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Thermal Decomposition Effects on Perforating Performance and Safety

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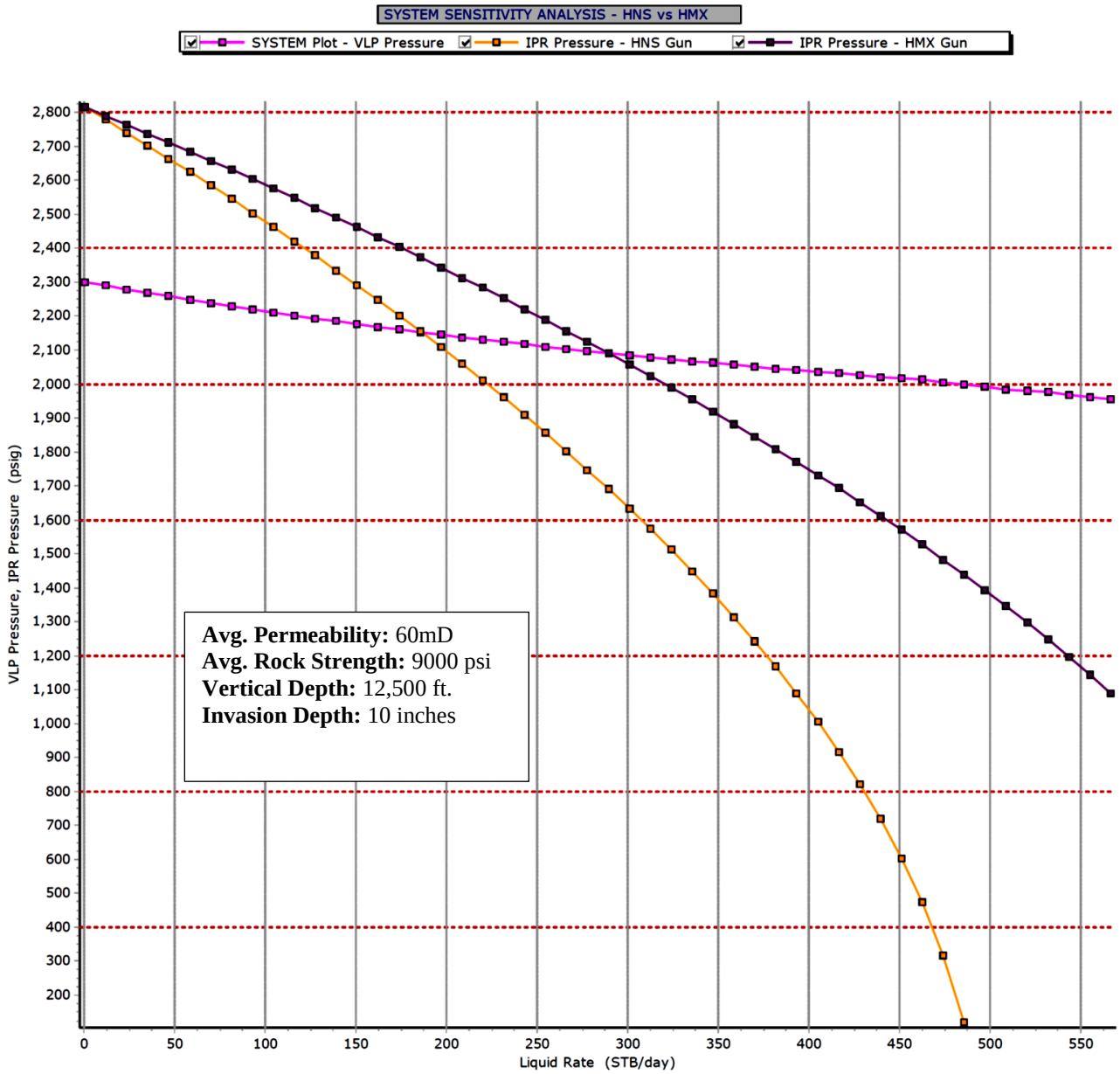

Figure 1: PROSPER SPOT IPR/VLP simulation results for HMX and HNS charges

From these examples, it is clear that the challenge in selecting the best explosive for an application is that "best" is a compromise between safest and best performing. When explosives are in a well, the high temperatures may change the state of the explosive or cause it to chemically degrade or decompose. This decomposition can change both the safety and performance of the explosive and the perforating system. Any process that is kinetically driven, such as chemical reactions, will depend on both temperature and duration of exposure. Therefore, considerations muse be made for how hot a well is and how long the perforating system may remain downhole before firing or recovering in the event of a misrun. There is an additional safety concern if a perforating system is pulled back up to the surface without detonating; thermally damaged explosive, such as HMX, may be more sensitive to handling. Or, the explosive may already be in thermal-chemical runaway and may explode on the surface. Thus, perforating system selection should balance both the performance and safety of the explosive under anticipated conditions (i.e. the temperature of the well and how long the explosive will be exposed to temperature). However, contingencies for unplanned setbacks to the perforating job must be considered during perforating system selection when these setbacks may expose the explosives to temperature for longer time durations.

