UNITED STATES DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION
1200 New Jersey Avenue SE
Washington, D.C. 20590

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

EXPERT REPORT OF HAROLD R. BLOMQUIST, PH.D.

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), and to assist NHTSA with the identification and verification of the root-cause(s) for the inflator ruptures.

2. As explained in more detail below, I have reviewed the studies conducted by experts within three independent laboratories, and have identified a consensus regarding the primary factors contributing to the root cause of the rupturing Takata inflators: simplified, the inflator design permits moist air to slowly enter the inflator, where the moisture-sensitive propellant slowly degrades physically due to temperature cycling. During subsequent air bag deployment in a crash, the damaged propellant burns more rapidly than intended, and over-pressurizes the inflator's steel housing causing fragmentation.

3. In my expert opinion, the scientific methodologies used to determine the factors contributing to root cause were properly applied. Those same factors were confirmed by replicating the observations in laboratory experiments. Based on my review of the expert laboratories' tests and analyses, I further conclude that, based on the age of a particular vehicle and the climate zone in which it is located, the length of time until the subject inflators present a risk of rupture ranges from six to twenty-five years from the date of inflator manufacture.

Qualifications

4. 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 for missile systems and automotive air bag applications. (My curriculum vitae is attached hereto as Appendix 1.)

5. My role as expert in support of the NHTSA-Office of Defect Investigations (ODI) team stems from: my specific experience formulating a phase stabilized ammonium nitrate (PSAN)-based gas generant 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 inflator presented at the national meeting of the American Institute of Chemical Engineers. Fundamental work from the TRW R&D included x-ray diffraction as a function of temperature, or T-XRD, at the University of Reno, which has been cited as the authoritative reference by the three investigating teams reviewed herein.

6. During my twenty years in automotive engineering and fifteen 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 test and analysis tools relied on by the various investigators to determine root cause of the Takata inflator fragmentation after aging in consumer vehicles, as further described below**.** This expertise informs my conclusions with respect to the rupturing Takata air bag inflators.

Air Bag and Inflator Rupture Overview

7. Air bags have been installed in passenger vehicles beginning in the 1970s, in high volume since being mandated in 1991, and rolled out to reach 100% required frontal air bags by September 1, 1998. When deployed, air bags are filled with gas produced by an inflator, many of which involve ignition and burning of pyrotechnic chemical mixtures called propellants. Propellants are formed into shapes that burn in layers, from the outside of the part towards the center, which serves to control the speed at which the gas is generated. Requirements for inflator performance are governed by each vehicle manufacturer’s specifications.

8. Since production began in or about June 2000, a family of Takata-manufactured inflators has contained a propellant that experts have found to degrade over time, sometimes causing excessive pressure to be generated during deployment, and potentially causing the steel inflator housing to rupture, propelling steel fragments outward. These metal fragments present vehicle occupants with the potential for injury or death. The overpressurization of the inflator and consequent rupture of the inflator’s housing is sometimes referred to as an “inflator rupture,” abbreviated IR. Both driver and passenger frontal inflators in this family of Takata inflators can experience an IR.

9. The affected Takata inflator family (i.e., driver and passenger inflators manufactured by Takata that do not contain a desiccant) deploys by igniting the **booster** propellant, designated by Takata as 3110, which in turn ignites the **main** propellant, designated by Takata as 2004 (which does not reference a date). These propellants are comprised of solid powders that are blended together and pressed to form the propellant part, akin to pharmaceutical tablets. Both propellant formulations and their manufacturing processes are proprietary to Takata. The main propellant contains PSAN, a moisture-sensitive oxidizer that, as described below, degrades the propellant part if exposed to moisture and temperature cycling.

