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Untangling the Combustion Continuum: From Burning to Detonation and Its Implications for EOD

By Roland Alford

Why Definitions Matter

Explosives engineers pride themselves on precision. Yet, when it comes to the vocabulary we use to describe the behaviour of energetic materials, there has long been ambiguity. Terms such as burning, deflagration, detonation, low-order, and high-order are often applied interchangeably or inconsistently. This lack of clarity may seem academic, but for practitioners working in ordnance disposal, testing, or accident investigation, it carries real-world consequences.

A new conceptual framework — the *Combustion Continuum* — has been developed to address this gap. By treating burning, deflagration, and detonation as points on a spectrum of chemical reaction rates, and by defining the transition points in clear physical terms, the continuum provides a robust foundation for classification. When extended to explosive articles (munitions), it offers a practical way to distinguish between low-order and high-order responses. This article brings together the latest thinking on the subject and explores its implications for our profession.

From Berthelot to the Present: An Old Debate

The distinction between different modes of explosive reaction has been debated since the late 19th century. Berthelot wrote of the “multiplicity of the modes of combustion,” observing that the same material could decompose without flame, burn briskly, or explode. For over a century, literature has offered competing definitions, often imprecise, leaving practitioners with rules of thumb rather than observable criteria.

In military circles, the phrases 'high-order' and 'low-order' entered use to describe whether a munition functioned as designed (full detonation) or not. Unfortunately, these descriptors were applied interchangeably to the explosive substance itself, leading to decades of conflation. Even in technical literature, reports of 'low-order detonation' or 'violent deflagration' appear, each meaning something slightly different to the author. The result is a body of literature filled with overlap and ambiguity. Against this backdrop, the *Combustion Continuum* represents an attempt to provide a rigorous, physically grounded lexicon.

Foundations of Explosive Reactions

Energetic materials release chemical potential energy through rapid oxidation or decomposition. Unlike conventional fuels, explosives contain within their molecules both the fuel and the oxidiser required for combustion. This internal balance of oxidising and reducing groups determines the reaction pathway and products.

Whether an explosive burns, deflagrates, or detonates depends not primarily on chemistry but on the velocity of the reaction front. This velocity, in turn, depends upon confinement, density, particle size, and initiation energy. An understanding of these fundamentals is vital for engineers

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working across the spectrum of explosive applications—from propellant grain design to demolition blasting.

For example, black powder burns in the open but, when confined, produces a violent crack or explosion — yet never detonates. How do we know if it burned, or deflagrated? Until recently, there was no definitive answer. The *Combustion Continuum* addresses this head-on.

The Combustion Continuum: A Unifying Framework

At its core, the continuum recognises that all energetic reactions are oxidation processes releasing heat, light, and gas along an axis of increasing speed of reaction:

- Burning: a relatively slow surface reaction. Gases escape freely, and there is no shock wave. Examples include open burning of propellant grains or flares.
- Deflagration: a subsonic but explosive reaction. Gases are produced faster than they can be vented, creating overpressure and an atmospheric shock wave. Examples include confined black powder or rapid propellant combustion.
- Detonation: a supersonic reaction front sustained by a shock wave within the material. Pressures reach the gigapascal scale, and the velocity of detonation is constant for a given explosive.

The significance of the Continuum is that it defines the transition points clearly:
- Burning → Deflagration: occurs when sonic choking of gases causes the formation of a shock wave in air.
- Deflagration → Detonation: occurs when the subsonic flame front accelerates and shocks-up into a self-sustaining detonation wave.

This framework allows engineers to categorize reactions not by subjective impressions of speed or violence, but by measurable physical phenomena, finally allowing them to say, with confidence, whether a reaction was simply combustion, a deflagration, or a detonation.

Deflagration Redefined

The new definition proposed by the is worth repeating in full:

Deflagration is an exothermic chemical reaction of a confined pyrotechnic, explosive or propellant, proceeding at a rate below the velocity of detonation of the material, the gas products of which produce an atmospheric shock wave as it explodes. (Alford et al. 2024)

This definition deliberately ties deflagration to the observable phenomenon of an explosion (or loud bang). It avoids vague terms such as “rapid burning” and makes the distinction measurable and unambiguous.