Time Temperature Considerations & Review of Industry Data & Practices

It is important to note that heating explosives above ambient temperature can, but does not always, result in performance losses or safety hazards. Explosives may be heated and remain thermally stable; under these conditions, performance may

even increase. However, when thermal stability limits are surpassed, performance losses and safety hazards can arise due to thermal decomposition. The severity and outcome of thermal decomposition at the well site vary depending on conditions and materials. These consequences are highly dependent on variables such as explosive type, purity, particle size, binder, pressed density and confinement of the explosive; these variables can be controlled by the explosive manufacturers. Other variables, such as temperature, exposure duration and heating rate relate to the perforating operation and well environment.

The thermal decomposition of an explosive produces heat and reaction product gases. The gases will cause pressure to build inside the perforating gun. In the event of a misrun, this increased pressure can create a safety hazard when breaking down the perforating gun on the surface. Furthermore, thermal decomposition can lead to a self-perpetuating (i.e. autocatalytic) reaction, or thermal runaway, and cause an explosion. As a result of thermal runaway, the perforating system may perforate off-zone with potential environmental and economic impact. In the event of a misrun, explosion may occur on the surface, after the gun has been recovered from the well, resulting in substantial damage to the surrounding infrastructure and/or loss of life.

Thermal runaway is heavily influenced by the well environment. Thermal runaway occurs when heat from thermal decomposition builds within the explosive faster than it dissipates. Figure 2 illustrates that the thermal decomposition rate increases exponentially as temperature and exposure time increase. Rapid thermal decomposition rates lead to thermal runaway. Once thermal runaway has started, it is often impossible to quench the reaction and prevent an explosion, even if the heat source is removed. Fortunately, the critical temperature at which explosion will occur as well as the time to explosion can be calculated by using explosive properties, charge geometry, exposure temperature and exposure time; thus this hazard can be mitigated.

Additionally, explosive performance in detonators, boosters, detonating cord and shaped charges may deteriorate when overexposed to temperature. This performance loss results from decomposed explosive, which does not contribute to the explosive output of the device or changes explosive density and porosity. In addition to direct performance losses, devices like shaped charges may suffer indirect performance losses with much higher consequence. Reaction product gases from decomposing explosive may push the shaped charge liner out of the charge as pressure builds behind the liner, which would render the shaped charge ineffective.

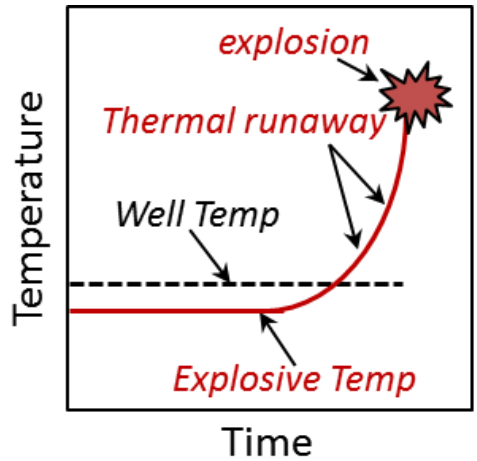

Figure 2: Thermal history of an explosive prior to thermal explosion.

To address these issues, explosive manufacturers in the oil and gas industry publish charts with temperature limits for explosives at different exposure times. A typical chart is shown in Figure 3. These charts have been successfully utilized by the industry for decades. However, it is not always clear if the limits on the chart are safety or performance limits. Some manufacturers claim the limits are safety limits with critical temperatures not to be exceeded. Other manufacturers claim that the limits are performance based. As a result, the consequences of exceeding the limits are unclear for end users.

Furthermore, there is uncertainty on the origins of the data for the temperature exposure charts. Most speculate that these charts originate from test results published by the national laboratories. Testing conducted by the national laboratories focused on determining critical temperatures and explosion hazards related to safety only. However, both safety hazards and performance losses are important for effectively planning perforating jobs.

Additionally, uncertainty on the test methods and materials used for these dated tests raises questions on the broad applicability of the charts. Often times, laboratory tests utilize carefully prepared, high purity, explosive powders which are not economical in commercial practice. Over the years, technological advances in synthesizing explosive powders and new

binder technologies suggest further dissimilarities between modern commercial grade explosives and the explosives originally tested. At elevated temperatures, commercial grade explosives may exhibit different thermal decomposition behavior. These differences could impact safety hazards and performance losses. As a result, explosive users must take a conservative approach when selecting proper explosive devices based on the charts.

In general, the existing time-temperature curves provided by manufacturers are imprecise, simplistic and ultimately, insufficient. Improved guidance on thermal stability limits of explosives could significantly improve optimal perforating system selection and operational safety resulting in a substantial increase in well production. There also needs to be clear differentiation between the assessment of performance and safety. Again, documentation associated with prevailing curves, such as the example in Figure 3, are not explicit about the conditions at which the data was captured with respect to explosive purity, particle size, addition of binders, and the associated test conditions and apparatus utilized. Additionally, points on the graph appear to have been extrapolated to create straight lines, which may or may not reflect reality, and merits further scrutiny. The conditions under which these explosives exceed safe limits and become unstable have not been well characterized. Consequently, these charts should be updated with a comprehensive safety and performance, time-temperature model.

