distribution), GM and OATK did not gather this type of data routinely.

240. An additional point worth noting is that wafers containing as-built moisture levels are degrading in both GM and OATK Aging Studies within a few hundred cycles, implying moisture intrusion is not required for degradation to begin.[133] GM added 5 new-build PSPI-L inflators to the GM Aging Study which were monitored for diameter growth, 2 or 3 in each Thermotron. In the OATK Aging Study approximately 75 or more inflators[134] of each variant contain as-built moisture level with some tested at each cycle temperature and at each interval. This indicates to me, in both the GM and OATK Aging Studies, that there is no delay in the onset of the degradation process.

241. One potentially significant weak point in GM's characterization of the OATK Aging Study design is GM's assumed 56-cycle "equivalent year" derived by GM prior to the study from the number of days in Miami, FL above 90 °F per year.[135] This was implemented in both the limited scope GM Aging Study and the broader scope OATK Aging Study. GM reasoned that if Miami, FL has 56 days at the peak temperature, then aging 56 cycles equals one year. This presumes that the only days when propellant damage occurs is on days that reach peak temperatures of 90 °F. However, this is not correct, as is demonstrated by the fact that inflators exposed to lower temperatures (for example, in the milder climates identified in the Coordinated Remedy as Zones B and C) still experience propellant degradation and inflator rupture, just at a slower pace. As indicated previously, particle ripening plays a role in density loss, which depends on daily cycling of temperature and not on high temperature 365 days per year.

242. Another potential weak point in the study design is GM's belief that cycle duration could be shortened to four hours without compromising or altering the type of degradation caused to the propellant under the changed duration condition. GM reduced the cycle duration to 4 hours since it believed both temperature and pressure had time to equilibrate in that time. OATK verified the time required to come to pressure equilibrium is 2 hours or less.[136] Moisture equilibration within propellant 2004 appears much slower, perhaps more than 5 hours as temperature rises (during a lab cycle) and at least 20 hours as temperature cycle goes down.[137] GM also did not provide any information as to whether the propellant itself has come to thermal equilibrium during the shortened cycle, which is important because the equilibrium point for moisture content of propellant 2004

133 GM Briefing: August 23, 2017, GM at 94-97, OATK at 101-113.
134 GM Second Petition, Exhibit D - Scope of work, Inflator Matrix.
135 GM Second Petition, Exhibit D.
136 GM Briefing: August 23, 2017, page 303.
137 GM Briefing: August 23, 2017, page 189.

(or 3110 for that matter) changes with temperature and drives moisture migration between the two propellants.[138] If the propellant wafers or tablets do not get to the temperature extreme, then moisture re-equilibration is not as complete in the abbreviated cycle as it is in a 24-hour cycle.

243. As a matter of good test design, it is important to verify that propellant temperature and moisture concentrations, in addition to pressure, all equilibrate to the degree observed in the field during daily cycling.

244. For the GM and OATK Aging Studies the two methods for acceleration were combined, with the result that for estimating service life, critical laboratory aging studies defined as equivalent to one year of aging in the field laboratory exposure (stress) of 56 cycles at 4-hours/cycle duration.[139]

245. Importantly, GM's acceleration scheme may not model the real-world propellant degradation that is rooted in particle ripening. Ripening depends in part on temperature cycling (in addition to water solubility and micron scale particle size) and not on peak temperature. The importance of cycling to ripening should not be confused with the importance of peak temperature in facilitating moisture transfer from booster propellant 3110 to main propellant 2004, which is how peak temperature is most relevant to propellant degradation. Translation of the ripening that occurs over 365 annual cycles to 56 cycles ignores any ripening that may be occurring outside the 56 "worst" days that were used to define the acceleration scheme for one year. This may account, at least in part, for the low void count observed in the very limited micro-CT data that was gathered and also the absence of elevated peak pressure with inflator age in the simulated accelerated aging study, both of which are contrary to the trends in the MEAF data, which by its nature is truly representative of real-world degradation process.

Analysis and Opinion of High Internal Inflator Pressure Deployments During Testing

246. In the 2018 briefings to NHTSA, GM revealed a YP inflator from Texas that experienced a very high peak pressure of 91 MPa during ballistic testing at Takata.[140] Peak internal pressure of 91 MPa is more than double the Maximum Expected Operating Pressure and is approaching the internal pressure sufficient to overwhelm the structural strength of the inflator housing, i.e. to cause a rupture. In engineering terms, this represents extensive propellant degradation, a structural safety factor close to zero, and variation in inflator performance far beyond a minor drift with age that is considered acceptable. Instead of being a sign that GM's YP and YD inflators are safe and immune from rupture, this result confirms the SPI YP inflator variant follows the same pattern as all the Takata non-desiccated PSAN inflators.[141] Specifically, cumulative propellant density and ballistic changes seem minor until, after approximately 10 years of aging in the field in Zone A, degradation causes increased operating pressure observable in some laboratory tests. Given time, propellant degradation can put the inflator at risk of rupture. This 91 MPa test result in a YP variant inflator, which enjoys all alleged design

[138] The "migration" of moisture from propellant 3110 to propellant 2004 at high cycle temperatures is a direct reflection of changes in the equilibrium point for each material with temperature.
[139] GM First Petition, Exhibit D.
[140] GM Briefing: February 12, 2018 and April 9, 2018.
[141] Other than the Alpha population, which suffers from manufacturing defects.

advantages, is the warning flag that the propellant in these inflators is degrading and risk rupture.

