

Introducing the combustion continuum to define the transition points between burning, deflagration, and detonation regimes of energetic materials

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ABSTRACT

This paper introduces what the authors term Combustion Continuum which treats oxidation reactions of energetic materials as lying on a continuum in which the variable is the speed of reaction. It divides the continuum into three regions, burning, deflagration, and detonation (BDD) and defines the transition points between each region and describes various observable effects that allow definitive identification of the type of reaction. The transition point between combustion and deflagration is defined as the onset of an atmospheric shock wave, which is the first time deflagration has been defined in such a way that the point of transition can be observed and fixed. The transition point between deflagration and detonation is well defined elsewhere and is the point at which the reaction shocks-up to produce a shock wave driven detonation front. This approach contrasts with most literature that treats burning, deflagration and detonation as interrelated forms of energetic reaction with none giving precise definitions that allow a full understanding of the difference between them and most critically, how to determine whether a reaction is burning or deflagration.

KEYWORDS

BDD; Burning; combustion Continuum; deflagration; detonation; explosion

Introduction

Within the field of explosives, it is normal to talk about the velocity of detonation and brisance to describe any given explosive and to give an indication of its power. At a deeper level, shock waves and equations of state describe what occurs during detonation, pressure–volume relationships, and give a precise definition that allows us to understand why and more importantly when a material no-longer simply explodes but detonates.

It is known, for instance, that unconfined black powder burns rapidly, and that providing confinement increases both the pressure and the speed of reaction that leads to it exploding. While black powder clearly explodes when under confinement, it does not detonate and is the most well-known

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example of what are known as low explosives, explosives that are incapable of detonating. Conversely, those that do detonate are called high explosives.

As early as 1892 Berthelot wrote about the Multiplicity of the Modes of Combustion (Berthelot 1892, 52) in which he describes dynamite decomposing without flame, brisk burning or explosion. This must surely be one of the earliest descriptions of the different ways an explosive substance can react.

What is known about the point at which burning black powder explodes? Is there, like detonation, a clear and precise definition that may be applied? Is there a clear transition point at which it can be stated that it has exploded or is it not defined? This paper aims to unpick these terms to answer these questions.

It is generally understood that some high explosives can be ignited and simply burn to completion (Davis, Lee, and Cooper 1998, 189). Most high explosives require a shock to trigger detonation, however under different conditions, the rate of reaction of a burning explosive may increase to the point at which it deflagrates, and this may then transition to a full, steady-state detonation. This paper investigates these reactions and different regimes, which are all essentially the same chemical reactions and which may be thought of as lying on what the authors call the *Combustion Continuum*.

Energetic material reactions

Explosion

Understanding explosions is fundamental to developing a full understanding of the energetic material reactions so it is somewhat surprising to learn that there is little agreement on the precise definition of explosion apart from there being general agreement that there are three types of explosion; physical (such as a balloon bursting), chemical and nuclear (McLain 1980, 121).

Unlike combustion, deflagration and detonation which are types of chemical reactions, an explosion is normally simply defined as a *sudden expansion of gas* which is not, itself, restricted to chemical reactions (Venugopalan 2015, 51).

Venugopalan defines explosion as “*a process of rapid physical or chemical transformation of a substance, accompanied by an extremely rapid transition of its potential energy into mechanical work*” (Venugopalan 2015, 52). Physical transformation can refer to any rapid expansion of gas, normally due to a sudden release from a state of confined compression while a chemical transformation is a chemical reaction that rapidly liberates a gas and can involve both gaseous and condensed (liquid or solid) explosive substances.

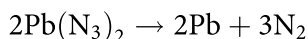
What constitutes *rapid* and when a rapid expansion of gas becomes an explosion is not defined in any of the definitions found in literature (Cooper 1996; Johansson and Persson 1970; Venugopalan 2015).

Keller et al. gave a definition specifically for gas explosions introduces the idea of a shock wave being associated with explosions. They define explosions as a “*fast Combustion of a gas mixture releasing heat, hot combustion gases, and a shock wave. Explosions can be further subdivided into the two main cases of deflagration and detonation*” (Keller et al. 2014). This is significant as it is one of the few definitions found that expressly states that an explosion results in a shock wave and that a deflagration is a form of explosion. Given that detonation is defined as a reaction progressing fast enough to form a shock wave in the explosive substances (Cooper 1996, 170), Keller’s definition is clearly referring to a different shock wave when he talks of deflagration. This is key to understanding what an explosion is.