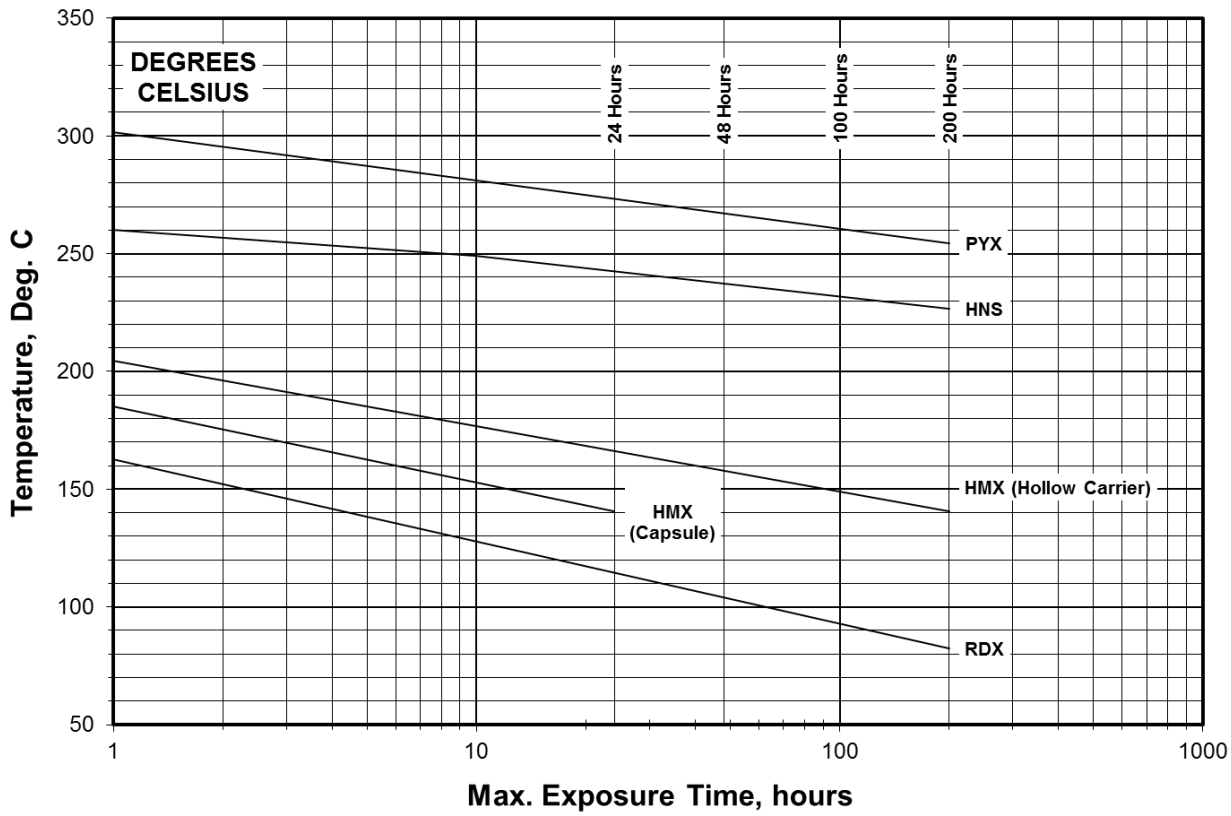

Figure 3: Typical manufacturer published temperature limits for different exposure times.

Current Methods for Assessment

Currently, the industry uses the API RP 67 Recommended Practice for Oilfield Safety and the API RP 19B Recommended Practices for Evaluation of Well Perforators for industry guidance, in combination with manufacturer supplied time-temperature curves. Both recommended practices are currently undergoing revision. These two recommended practices offer some insight on the safety and performance effects associated with thermal exposure. However, neither adequately addresses thermal stability to the extent desired by explosive users within the industry.

From a safety perspective, the current edition of API RP 67 (Second Edition) provides limited direction on thermal exposure. Specifically, the recommended practice provides guidance when HMX is exposed to temperatures which may cause a phase change to the more sensitive delta phase. The next revision will provide additional guidance for HMX sensitivity after thermal exposure. This guidance will be developed through a series of sensitivity tests on oilfield grade HMX powders which have been thermally conditioned to create the delta phase. Additionally, the next revision will also include a generalized section on thermal decomposition, thermal runaway and safe handling practices if thermal runaway is suspected. Inclusion of this section will mark a significant improvement over the current edition but is based largely on theoretical conditions.

Therefore, actual testing with oilfield explosive devices will provide the groundwork to more specifically address these important topics.

From a performance perspective, the API RP 19B Section 3 recommended practice outlines procedures for evaluating shaped charge and system performance under the influence of temperature. The Third Edition of the recommended practice requires testing a complete perforating system including firing heads and TCP transfer where applicable. Under the recommended practices, the perforating system is held at temperature for a minimum prescribed time and fired at temperature into steel plates. Perforating system manufacturers infrequently conduct these tests in part because of the complexity and cost of the test. Additionally, end users typically do not require these tests when selecting explosives.

