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Title: LANL Skid Testing Summary

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LANL Skid Testing Summary

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Background to LANL skid test research

- Motivation
  - Scatter and outliers in existing skid test data;
  - Lack of physical basis for existing working theories of frictionally-induced ignition;
  - Observation of opportunities for design improvements in skid test methodology.
- Goals
  - Develop a fundamental understanding of frictionally-induced ignition mechanisms involving glancing impacts of PBX charges on various surfaces, and confirm that these mechanisms are fully consistent with classical friction theory;
  - Explain the unsatisfactory scatter in existing data;
  - Develop a more fundamentally sound methodology for testing, incorporating better control and diagnostics;
  - Design and test a replacement for the existing LANL/Pantex skid test;
  - Use a fully quantitative approach to inform the safety strategy for consolidated charge handling at LANL, Pantex and elsewhere.

Early accidents

- PBXs exhibit a new type of accidental ignition hazard:
- Accident 1 – AWE 1959
  - 30 lb hemisphere of EDC–6 (98% HMX, 2% terylene fiber) fell 18 inches off electric cart onto concrete roadway, bounced out of cardboard box, and apparently detonated.
  - Exact mechanism unknown.
  - 2 killed, 1 injured.
- Accident 2 – LANL 1959
  - 7.5 lb cylinder of PBX 9404 (94% HMX, 3% NC, 3% CEF) detonated during drilling operation.
  - Exact mechanism unknown.
  - 2 killed
- Accident 3 – LANL 1959
  - 104 lb hemisphere of PBX 9404 detonated, it is believed while being placed on burning ground for disposal.
  - Exact mechanism unknown.
  - 4 killed.

Non-shock ignition of explosives

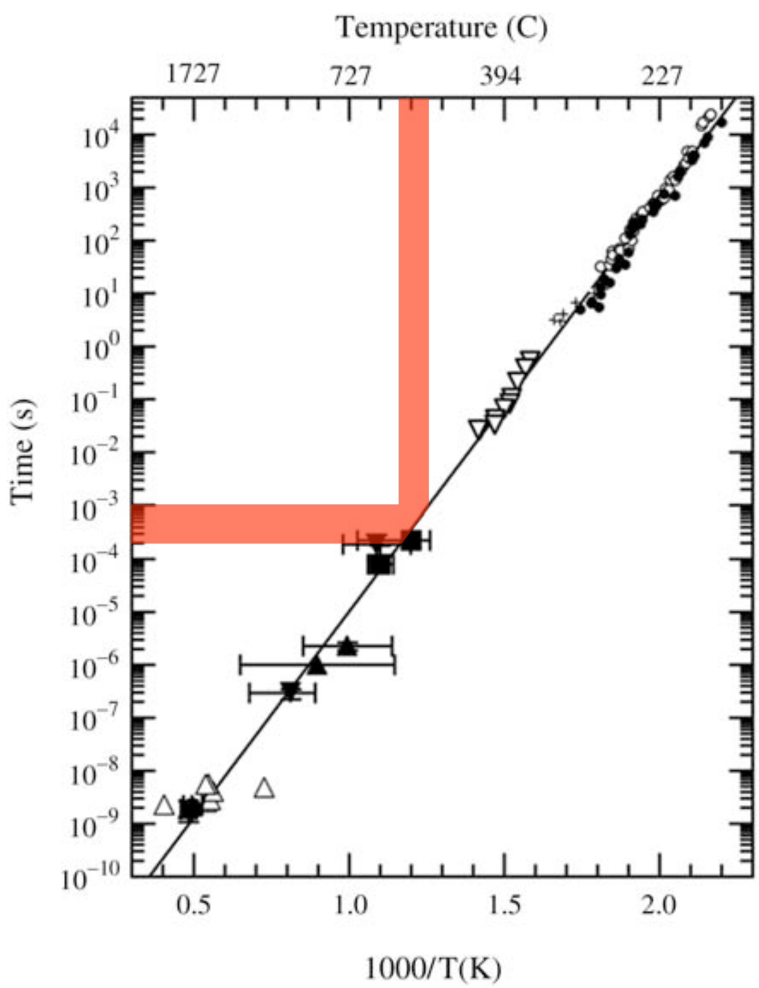
- Explosives comprise energetically metastable molecules that are separated from their lower-energy decomposition products by an activation energy barrier that can only be overcome by heating (note that this is even true of detonation, where the shock rapidly heats the explosive).
- At ambient temperature this barrier is effectively impassable, and the decomposition rate is zero.
- Above a certain critical temperature the vibrational energy of the molecules allows the barrier to be overcome and decomposition occurs, at a rate exponentially dependent on temperature.
- The decomposition steps are typically:
  - Rate-limiting, solid-state (no gas produced), endothermic, bond breaking;
  - Exothermic intermediate species production;
  - Fast, highly exothermic gas-phase recombination reactions (aka flames) that liberate the bulk of the energy.
- In this sequence, we refer to the onset of the gas-phase reactions as ignition, and we know that the time to reach ignition for many explosives (including HMX) is a simple exponential function of inverse temperature (1/T).