Interestingly, most descriptions of explosions lack any mention of noise even though they are intuitively understood to be noisy events. If the noise is included as a required part of what defines an explosion, the definition immediately starts to become more specific (Departments of the Army and Air Force 1955). Just as the crack of a whip is caused by the tip of the whip breaking the sound barrier, the crack, bang or boom of an explosion is caused by the formation of a shock wave in the air around the event (Krehl, Engemann, and Schwenkel 1998) and this is the shock wave Keller is referring to. It is important to distinguish this shock wave in the air, which can often be seen in videos of explosions, and which travels faster than the speed of sound in air, from a detonation shock wave traveling through the explosive, traveling at the velocity of detonation of the explosive, that continually shocks the explosive to detonation at the shock front.

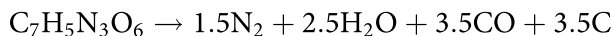
Oxidation reactions

Energetic materials, such as propellants and explosives, undergo combustion which is a general term used to describe oxidation reactions which produce heat, light, and gas. Most explosives, and all organic explosives, contain at least some of the oxygen in their molecules required for their decomposition to occur (Cooper 1996, 19, 49). This paper focuses on organic explosives, both pure explosives such as TNT and compositions such as modern PBXs but not all statements may hold true for some inorganic explosives such as lead azide. As can be seen from the chemical formula $\text{Pb}(\text{N}_3)_2$, lead azide does not contain any oxygen but instead liberates gaseous nitrogen:

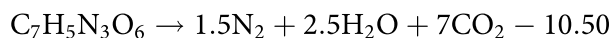


If they have the correct number of oxygen molecules to fully react, they are oxygen balanced, but some explosives have either too much or too little oxygen to fully react or result in less stable gases such as carbon monoxide or nitrogen oxide being formed.

TNT, which has historically been one of the most important explosives, is notably oxygen imbalanced so normally undergoes the following reaction during a detonation:



(Cooper 1996, 24)



(Akhavan 2004, 86)

A newly proposed alternative reaction is:



Note that this produces ammonia and hydrogen gas which would then react with atmospheric oxygen as a secondary reaction to produce water.

The formation of ammonia would be significant as it has a distinctive smell that can be identified without the need for chemical analysis and, indeed, the lead author has noted that incomplete reactions, such as those produced by low-order techniques against bombs filled with cast RDX-TNT (see Figure 7), are often accompanied by the characteristic smell of ammonia. Large lumps of the composition often show signs of combustion such as melted surfaces and carbon soot. Both the ammonia smell and presence of carbon imply that the newly proposed reaction is likely to have occurred.

Analysis of combustion products TNT could be carried out to confirm this but, a more detailed explanation of equations of state is beyond the scope of this paper. All explosives in this paper are treated as ideal explosives without variations in density or the presence of hotspots. See Davies (Davis 1998) for a more detailed explanation of equations of state.

It should be noted that combustion and burning are often used interchangeably. Combustion is the more general term for all exothermic oxidation reactions, including detonation, while burning is normally used to describe full combustion that produces a flame (Bailey and Murray 1989, 2:21). This paper uses the term combustion in preference to burning, except where other authors have used burning in their definitions or where terms are widely used in the field, for example “burn-out.”

Combustion continuum

It has been discussed that all the reactions are similar oxidation reactions, chemical analysis does not appear to offer a useful way of distinguishing between the different types of energetic reactions. It is known that the rate of reaction does change with the conditions, so it is therefore helpful to

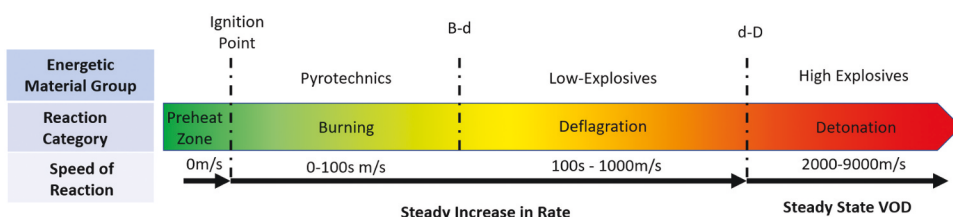


Figure 1. Oxidation of energetic materials occurs on an “combustion continuum” from no reaction to ignition to burning, deflagration and ultimately detonation. The precise points at which one regime transitions to another (B-d or d-d) needs to be clearly understood and defined.

consider them all to be on what the authors have called the combustion continuum as shown in Figure 1.

There are three basic categories or regimes of reaction on the continuum: burning, deflagration, and detonation (BDD). It is no coincidence that energetic materials can also be categorized in three groups: pyrotechnics which are designed to combust; low-explosives which deflagrate and high-explosives that detonate.

It is worth noting that under specific conditions, many but not all propellants can be caused to deflagrate or detonate and conversely most high-explosives can be caused to combust or deflagrate.