Historical Background/Status of Takata Investigation

10. Two populations of Takata airbag inflators have propelled dangerous steel fragments into the driver and passenger compartments of consumer vehicles. One group was not manufactured as designed and intended, and all vehicles affected by such manufacturing flaws have been recalled for inflator replacement. The other population was ostensibly manufactured as intended, but does not withstand normal climatic cycles, presenting a defect that arises some number of years after installation in the vehicle. Only part of the second group is presently under recall.

a. With respect to the first population, Takata had propellant manufacturing/handling control problems in the early years of inflator production. These manufacturing control problems led to injury and/or fatal events during deployment of some driver air bags and injury during deployment of some passenger air bags. This population is referred to as the *alpha* population, characterized by low density in the main propellant. It is bounded by specific date ranges of production at Takata. These inflators all have been recalled and are outside the scope of this discussion. That being said, some useful fundamental data was gathered during root cause studies of the *alpha* inflators and that data remains relevant to the current topic.

b. Later a second, *beta* population appeared, which manifests as a high pressure excursion during combustion that can lead to IR outside the range of the *alpha* manufacturing control problems. Typical *beta* units ignite and pressurize as designed initially but, part way through the event, pressure rises rapidly constituting an excursion to high pressure, which, in the extreme, can cause IR. Assessment of sibling units from within the same lot indicates that defective *beta* inflators are generally free of known manufacturing defects. In other words, it appears the inflators were manufactured as intended and passed all lot acceptance tests and vehicle manufacturer specifications. To date, the shortest length of time between the date of inflator manufacture and date of IR in a *beta* inflator has been approximately 7.5 years. There is no way to determine the extent to which any particular installed inflator is safe in the field, so all units of the same design must be considered susceptible to IR. Another complicating factor is that designs within the affected inflator family are optimized to meet specific vehicle manufacturer mounting and performance requirements, resulting in twenty-plus variants of driver and passenger inflators.

11. Takata has conducted extensive tests of field-returned inflators to characterize the extent to which high-pressure excursions occur for each affected inflator/vehicle platform as a function of model year and state or U.S. territory in which the vehicle is repaired. The configuration information and test results are recorded in a Master Engineering Analysis File (MEAF). In states and territories representing the most challenging conditions of heat and humidity, high pressure excursions are manifest in the *beta* population only after aging in the field, typically more than six years, and even then only in units that appear to represent worst case scenario regarding moisture protection (such as inadequate sealing).

Materials Reviewed

12. As a technical expert on behalf of NHTSA, my initial efforts focused on reviewing reports submitted to NHTSA by Takata, which included subcontracted work at Pennsylvania State University High Pressure Combustion Laboratory, PSU-HPCL, and the Institute of Chemical Technology, a German scientific laboratory specializing in energetic materials and air bags operated by Fraunhofer Gesellschaft, abbreviated as FhG-ICT. Both teams possess the equipment and in-depth know-how appropriate for conducting a failure analysis to identify the fundamental factors contributing to the root cause of propellant changes over time and how that leads to aggressive performance, including in some circumstances fragmentation of the inflators.

13. Since my initial review, periodic updates have been provided by Takata and FhG-ICT through on-site visits and videoconferences. These updates have allowed me to monitor their progress in defining the defect and investigating the nature of its root cause. The most recent update from Takata and FhG-ICT occurred in late-March 2016.

14. American Honda Motor Company (AHM) has independently engaged Exponent, Inc., an engineering and scientific consulting company headquartered in Menlo Park, CA, to investigate the defect. AHM and Exponent have provided periodic updates to NHTSA, in which I have participated, most recently in late-March 2016.

15. In December 2014, several affected automakers established a consortium to independently investigate these failures: the Independent Testing Coalition (ITC).[1] The ITC in turn contracted the investigation to Orbital ATK, a company with extensive scientific, engineering, and laboratory capabilities. I participated in briefings with Orbital ATK in November 2015 and February 2016.

16. Takata, supported by its contractors, has also made significant contributions to understanding the nature and scope of the inflator ruptures, and factors contributing to root cause. Two are prominent: (a) bounding the scope of the problem for all design variants in terms of age, climate, and frequency of high pressure event; and (b) disciplined scientific study of the physical degradation of the propellant and its ballistic consequences.