In an effort to reduce the complexity of the API RP 19B Section 3 test, the new edition adds an alternate test method. Under the alternate test method, the perforating system is thermally conditioned, allowed to cool and fired at ambient conditions. Separately, single charges are fired at temperature to evaluate performance.

The two potential test methods for API RP 19B Section 3 do not adequately evaluate effects on performance. Testing is conducted under specific time and temperature conditions and does not provide information needed to understand how performance changes when deviating from the test conditions. Additionally, test conditions are typically selected within the published temperature limits, and the testing is generally not conducted in targets representative of downhole formations.

Furthermore, the simplified test method broadens the gap between test conditions and the downhole environment. For instance, perforating system effects are not captured. Test results from the single shot geometry may be affected by pressure buildup from thermal decomposition at elevated temperatures. Since the recommended practice does not specify a test configuration, these effects may not be captured depending on the test configuration used.

In addition to full scale testing, there are three main lab-scale tests used to assess thermal stability: (1) vacuum thermal stability (VTS) test, (2) ampoule test, (3) One Dimensional Time to eXplosion (ODTX). These tests measure different phenomena and conditions and their results are not directly interchangeable with each other. They are all safety-derived tests and, while they may provide information about the change of the material during heating, none of them will provide guidance on performance. The advantage of all these tests is that they are lab-scale tests that can be executed efficiently and affordably. The disadvantage is that some of these tests are so different from the end application that a direct application of the results could result in inaccurate and unsafe guidelines.

The vacuum thermal stability (VTS) test has a long history as a thermal stability test for explosives and propellants.[1-4] In general, the test involves heating a small amount of powder in an evacuated container for many hours; the pressure change is measured and outgassing volume is reported. The underlying assumption is that the outgassing results from decomposition of the explosive. The experimental parameters such as mass, temperature, and duration vary significantly among practitioners; the STANNAG requirement calls for heating 5 g of explosive at 100°C for 40 hours in a glass tube with 25 cm^3 volume[3] while MIL-STD-1751A specifies different temperatures, times, and sample sizes for acceptable variants. [1]

A related test with an equally long history, the chemical reactivity test, was developed at Lawrence Livermore National Laboratory. It is essentially similar except that the quantity and composition of the evolved gases is measured, providing direct measurement of explosive decomposition. In addition, the tests are conducted in steel apparatus, thereby avoiding safety problems with pressurized glass. The sample size is 0.25 grams in 17 cm^3 volume, with temperatures typically between 80 – 120°C and exposure times of 20 hours. [5-7] In general, this type of test is best suited as an accelerated aging test to provide experimentalist confidence in the stability of their materials at or near room temperature. The conditions used in these tests are milder than many wells and it may be difficult or impossible to extrapolate results from a 100°C-120°C experiment to higher temperatures.

Baytos from Los Alamos Scientific Laboratory performed VTS experiments in which 0.3g of powdered explosive was heated between 150 and 175°C for up to 90 days; any experiment that exceeded 15 cm^3/g of outgassing was aborted promptly.[4] Baytos reported evolved gas of 15-30 standard cm^3 for the tests at 150 and 175°C, which roughly correspond to sample decomposition of 9-16%. While the temperatures and times are relevant, the explosive density and vessel volume are quite different from the explosive configurations in a perforating system. When an explosive begins to decompose, the initial product gases are highly reactive; in a small volume or when contained within a very dense explosive part, these gases heat the surrounding material and chemically attack the explosive resulting in autocatalytic reactions that accelerate rapidly to explosion. However, if the vessel has a large headspace volume (i.e. the volume of space that is gas or free volume shown in Figure 4) relative to the explosive volume, as it is in Baytos and the other vacuum thermal stability tests, these reactive gases will expand up into the open volume inhibiting the autocatalytic chemistry and dissipation of the thermal energy. This explains the rather high extent of decomposition without ensuing explosion. Consequently, this test may provide a false sense of safety.

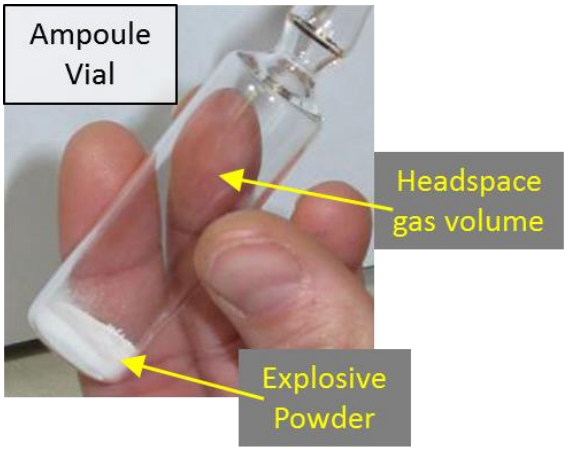

Figure 4: Ampoule vial with powder explosive.[8] The headspace gas volume is the volume of the vessel that is not occupied by the explosive.