The first question the authors set out to answer is therefore: *“Is it possible define a specific and measurable point at which a combustion reaction transitions to a deflagration?”*

Referring to Figure 1, the same question is framed as defining B-d (the Burning to Detonation point) and d-D (the Deflagration to Detonation point) such that it would be possible to observe or measure a defined change which would indicate this transition had occurred.

The following sections attempt to describe each of the reaction categories and to examine existing definitions found in literature. Where they are lacking, new definitions are proposed that are accurate and consistent with each other.

Burning

Burning is an exothermic chemical oxidation reaction that occurs at the surface of a material (Figure 2) that occurs in various zones of reaction, generally with the formation of a flame. The reaction proceeds at a rate in which the surrounding atmosphere can dissipate the energy and combustion gases as fast as they are released meaning that no shock wave is generated by the reaction (see Figure 4a).

In an energetic material, the rate of reaction may accelerate to the point at which it transitions into deflagration.

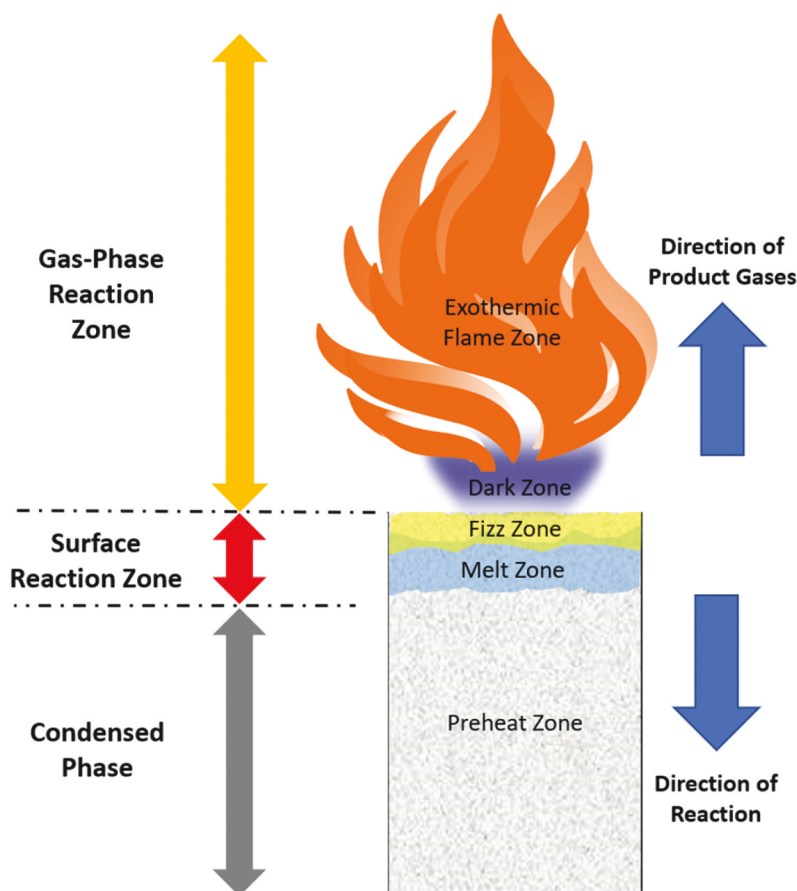


Figure 2. Combustion of a solid can be separated into different reaction zones with the reaction occurring at the surface of the material. Adapted from Venugopalan S (Venugopalan 2015).

Johansson and Persson give a technically accurate definition for burning that summarize this well:

Burning of condensed explosives is an exothermic surface decomposition or reaction between ingredients, supported by heat transfer from the gaseous products. (Johansson and Persson 1970, 5)

Deflagration

Definitions in literature generally distinguish between combustion and deflagration by describing deflagration as *rapid burning* (MOD 1972, 245) or *combustion* without defining what is meant by rapid. This is too imprecise to be of any use.

Deflagration is generally understood to be a oxidation reaction that is more rapid and violent than combustion although the word deflagrate comes from the Latin verb *deflagrat* meaning “burnt up” (Deflagrate n.d.) and literally

means burning or combusting. In general, it can be stated that combustion and deflagration are essentially the same chemical oxidation reactions in which combustion is used to describe slower reactions and deflagration for rapid reactions. Venugopalan categorizes deflagration (and burning) as a surface phenomenon meaning that it progresses by progressively burning layer by layer (Venugopalan 2015, 55) and therefore without initiating a shock-front. This defines the upper boundary of deflagration (d-D in Figure 1).