Expert Opinion - Root Cause

17. On behalf of NHTSA, I have reviewed the research and analyses conducted by, and the data obtained from, each of the investigators identified above.[2] Based upon that review, I conclude that all non-desiccated Takata frontal driver and passenger inflators contain a

[1] The Independent Testing Coalition is comprised of: BMW, Fiat-Chrysler, Ford, GM, Honda, Mazda, Mitsubishi, Nissan, Subaru, and Toyota.

[2] Unless otherwise stated, my findings, conclusions, and opinions in this report are based on my combined review and consideration of the testing and investigations of all the independent experts identified in paragraphs 12-16.

propellant that degrades over time. The degradation is principally the result of long term daily temperature cycling of moist propellant.

More specifically, the PSAN oxidizer in inflators that degrade is (A) not sufficiently protected by the inflator seals, allowing moisture to migrate into the inflator air space, and then be adsorbed onto PSAN particles from the humid air space. (B) Over time, many temperature cycles occur, causing changes to PSAN particles resulting in cumulative structural damage in the main propellant.[3] (C) During combustion, the damaged propellant transitions from surface burning to burning *en masse,* causing a rapid pressure rise (excursion) inside the inflator, which in turn, causes the steel housing to fail violently, propelling metal fragments.

18. There is a general consensus among Takata, PSU-HPCL, FHg-ICT, Exponent, and Orbital-ATK regarding the root cause, summarized in subparagraphs a. through c. below.

a. **Marginal Seal Design Permits Moist Air Intrusion.** Ballistic tests of more than 220,000 inflators indicate a pattern in frequency of high pressure ballistic events for each design within this family of Takata inflators that corresponds to geographic region, age of the inflator, effectiveness of seals, and vehicle platform (the last factor can affect in-vehicle temperature and humidity near the inflator). Takata and supporting labs have conducted physical disassembly of more than 27,000 inflators returned from the field. For some units the quality control (QC) helium leak test conducted during original production was repeated, and results indicate that leak rates for some field-aged inflators were higher than the maximum production specification limit value (three of fifty inflators in one series). All *beta* units originally passed this QC method of hermeticity verification at a Takata production facility, which calls into question the efficacy of that QC method. Moisture levels in booster and main propellants retrieved from dissected inflators are consistent with in-specification levels in the first years of field exposure, but later many inflators are above specification and the moisture levels steadily increase over time, consistent with leak rate data and diffusion rates through the seals. Moisture increase is steepest in units from areas known for high humid air and high solar load. The rate is a combination of diffusion through the seals and leakage due to poor seal performance.

The rate of moisture gain in the main propellant is influenced by the booster propellant. Several studies indicate that the booster propellant works like a desiccant,[4] suppressing moisture gain in the main propellant during the early years. When laboratory tests exclude the booster propellant, moisture in the main propellant increases linearly with time when exposed to humid air. However, when the booster propellant is present at levels proportional to that used in Takata inflators, the booster propellant gains moisture linearly while the main propellant gains very slowly until moisture in the booster propellant is above 2% as measured by weight (2 wt%). This desiccant behavior reverses at elevated temperatures (in the range of solar loaded vehicles in high absolute humidity areas), described less accurately as the booster

[3] As explained in further detail below, cumulative damage occurs by the spontaneous process of Ostwald ripening of the PSAN oxidizer particles, which is driven by temperature cycling.

[4] A **desiccant** is a hygroscopic substance that induces or sustains a state of dryness (desiccation) in its vicinity. The booster propellant was not originally designed to act as a desiccant, and it is very different from the desiccant used in the desiccated family of Takata PSAN inflators.

propellant transferring moisture to the main propellant. In sum, the booster propellant serves to slow the moisture increase in the main propellant for a period of time until the booster reaches a certain level of moisture content, at which time the main propellant absorbs moisture at a faster rate, including moisture from the booster.

b. **Propellant Exposed to Moist Air and Temperature Cycling Degrades Physically Over Time.** The consequence of moisture gain combined with temperature cycling is measureable structural changes in the main propellant.