Deflagration in Engineering Context

Deflagration is often oversimplified as 'rapid burning,' but this masks its true character. In deflagration, propagation occurs through heat transfer, mass diffusion, and chemical decomposition. The process is pressure-dependent: higher confinement increases the rate, and at certain thresholds, deflagration may transition to detonation (DDT). Pressure-time traces of deflagration show a gradual rise compared to the near-vertical spike of detonation, but they still

indicate significant overpressure capable of rupturing vessels and structures.

It represents a credible hazard regime distinct from both benign burning and catastrophic detonation, and its correct identification has direct implications for design, storage, and risk assessment.

Detonation and the Deflagration-to-Detonation Transition

Detonation is easier to define and is well understood. It is a supersonic process in which a shock wave compresses the unreacted explosive, causing decomposition immediately behind the front. Unlike deflagration, which can vary in speed, detonation occurs at a constant velocity for a given explosive under defined conditions.

The deflagration-to-detonation transition (DDT) remains of critical importance in safety and munitions design. Confinement plays a central role. A burning explosive under confinement can accelerate, compressing unreacted explosive ahead of it until conditions allow detonation. Understanding and preventing unintended DDT is at the heart of insensitive munitions research and is directly relevant to accident scenarios.

Extending the Continuum to Explosive Articles

The *Combustion Continuum* applies to explosive substances. However, engineers often deal with explosive articles—complete devices that include explosive fill, casing, fuze, and other components. The behaviour of the article is the result of both the chemical reaction of the explosive and the mechanical properties of the casing.

When the explosive detonates, the munition functions largely as designed. The casing fragments into high-velocity pieces following Gurney's classical model. This is termed a high-order event. Conversely, when the explosive deflagrates, the casing is simply pressurised until it fails. The munition bursts into a few large, slow-moving fragments, often with a modest fireball. This is a low-order event.

To extend the framework, three terms are introduced:
- Burn-out: the explosive fill burns without violent rupture of the casing.
- Low-order: the explosive deflagrates, pressurising the casing until it ruptures less violently than detonation.
- High-order: the explosive detonates, fragmenting the casing violently as intended by design.

The critical clarification is that deflagration is a chemical process of the explosive substance, whereas low-order is the physical outcome observed in the article. The two are causally related but not identical.

Why This Matters for EOD

For EOD operators, distinguishing between high-order and low-order outcomes is not academic. The goal of many disposal techniques is to avoid a full detonation while still neutralising the hazard. Whether a munition has low-ordered or high-ordered determines the safety of the operation, the risk to nearby infrastructure, and the environmental consequences.

Historically, reporting has been inconsistent. Operators might describe a result as a “violent deflagration,” a “low-order detonation,” or simply a “misfire.” Without a common lexicon, lessons are easily lost, and results are difficult to compare.

Observable Evidence: Reading the Forensics

In controlled laboratory settings, high-speed cameras and pressure sensors can record every microsecond of a reaction. In the field, EOD operators rarely enjoy such luxury. Instead, they must “read” the aftermath:

• High-order events leave fine, widely scattered fragments, large craters, and often extensive collateral damage.
• Low-order events leave the casing in a few large pieces, sometimes even recognisable halves, with far less damage to surroundings.
• Noise and blast overpressure differ by an order of magnitude. Underwater studies of sea mine disposal, for example, found peak pressures from high-orders were typically 20 dB greater than equivalent low-orders.

Such physical evidence, properly documented, provides the most reliable record of what occurred if operators know what to look for and how to “read” the signs after the event.

The continuum framework, when combined with clear definitions for low-order and high-order, provides a way out of this confusion. It offers EOD practitioners observable criteria: fragment size, casing breakup, crater formation, and noise levels can all be used to distinguish categories reliably. This distinction also serves to guide the operator in the selection of the most appropriate tool and technique to apply.

Without a clear understanding, the desire to make a “big bang” is not tempered by a clear understanding of the difference between a low-order and a high-order in terms of potential environmental effects and the likelihood of collateral damage. Examples in recent years include an EOD event in Munich in which a British bomb was deliberately detonated. Inadequate mitigation was used and this led to significant structural damage and fires in a radius of over 300m. Closer to home, a WWII German bomb was high-ordered in Exeter, again causing significant damage to property. Had the operators in both incidents had a more informed understanding of the difference between a low-order and a high-order, they might have made different choices on how to deal with the bombs.

