

Chapter 2

Energy Distribution in the Blast Fragmentation Process

Braden Lusk and Jhon J. Silva

Abstract The study of energy distribution in a blast fragmentation process is the subject of active research. The complexity of the phenomena and the high intensity and speed of some of the physical processes occurring during an explosion such as high pressures and temperatures make measuring of the energy distribution a very difficult task. Because of the limitation of current technologies to measure the actual energy released in an explosion, the assessment of energy distribution is done considering the balance between the ideal energy stored in the explosive and the effects of the released energy in the surrounding media. To study the ideal amount of energy in the explosive, it is necessary to use thermophysics and thermodynamic principles, while the effects in the surrounding media are explained using materials deformation theories, material fracture models, and dynamics. This chapter will review the basic principles behind the assessment of the ideal energy in the explosives and discuss the most accepted theories about the distribution of the energy in the surrounding media when an explosion takes place.

Keywords Explosive energy • Fracture • Vibration • Detonation
Blasting • Fragmentation

2.1 Introduction

In the rock blasting process, there are two main considerations: the explosive and the confining rock media. The effects of the energy released by the explosives in the rock media and measured as fragmentation, ground movement, and vibration among others, are dependent on the characteristics of the explosive products.

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It is also a function of the initial conditions and the properties of the rock media. The varying levels of initial conditions and properties of the rock media are often characterized simply as confinement. When the energy is released from the explosive, a chemical reaction involving a fast oxidation reaction occurs. As a consequence of the oxidation, a significant amount of heat is generated. The heat increases the temperature of the gasses, expanding the gasses into a volume much larger than the original volume. As a result of the rapid expansion of the gasses, a high pressure is developed. The high pressure in the gasses will perform different tasks in the confining media in the form of plastic and elastic deformation, movement, rock damage and fracturing, among others. The release of energy in the explosive involves changes of the matter between different states from solid to liquid and gaseous and also will produce changes in its chemical state. Engineers and scientists use *thermophysics* principles to assess the temperatures and amounts of energy required to change the matter (the explosive) between the different states. On the other hand, they use *thermochemistry* to study variations in the chemical state. Both disciplines allow us to quantify the changes in internal energy (U) and enthalpy (H) [3]. A low input energy is required to start the process of releasing the internal energy stored in the explosive. In the initial stage, the bonds in the molecules are broken in an endothermic process. Once the process has started, the changes in the chemical state of the explosives will allow the formation of products resulting in the liberation of the energy of the explosive in an exothermic reaction [5, 7]. To better understand the balance of energy stored in the explosive, this chapter will review the basic physical concepts of heat, temperature, and work.

Because the explosive matter changes between different states, the chapter will also review the heat capacity, latent heat of fusion, heat of vaporization, and heat of transitions. Changes in the chemistry of the explosives will produce heat of reaction, heat of formation, heat of combustion heat of detonation, and heat after burn. Chemistry and state changes are usually measured and quantified by assessing the internal energy and the enthalpy of the explosive.

To study the tasks or effects of the energy released by the explosives in the surrounding media, it is also necessary to review the concepts of rock fracture and rock fragmentation. Rock fracture deals with the study of generation and propagation of one or more cracks while rock fragmentation not only studies generation and propagation of many cracks but also the total energy consumed by the surrounding media and the final size distribution of the fragments [14]. Fragmentation also includes rotation and movement of individual rock particles, which produces grinding during movement. To better understand the rock fragmentation process, this chapter will review the Griffith energy balance concept, the strain energy released rate, fracture surface energy, and the fracture surface energy consumed. It is commonly accepted that the release of energy from the explosives in the rock media will be distributed in different functions such as: (1) the energy that produces plastic deformation in the crushed zone adjacent to the blasthole and is used in the borehole expansion, (2) the energy to create new cracks and new surfaces in the fractured zone, (3) the energy used to extend and open the current cracks in the fractured zone, (4) the energy to mobilize the rock fragments and provide an initial

velocity to flying rock fragments, (5) the energy that provides initial angular velocity to rotating rock fragments, (6) the energy consumed in heating the rock mass, (7) the seismic energy carried by the stress waves out of the fractured zone, and (8) other forms of energy including radiant energy in form of electromagnetic radiation, sound, light, and others.

All of the functions described briefly above consume portions of the overall energy contained in the explosive product. The distribution of this energy is dictated by many factors. Each function is critical in the analysis of the fragmentation process. As a finite quantity of energy exists in a column of explosive, the sum of energy consumed by all functions must be equal to that available. Many of these functions are well defined in the literature and practice; however, the overall energy balance and some specific functions are not clearly understood and thus are debated widely in the literature. This chapter discusses some of the most accepted and proposed distributions found in recent research.