Hot spot vs. bulk ignition

- If an explosive is bulk heated, then the simple relationships between temperature and reaction rate govern the response, since energy losses by thermal and mass transport are negligible.
- However, if the heating is very localized, then there are competing processes:
  - Heating due to the original heat source;
  - Heating due to exothermic decomposition;
  - Heat loss by thermal transport (conduction) and mass transport (advection).
- If heating exceeds heat loss, then the hot spot is supercritical, and will grow to ignition in a time dependent on its size and temperature (hotter and larger ignite faster), otherwise it will extinguish.
- This energy balance is commonly referred to as the Frank-Kamenetskii relationship.
- Ignition via hot spots requires higher temperatures than ignition from bulk heating.
- Growth of hotspots to ignition does not mean that the ignition will necessarily propagate – it can still fail.

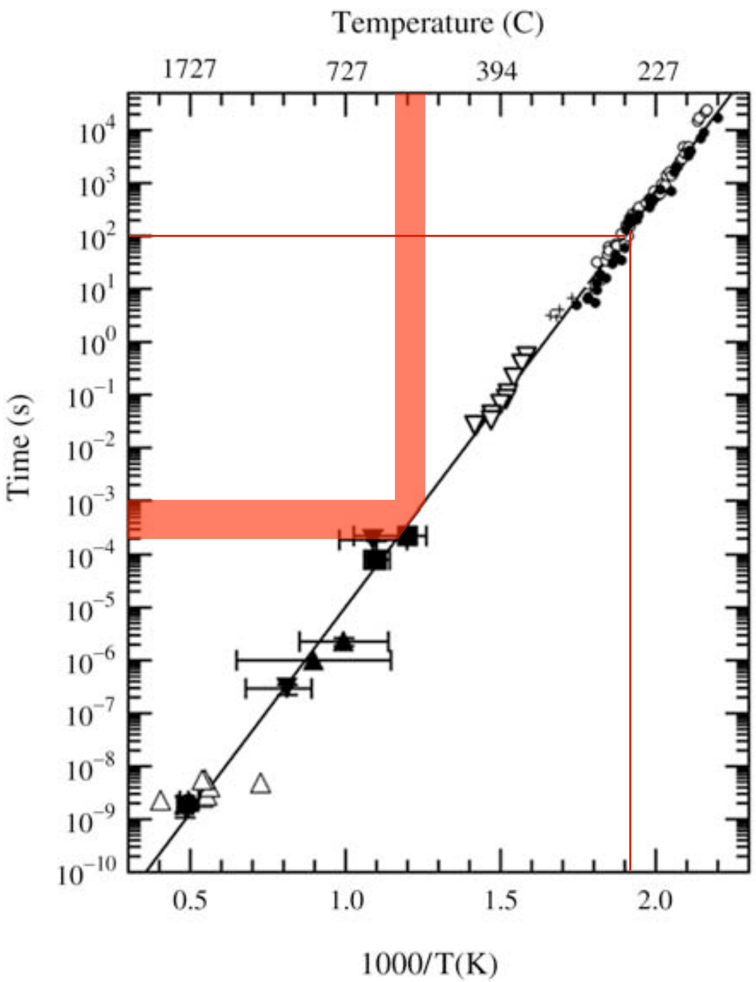
Ignition during an impact event

- Ignition of an HMX-based PBX on the timescale of an impact event (~ 1 ms) requires temperatures of the order of 500 - 600 ˚C;
- PBXs are weak solids – deforming them does not deposit much energy. Note that for bullet impact on bare PBX 9501, for example, the threshold impact velocity for onset of reaction is greater than 100 m s^{-1}, which produces strain rates far higher than are encountered in a drop test;
- Prompt ignition at high strain rates:
  - pinch processes (e.g. Steven Test, drop weight);
  - pressure / shear;
- or other sources of heat:
  - hot casing fragments;
  - frictional heating.