Reassessing Existing Scales

Existing military and NATO scales for categorising explosive reactions often blur the line between substance and article. For example, a “burn to detonation” might be listed under burning, even though it is in fact a partial detonation. Similarly, terms like “violent deflagration” create ambiguity by conflating chemical speed with mechanical violence. This not only confuses the picture but also indicates that the authors of the various scales were, themselves, unclear on the distinction. This is not necessarily a criticism but is an artefact of the historical lack of clarity that has been applied and taught within the community.

By contrast, the proposed combined scale based on the *Combustion Continuum*, aligns *substance reactions* (burning, deflagration, detonation) with *article responses* (burn-out, low-

order, high-order). This dual-level framework preserves clarity while remaining usable for practitioners.

Implications for Insensitive Munitions and UXO Clearance

The implications of adopting the continuum go beyond semantics:

- Insensitive Munitions (IM): Understanding and preventing unintended DDT is central to IM design. The continuum helps articulate why certain tests (such as slow cook-off) produce low-order responses rather than full detonation.
- Underwater UXO clearance: Deflagration-based techniques are increasingly promoted to reduce acoustic impact on marine life. Studies confirm that low-order disposal methods produce dramatically lower sound pressure levels compared with high-order detonations.
- Training and Reporting: Clear terminology allows EOD schools and operators to train, report, and share experience consistently, reducing the risk of misinterpretation across organisations and nations.

A Template for Clarity

The value of the *Combustion Continuum* lies in its simplicity. By rooting definitions in observable shock phenomena, it cuts through a century of ambiguity. By extending the framework to munitions, it provides the EOD community with a practical lexicon. The following concise definitions capture the essence:

Burning: Surface oxidation of an energetic material without shock wave formation.

- Deflagration: Subsonic chemical reaction of a confined energetic material producing an atmospheric shock wave (an explosion).
- Detonation: Supersonic shock-driven reaction propagating at the velocity of detonation.
- Low-Order: A munition's explosive fill deflagrates, pressurising the casing until it bursts less energetically than in a detonation.
- High-Order: A munition essentially functioning as designed, with the explosive fill detonating and casing fragmenting violently.

These definitions can serve as a common language across research, operations, and policy.

Conclusion: Towards Consistency and Safety

Explosives engineering sits at the intersection of science, engineering, and field practice. Ambiguous terminology has too often hindered communication between researchers, designers, and operators. The *Combustion Continuum* and its extension to munition reactions provide a unifying model that is both scientifically rigorous and practically useful.

For those engaged in explosive ordnance disposal, the framework offers more than semantics. It offers a way to describe, analyse, and learn from each intervention with consistency. It ensures that when we say a munition has "low-ordered," we mean the same thing across nations, services, and decades.

Clarity in language leads to clarity in understanding. And in our profession, clarity can mean the difference between success and catastrophe.

This article is based on the following journal publications by the author and his collaborators:

Alford, R., Hazael, R., & Critchley, R. (2024). Introducing the combustion continuum to define the transition points between burning, deflagration and detonation regimes of energetic materials. Journal of Energetic Materials. doi:10.1080/07370652.2024.2446903.

Alford, R., Hazael, R., & Critchley, R. (2025). Using the combustion continuum to distinguish between explosive material and explosive article reactions for a unified scale in ordnance disposal categorisation. Journal of Energetic Materials. https://doi.org/10.1080/07370652.2025.2472671

(2059 words)