247. GM provided additional information to parse this SPI YP as a “Gen1” inflator versus later YP inflators GM then denoted as “Gen2.” Based on the information provided by GM, the “Gen2” YP inflators differ from the “Gen1” inflators in that they shift from propellant 3110 booster tablets to propellant 3110 booster granules in the initiator assembly, a minor decrease in the amount of propellant 2004 tablet weight, the use of a cup instead of a sleeve with orifice plate to hold the propellant tablets, and the addition of ceramic cushions with springs in place of spring alone. The tablet cup and ceramic cushion do not provide any protection to the propellant or special resiliency to the inflator against rupture, as discussed above. GM argues that reducing the quantity/number/volume of tablets softens ignition and speculates that this leads to less tendency to high pressure deployments due to degradation of main charge propellant wafers. It is more logical to say that both “Gen1” and “Gen2” inflators use the same number of 8 mm wafers, have the same vent-area, and experience the same in-vehicle environmental conditions, yet a “Gen1” YP inflator experienced 91 MPa, a pressure sufficient to risk of rupture of Takata PSAN inflators. While the discussion of minor differences is interesting from a technical and research perspective, it does not provide information from which to distinguish between GM’s identified “Gen1” and “Gen2” YP inflators regarding risk of inflator rupture. This is especially true in light of the rupture for the nearly identical SPI DH/MG inflator variant previously noted, which shares most design attributes, the same diameter growth rate, a T1 temperature band vehicle environment, very similar vent area, and, relative to GM’s claimed distinction between Gen1 and Gen2, a tablet load of 3.5 grams like the Gen2 YP inflators (presuming that is an advantage).

248. It is important to appreciate that the GMT900 SPI YP inflator tested in January 2018 that experienced internal pressure measuring 91.1 MPa enjoys all the design and environmental advantages enumerated by GM as providing improved resiliency. The inflator is identical to the SPI DH/MG with regard to tablet load, propellant wafers (same number of 8 mm wafers), inflator vent-area, and vehicle environmental advantages as witnessed by the identical rate of wafer growth. Despite these advantages, the field recovered SPI DH/MG inflator ruptured (at a rate of 1 per 6,771 tests) and the SPI YP inflator generated an internal pressure at 91.1 MPa demonstrating a near-zero safety margin for rupture and is only one year younger than the ruptured inflator. It is my opinion that the 91.1 MPa deployment for the YP inflator in ballistic testing is clear evidence that the YP variant is experiencing gradual propellant degradation on a continuum that leads to ruptures and/or abnormally high internal inflator pressures as the inflators continue to age beyond 10 years.

249. There are other high internal inflator pressure events observed in field aged YP and YD inflator testing. The MEAF file shows three other abnormally high pressure deployments of GMT900 inflators in addition to the YP deployment at 91.1 MPa described above. There are two YP inflators that experienced 61.74 and 57.7 MPa

deployments (approximately 5 standard deviations above the expected mean[142]), and the third is a PSPI-L YD inflator that experienced 57.03 MPa during deployment (4.4 standard deviations above the expected mean). All four high pressure deployment inflators were returned from MY 2007 GMT900 vehicles in the field, located in Zone A, with 9.5 to 10.5 years of field aging. Separately, closed bomb testing of wafers retrieved from a Gen2 inflator also from a MY 2007 GMT900 vehicle showed abnormally high pressures in three wafers. This implies propellant damage is occurring and does cause increased pressurization. In my opinion, these events confirm that GMT900 inflator variants are gradually degrading as noted by density loss and moisture increase and, to a degree, diameter increase; that is, the YD and YP variants are on the same continuum leading to inflator rupture as the SPI DH/MG variant, aged 11.6 years in the field, for which rupture has been observed.

Analysis and Opinion of the OATK Model

250. OATK has steadily improved its Model of the degradation process since August 2017. In June 2018, OATK provided results from thousands of Model runs distilled into a probability of failure for the GMT900 and Vibe inflator variants representing each variant in all three temperature bands, T1, T2, and T3. The Model appears to provide good general insight into the relative progress of degradation given specific inputs. However, the prediction that to reach a 0.01 probability of failure will take more than 30 years of aging does not capture the observed real-world rupture risk. In fact, ruptures and abnormal high pressure deployments in YP and DH/MG field returned parts have been observed after approximately 11 years of field aging in Zone A. In my opinion, this implies the Model-predicted rupture rate underestimates the risk to consumers.

251. The OATK Model is anchored in results from the OATK Aging Study in terms of density change and the tendency towards high internal inflator pressure deployments. The OATK Aging Study results do not consistently follow the observations from field aged inflators so, in my opinion, probabilities based on those results should be viewed with caution.