Berthelot describes the gas products having inadequate time to displace, resulting in the production of a “first shock.” *“The reaction induced by a first shock in a given explosive substance propagates itself with a rapidity which depends on the intensity of the first shock.”* (Berthelot 1892, 55). He then goes on to describe how that shock can lead to a “new shock” which can be transmitted layer by layer through the material (Berthelot 1892, 53) which is clearly a detonation shock wave and which is therefore distinct from the first shock he refers to.

He readily conceded, however, that he did not fully understand the phenomena and was unconvinced of a difference in nature of combustion and detonation and “a *line of absolute demarcation between the two orders of magnitude.*” More than a century after Berthelot wrote his treatise, the transition from deflagration to detonation is now well understood, however the *absolute line of demarcation* between simple burning and deflagration is still not clearly defined beyond stating that “*the propagation of the deflagration (produces) a true explosive wave which travels with a rapidity incomparably greater than that of a simple inflammation.*”

The rate at which all chemical reactions occur, including the rate at which a material combusts, can be accelerated by increasing the pressure of the reaction (Akhavan 2004, 52). This may be achieved through confinement. Conversely, reducing in the surface area of powders by compression to increase the density, reduces the ease of ignition and thus slows its inflammation (Shidlovsky 1964, 95).

Black powder is a low-explosive, which is an explosive that does not detonate. In its unconfined state it merely burns, but when confined, even in a cardboard tube (Lancaster et al. 1972, 119), the reaction accelerates to the point at which the gun powder explodes, observed as a loud crack or bang without detonating. In doing so, it was deflagrating and, because it was confined, the oxidation occurred without the need for atmospheric oxygen as there was no way for atmospheric oxygen to reach the reaction.

It seems to the authors that confinement is an almost universal requirement for a material to deflagrate, and it therefore follows that the reaction must proceed using only oxygen from within the molecule or composition. Some materials such as ammonium nitrate have been known to burn to detonation, for example in 2020 in Beirut but it is believed that this only occurs in very large quantities of ammonium nitrate where the mass of unburnt material provides

confinement to the reaction (Due-Hansen 2018). This gives an understanding of the conditions required to cause an energetic material to deflagrate but does not define precisely when it ceased to be combustion and became a deflagration.

To understand this, it is worth examining some of the existing definitions both in the literature and in technical publications.

Maienschein et al. use the term “*deflagration*” to indicate the rapid oxidation of the energetic material using oxygen that is part of the molecular structure of the energetic material, as opposed to combustion with an external source of oxygen (Maienschein et al. 2004). This definition seems to fit with the idea that confinement is needed. The reaction must proceed faster than is possible with only atmospheric oxygen.

Williams defines deflagration as a “*reaction front propagating into a combustible at a subsonic velocity, in which forward diffusion raises the temperature to a value at which reaction proceeds at an appreciable rate*” (Williams 2003). This definition is vague in its use of “*appreciable rate*” as a measure of the speed of reaction. Similarly, Venugopalan says deflagrating materials “*burn violently*” and lists a number of characteristics that are not distinct from normal combustion (Venugopalan 2015, 52).

During combustion, the gas products flowing away from the reaction zone behave as compressible fluid and the maximum theoretical velocity that any fluid can flow at is called the *sonic velocity* (Walters 2000). This is a constant for any fluid at a particular temperature and pressure and density. The ratio between the velocity at which the gas travels and the *sonic velocity* is the *Mach number* ($M = v/v_s$) (Shapiro 1953, 45).

When a gas flows slower than the sonic velocity the Mach number is less than one and it is *subsonic*. When the gas velocity reaches the sonic velocity, it is traveling at Mach 1 (Figure 5b). If a combustion reaction produces gas faster than it can flow away from the reaction front ($Mach > 1$) it backs-up and compresses in what is called *sonic choking* at which point a *shock wave* forms (Shapiro 1953, 126). This shock wave manifests itself as a crack or sonic boom and this can be considered the point at which the material explodes (Figure 4(b)). This gives rise to a relatively modest shock pressure (for example in the order of 100-500kPa) compared with that formed at the deflagration–detonation interface, which might be in the giga Pascal-range. The rise time of both is normally considered to be virtually instantaneous in the near-field however the conventional Friedlander waveform at greater distances from the source of the explosion can often feature a slightly progressive rise whereas the very concept of a far-field measurement of the pressure from the detonation front within an explosive is meaningless.

Figure 3 illustrates the part of the oxidation continuum that describes both combustion and deflagration, listing the conditions for both combustion and deflagration and proposes that the transition occurs when there is an explosion.