2.2 Stored Energy in the Explosives and Release Balance

The energy produced when explosives react is an oxidation process. A similar process occurs in a combustion reaction. The main difference between the two chemical reactions (detonation and combustion) is the high velocity of the reaction in an explosion. In the simplest definition, an explosion can be defined as a chemical process in which a substance reacts with oxygen and releases heat. Under this concept, the explosive can be called the reactant, and the source of oxygen is called the oxidizer. During the process, new chemical substances or products are created from the reactant and the oxidizer. In chemistry, the difference between the internal energy of the reactant and the products is called heat of reaction. In the case where the reactant is an explosive such heat is known as heat of explosion. The amount of heat generated in an explosion is indirectly measured by the energy content in an explosive. It is related to the characteristics of the explosive material and the available quantity of oxidizer to burn all the reactant to its most highly oxidized products. The resulting products will have the lowest internal energy. The relevant characteristics of the explosive are quantities often determined experimentally. Because of the speed of the reaction and the complex process involved in an explosion, some of the quantities can be measured, but others need to be estimated from secondary information. Among the most significant characteristics of an explosive used to estimate the level of energy stored in the explosive are (1) density, (2) detonation velocity, and (3) detonation pressure. Based on these parameters, it is possible to assess the theoretical energy available in the explosive and the energy available to do useful work. The amount of oxidizer required can be determined using oxygen balance analysis of the explosion phenomena.

The chemical reaction of the explosion needs to generate expanding product gasses. If no gasses are generated in the process, the released energy of the explosive will remain in the reactant as heat and no mechanical work will be

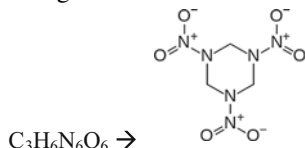
transferred from the explosive to the surrounding rock. In this, we explain the oxygen balance analysis and include a discussion of the most significant explosive properties relevant to the stored energy.

2.2.1 Reaction Product Hierarchy

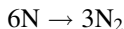
Most of the industrial explosives consist of carbon, hydrogen, nitrogen, and oxygen and are called CHNO explosives [3]. The order of products formed during an explosion is known as the reaction product hierarchy. The “rules of thumb” state that:

1. All nitrogen becomes N_2 ,
2. All available oxygen goes first to convert hydrogen to water H_2O ,
3. Any oxygen left after H_2O formation burns carbon to CO ,
4. Leftover oxygen from step (3) converts CO to CO_2 ,
5. Leftover oxygen from step (4) forms O_2 and is available for use in secondary reactions,
6. Traces of NO_x (mixed oxides of nitrogen) are always formed, and
7. Any leftover carbon becomes solid residue.

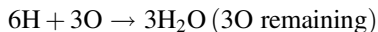
A practical example is the reaction of cyclotrimethylenetrinitramine (O_2NNCH_2)₃, best known by the Research Department Formula X (RDX). Its oxidizing reaction is as follows:



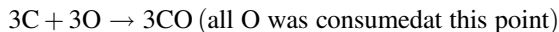
1. All nitrogen becomes N_2 :



2. All available oxygen goes first to convert hydrogen to water H_2O



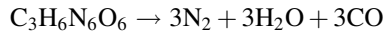
3. Any oxygen left after H_2O formation burns carbon to CO



4. Leftover oxygen from step (3) converts CO to CO₂.

There is no O, so no CO₂ is formed

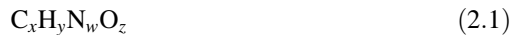
So the overall reaction of RDX is:



This is the initial reaction sequence of RDX, but some products remain reactive after the initial reaction is complete and they will undergo to further reactions [3].

2.2.2 Oxygen Balance (OB)

The amount of energy stored in the explosive and the amount of energy that can be released is related to the capacity to bring the reactant to its most highly oxidized products. If there is enough oxygen in the process, the heat of explosion will be maximized, and the production of gaseous products will be optimum. Knowing the required amount of oxygen is fundamental to knowing the optimum performance conditions for the explosion. The calculation of the oxygen balance is straightforward and can be done assuming that the general formula for the explosive is:



Assuming that all the carbon could be oxidized to carbon dioxide (CO₂) and all hydrogen is transformed into water (H₂O), then Eq. 2.2 gives the number of oxygen atoms required for exact balance after explosion.

$$\text{OB} = z - 2x - \frac{y}{2} \quad (2.2)$$

If OB in Eq. 2.2 is zero or positive, then there is enough oxygen for the explosion. However, a negative value will indicate a lack of oxygen in the reaction, meaning not all the energy is released in the process. If the OB is expressed in terms of the weight of oxygen compared to the weight of explosive (considering that the atomic weight of the oxygen is 16), Eq. 2.2 becomes:

$$\text{OB}(\%) = \frac{1600}{\text{MW}_{\text{expl}}} \left(z - 2x - \frac{y}{2} \right), \quad (2.3)$$

where MW_{expl} is the molecular weight of the explosive.