i. The main propellant begins life at maximum moisture levels of 0.05 to 0.12 wt% (depending on the year of production) and burns layer by layer as designed.[5] But moisture intrusion occurs during field aging, increasing moisture levels to 0.1~0.20 wt% and above in "sealed" inflators. Field aging includes diurnal (daily) and annual temperature cycling. When the main propellant is above 0.1~0.2 wt% *continued temperature cycling* facilitates a process similar to Ostwald ripening wherein smaller PSAN oxidizer particles merge onto large ones, forming more thermodynamically stable larger particles, thereby resulting in the formation of pores/channels within the propellant. The evidence in support of this theory includes SEM electron microscope images (500x magnification), which show that the small gaps between particles in un-aged propellant samples become larger in aged samples. Using Energy Dispersive X-ray (EDX) or Wavelength Dispersive X-ray (WDX) detectors attached to SEM provide elemental analyses of individual ingredient particles which are observed in the SEM image, often artificially colored by the image software for presenting the data. Using this technique microscopists conclude that the particles corresponding to PSAN crystals are becoming larger as the samples age, coincident with small particles disappearing. Ripening during temperature cycling is favored for highly water soluble materials and PSAN is very highly soluble in water.

ii. Formation of pores/channels in the main propellant leads to changes in propellant density, most easily noted in larger parts like wafers used in passenger side inflators. This is an indirect result of the PSAN changes caused by reduced cohesion between particles. The density change manifests as increased diameter measurable by calipers once the inflator is disassembled. Alternately, a non-destructive x-ray technique, computed tomography (CT scan), has been calibrated to measure the wafer diameter without disassembly and that process is now automated. The use of CT scans has contributed greatly to the investigation by affording a means to pre-select high risk inflators for use in root cause analysis.

iii. The observations of moisture driven degradation are verified experimentally using inflator surrogate devices, each of which is unique to the participating lab. Lab pressed propellant parts or production propellant specimens have been studied. These allow for *in-situ* moisture increase in the main propellant (or the booster propellant) for subsequent testing under simulated temperature and humidity cycling where no further moisture ingress is occurring. Testing of main propellant pre-

[5] This design incorporates controlled ignition fracturing of the manufactured propellant part, so layer by layer burning actually occurs after fracturing.

conditioned *in-situ* to above 0.1~0.2 wt% and cycled from above 0 °C to hot, for example 70~90 °C, show pore formation and increased crystal size of PSAN after several cycles, indicative of ripening (larger crystals are more stable thermodynamically). Measurements used to directly characterize these changes are SEM, 2-D x-ray diffraction (2-D XRD), porosimetry (gas or mercury), and density. SEM images of both the surface and interior (after breaking the propellant wafer) indicate moisture driven change can occur beyond the surface even in relatively new propellant parts. Porosimetry measurements provide dimensions of the pores such as total pore volume and diameter of the pore openings, which show increase over time in the field. In 2-D XRD, certain features in the diffraction pattern which are associated with larger crystals are increasingly prevalent in moistened specimens as temperature cycle count increases. Density derived from caliper measurements (envelope density) can also indicate the extent to which change has occurred, but is sensitive to operator technique.[6] In sum, *at increased moisture levels in the main propellant,* ***temperature cycling*** *causes progressive physical degradation of the main propellant by pore formation.*

iv. As noted at subparagraph 18.a., significant geographic and vehicle platform biases have been observed in testing of returned inflators. These biases arise from the interaction of two contributing factors: (1) absolute humidity varies geographically and determines the moisture level in the air available for ingress, and (2) solar loading aggravates the high temperature value during the diurnal cycle which drives the extent to which booster propellant desorbs moisture, increasing the moisture level in the space around the main propellant.[7] Moisture in vehicle interior components also varies by platform, contributing to local humidity available for ingress.

c. **Over-Pressurization During Air Bag Deployment.** Combustion driven devices, like rockets, guns and air bag inflators, can operate safely when there is a balance between the rate at which gas is generated and the rate at which the gas vents and the peak pressure is safely within the structure's capability. The designer of an inflator creates this balance by manipulating the propellant surface area (geometry) and adjusting the flow area of the vent ports. Typically, the vent ports do not change during deployment, so any increase in propellant area burning tips the balance towards increased pressure and in the extreme can cause the structure to fail catastrophically.