Kneisl recently published a new stability test called the Ampoule Test.[8] The test, which is similar to the vacuum thermal stability test, involves heating 1 g of explosive powder in a 10 cm^3 glass vial for 2 to 2000 hrs. up to 350°C. The outgassing is measured post-experiment; the experiment can measure up to 300 cm^3/g, which is significantly higher than the outgassing from other versions of the VTS test. The higher temperatures and longer duration make this test more relevant to perforating applications. The smaller volume of the glass vial is also an improvement. However, this test still measures outgassing from a powder in a vessel with a relatively large amount of headspace shown in Figure 4. The same experiment performed on a high-density pressed part in a vessel with little or no headspace might produce thermal runaway response at lower temperatures or shorter timeframes. This test could be used to develop kinetic models for degradation and outgassing which would be extremely useful in predicting the pressurization as a function of time and temperature. However, such a kinetic model would not reliably predict thermal runaway or thermal explosion of a material.

The One Dimensional Time to eXplosion (ODTX) test was designed by Lawrence Livermore National Laboratory, with first publication in 1976 and continued application and refinement since then. References [9-15] represent a selection of publications on this technique. In this test, a ½ inch diameter sphere of explosive is heated with an isothermal (i.e. constant temperature) boundary condition until it explodes; the time to explosion as a function of the boundary temperature is the resulting data. The apparatus shown in Figure 5 consists of two aluminum blocks that each have a ½ inch diameter hemisphere machined out to accommodate the explosive sphere. The anvils are preheated to the desired temperature and time-zero is defined as the time when the explosive is inserted between the anvils. Typically, there is no headspace and the anvils are held together with a 15,000 psi load cell which prevents the reaction from quenching early due to gas venting. Recently, the test was modified to include a pressure measurement during heating. In general, one cannot use the results of this test directly to predict the response of a large explosive charge because of scalability issues. Instead, this test is used to help parameterize or validate a thermal-chemical explosion model. However, in the case of perforating shaped charges, the thickness of the explosive (approximately ½ inch between the liner and the case) is close to the diameter of the ODTX sphere; consequently it is reasonable to use the results of this test, with simple adjustments to account for the difference in heat transfer through a sphere or a flat slab.

While the ODTX test is useful, there are still important dissimilarities with actual perforating systems. The ODTX test, by definition, is one dimensional. The potential for thermal explosion in a shaped charge is at least two dimensional. Also, in the ODTX test, the surface of the explosive is nearly instantaneously brought to the exposure temperature. In most wells, the explosive is slowly raised to temperature, in part because the well gradually gets hotter with depth but also due to the transient response of the perforating system until thermal equilibrium is reached. Results from ODTX testing could show thermal stability limits higher than reality, especially for exposure times less than ten hours common in many perforating jobs.

While all three methods described above – vacuum thermal stability test, ampoule test, and ODTX – provide insight into safe temperatures and exposure times for explosives, they are designed to measure different physical and chemical processes. While the data from a given test may be used to compare different explosives in a qualitative manner, comparison of results from different tests and different materials may be confusing at least or misleading at worst.

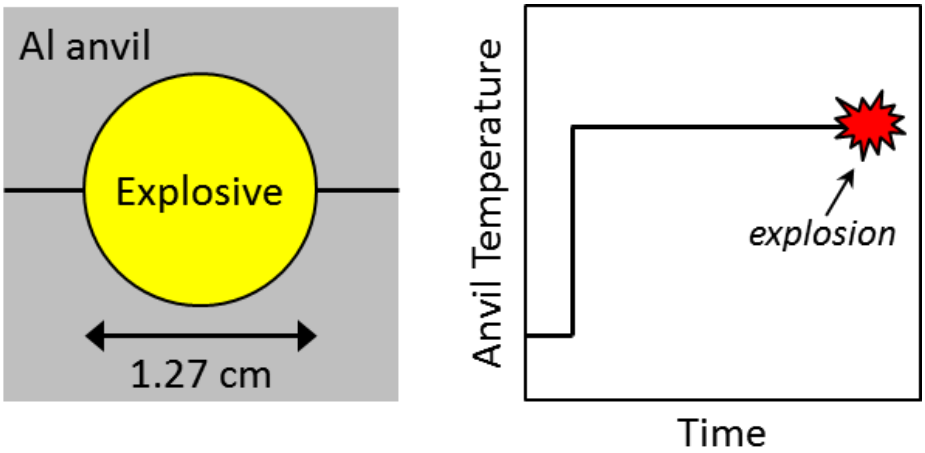

Figure 5: ODTX cross-section (left) and anvil temperature (right).

A comparison of time-temperature data from several tests is shown in Figure 3, along with a few manufacturers' recommendations for time-temperature limits[16-18]. LLNL ODTX data[9-12] show the time to explosion as a function of temperature for HMX and LX-10, an HMX based explosive, for the ½ inch diameter spherical samples. It is important to note that the lowest temperature ODTX data represent the critical temperature for the material under the test configuration – reducing the sample temperature by a few degrees gives no explosion in times up to 70 hours. This fact emphasizes the importance for accurate curves in evaluating the tradeoff between performance and operational safety.