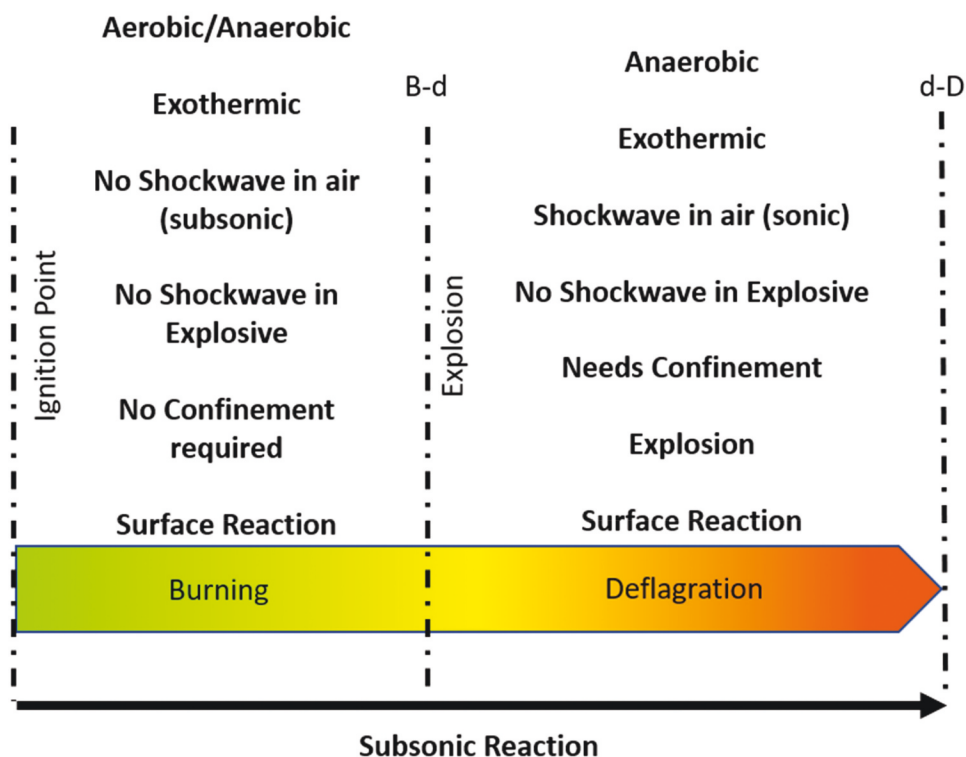


Figure 3. Burning and deflagration are both oxidation reactions in the subsonic realm. The transition from burning to deflagration (b-d) occurs when of a shock wave forms in the surrounding medium resulting in an explosion.

The authors propose that this is what essentially defines deflagration. Ellern talks about “confusion” when using deflagration to describe explosives that are not detonating and concludes that “*it would perhaps be preferable to restrict the word deflagration to fast exothermic reactions that are regarded as explosions*” (Ellern 1968, 397). This definition holds true for non-detonating, low-explosives, such as black-powder which burn when unconfined but explodes when confined but which is incapable of detonation under any conditions.

The authors suggest that if the reaction has caused an explosion, but the velocity of combustion remains below the velocity of detonation the reaction is a deflagration. Based on this, the authors propose the following new definition for deflagration in which B-d in Figure 1 is the point at which the material explodes, forming a shock wave in the air. This can be summarized as follows:

Deflagration is an exothermic surface 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.

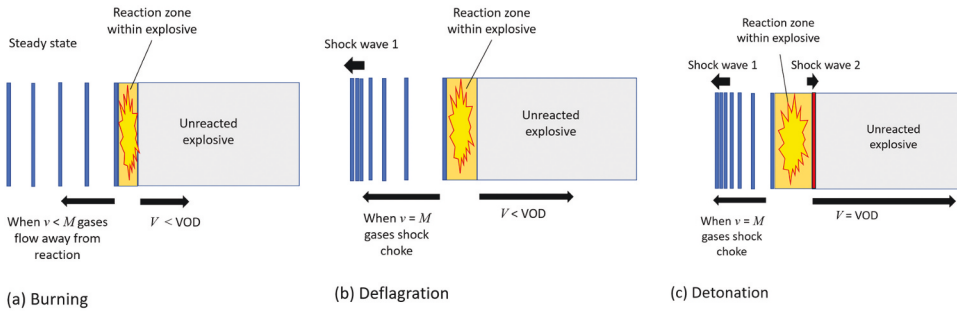


Figure 4. As the reaction proceeds through the explosive, the resultant gases flow away from the reaction. (a) During combustion, the gases flow freely away and have little or no influence on the reaction. (b) A deflagration occurs when the production of gas occurs faster than they can flow away from the reaction zone, leading to a shockwave forming (velocity v is greater than mach 1 (M) which manifests as an explosion. (c) Detonation occurs when the confinement from the shockwave in the gases accelerates the rate of reaction beyond the velocity of detonation, forming a second shock wave in the explosive that initiates due to shock rather than thermal effects.