252. As noted earlier, high pressure and rupture events are relatively rare in Takata's non-desiccated PSAN inflator population[143] for all vehicle platforms, with rupture rates for most variants well under 1%. Modeling at sufficient fidelity to predict low frequency events is challenging. Due to the commonality of design and vehicle environment characteristics, for the GMT900 YD and YP and the non-GM DH/MG platform vehicles, the OATK Model would be expected to produce nearly the same probability of rupture. The Model output for YP and YD variant inflators in temperature band T1 provided a 0.01 (i.e. 1%) probability of failure at a time greater than 30 years. Since Model inputs would be essentially the same as for the DH/MG variant in T1, the Model should predict one rupture in approximately 6,771 ballistic tests of inflators, which occurred at 11.57

142 Expected values are from MEOP data submitted to GM in Takata's QFS test results for YD and YP. At GM, QFS is Qualification For Sourcing process by which a supplier's part is deemed acceptable for use. It is extremely unlikely that normal product variation accounts for these pressures exceeding the ambient MEOP, which is the mean peak pressure plus three standard deviations.

143 Ruptures are less rare in the Alpha population in particular, which, as discussed earlier, suffers from manufacturing defects that lead to various causes for accelerated burn rates of the propellant and, ultimately, inflator rupture.

years of field exposure, far less than the 30 years provided by the Model. The Model is not currently able to predict this rupture, so its value at the moment is suspect. In the future, it may be possible to set the Model to provide probabilities for pressure rising to, for example 91, 62, or 57 MPa (twice), as observed in testing of the more than 4,200 lab deployments (per the Takata MEAF).

Conclusions

253. All variants of Takata's non-desiccated PSAN inflators show reduced density over time, with some changing faster than others. The result of that effect is that some platforms rupture more often than others, ranging from zero to more than 1%. Despite the gradual change, during the first 10 years in the field, nearly all inflators deploy at normal pressure.[144] Beginning around 10 years of field aging, the cumulative propellant degradation causes some Takata non-desiccated PSAN inflators to register abnormally high internal pressure, and given more time some rupture. Aging studies at GM and OATK confirm that this is a design defect: no wafers of propellant 2004 are stable. Put another way, every wafer in all test inflators are experiencing gradual reduction in density, sometimes observed as diameter increase.

254. After reviewing the Petition claims and information GM provided to NHTSA my conclusion is that the design and environmental features GM identified as being unique such "that the GMT900 inflators are uniquely resilient against heat/humidity induced rupture risk" is unfounded because the GMT900 vehicle platform and YD and YP inflator variants have not been shown to provide any special resistance to inflator rupture or the causes thereof. The GMT900 platform is very similar to other vehicle platforms whose inflators have exhibited gradual degradation on a continuum that leads to ruptures and/or abnormal pressures as they continue to age beyond 10 years. The YP and YD inflator variants contain several features that GM posited provide additional protection against rupture, but GM did not provide compelling evidence that supports those claims.

255. GM, however, has concluded that the YD and YP variant inflators installed in GMT900 vehicles do not present an unreasonable risk to safety now or long into the future. It posits the GM inflator variants are uniquely resistant to the failure process due to the combination of unique inflator design differences and the unique GMT900 vehicle environment, conferring unique status to their variants. GM does not claim these features were chosen for the purpose of mitigating density reduction in propellant 2004. GM did not provide compelling evidence that supports the claims of uniqueness or special resistance against rupture.

256. GM's claims that unique inflator variant features and unique vehicle environment features are responsible for the zero rate of failure to date. Except for vehicle temperature, there is no data supporting the claim that other features, unique or not, affect density change in propellant 2004 that subsequently risks inflator rupture.

257. It has been well established by testing at Takata that peak temperature during daily temperature cycles, expressed in the OATK Model as temperature bands T1, T2,

[144] Again, the Alpha population suffers from manufacturing defects that cause ruptures at higher rates and younger inflator ages than for the Takata PSAN inflator population at large.

and T3, is a significant factor in the rate at which density reduction occurs. Aging studies at GM and OATK confirm Takata's conclusion that inflators exposed to T1 daily conditions age slower than those exposed to T2 conditions, which age slower than those exposed to T3 conditions. While the rate of propellant degradation is lower, nevertheless, a lower rate does not definitively predict inflators are safe in consumer vehicles into the future. That said, each individual inflator is unique and the temperature band alone is not predictive. The actual rate of propellant degradation in any given inflator is affected by many details of manufacturing variability (actual leak rate), vehicle configuration (i.e. fabrics, carpeting, etc.) and vehicle usage (i.e. air conditioning, indoor/outdoor parking, etc.). These factors interact to change cabin humidity and moisture intrusion in the inflator, but were not studied.

258. GM made specific claims regarding unique features that make the GMT900 inflators safe but, other than confirming temperature band is significant regarding the rate of degradation, GM expended little effort over the last two years to methodically study the claimed features in order to substantiate their effectiveness. GM presented almost no data to quantify how the other claims mitigate density reduction.

259. Many of GM's enumerated features that allegedly make the GMT900's YD and YP variants uniquely resilient to rupture are, in fact, not unique to the GMT900 variants. As outlined in the analysis and opinions section above, the features of low peak cabin temperature (accepting GM's claim in the T1 temperature band), use of 8 mm wafers, and propellant to vent-area ratio are not unique to the YP and YD variant inflators. The bulkhead anvil, ceramic cushion, and steel endcap features are unique, but data did not show they serve as countermeasures to factors that drive the root cause of this defect.