Furthermore, VTS data from Baytos[4] show the time required to exceed 15 cm^3/g outgassing. Ampoule test from Kneisl data are simply the length of time that data were collected,[8] and therefore represent a lower limit on the time required to achieve thermal runaway (as in ODTX) or to achieve the level of outgassing in Baytos' results. The manufacturers' guidelines are presented as time limits for a given temperature beyond which use of the device is not recommended.

For a simple single-step rate-limited reaction, the data displayed in the Arrhenius form of Figure 6 will be linear with the slope proportional to the activation energy. While the decomposition of explosives is not a simple single-step process, ODTX data for CHNO (i.e. carbon-hydrogen-nitrogen-oxygen) explosives generally display a fairly linear relationship in this type of plot. In Figure 6, the manufacturers' data are consistent with extrapolation of the LLNL ODTX data. This suggests that both sets of results represent similar chemical reactions, although the actual physical meaning of extrapolation of ODTX data to temperatures below the critical temperature of the sample is unclear. Baytos's VTS data shows considerably longer reaction times, and Kneisl's results show a lower limit that is still higher than the ODTX reaction times, consistent with the Baytos data. Note that these reaction times are for partial decomposition of the sample, not runaway thermal explosion, and therefore represent a lower extent of reaction than the ODTX data. As discussed above, both Baytos' and Kneisl's data are measured with powder samples in the presence of high headspace volume, and both factors inhibit the autocatalytic decomposition that occurs in explosives. This additional headspace likely explains why these data show longer reaction times than the ODTX results.

An additional factor that should be considered is the purity of the explosive being tested, as the presence of impurities can dramatically influence explosive stability. While the HMX and LX-10 used in the ODTX test were MIL-SPEC quality, the purity of the samples in the other tests is unknown. However, impurities would not explain the longer times for the Baytos and Kneisl data, as any impurities that may have been present would reduce the stability, not increase it. Looking forward, purity of explosives being tested should be known and should be consistent with explosives used in perforating systems.

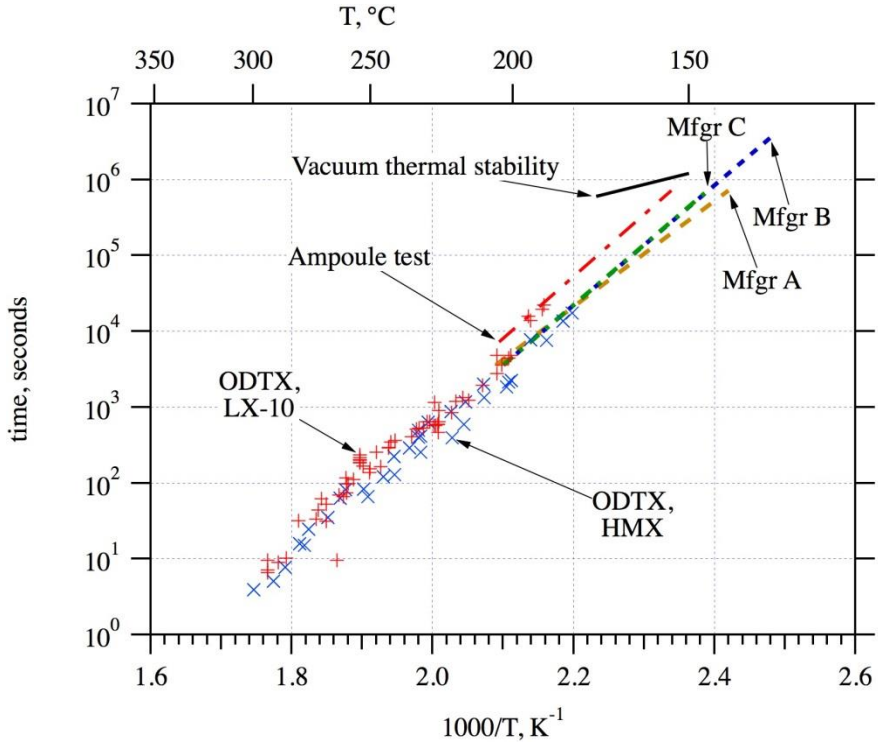

Figure 6: Comparison of LLNL ODTX data for pure HMX and for LX-10 (95% HMX, 5% Viton-A) with three different manufacturers' recommendations for time/temperature limits and with VTS and ampoule test results.

In summary, the current methods provide different qualitative relative insights into the safe temperature and exposure times for explosives in a perforating system. The outgassing tests (VTS and Ampoule) provide data on low-extent thermal decomposition; while thermal decomposition surely affects explosive performance and safety, there is not an obvious way to derive a quantitative relationship among these properties. The ODTX test is designed to provide data on time to explosion as a function of temperature, and is applicable to informing time-to-explosion decisions since the ODTX sample diameter is very close to the explosive charge thickness in typical perforating systems. However, the ODTX test does not provide any information on explosive performance or handling safety.