Detonation

In contrast to deflagration, detonation is much easier to define. Just as deflagration occurs at subsonic rates of reaction without the presence of a shock wave in the energetic material, detonation occurs when the reaction front is preceded by a steady shock wave (Figure 4c) (Lee 1998, 194).

Figure 5b shows the almost instantaneous rise-time typical of a detonation which can be contrasted with the more gradual pressure rise during a deflagration (Figure 5a).

As described earlier, subsonic combustion during deflagration occurs at a rate at which the combustion gases can flow away from the reaction front.

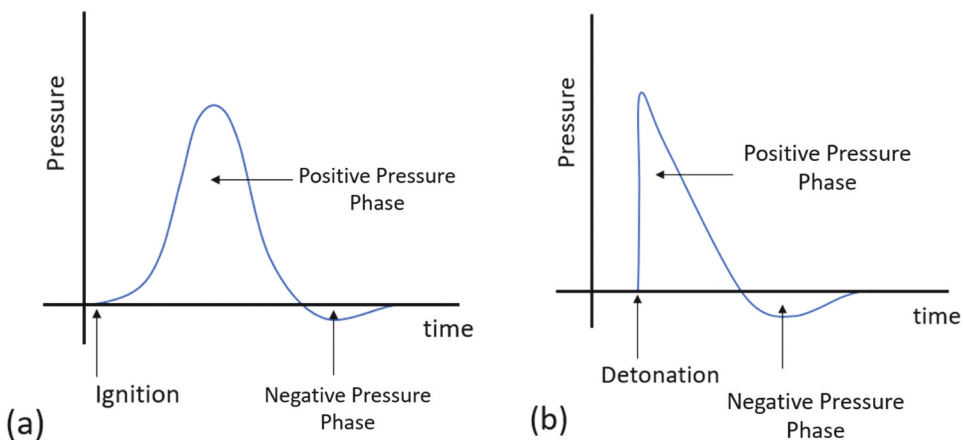


Figure 5. Typical time-pressure histories of (a) a deflagration and (b) a detonation. Note the slow rise time of the deflagration compared with the near-instantaneous rise during a detonation.

When the gas reaches a velocity equal to the sonic velocity of the gas at that temperature, sonic choking occurs and a shock wave forms in the reaction products (Walters 2000) (Figure 5(b)). This increases the pressure in the reaction zone until it rises suddenly (shocks up) and a shock wave forms, traveling through the explosive in the direction of the reaction. This shocks the unreacted explosive in advance of the reaction front initiating chemical decomposition of the unreacted explosive causing it to detonate. This reaction occurs at the velocity of detonation of the explosive and is a constant for the explosive under any given set of conditions. Note that there are some explosives, for example dynamites, which have two discrete detonation velocities depending on the diameter of the charge and the method of initiation (Cook 1958, 51; Johansson and Persson 1970, 51).

Cooper defines a detonation as “*a supersonic reaction in which the reaction occurs just behind the interface between a shockwave and the unreacted material as a result of the shock wave compressing and heating the explosive initiating the chemical reaction*” (Cooper 1996, 254).

Cooper’s definition is both succinct and accurate. He further adds:

A detonation is a shock wave with a rapid exothermic chemical reaction occurring just behind the shock front. In a given explosive sample, the wave speed is constant; the shock velocity does not speed up or slow down after the material has been initiated. (Cooper 1996, 6251)

It is known that the mass reaction rate or propagation velocity of a detonation is in the region of 10^3 to 10^4 faster than that of deflagrations (Schumacher 1972, secs 12–4) which explains why deflagration events are far less violent than detonations.

The Deflagration-Detonation area of the Oxidation Rate Continuum can therefore be described by Figure 6.

Deflagration-to-detonation transition

The process that causes a deflagrating to detonate is called the deflagration-to-detonation transition and is essential to understanding how explosives initiate and how to produce safer explosives.