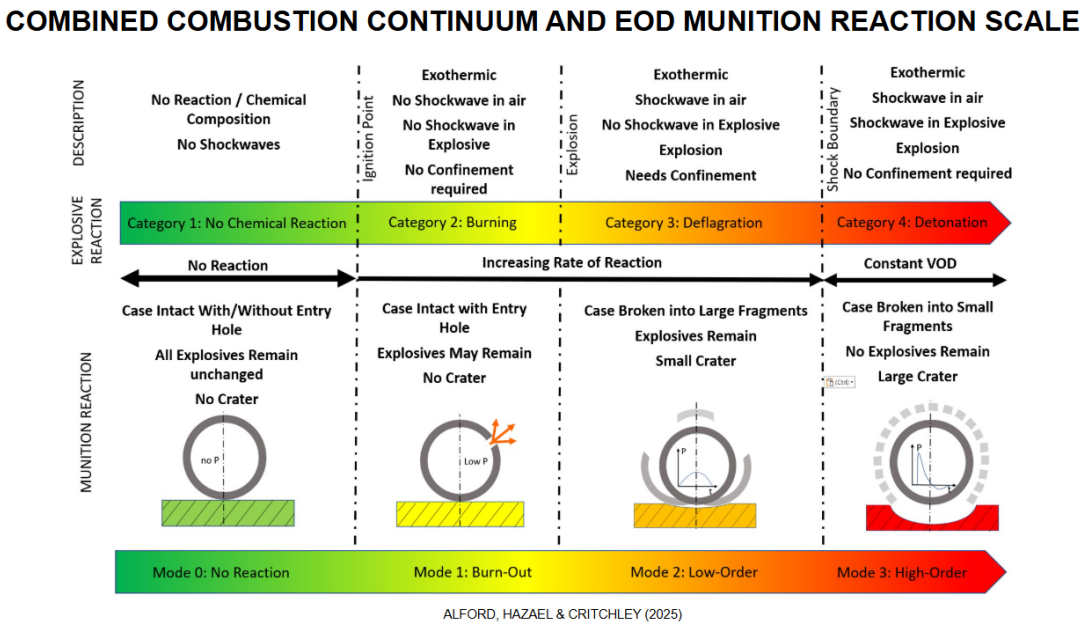


Figure 1: Combined Combustion 12 Continuum & EOD Munition Reaction Scale

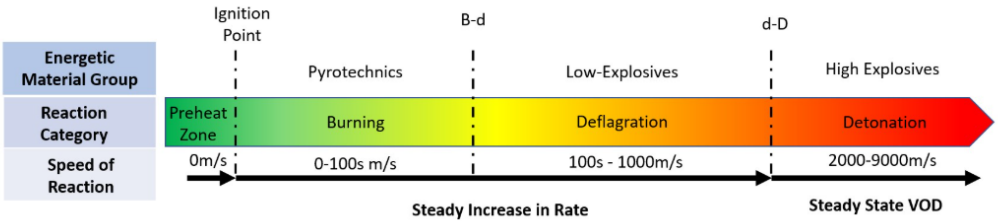


Figure 2: Combined Combustion Continuum Cont.



Figure 3: 155mm Projectile



Figure 4: 20kg Detonation

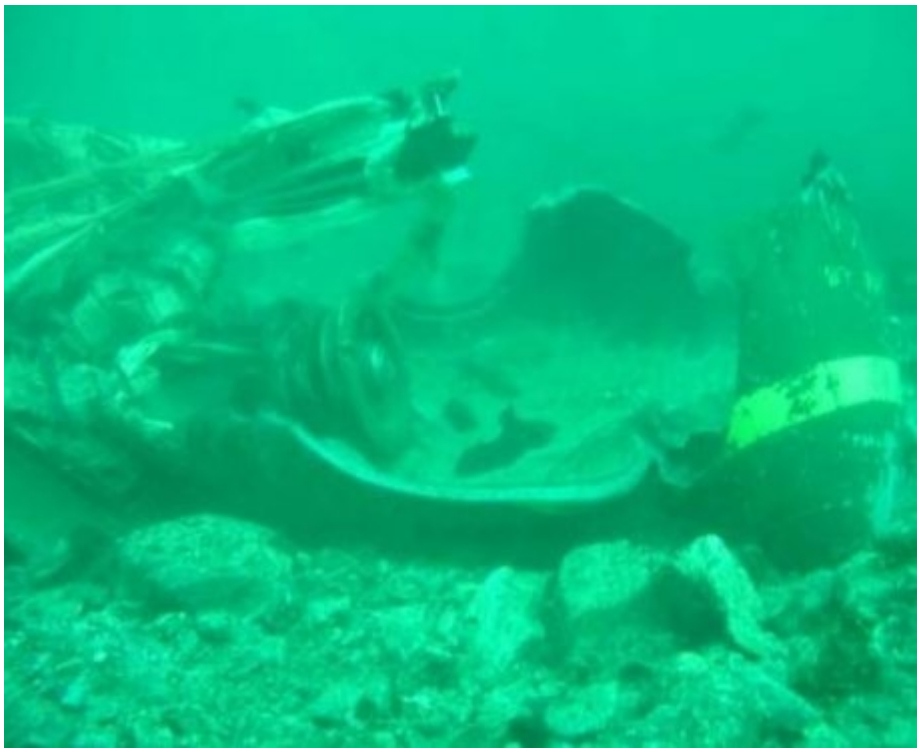


Figure 5: Mk20 Bomb Underwater



Figure 6: 155mm Projectile



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