Opportunities for Improvement

It is apparent that there is a need for a better modeling tool to evaluate the performance-safety compromise during perforating system selection. This tool should separately assess performance and safety limits and be user friendly. This calculator would be a substantial improvement for the perforating industry and would allow for the best selection of an explosive under the unique conditions of each well. Well site personnel could input simple or complex time-temperature scenarios into the calculator in order to select the safest and best performing explosives for the specific application. In scenarios such as the example described above, where the e-line perforating gun would only spend a brief period in a very hot zone (i.e. the reservoir section), one could analytically assess the impact of that hot-zone on the explosive stability. In the event of a misrun, personnel at the well site could input the thermal history of the gun during the misrun and calculate the real-time state of the explosive in order to establish whether it is safe to pull up to surface or best left in the well to cool off.

The ideal tool would provide highly accurate thermal stability information for existing and new perforating systems with no additional future testing. This ideal tool is probably not possible, cost prohibitive, and certainly not practical. Therefore, there is a compromise between cost, testing accuracy and on-going maintenance of the tool required as technology advances. There is a need to establish a foundation of accurate, relevant thermal stability data and develop a tool to utilize the data as a foundation for the industry. New testing will be required as technology advances. Therefore, it is also necessary that this work establish practical test methods to evaluate new perforating systems and gather thermal stability data which can be used by the new tool. Without this path forward, the new tool may quickly become outdated.

This type of tool can take several forms, each with their own benefits and drawbacks. Predictive tools may be built numerically based on thermo-chemical material models combined with heat transport models and system geometry, utilize empirical data or combine both material models and empirical data. A series of preliminary tests are recommended to better

understand the current gaps in thermal stability knowledge and ultimately provide direction on the best approach for developing a predictive tool. The preliminary tests should evaluate perforating systems against existing time temperature curves as a baseline for the current accuracy of the curves. Additionally, ODTX experiments should be conducted to determine the explosive properties (i.e. particle size, binders, purity, etc.) which most significantly influence thermal stability. The main advantage of a material model based tool is its ability to predict across a broad range of thermal exposure temperatures, including very unique thermal exposure cycles. This type of tool would be limited to the specific explosive formulations tested; there are many explosive formulations in a single perforating system when the charge, detonating cord, detonators, boosters and other parts of the explosive train are considered. Therefore, an accurate and complete model requires extensive testing to qualify all explosive components within the system. This approach may also be limited by the willingness of manufacturers to release proprietary information on explosive formulations and component geometries necessary for model accuracy. Additionally, performance would need to be addressed in a separate series of tests and full scale tests would be required to validate the model.

The most rigorous method for the thermal explosion, thermal pressurization and performance assessment needed to develop this type of numerical model is to characterize thermal decomposition parameters with lab-scale experiments and assess performance in full scale perforating system tests. Then, the test results could be used to develop models which must be validated against full scale perforating system experiments to determine the accuracy of the predicted outcomes. While this effort requires an investment in capability development, it minimizes the frequency and extent of future testing as new perforating systems are developed. Simple models with limited parameters can be developed at a modest cost and will provide a ‘back of the envelope’ estimate; improved fidelity comes with further investment in material characterization and model improvements. Safe-handling guidelines after thermal exposure can be developed by performing small-scale safety tests on thermally damaged explosives as needed, although some of this work is already being conducted in the API RP 67 revision.

The key to an accurate numerical model is good, experimentally derived material properties. Because each explosive or explosive formulation must be characterized, the experiments must be easy and affordable. There are several standard laboratory tests which can be combined to characterize explosive formulations. Thermal transport properties (e.g. thermal conductivity, heat capacity, and thermal expansion) can be measured with commercial instruments such as Laser-flash diffusivity, differential scanning calorimetry (DSC), and thermal mechanical analyzer (TMA). [19] Chemical kinetic experiments using DSC are a simple, yet robust, method for developing chemical decomposition models.[20-25] High-pressure DSC experiments allow for pressure dependent chemical decomposition models.[23,26] Thermal-gravimetric analysis (TGA) experiments are easy to employ and provide good data to develop gas-pressurization models. All of these models can, and should, be tested and refined using larger scale thermal explosion or thermal-pressurization experiments. ODTX is a strong candidate experiment because it is simple to execute and simple to model.[10,11,15] The added bonus of ODTX is the coincident in size between the explosive in a shaped charge and the diameter of the ODTX sphere. Recent inclusion of pressure measurements in the ODTX, make it possible to derive robust gas-pressure models. The ampoule tests could also provide data for a gas-pressure model. These models should be validated against larger scale experiments in which a full perforating system is heated under controlled conditions until it explodes.[27-30] The advantage of doing testing on a full perforating systems is that secondary phenomena can also be monitored, for example delamination of parts, liner damage, etc. This experimental, modeling, and validation approach has been applied in other industries with good success. [15,21,22,30-35]

If a thermal decomposition model is well parameterized, it could serve as an excellent foundation for a performance model. In the simplest scenario, one could thermally degrade a charge to varying degrees and execute performance experiments. By doing this experiment at different levels of performance degradation and mapping that degradation with a thermal decomposition model, one could derive a correlation curve between thermal degradation and performance.[36] A similar approach could be used to correlate safe handling of the explosive with varying degrees of thermal degradation.[13,37]

Alternately, or in conjunction, empirical test data could be collected on the entire perforating system, bringing several key advantages. By evaluating thermal stability of the system, interdependencies of components within the system are captured, which is important because system components may exhibit higher thermal stability limits when tested independently. The results would also be applicable across a broad range of explosive formulations since many formulations present in perforating system components would be evaluated in a single test. Furthermore, thermal stability and performance degradation could be assessed in the same test series. The main disadvantage of an empirically derived tool comes from uncertainty in the loss of accuracy when extrapolating the test data to thermal exposure cycles unlike the tested cycles. For example, will the empirical tool capture effects such as holding the perforating system at a lower elevated temperature prior to introducing the perforating system to the final exposure temperature? Therefore, the test program would need to include a mechanism for characterizing the thermal exposure history of the perforating system to maintain accuracy.