In the case of RDX, the oxygen balance is given by:

$$\text{C}_3\text{H}_6\text{N}_6\text{O}_6 : x = 3; \quad y = 6; \quad w = 6; \quad z = 6$$

and

$$MW_{\text{expl}} = 12.01 * 3 + 1.008 * 6 + 14.008 * 6 + 16 * 6 = 222.126,$$

where 12.01, 1.008, 14.008, and 16 are the atomic weight of carbon, hydrogen, nitrogen, and oxygen, respectively. So Eq. 2.3 results for RDX in:

$$OB(\%) = \frac{1600}{222.126} \left(6 - 2 * 3 - \frac{6}{2} \right) = -21.61\%$$

In the case of RDX, the OB indicates that the combustion will be incomplete, and a large amount of toxic gasses such as carbon monoxide will be present. Commercial explosives target the OB close to zero to minimize the production of harmful gasses and optimize the explosive properties. The OB evaluation of explosives is a tool to improve the mixture of explosives (combination of negative with positive oxygen balanced explosives) but the analysis, and the explosion process is much more complex, and the final results cannot be predicted only using the OB concept.

2.2.3 *Properties of Explosives Related to Energy Stored in the Explosive*

2.2.3.1 Density

The density of the explosive is closely related to the velocity of detonation (VOD) of the explosive. The density is frequently used to estimate the VOD of the explosive. There are different definitions of density depending on the application and conditions including:

- Theoretical maximum density (TMD),
- Bulk density,
- Loaded density.

The TMD is the mass per unit volume of a single crystal of the explosive. It is sometimes referred as the “crystal density of the explosive”. Eremenko [6] proposed a relationship between the TMD and the hydrogen content of substitute organic molecules as:

$$\rho_{\text{TMD}} = a_i - k_i H, \quad (2.4)$$

where a_i and k_i are constants dependent upon the chemical structural group and H is the percentage by weight of hydrogen in the explosive molecule.

2.2.3.2 Velocity of Detonation (VOD)

The velocity at which the detonation wave travels through an explosive column is called the velocity of detonation. The performance of an explosive is often measured by its VOD. In general, a reduction in the VOD will cause a reduction in the detonation pressure as well as in the availability of the released energy of the explosive.

There are different methodologies to calculate the VOD of an explosive, ranging from empirical calculations based on the molecular structure of the explosive [3], up to direct methodologies such as the Mettengang method, which is based on the breaking of wires at known distances and the interruption of electrical currents while the explosive is detonated. VOD is also measured by monitoring the change in resistance in cables or probes embedded in the explosive during detonation. Among the variables affecting the VOD of explosives are: (a) the relationship between VOD and density; and (b) the diameter of the charge and its relationship to VOD are of particular interest for practical applications.

Although there is a relationship between VOD and density for most explosives, the relationship is not linear. However, for some industrial explosives such as trinitrotoluene (TNT) and pentaerythritol tetranitrate (PETN), intervals of the relationship between ρ and VOD can be considered linear and given by:

$$\text{VOD} = a + b\rho, \quad (2.5)$$

where a and b are empirical constants depending to the type of explosive and ρ is the density of the unreacted explosive. The explosive can have varying density according to the amount of void spaces in the total volume of explosive. If the zero void density is known [the theoretical maximum density (TMD)], the VOD at other densities can be estimated using Eq. 2.6 as:

$$\text{VOD} = \text{VOD}' \left(\frac{\rho}{\rho_{\text{TMD}}} \right) + 1.5 \left(1 - \frac{\rho}{\rho_{\text{TMD}}} \right), \quad (2.6)$$

where VOD' is the VOD at the TMD density.

Experimental testing has shown two important aspects of the diameter of the explosive and its relationship with the VOD. The first is the concept of the ideal VOD and the critical diameter or failure diameter. Figure 2.1 shows a plot of VOD versus diameter for ammonium nitrate fuel oil (ANFO) and two types of emulsions [11]. The ideal VOD, (VOD_i) can be seen as the VOD when the diameter of the explosive is infinite, at this point the, maximum VOD is reached for that specific explosive material. As the diameter becomes smaller, the steady-state detonation velocity decreases until the VOD is lower than sound speed in the unreacted explosive material. The steady state can no longer be maintained and the detonation can fail. This diameter is known as the critical or failure diameter (D_{crit}) or (D_f). The value of D_f depends on the confinement conditions, particle size of the