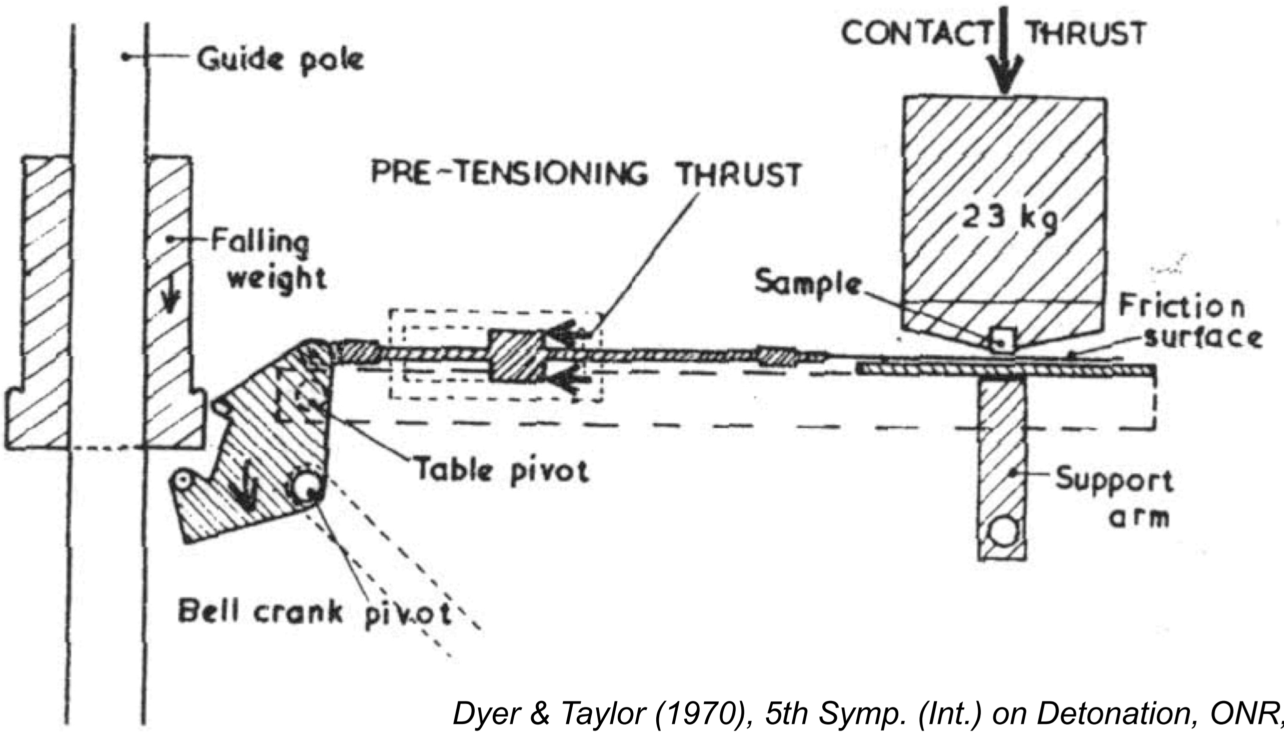
Other temperature considerations

- Bowden & Yoffe, (1950, 1952) demonstrated conclusively that in frictional interactions between two surfaces, the highest temperatures achieved are limited by the lower of the melting points of those two surfaces:
  - Melting of a surface leads to a lubricating layer and elimination of the energy deposition mechanism
- All the constituents of PBX 9501 have low melting points (< 260 ˚C) relative to the prompt ignition temperature of HMX;
- At these temperatures, even in bulk material, ignition would take 10s of seconds;
- **Significance: direct friction is incapable of heating HMX-based PBXs to ignition**.