260. All the Takata PSAN inflator variants share overriding design similarities, and vulnerability to the cause for density reduction. The most relevant comparison inflator variants share the same inflator family, wafer size (8 mm), vent area, and a T1 temperature band response to Zone A conditions with solar loading present. That combination of shared features likely explains GM's reporting that wafer growth rates in field aged inflators are nearly identical for GM (SPI YP) and non-GM (SPI DH/MG) variants in their respective vehicles. The growth rate can vary for each vehicle platform according to how vehicle details affect the temperature and humidity of air that is gradually entering the inflator, so it is fair to conclude that the contribution of vehicle details for the GM and non-GM compared here are essentially the same since the wafer growth is tracking in parallel. GM provided no data to support a conclusion that the SPI YP in the GMT900 vehicles represents a lower risk of rupture than the DH/MG in the non-GM platform.

261. I believe the density of wafers change in response to daily and yearly environmental cycles for all Takata non-desiccated PSAN inflators. Taken as a whole, I conclude that the reduction of density in all variants in their respective vehicle platforms forms a continuum representing gradual propellant degradation over time, particularly concerning after 10 years of field aging or field-representative lab aging. Every inflator sits somewhere on this continuum wherein a complex set of details influences the state of density at any time and the time when rupture will occur.

262. In reviewing the complete GM data set in Takata's MEAF, I conclude that the GMT900 variants include abnormally high pressure events, confirming that the YP and YD variants are on the same degradation continuum with all of the other Takata PSAN inflators.

263. In counterpoint to GM's claims, my conclusions specific to each claim are:

a. Thinner wafers are not unique to the GMT900 inflator variants and, further, do not provide special resiliency against inflator rupture. The 8 mm wafers used in the YD and YP variants are used in at least 21 other Takata inflator variants some of which have experienced ruptures. GM's YD and YP variants with 8 mm wafers are aging at the same rate as the non-GM platforms and one field-returned YP inflator recorded a 91 MPa peak internal pressure during ballistic testing, a near rupture. Thus far, three other YD and YP inflators experienced peak pressures that I consider abnormally high.

b. The use of a steel endcap was shown in testing to not provide a better O-ring seal than the corresponding aluminum endcap, so a claim of reduced moisture intrusion is proven incorrect.

c. Larger vent-areas is not unique in the sense that it is selected for the same design reason as all Takata inflator vent-areas are selected: to fill air bags in the required time during normal deployment. The bag is larger, so the vents are larger. The ratio of vent to mass is presumably an indirect reference to that design process. This does not render the YD and YP variants more resilient to rupture because the fixed vent area is already choked when the burning area suddenly increases around 10 milliseconds. Accordingly, internal inflator pressure *must* rise and does so exponentially before rupture. This doubling or more beyond the maximum expected operating pressure, driven by sudden doubling or more of the total burning surface area would essentially require a doubling of the vent area to be safe. The vent area used by GM does not change with increased pressure, therefore it does not offer unique protection against rupture. Moreover, GM's argument that the vent size on the YP and YD variants is beneficially resistant to abnormally high pressure events, including ruptures, is refuted by the rupture in a DH/MG variant that has a very similar vent area and furthermore ruptures in other 8 mm variants.

d. Propellant tablets in a cup in the SPI YP variant may be unique and may improve ballistic variability in normal inflator deployments. GM claims these tablets are better protected from moisture, which may be true, but during root cause investigations tablets were not shown to play either a major or secondary role in inflator rupture even when better exposed to moisture in the inflator headspace during every complete daily temperature cycle. What is known is that wafer diameter growth in the YP variant with a cup is the same as wafer growth for the YD variant with no cup. To the extent tablets degrade less when in a cup, they still would not have a major or secondary role in inflator rupture. GM did not provide data on the role that tablet condition played in any potential mitigation of propellant wafer degradation, which is the root cause of inflator rupture.

e. GM provided no information regarding how the use of a ceramic cushion (SPI YP only) with smaller springs, as opposed to a spring alone, reduces moisture intrusion or otherwise mitigates ruptures and/or abnormally high pressure deployments. Due to the lack of relevant information, no conclusion as to the merits of this feature can be drawn.

f. There is no evidence that use of a bulkhead disk with anvil (PSPI-L YD only) reduces moisture-induced propellant wafer damage that leads to inflator rupture. GM offered as a favorable "design feature" the storing of tablets of booster propellant 3110 in a cup that happens to experience interference by the bulkhead anvil during inflator assembly and data shows it does gain moisture. That moisture gain did not significantly change moisture level in propellant 2004 wafers in the OATK Aging Study inflators. Since it has no effect on moisture in propellant 2004, I conclude this feature has no significant effect on aging.

g. GM has not demonstrated that larger vehicle volume and use of solar absorbing window glass in the GMT900 vehicles reduce peak temperature at the inflator surface such that it prevents propellant degradation, and thereby mitigates the risk of rupture, in the YP and YD variant inflators. GM confirmed the Takata observation that peak temperature in the vehicle during the daily cycle is important. That is, the higher the peak temperature the faster degradation occurs. Based on testing of several vehicles (a very small sampling, given the importance and consequence of this defect), the GMT900 vehicles appear to fit in the lowest temperature band of peak temperatures experienced by vehicles in the field (i.e. T1). GM attributes this to the use of solar absorbing glass, but regardless of why, the peak temperatures for GMT900 being in the lowest temperature band is not a unique condition. All vehicles that fit in this T1 temperature band share this advantage and, nonetheless, some have inflators that experienced ruptures and abnormal high pressure deployments (including, for example, SPI DH/MG). GM discussed vehicle volume as a potential factor, but did not provide data differentiating vehicle volume from the contribution of peak temperature at the inflator when exposed to Zone A conditions.