Regardless of the approach taken to develop the predictive tool, full-scale perforating system tests will be necessary. The API RP 19B Section 3 test is recommended to be used as a foundation for performance-based experiments and validation of

thermal-explosion and thermal-pressurization models. For this work, the Section 3 test method should be revised to include a range of temperatures and exposure times so that the results can be used to accurately predict performance losses at untested conditions. The perforating systems should be fired at temperature, and the thermal cycling method of API RP 19B Section 3 should not be used in this work for reasons previously described. Additional revisions to the test methodology will likely be necessary to include methods for assessing temperatures within the perforating gun and instrumentation for measuring pressurization. For validation purposes, experiments should be conducted across a broad range of perforating system sizes to understand model accuracy. Subsequently, the modified Section 3 test for this work should be simplified and incorporated into an updated API RP19B Section 3 procedure to allow for the addition of new systems into the model as technology progresses.

Finally, development of the predictive tool may identify other issues which need to be addressed within the industry to maintain prediction accuracy.For instance, the purity of the explosive may need to meet prescribed and set standards. Explosive crystal size, morphology, and contaminates can all affect the safety and performance of the explosive, although the severity of the affects are under investigation as part of this research. Nevertheless, standard acceptance criteria for thermal safety and performance may be required; otherwise, each lot of material may have to go through the full characterization process described above before it can be modeled in the calculator. The binders and explosive density are also important variables in the performance and safety. Explosive lifetimes and chemical compatibility with other materials in the gun may also need to be assessed.

Conclusions

In summary, the thermal stability of explosives used in perforating systems is important for proper selection. Over exposure to temperature can lead to thermal decomposition of the explosive, effecting both operational safety and performance. Understanding thermal stability of oilfield explosives and perforating systems is necessary to understand and predict the system response to temperature over time. The key areas that need to be addressed include the potential for thermal runaway, pressure buildup as a result of thermal decomposition, safe handling for overexposed explosives and performance losses from degradation due to thermal decomposition.

Explosive selection for perforating jobs is ultimately a tradeoff between performance and safety. Existing time-temperature curves have provided useful guidance on explosive selection for decades. However, because of shortcomings in these prevailing curves, the industry stands to benefit with an improved explosive selection tool. This improved tool should be developed from new test data more directly related to the specific explosive powders and perforating systems utilized in the perforating industry.

Several key issues have been identified with the prevailing time-temperature curves:

- The curves do not distinguish between safety and performance outcomes, nor do the curves establish the interdependencies between the two.
- Test materials were likely high purity, lab-grade explosive powders which differ from oilfield explosives in purity, particle size and additives and are anticipated to have different outcomes
- Test materials were not likely configured with the same density, confinement and headspace common in shaped charges and other components in the explosive train in perforating systems.
- The curves appear to be extrapolated to as much as 1000 hours from ODTX data tested between 60 seconds and 24 hours, resulting in a loss of accuracy at an undetermined level.

Therefore, there is an important need to better qualify explosives for the perforating industry. However, various existing methods fall short.

- Vacuum Thermal Stability (VTS) – The VTS test method inhibits autocatalytic chemistry and promotes unrealistic thermal decomposition, both in opposition to decomposition mechanisms in perforating systems.
- Ampoule Testing – Ampoule testing offers an improvement over VTS testing, is best suited for predicting pressurization as a function of time and temperature but does not address thermal runaway.
- One-Dimensional Time to eXplosion (ODTX) – ODTX is well suited for assessing critical temperature and the potential for thermal runaway and benefits from a test setup which is comparable to shaped charges in perforating systems, but does not assess performance.
- API RP 19B Section 3 – The Section 3 testing aims to evaluate perforating system performance under the influence of temperature but is only reliable for predicting performance at the tested conditions.

Consequently, the recommended path forward combines the best existing experimental methods with the development of new

test or revised methods to establish safety and performance outcomes of thermally exposed explosives. First, preliminary tests are recommended to determine the accuracy of existing time-temperature curves as well as identify the key explosive properties which most significantly influence thermal stability. These results will then be used to scope future work and identify the best approach for developing a predictive tool. Once complete, the industry will be provided with the tool as an aid for explosive selection and evaluating the tradeoffs between safety and performance. Finally, recommendations will be made to update API RP67 with safe handling guidelines and API RP 19B Section 3 with an improved test methodology capable of feeding data into the modeling tool.

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