Takata and all four investigating laboratories developed in-house capabilities to test inflators and also developed heavy-wall hardware to allow faster and/or more extensive

[6] It has been noted that degradation in lab simulations of temperature cycling is similar to but not an exact match to that found in field return units.

[7] It is important to note the following about the interaction of high temperatures and temperature cycling regarding the degradation of main propellant: (1) all investigators have verified that aging at elevated temperature alone tends to dry out main propellant, and therefore does not cause the physical changes in the main propellant that can result in IR events; and (2) environmental stress simulation, or ESS, specifications do not appear to detect the problem because the temperature cycle protocols cause the main propellant to dry out on the hot cycle and, on the cold cycle, draw in surrounding air of very low humidity due to the extremely low temperature.

measurements. All found that, above some level of damage to the main propellant by pore/channel formation, combustion is likely to cause a pressure excursion event mid-way through the propellant burn (or deployment). The heavy-wall tests of main propellant show that high pressure excursion occurs without interaction with the rest of the inflator system present, meaning that ignition train, filter, burst shims, or module components are not contributing factors. Measurement of internal pressure (P_c) of the inflator or test device is critical, since incipient failures can also be detected as pressure excursions well short of fragmentation. In normal inflator tests, P_c peaks around 40 megapascals (MPa), whereas damaged propellant shows an abrupt transition to P_c at 80-100 MPa, at which point the structure fails catastrophically, venting the pressure by rupturing the inflator housing. In the closed bomb test, the structure does not fail, so normal burning propellant steadily pressurizes the closed bomb over 80 milliseconds (wafer propellant part). By contrast, the P_c history for damaged propellant shows a pressure excursion 15-50 milliseconds into the event. In one example the excursion is at 20 milliseconds, which corresponds to an instantaneous 4.75-fold surface area increase. In sum, the presence of pores in the main propellant cause abnormal burning, resulting in increased pressure that cannot be contained by the inflator housing.

19. I find the foregoing explanation and conclusions to be the product of rigorous scientific analysis and testing. The root cause described in paragraphs 17-18 represents the consensus of sound and reliable analyses conducted by multiple laboratories and consultants. In summary, I conclude that the inflator ruptures occur through the following factors and sequence of events:

(a) Affected inflators are inadequately sealed for protection of the moisture sensitive PSAN-based main propellant;

(b) Allowing moist air to enter the inflator air space; and

(c) Causing damage to the physical structure of the main propellant consisting of the formation of pores/channels.

(d) Over the course of years, the extent of damage progresses by a slow process driven by daily temperature fluctuations.

(e) Then, during combustion, the extremely hot gas enters the pores/channels;

(f) Which causes a transition from layer-by-layer burning to burning *en masse* that over-pressurizes the steel shell to cause catastrophic failure (rupture) with fragmentation hazard to vehicle occupants.

Estimated Length of Time to Propellant Degradation

20. The Exponent team has briefed NHTSA and me on the development of a time-resolved computer simulation of the process leading to high pressure excursions and/or IR events by linking (a) the moisture ingress process, (b) the progress of propellant deterioration, and (c)

the abnormal burning of the main propellant.[8] The results of the model appear consistent with ballistic test results and, therefore, serve as a valuable tool for evaluating the exposure time needed to sufficiently degrade the propellant to the point that an inflator poses an unreasonable risk to occupant safety.

21. Exponent used data and conclusions from various fundamental studies to quantify the interactions of climatic cycles with the vehicle (and the inflators therein) leading to the following key sub-models: (a1) time varying details of climate (temperature, humidity, and solar load), (a2) details of vehicle and inflator configuration, especially seal integrity, (a3) reversible moisture transport (movement) from the air in the vehicle to inflator air space, (b1) reversible inflator air space moisture interactions with all solid propellants, (b2) correlation of cumulative moisture fluctuation into/out of the main propellant to irreversibly damage the main propellant, and (c) correlation of the extent of damage in the main propellant to the shifts in pressure at which the inflator pressure excursion occurs.