264. Two critical features common to all Takata PSAN inflator variants and not enumerated by GM are also worth reiterating: Takata's moisture-sensitive PSAN propellant 2004 and the deficient seal system intended to protect the propellant are common to all designs. That seal system allows gradual moisture intrusion into the inflator that leads to increased moisture in propellant 2004 to the same degree in the GMT900 inflator variants as it does in other variants. Based on the root cause, I conclude there is no basis for expecting propellant wafer density loss (observable as the formation of fissures and pores) to be different for variants exposed to temperature cycling in the same temperature band.

265. I conclude that the gradual reduction in density measured for both the YD and YP variants clearly demonstrates these variants are drifting out of conformance to the safety requirements of SAE/USCAR 24-2. While this is not a regulatory standard, it is a consensus description of the minimum requirements for airbag inflators, crafted by highly experienced technical experts within the three U.S. vehicle manufacturers. The defect in Takata's non-desiccated PSAN inflators creates a gradual degradation of propellant,

which, by definition, is a lack of required propellant stability. The YP and YD variant inflators, the oldest of which are just now past 10 years in service, are beginning to experience abnormal pressures in the field aged population. This is evidence that required structural integrity, as expressed in the burst safety factor of SAE/USCAR 24-2, is being compromised.

266. I have reviewed GM's stress-strength analysis, which relied on inflators field aged less than 9 years. The near zero inflator rupture rate in all Takata PSAN inflators until after 10 years of field aging combined with the variable influence of a wide variation of vehicle utilization by consumers makes the analysis difficult to use with confidence.

267. I have reviewed GM's interpretation that the high-pressure deployments in field aged MY 2007 YP and YD variant inflators are not relevant to the Petition, and do not reach the same conclusion. GM distinguishes the 91 MPa near-rupture because it now identifies the inflator as a "Gen1" already under recall and further does not consider relevant the observed test pressures well above the typical 44 MPa peak pressure, at 57 and 62 MPa for the YP variant and at 57 MPa for a YD variant, because they did not result in rupture. If these test results were simply the extreme deployments expected within normal variation (i.e. the .01% expected to exceed the MEOP), values this high would also appear in younger inflators, but that is not seen in the data. All of these inflators enjoyed the unique alleged benefits identified by GM as distinguishing GMT900 inflators from other variants.

268. Additionally, GM also views another SPI YP inflator showing high diameter, high moisture level, and high chamber pressure in closed bomb testing to have resulted from some special cause defect, that is, something other than field aging is responsible. In light of the high pressure ballistic testing events and this high pressure closed bomb test result, it is my conclusion that these events are relevant to the state of propellant health and inflator rupture risk because high pressure due to uncontrolled burning (which is the result of aging and the associated propellant degradation) is a more likely conclusion.

269. Simply put, these test results from field aged inflators are consistent with expected increasing high pressure deployments and the root cause of gradual propellant degradation. The GMT900 variant inflators are only now entering the age, at approximately 10 years in the field, where high pressure and/or rupture events begin to occur in other Takata PSAN inflator variants that were installed in earlier MY vehicles and have therefore been in the field longer. These early high pressure deployments demonstrate that the YP and YD inflators are on the continuum of reduced density due to propellant degradation that leads to inflator rupture.

270. GM's acceleration scheme defined 56 cycles as representing a year and a 4-hour laboratory cycle was selected based on pressure equilibration considerations. This scheme presumes no degradation occurs during the balance of the year and that particle ripening is completed within the selected 4-hour cycle. It may also have underestimated, and therefore not evaluated, the need for verifying that the propellant wafers reach thermal equilibrium during the extremes of each cycle and, relatedly, verifying that moisture content in the wafers equilibrates during each cycle, which itself takes more than 4 hours at each extreme. In light of these weaknesses, I suggest caution when

applying results that are dependent on the GM cycle scheme to consideration of the health of the propellant in field aged inflators.

271. In my experience, it is critical that the failure mode observed in field aged parts be replicated by any laboratory accelerated aging study. The OATK Aging Study was ambitious, but did not replicate real world conditions, as evidenced by its inability to sufficiently replicate the void count found from Live D of field aged wafers. This may arise from the acceleration strategy, which overlooks or under represents two aspects of the failure process which contribute to void formation: moisture facilitated Ostwald ripening of smaller PSAN particles and equilibration time replicate moisture diffusion occurring during daily cycle, which can take 5-24 hours. Propellant in the OATK Aging Study also shows no tendency towards high pressure after reaching the diameter thought to cause accelerated burning and inflator rupture. Additionally, it is puzzling and unexplained that mid-moisture inflators, bearing a two-fold higher moisture, did not degrade significantly more than as-built moisture inflators, which was the expected result given the known and accepted root cause of the Takata PSAN inflator ruptures. Finally, the trend in density change during lab aging did not replicate field aging as a function of moisture content, where increased moisture should accelerate degradation. As a result, any application of the data from the OATK Aging Study should be done with caution and with a clear understanding of the Study's shortcomings.