If an explosive deflagrates while under confinement such that the products of combustion cannot escape, the pressure around the deflagration front will increase rapidly (Cooper 1996, 319). This will increase the rate of combustion and if the confinement can be maintained during this process, preventing the escape of the combustion products, the pressure waves from the deflagration region can compact and compress the unreacted explosive. Ultimately, this can cause pressure at the deflagration front to increase to the point where it shocks up and produces a shock wave in the unreacted explosive (Asay 2010, 5:18). Given enough run distance, and high enough temperatures and

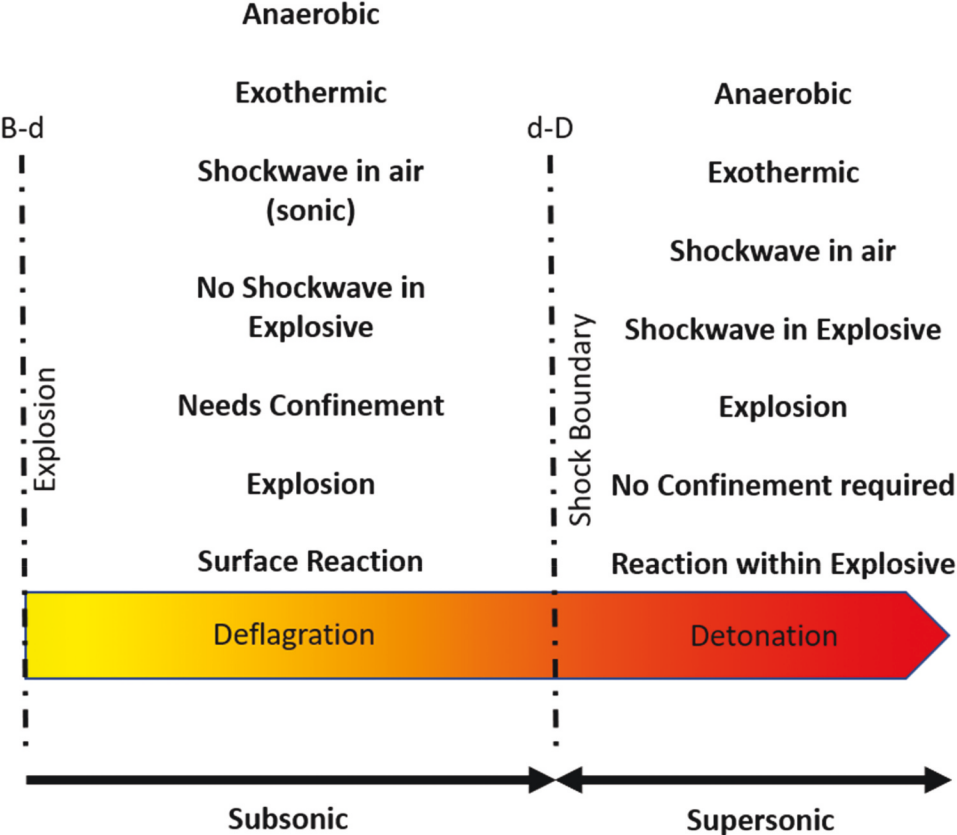


Figure 6. The deflagration to detonation (d-d) transition is defined by the shock boundary in the explosive at which a shock wave is set up travelling at the VOD, initiating the explosive at the shock front.

pressures, the shock wave is the final condition required to cause detonation. Paul Cooper states that “detonation requires a shock for initiation. Under certain circumstances and conditions, a burning or deflagration reaction can grow into a full steady-state detonation”(Cooper 1996, 319).

This process is called deflagration-to-detonation transition, or DDT (P. W. Cooper 1998). This is the mechanism that can cause munitions in a fuel fire to detonate as occurred in 1967 on the USS Forrestal (Cox 2017). This incident was instrumental in driving development into Insensitive Munitions (IM) compositions and there is extensive literature available (Anderson and Wauters 1984; Stewart 2004; Asay 2010, 5:3).

An accurate definition for DDT is “A *deflagration under confinement increases the pressure, the rate of reaction and the temperature, which may cause transition into a detonation*” (JSP 364) (MOD 2007). The author’s have not found any similarly accurate definition in the scientific literature so prefer to use this military definition.

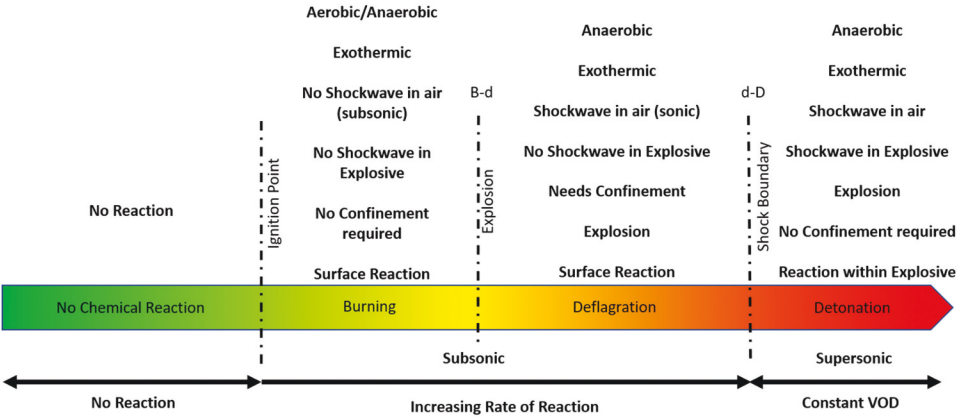


Figure 7. The full combustion continuum illustrates the transitions from burning, deflagration and detonation (BDD) as the speed of reaction increases, but the specific transition points to three main categories of reaction are defined by the onset of ignition, explosion and detonation.