22. The centerpiece of the simulation is estimating the cyclic, time-varying moisture level (humidity) in the inflator air space (i.e., head space) around the main propellant, including the influence of the booster propellant (time varying net effect of sub-models a1, a2, a3, and b1). The simulation tracks the cumulative moisture moving in to and out of the inflator headspace as an index of deterioration, referred to as "2004Flux Moisture" expressed as wt% of the main propellant.

23. Temperature cycling drives the change in headspace moisture which in turn drives cyclic adsorption/desorption of moisture on the PSAN surfaces. The Exponent team carefully studied the deliquescent behavior of the Takata propellants to provide the foundation for the cyclic sorption process, which feeds the irreversible damage process, Ostwald ripening (sub-model b2). The cumulative effect of ongoing ripening of PSAN particles is pore formation and growth within the propellant wafer or tablet.

24. The consequence of ongoing moisture flux is progressive, irreversible pore/channel formation. Studies by Exponent correlated the extent of that damage at the time of deployment (or ignition) to abnormal burning (sub-model c). The researchers discovered a key detail of that process: there is a relationship between the pore diameter and the shift to lower pressure for the excursion pressure in closed bomb tests.[9] In a series of experiments, as pore diameter increased, the excursion occurred at lower pressure. This relates to inflator IR events when the excursion pressure overlaps inflator operating pressure, resulting in catastrophic failure of the structure. The focus at Exponent on the excursion pressure as a figure of merit is similar to

---

[8] To fully understand the model, it would be useful to see additional details of the fundamental studies and how they influence the sub-models for the life estimation model. This could indicate the extent to which some uncertainties for inputs are factored in. However, even without this additional information, the model appears to be a reasonable and useful tool to estimate the length of time after which an inflator may pose an increased risk of rupture.

[9] In this test, propellant is ignited and burns in a closed steel vessel with transducers installed to record pressure during the time of the burn. The volume and propellant quantities are selected so pressure observed in the test simulates that observed in the inflator.

Integral Burning Rate, or IBR, that has evolved at FhG-ICT for Takata as a means to identify defective, aged propellant in similar closed bomb testing.

25. The pressure excursion is understood by the Exponent team as being caused by the sudden change in burning surface area and subsequent microburst of propellant pore walls in the main propellant.[10] A threshold for abnormal burning of 8% 2004Flux Moisture was derived from analysis of many closed bomb test results for wafers exposed to a series of temperature and humidity cycles of varying duration (which correlates 2004Flux Moisture to the shift of the excursion pressure). Conceptually, before the time of 8% 2004Flux Moisture, IR is not expected; after that time, the probability should correspond to the rate observed in the pressure excursion test data.

26. The Exponent team uses the integrated model to generate the 2004Flux Moisture, defined as the cumulative amount of moisture into and out of the inflator headspace expressed as wt% of the main propellant. My opinion is that this is a reasonable surrogate for the cumulative pore/channel formation by Ostwald ripening which is not easily measured but is dependent on moisture level and temperature cycling. In the model, changes in temperature, humidity, and solar loading - both diurnal and annual - are combined with assumed design characteristics (for example initial moisture level of propellants and leak rate for seals) and exercised as a function of time. The model appears to properly handle solar loading, which influences peak in-vehicle temperature. This accounts for a high rate of defect occurrence in high absolute humidity areas that also are high in solar load, since the peak temperature rises enough to desorb moisture from the booster propellant, making it more available for sorption by the main propellant. At any point in the virtual age of the inflator, the value of 2004Flux Moisture can be calculated and plotted over the life of the product.