Grit with pressed and cast explosives

Dyer & Taylor (1970) showed that the frictional interaction between a pressed or cast explosive and a rough surface is ineffective at producing ignition, but that the introduction of grit with a high melting point (relative to the ignition temperature of the explosive) does lead to ignition.



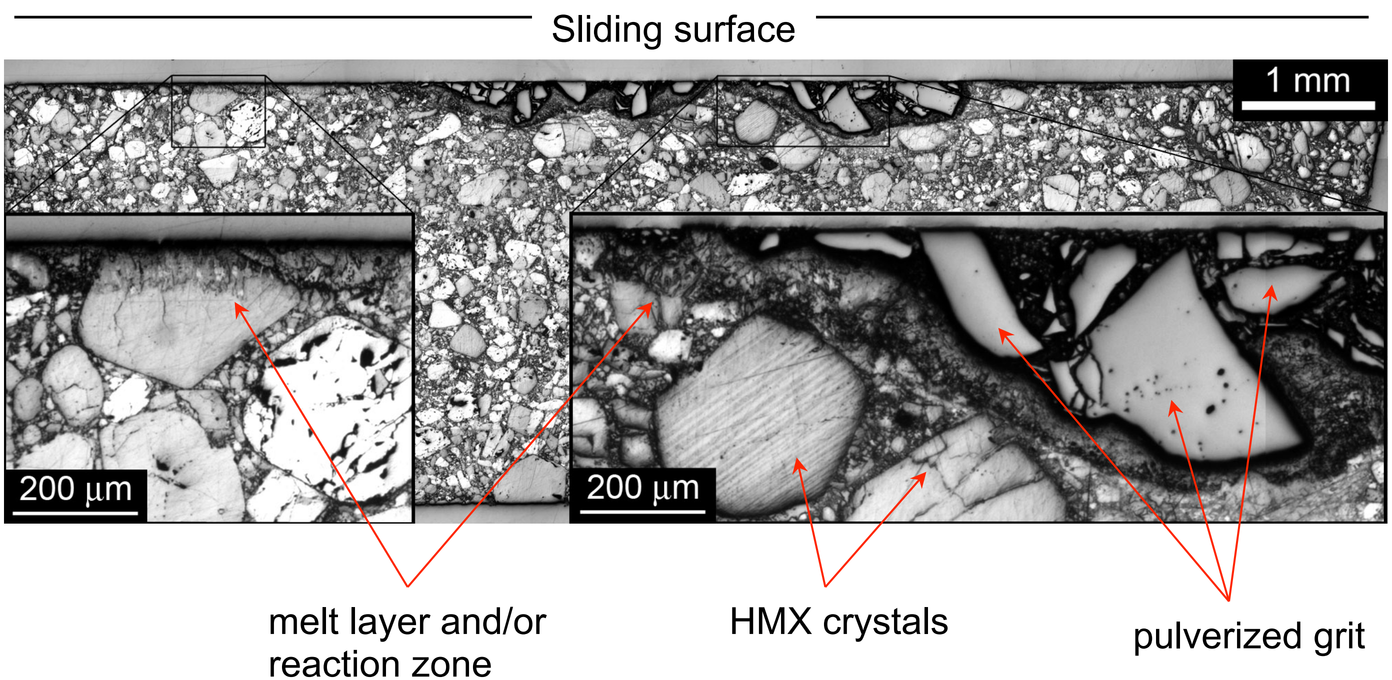
Dyer & Taylor (1970), 5th Symp. (Int.) on Detonation, ONR, pp291–300

Heating HE by grit – substrate frictional interaction

The primary hazard occurs when grit, trapped between the HE and a harder, high-melting-point substrate, embeds in the HE and is dragged across the substrate surface.

Tests using real grit, in the form of sand, have shown that the particles tumble, fracture and embed, followed by frictional heating leading to melting of the surrounding matrix.

These grit particles function as classical hot spots within the HE and, being limited only by the melting point of the sand or substrate, can be hot enough to cause prompt ignition.