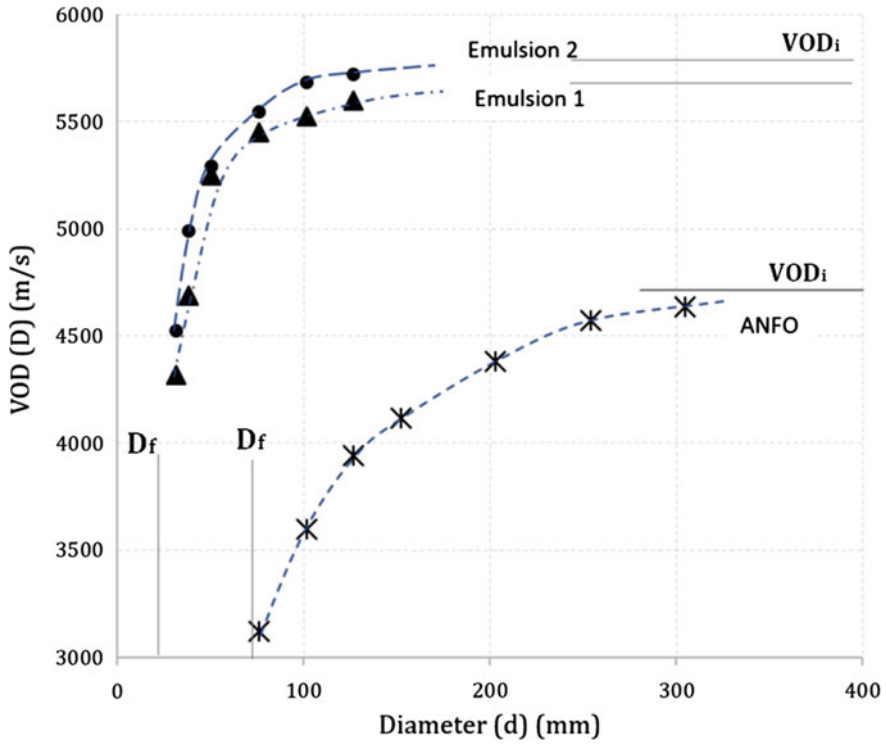


Fig. 2.1 VOD versus charge diameter. (Adapted from [3])

explosive material, initial density, and initial temperature of the unreacted explosive material.

Sun [3] proposed an empirical relationship (Eq. 2.7) between charge diameter and the VOD of an explosive.

$$\text{VOD} = \text{VOD}_{\text{ideal}} * e^{\frac{b}{d^2}}, \quad (2.7)$$

where b is a constant related to the explosive under consideration ($b = -2810$ for ANFO), and d is the diameter of the explosive charge.

2.2.3.3 Detonation Pressure

The detonation phenomena are a very complex process occurring in 3D conditions. Despite its 3D nature, the study of detonation is simpler to describe using 1D theories such as the Chapman–Jouguet (CJ), [8] the Zel’dovich [13], von Neumann [12], and Döring [4] (ZND) theories. The CJ theory assumes that the detonation

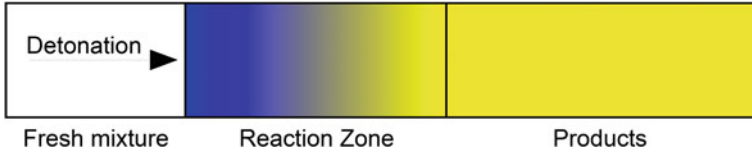


Fig. 2.2 Detonation process

process occurs in three zones called the fresh mixture (unreacted explosives), the reaction zone and the products zone (oxidized explosives) (Fig. 2.2).

Under the Chapman–Jouguet theory, the reaction zone shrinks to zero and the products are assumed to flow at a locally sonic speed relative to the shock, which is called the Chapman–Jouguet condition [8]. Using CJ theory, the detonation pressure can be estimated using Eq. 2.8.

$$P_{CJ} = \frac{\rho * VOD^2}{\gamma + 1}, \quad (2.8)$$

where P_{CJ} is the detonation pressure in gigapascals (GPa); ρ is the density of the unreacted explosive in g/cm^3 and γ is the adiabatic gamma function that can be defined as the ratio of specific heats of the detonation product gases; and VOD is the velocity of detonation in km/s.

The detonation product gases are molecules such as H_2O , CO_2 , CO , N_2 , etc. Assuming that for most industrial explosives and mixtures, the composition is similar at high temperatures and pressures, at the CJ condition γ can be assumed as 3 ($\gamma = 2.83$ and $\gamma = 2.73$ for PETN and TNT, respectively). Equation 2.8 can be written as:

$$P_{CJ} = \frac{\rho * VOD^2}{4} \quad (2.9)$$

2.2.4 Energy Stored in the Explosive

The energy stored in the explosive material can be calculated based on the chemical composition of the explosive, assuming that the chemical reactions have reached equilibrium and that all reaction products have the same temperature. To reach the chemical equilibrium, the OB should be close to zero as in many industrial explosives. The internal energy of a substance is defined as the total quantity of energy that it possesses by virtue of the presence, relative positions, and movements of its components molecules, atoms, and subatomic units. The kinetic energy is represented by the energy of vibration between the atoms of a molecule and the motion of electrons within the atoms. This portion of energy is determined by the

temperature and molecular structure of the substance. The potential energy is represented by the attractive and repulsive forces acting between molecules, atoms, electrons, and other atomic elements.

Before the calculation of the energy stored in the explosive, it is necessary to define some key terms.