27. Regional differences in the rate of IR are well documented by Takata. The magnitude of the influence of climatic factors for different locations can be evaluated by comparing model runs wherein inflator configuration is held constant and climatic cycle data representing each geographic region is used. To that end, the Exponent team calculated the length of time to 8% 2004Flux Moisture for hundreds of cities and presented it to NHTSA overlaid on a map of the United States.

28. As an initial validation of the model and imbedded assumptions, experts compared the merit of the 8% 2004Flux Moisture threshold to IR events recorded in the MEAF file for the PSPI-L inflator type. The Exponent team found a strong correlation: for the high absolute humidity region, IR events first appear in year 9, and the model predicts that 2004Flux Moisture for two cities in that region, Miami and Houston (slightly different climate inputs), will reach 8% in year 8.3 and 9.0, respectively.[11] Hence this team sees time to target flux of 8%

[10] An alternate interpretation is that excursion may be heat driven rather than pressure driven. As the walls of nearby pores/channels are simultaneously heated to the autoignition temperature of the main propellant, the affected portion of the propellant charge burns *en masse*. Laminar regression is the normal solid propellant burning mechanism, wherein one layer heats the next layer – and <u>only</u> the next layer - in order to sustain combustion. That said, thermal properties are always closely coupled to pressure in combustion since the efficiency of convective heat transfer to the surface increases with pressure.

[11] Exponent calculated the time to 8% 2004Flux Moisture values assuming the main propellant moisture equals 0.05 wt% maximum, which is the current manufacturing specification. Earlier in production, the specification was 0.12

2004Flux Moisture as **a viable means to define the length of time for propellant degradation sufficient to create a risk of inflator rupture, IR**. I concur with the Exponent team's sound analysis and conclusions regarding the measurement and modeling of the time to propellant degradation sufficient to create a risk of inflator rupture.

29. Examining results for key US cities suggests a geographic pattern of risk which NHTSA identifies as Zone A, Zone B, and Zone C. For example, Zone A includes cities like those discussed in paragraph 28. Under the Exponent model, the exposure time needed to degrade the main propellant sufficiently to create a rupture risk in Zone A varies between six and nine years. The exposure time needed in Zone B varies between ten and fifteen years, and includes cities like Phoenix, AZ and Washington DC (8% 2004Flux at year 11.8 and 12.6, respectively). The exposure time in Zone C varies from fifteen to twenty-five years and includes cities like Detroit, MI, and Denver, CO (8% 2004Flux at year 14.5 and 19.1, respectively).

30. This 2004Flux Moisture tool is relatively new, but represents a sound, reasonable, and credible science-based methodology to estimate the length of time until propellant degradation presents a risk of IR. The tool was exercised for the inflator variant exhibiting the highest IR rate, PSPI-L. NHTSA was also briefed on the sensitivity analysis of the model to certain model input parameters: climate, initial moisture in propellants, moisture ingress rates, and moisture communication. To some degree these inputs reflect key aspects of vehicle platform differences, but further research is needed to validate whether these model inputs handle the contribution of platform-specific details to correctly simulate real world performance degradation noted in the MEAF file.[12]

31. Very recent analysis by Takata may have identified a secondary pattern in the frequency of IR events in the MEAF data that correlates with vehicle curb weight, wherein lighter vehicles are, at a given age, more likely to exhibit IR-related events than heavier vehicles. In developing its new theory, Takata analyzed both wafer outside diameter data and high pressure events for returned parts. More analysis, testing, and review would be necessary to fully evaluate the correlations suggested by Takata's analysis, and any implications it might have for NHTSA's IR risk analysis and recall prioritization.

Conclusion

32. In conclusion, the root cause of the rupturing Takata inflators is moisture damaged main propellant which, over the course of time, transitions to burning *en masse* during deployment. The investigations have provided additional insight regarding the extent to which propellant damage is dependent on temperature cycling, which feeds both moist air movement into the inflator and the propellant physical damage due to pore formation. The booster

---

wt% maximum. Running the model for that input moisture level shifts time to 8% 2004Flux Moisture lower for Miami and Houston, to 6.4 and 7.6 years, respectively.