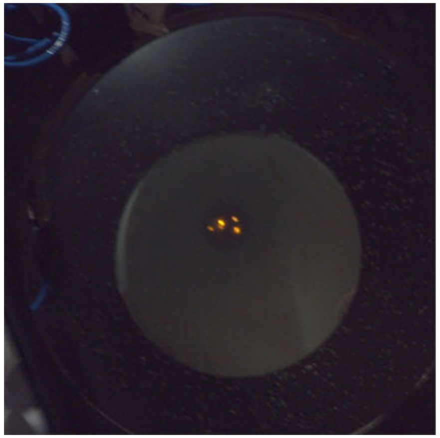
Propagation of deflagration

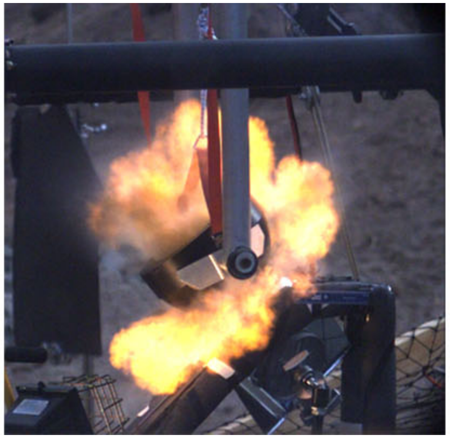
- Ignition is only the first step in a sequence that may result in HEVR;
- Unconfined, even damaged PBX 9501 burns slowly;
- If ignition occurs in HMX-based PBXs, the deflagration will propagate unless extinguished by depressurization;
- The deflagration rate depends, approximately linearly, on pressure and burning surface area;
- Although these relationships are both linear, in a confined explosive charge the combination of self-pressurization due to hot, gaseous reaction products and increasing accessible surface area due to pressurization-induced cracking can lead to a rapidly increasing (non-linear) reaction rate;
- This leads to a race between reaction build up and depressurization due to charge disintegration, but these are the conditions that permit the transition to HEVR and, potentially, deflagration-to-detonation transition (DDT);
- For an unconfined explosive charge, such as a bare hemi, confinement may be provided in two ways:
  - The initial, brief confinement at the impact surface contact area;
  - Inertial confinement of the explosive mass if the deflagration penetrates into the bulk via cracks.
- Loss of confinement may lead to depressurization-induced extinction.

Test methodologies

- Traditional skid testing appears to have evolved independently of existing scientific understanding of the underlying processes, and been based on a more empirical, engineering approach to the problem;
- The heating mechanism was assumed to be friction between the explosive and the impacted surface;
- The relevant variables were assumed to be:
  - Impact angle;
  - Impact speed;
  - Target roughness;
  - Target thermal diffusivity;
  - Target specific heat capacity.
- The dominant mechanism – loose grit – was completely overlooked;
- Even when grit bonded to steel surfaces was used, it was not realized that the outcome was determined by whether any of the grit particles became dislodged, embedded in the explosive, and were dragged across the surface.
- No distinction was made between ignition and propagation – the tests were insufficiently sensitive to detect quenched ignition;
- Test protocols did not result in well-controlled impacts.

Level of reaction





VISIBLE IGNITION SITES

Isolated ignition sites that do not coalesce and extinguish when the charge bounces

FLAME GROWTH INTO CRACKS

Multiple ignition sites that coalesce, with flame spread into cracks in the charge.

The ignition quenches before extensive propagation due to bounce or intersection of the cracks with the outside of the charge.

CRACK PRESSURIZATION

Flame spread into cracks causes sufficient pressurization to fragment the charge, leading to combustion of rubbleized explosive.

This looks more significant than it is – only a few grams of explosive are consumed, with the remaining mass unreacted.