2.2.4.1 Heat of Reaction

Using thermochemistry concepts, the heat of reaction can be defined as the difference in the internal energy when a chemical substance changes states due to changes in the bond between molecules. The heat of reaction is also known as the enthalpy of reaction. When a chemical reaction occurs at constant pressure and temperature, the heat developed (released or absorbed) is equal to the change in enthalpy.

$$\Delta H = \Delta U + P\Delta V, \quad (2.10)$$

where ΔH is the change in the enthalpy, ΔU is the change in the internal energy, P is pressure, and ΔV is the change in the volume. Using the ideal gas law, Eq. 2.10 can be written in the form of:

$$\Delta H = \Delta U + \Delta nRT, \quad (2.11)$$

where Δn is the difference of gaseous moles for products and reactants, R is the gas constant (8.3143 J/mole), and T is temperature (298.15 K).

For example, if gaseous hydrogen molecules are burned with gaseous oxygen molecules to form water in the gaseous state:



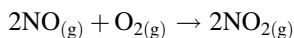
In the initial state, there are (H–H) bonds and (O–O) bonds that are destroyed to create in a final state (H–O) bonds. The internal energy stored in the bonds in the initial state are different from those in the final state. The difference is the heat of reaction. Because the heat of reaction is measured regarding the changes in the state, it is necessary to define a “standard state” defined as 25 °C (298 K) and 1 atm of pressure for engineering purposes. The heat of reaction at the standard state can be calculated as the difference between the standard heats of formation of the products and the standards heats of formations of the reactants (Hess’s law).

$$\Delta H_r^o = \sum \Delta H_{f(\text{products})}^o - \sum \Delta H_{f(\text{reactants})}^o, \quad (2.13)$$

where ΔH_r^o is the heat of reaction at the standard state and ΔH_f^o is the heat of formation at the standard state. The heat of formation can be considered a special case of heat of reaction and is defined next.

2.2.4.2 Heat of Formation

This is the enthalpy change involved in making a particular compound, or molecule, from its elements where both the elements and the final compound are at standard-state conditions. For example, nitrogen dioxide ($\text{NO}_{2(g)}$) is formed from the combination of nitrogen oxide ($\text{NO}_{(g)}$) and one molecule of oxygen [2O atoms, ($\text{O}_{2(g)}$)] all in gaseous state.



From calorimetry information, it is known that the values for the standard enthalpy of formation for the compounds involved in the reaction are:

$\text{O}_{2(g)}$	0 kJ/mol, reactant
$\text{NO}_{(g)}$	90.25 kJ/mol, reactant
$\text{NO}_{2(g)}$	33.18 kJ/mol product

So, the heat of formation can be calculated using Eq. 2.13 as:

$$\Delta H_r^\circ = 2 \text{ mol} * \frac{33.18 \text{ kJ}}{\text{mol}} - \left\{ 2\text{mol} * \frac{90.25 \text{ kJ}}{\text{mol}} + 1 \text{ mol} * 0 \frac{\text{kJ}}{\text{mol}} \right\}$$

$$\Delta H_r^\circ = -114.1 \text{ kJ}$$

In this example, ΔH_r° is negative, meaning that heat is liberated during the reaction and the process is exothermic, on the contrary, positive values mean that it is necessary to supply energy to the reaction and the reaction will be endothermic.

2.2.4.3 Heat of Detonation (Detonation Energy)

The detonation energy is the heat of reaction of the explosive going to explosive products. It does not include any heat generated by secondary reactions of the explosive or its products with air. At this point, it is necessary to highlight that the detonation energy calculated using Eq. 2.11 will be different from the energy in a real detonation. Reviewing Eqs. 2.10 and 2.11, it is apparent that the heat of reaction is also a function of the temperature, volume, and pressure at the moment of the reaction. Some properties of the explosive such as the density and VOD, and some detonation properties such as the detonation pressure along with characteristics of the surrounding media where the detonation take place will affect those variables, thus affecting the detonation energy.

There are different methodologies to measure the detonation energy experimentally in the lab (using a bomb calorimeter device) or in the field under some limitations. The bomb calorimeter device works by measuring the temperature increase of the water surrounding detonated explosives confined in a chamber