272. Similarly, OATK's predictive Model is anchored in key ways to the data derived from OATK's Aging Study, so any weaknesses in the Aging Study may partially explain the Model's inability to predict observed high pressure events and ruptures of field aged inflators. The Model predicts probability of failure at greater than 30 years for GMT900 inflators in temperature band T1 conditions, despite the fact that field aged parts at approximately 10 years are reaching pressures of 91 MPa in the YP variant and rupture pressure in the DH/MG variant. While my knowledge of the Model is currently not detailed, these readily apparent areas for improvement suggest caution should be used when applying the Model's results.

273. In summary, my conclusion is that Takata's non-desiccated PSAN inflators, including those used in the GMT900 vehicles, are all susceptible to propellant degradation as-built, and the rate of degradation accelerates where moisture intrusion has increased the moisture levels inside the inflator. Propellant 2004 degradation progresses over time with the result that during inflator deployment in a crash the propellant can burn in an uncontrolled manner causing an inflator rupture. At present, based on all available information, it is not possible to predict when inflators will rupture with any precision.

274. Further, the most current information shows that, except when a manufacturing defect is at play as in the Alpha population, rupture-inducing degradation generally does not occur in the field in less than approximately 10 years. GM's various research projects and studies have not shown that propellant 2004 in the SPI YP and PSPI-L YD inflator variants is better protected or degrades at an appreciably slower rate than other, nearly identical Takata PSAN inflator variants. Based on the information available, the rupture risk for the GMT900 inflator variants is not appreciably different than other Takata PSAN inflator variants and particularly not different from other variants that enjoy nearly

all of the inflator feature and vehicle environment advantages GM claimed as unique to the GMT900 inflator variants and vehicle environment.

Respectfully submitted,

H.R. Blomquist, Ph.D.

Appendix A

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EDUCATION
Ph.D. in Chemistry, 1980, Duke University, Durham, North Carolina
B.S. Chemistry, 1975; M.S. work in Chemistry, 1976, Illinois State University, Normal, IL

HONORS AND AWARDS
Chairman's Award for Innovation, TRW Corporation Award, 1992
Chairman's Award for Innovation, TRW Corporation Award, 2001
DuPont Summer Fellow (while attending Duke)

EXPERIENCE
2015 to present: President HRB Research, LLC - Technical expert advising the Office of Defect Investigation (ODI) staff regarding root cause investigations of defective Takata airbags. ODI is a department within the National Highway Traffic Safety Administration, NHTSA, in turn a part of the US Department of Transportation, or US-DOT. Special focus is on the degradation over time of energetic chemical materials leading to aggressive combustion leading to structural failure, exposing the public to steel fragments. Similarly assisted the Australian government with their approach to recalling Takata inflators. Also provided expert report to settle an airbag related contract law case in Canada.

2010 - 2014: Nammo Talley Inc.
Director, Research – position directed small teams focused on DOD needs for unique Energetic Materials (propellants, explosives, and pyrotechnics) and the devices wherein they function. One team operated an ISO compliant test laboratory conducting chemical analysis, material properties tests, DOT-PHMSA hazard classification tests, and component level explosive and ballistic tests. Chemical methods of analysis include characterization of raw materials and products by thermal analysis, spectroscopy, chromatography, and wet chemical methods. Research teams were focused on energetic material components of ejection seat components, small rockets, small warheads, artillery components, and shoulder-fired weapons.

1990 - 2010: TRW Vehicle Safety Systems
North American Manager, Inflation Product Engineering Group - Originally hired as Manager Propellant and Combustion Engineering Research Laboratory. Long range focus was on cost driven innovative airbag inflation designs and seatbelt pre-tensioners employing a mixture of in-house staff and external resources (universities and DoE labs). Primary duties include leading design and development of energetic materials, chemical processes, and proof of concept inflator designs. Additional duties include conducting root cause investigations, litigation support, and guiding regulatory compliance (DOT-PHMSA, EPA, OSHA, NIOSH, ACGIH). Chaired the

Propellant Technology Working Group, which provides formative input to company's strategic plans via the company's propellant steering committee.

1987 1990: Olin Rocket Research Corporation
Manager/Chief Chemist, Propellant Development Responsibilities included managing 35 R&D professionals plus support staff conducting several DoD focused projects and providing analytical support of the business (testing chemical, mechanical, ballistic, explosive hazards, and production QA support). Projects include conception and reduction to practice of insensitive munitions (IM) high energy propellants including chemical process scale-up (2,000 gal reactor) of a novel energetic polymer.

1980 1986: Aerojet Strategic Propulsion Corporation
Chemistry Specialist, Scientific Staff / Chemical R&D Department. Principal Investigator on advanced technology R & D projects including formulation and process engineering in support of propulsion technology for strategic missiles and large caliber ammunition. Technical contributor on proposals to Air Force, Army, and internally funded activities. Served on investigating committees to review critical processes and failure mode analysis.