The combustion continuum: burning deflagration, detonation (BDD)

Combining the elements from Figures 1, 3 and 6 above gives the full *combustion continuum (BDD)* which is useful in visualizing the relationships and differences between burning, deflagration and detonation regimes. It also summarizes the conditions required to achieve each of the states of combustion. It is possible to now understand clearly when a burn transitions to a deflagration, which has tended to be a vague and ill-defined point.

Figure 7 presents the same information from with the emphasis on the three reaction groups, Burning, Deflagration and Detonation (BDD).

Definitions of burning, deflagration, detonation (BDD)

Table 1 presents a list of terms and definitions discussed above which are selected for their consistency with each other.

Conclusions and recommendations

The Combustion Continuum divides combustion into three distinct regimes, namely burning, deflagration and detonation (BDD). It also clearly defines the transition points between each of those regimes in terms of shock waves which are observable phenomena that allow the precise and accurate identification of which regime a reaction has occurred in.

It is recommended that the Combustion Continuum be recognized and used as a valid and useful tool for identifying and describing combustion reactions. No existing models for the different forms of

Table 1. Summary of energetic materials definitions.

Term	Definition
Burning	<i>Combustion or burning of condensed explosives is an exothermic surface decomposition or reaction between ingredients, supported by heat transfer from the gaseous products. (Johansson and Persson 1970)</i>
Deflagration	<i>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)</i>
Deflagration to Detonation Transition	<i>A deflagration under confinement increases the pressure, the rate of reaction and the temperature, which may cause transition into a detonation” (MOD 2007)</i>
Detonation	<i>A detonation is a shock wave with a rapid exothermic chemical reaction occurring just behind the shock front. In a given explosive sample, the wave speed is constant; the shock velocity does not speed up or slow down after the material has been initiated. (Cooper 1996)</i>
Explosion	<i>A chemical reaction or change of state which is affected in an exceedingly short space of time with the generation of high temperature and generally a large quantity of gas. An explosion produces a shock wave in the surrounding medium. The term includes both deflagration and detonation. (Glossary of EOD terms, American Language Course, Defense Language Institute) (NATO EOD Centre of Excellence 2017)</i>
Explosive	<i>An explosive substance is a solid or liquid substance (or mixture of substances) which is in itself capable by chemical reaction of producing gas at such a temperature and pressure and at such a speed as to cause damage to the surroundings. Pyrotechnic substances are included even when they do not evolve gases. (Globally harmonized system of classification and labelling of chemicals: GHS) (Vereinte Nationen 2015, 12)</i>

combustion give a clear definition of the transition point between burning and deflagration. This clarity allows researchers to be more precise in their descriptions of events in a way that has hitherto been lacking.

It is further recommended that the following new definition for deflagration is adopted into the existing lexicons as it includes the description of the atmospheric shock wave which occurs at the transition from burning to deflagration and is therefore critical to the definition:

Deflagration

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).

Ethical statement

I, Roland Alford, consciously assure that for the manuscript *Introducing the Combustion Continuum to Define the Transition Points between Burning, Deflagration and Detonation Regimes of Energetic Materials* the following is fulfilled:

- (1) This material is the authors' own original work, which has not been previously published elsewhere.
- (2) The paper is not currently being considered for publication elsewhere.
- (3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
- (4) The paper properly credits the meaningful contributions of coauthors and co-researchers.
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- (6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
- (7) All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

The violation of the Ethical Statement rules may result in severe consequences.

I agree with the above statements and declare that this submission follows the policies of the journal as outlined in the Guide for Authors and in the Ethical Statement.

Role of funding source

This work was sponsored by Alford Technologies Ltd who provided logistics and technical resources for the research but played no role in the study design, collection, analysis and interpretation of data, the writing of the report and the decision to submit the paper for publication.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Introducing the combustion continuum to define the transition points between burning, deflagration, and detonation regimes of energetic materials

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2024-12-31

Taylor & Francis

<https://doi.org/10.1080/07370652.2024.2446903>

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*, Available online 28 December 2024