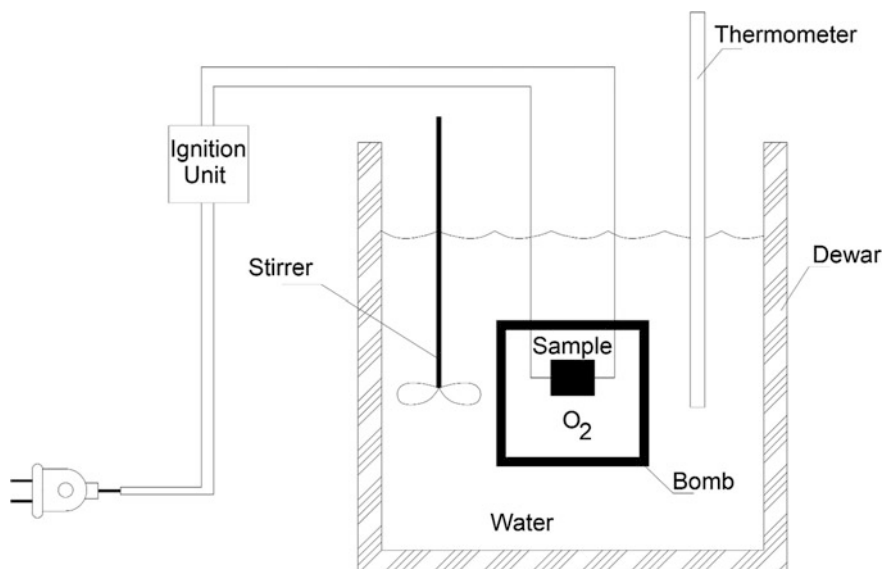


Fig. 2.3 Bomb calorimeter device

(stainless steel bomb). Figure 2.3 shows a basic schematic of a bomb calorimeter device.

For example, the detonation energy of the explosive RDX with the elemental formula given by $C_3H_6N_6O_6$ can be calculated using Eq. 2.13. The overall reaction using the reaction product hierarchy rule of thumb for RDX is:



From calorimetry information, it is known that the values for the standard enthalpy of formation for the compounds involved in the reaction are:

$C_3H_6N_6O_{6(s)}$	14.7 kcal/g mol, reactant
$N_{2(g)}$	0 kcal/g mol, product
$H_2O_{(l)}$	-68.317 kcal/g mol product
$CO_{(g)}$	-26.415 kcal/g mol product

So the heat of formation can be calculated using Eq. 2.11 as:

$$\Delta H_r^o = \left\{ 3 * \frac{0 \text{ kcal}}{\text{g mol}} + 3 * \frac{(-68.317) \text{ kcal}}{\text{g mol}} + 3 * \frac{(-26.415) \text{ kcal}}{\text{g mol}} \right\} - 1 * \frac{14.7 \text{ kcal}}{\text{g mol}}$$

$$\Delta H_r^o = -298.9 \text{ kcal/g mole}$$

If that value is compared to the experimental value of -335.4012 kcal/g mol [3], there is a difference of 36.5012 kcal/g mol or -10.9%. The difference is due to

changes in pressure and temperature in a real detonation. Also, when the reaction product hierarchy is changed, for example, assuming that all the hydrogen burns to H_2O and all the remaining oxygen react with the carbon to form CO_2 , the theoretical estimated will be different from the previous calculation.

2.2.4.4 Energy as Expansion Work

Ideally, if the reaction products can be expanded all the way down to atmospheric pressure, the expansion work (the work that the released gaseous detonation products exert on the borehole wall) should be almost equal to the detonation energy. If the detonation process is plotted using the pressure–volume (p – v) Hugoniot plane (Fig. 2.4), the expansion work can be defined in Eq. 2.14.

$$E_w = \int_{v_1}^v p \, dv - \frac{u^2}{2}, \quad (2.14)$$

where E_w is the expansion work and u is the particle velocity in the detonation process. If the expansion work is expressed using the main variables in the problem, the expansion work can be expressed using:

$$E_w = \frac{P_{CJ}}{2\rho_{CJ}}, \quad (2.15)$$

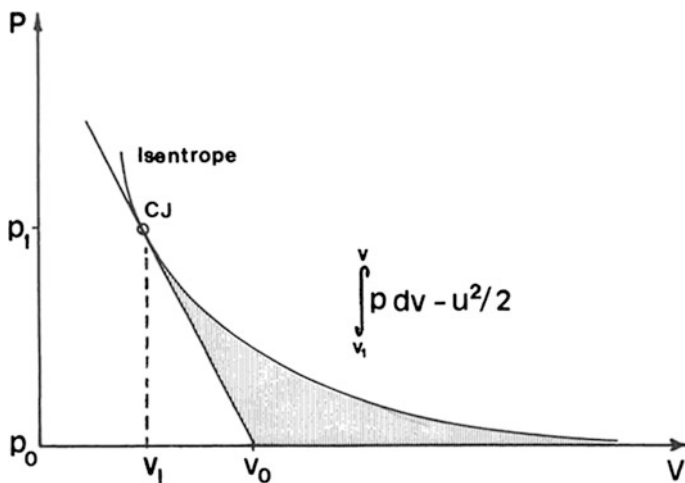


Fig. 2.4 p - v Hugoniot plane

where P_{CJ} is the detonation pressure (Eq. 2.8) and ρ_{CJ} is the density, both variables at the Chapman–Jouguet condition. The density at the CJ condition can be expressed as:

$$\rho_{CJ} = \frac{1 + \gamma}{\gamma} \rho_o, \quad (2.16)$$

where ρ_o is the initial density of the explosive (unreacted explosive) and as seen before γ is the adiabatic gamma constant. Combining Eqs. 2.7, 2.8 and 2.15 in Eq. 2.14, the expansion work can be calculated as:

$$E_w = \frac{\gamma}{2(1 + \gamma)^2} \text{VOD}_{\text{ideal}}^2 * e^{\frac{2b}{d^2}} \quad (2.17)$$

This expression allows us to examine the incidence of VOD and charge diameter in the expansion work. Higher VOD will result in higher E_w . Also, considering that parameter b is always negative, decreasing the diameter will decrease the expansion work (E_w).