AFFILIATIONS

American Chemical Society (ACS)

Chairman, Sacramento Section
Steering Committee, Western Regional Meeting
Local Coordinator, International Chemistry Olympiad
Judge, Intel Science and Engineering Fair (ISEF)

Memberships: Society Automotive Engineering (SAE), American Institute of Chemical Engineering (AIChE), American Institute of Aeronautics and Astronautics (AIAA), North American Thermal Analysis Society (NATAS), frequent participant in JANNAF subcommittee meetings (joint Army, Navy, NASA, Air Force)

PUBLICATIONS

Keynote Address: **Investigation of Takata Airbag Propellant Degradation**, 43rd International Pyrotechnic Society Seminar, Colorado Springs, CO, 9 July 2018

Expert Report regarding Root Cause of **Takata Airbag Inflator Fragmentation**, provided to support NHTSA recall activities, May 4, 2016, found at
http://www.safercar.gov/rs/takata/pdfs/Expert_Report-HRBlomquist.pdf

Risk Managing Critical Materials for CAD-PAD Manufacture
Critical Energetic Materials Working Group for OSD, Industry Day, Washington D.C, 3 September, 2014.

Critical Ingredient Replacement – Red Iron Oxide
10th Biennial CAD-PAD Technical Exchange Workshop, 20-22 May, 2014. H. Lambert and H.R. Blomquist

Status: Chemical Systems for Airbag Inflation 2004

Presented to DX2 staff at Los Alamos National Laboratory, or LANL, H.R. Blomquist, 2004

ISTC Project 1882

US liaison for US State Department funded Energetic Material Synthesis project with Russian Academy of Science, Institute of Chemical Physics, 2000-2003

A Safe Method for Manufacturing Gas Generator Propellant Composed of Ammonium Nitrate and HMX

AIChE National Meeting – 2003. H.R. Blomquist, E.S. Gurley and W.P. Sampson

Characterization of Combustion Species by Real Time FTIR Spectroscopy at Gas Generator Operating Pressure

5th International Conference on Special Topics in Combustion, Stresa, Italy, 2000. H.R. Blomquist, Stefan T. Thynell and C.F. Mallory, Pennsylvania State University. Monograph available Begell House Publishing.

Combustion Imaging of Heated Gas Hybrid Inflator Systems

AIAA Journal of Propulsion and Power, November 1999**,** H.R. Blomquist, A. Helmy, (TRW) and Ken Kuo, director of High Pressure Combustion Laboratory, Pennsylvania State University

Current Issues in Airbag Inflator Modeling

Airbag 2000+ Conference Papers, November 26 and 27, 1996, Karlsruhe, Germany. H.R. Blomquist (TRW) P.B. Butler and J. Freesmeier, University of Iowa. Monograph available from Fraunhofer Institute Chemische Technologie

Performance Simulation of Combustible Gas Airbag Inflators

November 26 and 27, *1996,* Karlsruhe, Germany. H.R. Blomquist, TRW, P.B. Butler and J. Freesmeier, University of Iowa. Monograph available from Fraunhofer Institute Chemische Technologie

Does Ballistic Tank Testing Simulate Occupant Exposure To Harmful Effluents

NHTSA Airbag Effluent Panel, 19th Annual Workshop on Human Subjects for Biomechanical Research, Nov. 1991**,** H.R. Blomquist

Optical Sizing of Particles Generated by Propellant Combustion

Heat Transfer Conference, Marrakech, Turkey (2003), S. Ghosal, S. Manickcavasagasm, M.P. Menguc, (University of Kentucky) J. Sheng, H.R. Blomquist, (TRW).

Multi-mission Missile Propellant

US Air Force Rocket Propulsion Laboratory (confidential), contract final report, 1987. H.R. Blomquist, A.E. Oberth, M.M. Konarski, R.S. Bruenner, R.B. Steele, and R.V. Alexander. 192 pages.

High Performance Propulsion for 120mm Gun
US Army Ballistic Research Laboratory (confidential), contract final report, 1986, 102 pages.

Facile Synthesis of 2Substituted Cyclopentanones
Tetrahedron Letters, 1982, 23, 3883.

Cyclohexenones by Barton Fragmentation of Tertiary Alcohols Derived from Furanone/Alkene Photoadducts
Journal of the American Chemical Society, 1982, 104, 4990.

My U.S. registered airbag related patents are the following:

	Patent No	Description of Patent	Filed	Registered
	WO2017172170A2	Countermass liquid for a shoulder launched munition propulsion system	February 29, 2016	
	6,902,637	Process for preparing free-flowing particulate phase stabilized ammonium nitrate	January 23, 2001	June 7, 2005
	6,875,295	Cool burning gas generating material for a vehicle occupant protection apparatus	December 27, 2001	April 5, 2005
	6,860,208	Nitrocellulose gas generating material for a vehicle occupant protection apparatus	January 4, 2001	March 1, 2005
	6,802,533	Gas generating material for vehicle occupant protection device	April 19, 2000	October 12, 2004
	6,6350,131	Gas generating material for a vehicle occupant protection apparatus	March 26, 2001	October 21, 2003
	6,627,014	Smokeless gas generating material for a hybrid inflator	August 7, 2000	September 30, 2003