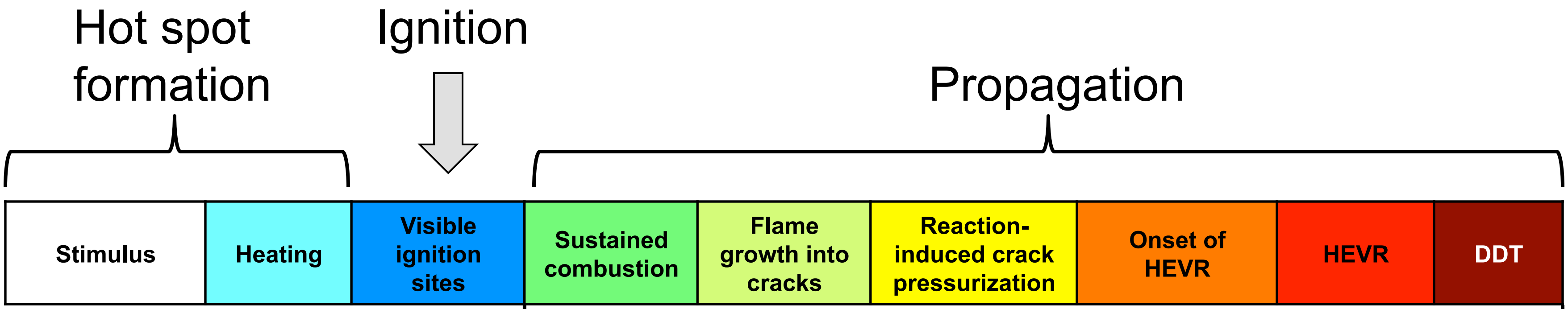
HEVR

Flame spread into cracks leads to rapid pressurization and reaction buildup, with the inertial confinement of the charge mass sufficient to permit transition to HEVR.

Most, or all, of the explosive is consumed. Transition to detonation may or may not occur, but local effects are extremely severe either way.

This is just a representative image – we have not observed HEVR in our tests.

Comparison of the old LANL/Pantex skid test with level of reaction



Reaction level	0	1	2	3	4	5	6
Description	No reaction	Scorch marks on HE	Puff of smoke, no flame, cracks in HE	Mild violence, flame, cracks in HE, little HE consumed	Medium violence, flame, major part of HE consumed	Violent burn, all HE consumed	DDT

HEVR

Frictional processes: what we know

- Glancing impacts (skid) of PBXs ***do*** present a real hazard:
  - Past accidents with PBXs where drops led to HEVR or detonation;
  - Experimental testing over the past 40 years has produced documented HEVR events from drop tests.
- Direct frictional heating of PBXs ***cannot*** lead to ignition in a skid event:
  - Established frictional theory, confirmed many times by experiment, tells us that friction will not heat a PBX to a Temperature greater than its melting point (150˚C – 250˚C for the components of PBX 9501), no matter how rough the impact surface;
  - The duration of surface confinement in a skid event (contact time before bounce) is approximately 1 ms;
  - Extensive data and theory on time to ignition indicate that ***a temperature of over 600˚C is required to achieve ignition on that timescale, even for bulk heating;***
  - Carefully conducted experiments involving ***skid tests on clean surfaces demonstrate no ignition for any drop heights tested***.
- Other impact processes in skid tests do not deposit enough energy to cause ignition:
  - Impact tests on PBXs demonstrate that impact velocities of over 150 ms^{-1}, which access high-strain-rate visco-plastic processes, are required to get ignition – velocities much greater than achievable in a drop event;
- The frictional interaction of grit particles (or other high-melting point fragments) that embed in the explosive and are dragged across a high-melting point surface can produce enough heat to produce supercritical hotspots in the explosive:
  - Both modeling and experimental data, from as far back as the 1950s, shows this phenomenology;
  - Recent highly controlled experiments with the LANL skid test pendulum has directly observed ignition by this process.

What we know, continued

- The ignition sites that we observe generally quench before significant reaction spread:
  - The deflagration process is quenched at the surface when the charge bounces, and may be quenched in the cracks when those cracks intersect the unconfined surface of the charge;
  - We observe both these quenching mechanisms directly in the skid tests.
- Previous testing methodologies have produced inconsistent results, including occasional HEVR events from moderate drop heights, due to a lack of understanding of the ignition mechanism (grit) and failure to control the presence or absence of that mechanism:
  - Testing focused on the wrong parameters:
  - Even when grit bonded to steel surfaces was used, it was not realized that the outcome was determined by whether any of the grit particles became dislodged, embedded in the explosive, and were dragged across the surface.
- The ignition process is deterministic – we can predict it – but the reaction growth process is stochastic – and we presently cannot accurately predict it.