2.2.4.5 Final Remarks

Thermodynamic and thermophysics analysis allows for the calculation of the energy stored in the explosive through the calculation of the heat of formation and heat of reaction; however, whether the assumption of reaction product hierarchy is valid or not would influence such calculations. The expansion work energy can be assessed using Eq. 2.13 or 2.14. Nevertheless, three variables can change the energy attributed to an explosive the: (a) pressure (confinement), (b) temperature, and (c) volume conditions. For example, in a detonation in a rock mass, the generated gasses will begin to escape to the atmosphere through openings and cracks. The temperature, volume, and pressure vary, changing the equilibrium of the reaction between products and reactants, thus changing the expansion work energy. So the actual amount of energy delivered in a blast is unknown but can be estimated from the amount of energy stored in the explosive and the assessment of the amount of energy as expansion work.

2.3 Balance and Use of the Expansion Work Energy Delivered to the Surrounding Rock

Significant research has been performed to determine specific applications of energy produced from the detonation of explosives for rock blasting. The debate is ongoing with regards to the actual quantities of energy expended in different aspects of the blasting process. The release of energy and subsequent fragmentation,

movement, vibration, and heat is a very complex process dependent upon many site condition variables and field explosive conditions. The complexity of the conditions and the varying degrees of detonation within the borehole complicate the calculation and partition of the released energy. Many researchers have contributed to the body of knowledge in specific applications of energy; however, the complete process is yet to be quantified accurately. Most analysis has resulted in large percentages of energy remaining unaccounted for. The following sections introduce some common descriptions of energy partitions found in the literature.

The actual energy released by the explosive and manifested as high-pressure and high-temperature gas products will act on the surrounding rock to initially produce expansion work. The energy balance can be expressed by [10]:

$$E_{AEE} = E_F + E_S + E_K + E_R + E_{NM}, \quad (2.18)$$

where E_{AEE} is the actual energy of the explosive, E_F is the fragmentation energy, E_S is the seismic energy, E_K is the kinetic energy, E_R is the fragments rotation energy, and E_{NM} is the energy in forms that are very difficult to measure. Among the energy difficult to measure are:

- Energy used to expand the borehole,
- Energy to produce cracks in the fragments,
- Energy using to heat the rock mass,
- Energy conveyed as the gasses venting to the atmosphere through stemming and joints,
- Energy of plastic work, radiation, and acoustic energy.

The following sections discuss the measurable form of energy in a mining blast.

2.3.1 Fragmentation Energy (E_F)

The primary objective of a mining blast is the production of new fragments from the rock mass. If the energy required to create a new unit fracture (γ_F) is known, the fragmentation energy can be expressed as [9]:

$$E_F = A_F \gamma_F, \quad (2.19)$$

where A_F is the surface area of the fragments generated by the blast. γ_F can be estimated using Griffith theory through the fracture toughness (K_{IC}) and the elastic modulus of the intact rock. Such analysis considers only one crack or fracture. Another approach uses the size reduction laws used in comminution. This approach uses Rittinger's law, where the work required to reduce the sizes of fragments from a state a to b is calculated using the average particle diameters before and after crushing, and the Rittinger's coefficient (K_R). In a mining blast, the second option is

more appropriate because many fractures are involved in the mine blasting process. In that case:

$$\gamma_F = \frac{1}{K_r} \quad (2.20)$$

The value for A_F can be estimated from the muck pile size distribution after blasting, although existing cracks must be identified and their surface area accounted for as preexisting cracks. This process is difficult even with detailed joint mapping.

2.3.2 Seismic Energy (E_S)

Assuming that the energy transferred to the rock in the form of seismic waves can be estimated as the integral of the energy flow passing through a surface of control at a given distance, the seismic energy can be estimated as [10]:

$$E_S = 4\pi r^2 \rho C_p \int_0^\infty v^2 dt, \quad (2.21)$$

where r is the distance from the source, ρ is the rock density, C_p is the wave velocity in the radial direction (assumed as the P -velocity), and $v^2 = v_r^2 + v_t^2 + v_v^2$. v_r , v_t and v_v are the particle velocities recorded in a seismograph for the radial, transverse, and vertical component, respectively. Equation 2.21 is based on many assumptions and hypotheses far from the actual conditions in a mining blast and must be considered as a rough estimation of the seismic energy from a blast [10].