[12] It may be possible for additional testing to demonstrate that inflators in certain vehicle platforms, models, or configurations take a longer time to present an increased IR risk than the conservative estimates generated by the Exponent modeling. To date, however, no such testing and results have been presented.

propellant forestalls damage by acting as a desiccant, the effectiveness of which varies with climate. Nevertheless the main propellant exposed to moisture will eventually degrade by temperature cycling to the point of risking inflator rupture at an age ranging from six years in regions which feature high humidity and high solar load to twenty-five years for colder regions where humidity is lower and temperature coupled to solar load do not interfere with booster propellant acting as a desiccant to protect the main propellant.

Respectfully submitted,

H.R. Blomquist, Ph.D.

Appendix 1 - Curriculum Vitae

Harold (Harry) R. Blomquist, Ph.D.

President, HRB Research

blomquistresearch@gmail.com

Gilbert, AZ 85234

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 - 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.

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 3-5 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

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

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

US liaison for US State Department funded ISTC Project 1882
Energetic Material Synthesis project with Russian Academy of Science, Institute of Chemical Physics

AIChE National Meeting – 2003
A Safe Method for Manufacturing Gas Generator Propellant Composed of Ammonium Nitrate and HMX, H.R. Blomquist, E.S. Gurley and W.P. Sampson

5th International Conference on Special Topics in Combustion, Stresa, Italy, 2000.
Characterization of Combustion Species by Real Time FTIR Spectroscopy at Gas Generator Operating Pressure, H.R. Blomquist, Stefan T. Thynell and C.F. Mallory, Pennsylvania State University. Monograph available Begell House Publishing.

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

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

NHTSA Airbag Effluent Panel, 19th Annual Workshop on Human Subjects for Biomechanical Research, Nov. 1991
"Does Ballistic Tank Testing Simulate Occupant Exposure To Harmful Effluents", H.R. Blomquist

Heat Transfer Journal
The Classification of Particles Generated by Propellant Combustion
H.R. Blomquist, J. Sheng (TRW), and Pinar Menguc, University of Kentucky.

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

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

Facile Synthesis of 2-Substituted 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.

25+ Patents – Listing US Version Only

1 6,902,637 Process for preparing free-flowing particulate phase stabilized ammonium nitrate
2 6,875,295 Cool burning gas generating material for a vehicle occupant protection apparatus
3 6,860,208 Nitrocellulose gas generating material for a vehicle occupant protection apparatus
4 6,802,533 Gas generating material for vehicle occupant protection device
5 6,635,131 Gas generating material for a vehicle occupant protection apparatus
6 6,627,014 Smokeless gas generating material for a hybrid inflator
7 6,605,167 Autoignition material for a vehicle occupant protection apparatus
8 6,591,752 Ignition material for an igniter
9 6,588,797 Reduced smoke gas generant with improved temperature stability
10 6,513,834 Monopropellant smokeless gas generant materials
11 6,468,370 Gas generating composition for vehicle occupant protection apparatus
12 6,410,682 Polymeric amine for a gas generating material
13 6,319,341 Process for preparing a gas generating composition
14 6,296,724 Gas generating composition for an inflatable vehicle occupant protection device
15 6,238,500 Smokeless gas generating material
16 6,231,702 Cool burning ammonium nitrate based gas generating composition
17 6,231,701 Vehicle occupant protection device and solid solution gas generating composition therefor

18	6,228,193	Vehicle occupant protection device and solid solution gas generating composition therefor
19	6,195,996	Body of gas generating material for a vehicle occupant restraint
20	6,149,746	Ammonium nitrate gas generating composition
21	6,143,104	Cool burning gas generating composition
22	6,136,112	Smokeless gas generating composition for an inflatable vehicle occupant protection device
23	6,117,255	Gas generating composition comprising guanylurea dinitramide
24	6,113,713	Reduced smoke gas generant with improved mechanical stability
25	6,004,410	Apparatus comprising an inflatable vehicle occupant protection device and a gas generating composition therefor