	Patent No	Description of Patent	Filed	Registered
	6,605,167	Autoignition material for a vehicle occupant protection apparatus	September 1, 2000	August 12, 2003
	6,591,752	Ignition material for an igniter	February 12, 2001	July 15, 2003
	6,588,797	Reduced smoke gas generant with improved temperature stability	April 15, 1999	July 8, 2003
	6,513,834	Monopropellant smokeless gas generant materials	August 29, 2000	February 4, 2003
	6,468,370	Gas generating composition for vehicle occupant protection apparatus	April 19, 2000	October 22, 2000
	6,410,682	Polymeric amine for a gas generating material	January 3, 2001	June 25, 2002
	6,319,341	Process for preparing a gas generating composition	May 25, 2000	November 20, 2001
	6,296,724	Gas generating composition for an inflatable vehicle occupant protection device	July 21, 1998	October 2, 2001
	6,238,500	Smokeless gas generating material	July 26, 1999	May 29, 2001
	6,231,702	Cool burning ammonium nitrate based gas generating composition	June 5, 1998	May 15, 2001
	6,231,701	Vehicle occupant protection device and solid solution gas generating composition therefor	February 17, 1999	May 15, 2001
	6,228,193	Vehicle occupant protection device and solid solution gas generating composition therefor	March 31, 1998	May 8, 2001
	6,195,996	Body of gas generating material for a vehicle occupant restraint	December 21, 1999	March 6, 2001

	Patent No	Description of Patent	Filed	Registered
	6,149,746	Ammonium nitrate gas generating composition	August 6, 1999	November 21, 2000
	6,143,104	Cool burning gas generating composition	February 20, 1998	November 7, 2000
	6,136,112	Smokeless gas generating composition for an inflatable vehicle occupant protection device	October 26, 1999	October 24, 2000
	6,117,255	Gas generating composition comprising guanylurea dinitramide	July 22, 1999	September 12, 2000
	6,113,713	Reduced smoke gas generant with improved mechanical stability	July 22, 1999	September 5, 2000
	6,004,410	Apparatus comprising an inflatable vehicle occupant protection device and a gas generating composition therefor	July 28, 1998	December 21, 1999

Appendix B – OATK Results Summary Chart (from GM Briefing: August 23, 2017, pg 41)

Technical Effort	Brief Description	Summary
Wafer OD and Density	Wafer OD and Density Change in wafers under scientific aging	Higher temperature and higher moisture results in faster growth
Inflator Ballistic Tank Testing	Characterize aged inflators using industry standard tank test	Matched field return results in every aspect including t/P trace for ED events
Ballistic Closed Bomb testing	Validate ballistic characteristics of aged wafers	ED prone wafer ballistics consistent with that ED behavior
Inflator Ballistic Modeling and Analysis	Model all sytems to explain ballistic results	Coherent narrative on inflator differences connecting to ED
Statistical Analysis of Field Data	Review of "MEAF" in conjunction with vehicle field exposure studies	Same inflator in different vehicles shows quite different response. Different vehicles achieve different temperatures under same environmental conditions
Moisture in Inflators for Scientific Aging	Testing dissected inflators at time zero and each aging cycle for moisture content for all energetics	Data confirmed that total moisture was not changing significantly (no leakage, very little if any moisture from decomposition of energetic materials)
Moisture in Virgin and Field Return Inflators	Compare moisture levels in virgin inflators with field returns	Trends as expected with field returns showing more moisture. AI-1 weight loss is low.
Moisture Dynamics Inside Inflators	Develop understanding of how moisture moves between energetic formulations	Moisture moves in and out of 2004 and 3110 easily. Will migrate over time to bentonite in 3110 which is a desiccant. Level of moisture for maximum transfer is sub-saturation of bentonite in 2004 plus 3110.
Inflator crimp diameter	Examine manufacturing and design for leakage to allow ingress of excess moisture	Specification ranges allow for significant differences in crimp that can lead to low squeeze on o-rings.
O-ring analysis and aging	Examine virgin and aged o-rings for damage that could result in increased leakage over time	O-ring aging reults in slow and modest reduction in capability. Field return o-rings show evidence of a wide range of compressions consistent with crimp/squeeze data.
CT Measurements of Inflators	Measure every wafer OD and stack height in inflators	Saw early distortion of wafers near water addition. Did not distort further. Stack height showed fusion of wafers especially in SPI-YP (dual spring)
Quench Testing	Interrupt combustion process immediately after ignition to examine fracturing of wafers	Larger wafers do not break up as much. Aged break up lower than initial. Wafers nearest closure break up more.
Wafer Crush Strength	Examine whether wafer strength degrades sufficiently over time to explain failures	Wafer strength is more affected by moisture content than aging. Change appears insufficient to explain failures.
SEM of Propellant	Obeserve propellant surfaces under extreme magnification for changes during aging.	More highly aged propellant shows significant signs of degredation. Higher moisture affects significantly.
Micro CT of Propellant	Look for porosity in propellant bulk	Signs of increased porosity due to very small pores in aged samples.
Gas Diffusion through Propellant	Searching for method to directly measure porosity and permeability	Diffusion is reduced on exposure to moisture in propellants and generally increases in aged samples.
Infaltor Leak Testing	Attempt to determine leakage rate that can give insight into moisture ingress.	Leakage occurs through every opening in the inflator. Reported rates vary widely and are difficult to measure. In field returns with greater than average moisture, amount cannot be rationalized by diffusion through the o-ring.
AI-1 Tablet Testing	Evaluate hypotheses that AI-1 color is an indicator of pending ED or is a source of water inside inflator	AI-1 tablets exposed to moisture in YD inflator exhibited the largest color change. Weight loss was minor and not a signficant contributor to moisture in inflators.