What we don't know

- The observed ignitions are the onset of gas-phase reactions (the flames are visible) – they do not indicate HEVR and we currently cannot estimate the probability of growth of ignition to HEVR:
  - We observe ignition sites, some flame spread into cracks and, under some conditions (especially drops from higher levels), small fireballs in which a small amount (less than a few grams) of highly fragmented explosive is consumed;
  - We have observed that the degree of reaction spread before quenching generally increases with drop height (with some caveats);
  - We observe the quenching mechanisms (depressurization) discussed earlier;
  - We have not observed HEVR for the configurations and drop heights tested (up to 12 ft), and cannot currently estimate probability from the available test data.
- HEVR requires both ignition and growth, and even though the ignition process itself is deterministic, we have insufficient data on handling conditions to estimate the probability of a dropped charge hitting grit:
  - For a given drop event, the probability is a function of the grit density on the impact surface.

What we suspect

- We are working in the low-probability tail of of several statistical distributions:
  - There is a low probability of a charge being dropped;
  - There is a low probability of the dropped charge hitting a high-melting-point surface in the presence of grit – thus producing ignition sites;
  - There is a low probability of such ignition sites, if the occur, growing to HEVR before quenching occurs.
- The reaction growth process is favored by certain parameters:
  - Charge brittleness (propensity to crack on impact and pressurization), which accounts for the much better performance of PBX 9501 than legacy formulations such as PBX 9404;
  - Drop height – higher drops cause more cracking, which is the route by which the deflagration gets into the bulk of the charge, permitting inertial confinement to take over. Even though the same cracks provide a quenching route, meaning we have a competition, reaction growth likely wins;
  - Low surface thermal conductivity / diffusivity – minimizes thermal transport away from the deflagrating material.

What this means

- Our current knowledge supports implementation of controls that are consistent with DOE-STD-1212-2012 requirements:
  - We now understand that the mechanism of hotspot and ignition production in drop events depends on both a high-melting point surface and grit contamination*;
  - Simple mitigation of either of these factors makes the likelihood of even an ignition event, let alone an HEVR, vanishingly small.
  - A combination of low-melting-point floors (e.g. rubber mats) and low-melting-point work surface (including the use of aluminum, where several mechanical properties combine to mitigate ignition), along with housekeeping (wiping of surfaces) is highly effective at mitigating the potential for this mechanism to become operative.
- Our work to date has enlightened our understanding:
  - Our improved tests demonstrate that ignition sites can arise at drop heights much lower than that understood in previous tests, where the diagnostics were inadequate to detect anything less than significant reaction;
  - While our current safety envelope is adequate, there is not a fully quantified separation between the outcomes of quenched ignition and HEVR: more work is needed to establish this boundary, ***quantitatively***.

* except in the case of very high grit particle density, when grit-on-grit interactions can cause heating.

Energy criterion

- The current use of a simple energy criterion to define a safe operating envelope may, ultimately, need to be rethought:
  - explosive response is rarely determined by total energy;
  - shock response is governed by a function of the form $p^2\tau$;
  - non-shock ignition is more accurately determined by power per unit volume;
- 12 ft-lbs is very conservative in the absence of rapid energy localization.
- 12 ft-lbs is enough to produce a 2 mm diameter hot spot at 650° C if delivered quickly compared to characteristic thermal transport times.
- The minimum critical Frank-Kamenetskii energy is too low to be a useful criterion.
- Our primary mitigation is not the total energy, but control of how we partition it in time and space.

Conclusions

- Our improved understanding of the processes occurring during complex drop / skid events has explained the previously observed scatter in skid and drop test data, and provided new insights into effective mitigation strategies. However, it has been perceived to undermine our current safety assumptions, which is inaccurate.
- We have no reason to believe that our safety margin from HEVR (the event of concern) is any different to that previously assumed – we just have a much better experimental and theoretical basis by which to measure it more accurately.
- Until this work is complete or, at least, more mature, we cannot draw any conclusions on whether we are more or less safe than we thought, but we know that use of cushioned surfaces, along with sensible housekeeping, mitigates the potential activation of the skid-grit mechanism.

References

This material is a summary of the following LANL technical report:

Report #: LA-UR-13-25703

www.osti.gov/servlets/purl/1088887/