The seismic energy is also difficult to describe due to the attenuation and damping that occurs as the seismic energy travels away from the origin of the blast. The seismic energy is thought to begin as shock in the rock mass very near the borehole. It transitions to a more elastic vibration wave as it travels through the rock media away from the explosive. Some of the initial energy is utilized in elastic deformation in the rock mass, which is difficult to quantify and even more difficult to measure in a dynamic environment.

2.3.3 Kinetic Energy (E_K)

In a mining bench blast, if the velocity of the rock face $v(y)$ is known at different heights where y is the vertical position in the face, and assuming that the lateral variations of the velocity are of second order (i.e., the velocity is constant in a

horizontal section of the highwall), the kinetic energy can be roughly estimated using Eq. 2.22 [2].

$$E_K = \frac{1}{2} S * B_h \int_0^H \rho(y) * [v(y)]^2 dy, \quad (2.22)$$

where S is the spacing of the blast, B_h is the mean horizontal burden, and H is the total height of the bench. Equation 2.22 assumes that the highwall is composed of various layers of rock with different densities. If the bench is in the same type of rock or the variation of the density is minimum, then Eq. 2.22 can be simplified as:

$$E_K = \frac{1}{2} S * B_h * \rho * H * v_b^2, \quad (2.23)$$

where ρ is the average rock density and v_b is the average rock face velocity. The translational kinetic energy is relatively simple to quantify using the principles of physics because it can be visually verified through video analysis.

2.3.4 Fragments Rotation Energy (E_R)

Once the fragments are ejected from the original position, they not only follow a trajectory but also rotate during the displacement. Assuming all fragments are spherical with different sizes, the rotation energy can be calculated as [2]:

$$E_R = \sum_{i=1}^N \frac{4}{5} \pi^2 m_i r_i^2 f_i^2 \quad (2.24)$$

where m_i is the mass, r_i is the radius, and f_i is the rotational frequency of the i th fragment and N is the total number of fragments considered in the analysis. Rotational kinetic energy is somewhat more difficult to quantify because fragments have irregular shapes and rotational angles are not simple to measure even with video analysis.

2.3.5 Energy Nonmeasurable (E_{NM})

As explained earlier the nonmeasurable energy is made up of energy used to expand the borehole, to produce cracks in the fragments, and to heat the rock mass; energy escaping from the borehole through the collar as the gasses vent; and energy used for plastic work, radiation, and acoustic emissions.

If it is assumed that the surrounding rock to a blasthole is homogeneous and there are no joints or cracks, the gases generated as product of the oxidation of the explosive will expand the borehole. In most field applications, this assumption is invalid; however, it is obvious that the initial expansion of the borehole will require expansion energy. The expansion energy can be estimated using expansion cavity theories [1]. If the properties of the surrounding rock are known and the expansion volume of the blasthole is measured, the expansion energy can be estimated.

Some energy is used to generate macro- or microcracks within a fragment of rock as a consequence of the blast. Such type of cracks are different than the fragmentation energy and are fundamental for the downstream mining process of crushing and grinding. This energy is conceptual and there is not a methodology for its assessment. This energy is also sometimes referred to as rock damage.

A blast event is an exothermic process. The high-temperature gases produced by the oxidation of the explosive will heat the surrounding rock in a differential of temperature unknown at this moment. In theory, if the change in the temperature of the surrounding rock is measured, the energy heating the rock mass can be evaluated.

Commonly, stemming is the amount of inert material put in the blasthole, on top of the explosive column, to confine the gases. Having an optimum grade of confinement is important to transfer the energy efficiently from the explosive to the ground. If a large amount of gas escapes from the borehole through the collar, the energy transferred to the ground will be lower than in the case where the gases are properly confined. Stemming is related to the size of the material used, its geotechnical properties, and the diameter of the blasthole. The stemming energy can be estimated by measuring the gas pressure in the borehole close to its collar [1].

2.3.5.1 Energy of Plastic Work, Radiation, and Acoustic

In a mining blast energy is expended to do plastic work, in radiation and as sound. However, there is not a practical way to measure this, so the magnitude is unknown at present.

2.4 Application of Energy Input for Ground Fragmentation

The previous sections have briefly described the quantity of energy available from the detonation of explosives. The simplistic use of this energy during the fragmentation process was also described. The basic concept is simple to understand; however, the complex mechanisms that dictate the specific partitions of energy used for each component of the energy balance are not widely agreed upon in the

literature. The calculations are complex, and measuring these energy expenditures in the field proves even more difficult.

In most cases, mining operations can choose to analyze energy utilization on a cost basis. In simple terms, operations that employ blasting will purchase explosives (energy) for the specific purpose of fragmenting rock mass material. The energy used for specific energy balance components is somewhat less important than the resulting fragmentation and remaining rock characteristics. The overall operation must continue to process the material through digging, hauling, crushing, grinding, liberating minerals, and managing waste and byproducts. Obviously, these specific processes are dependent upon the mining method, deposit and mineral type, and final product. These subsequent processes will be more or less efficient based on the success of the blasting phase of the operation. The concept of mine-to-mill optimization considers the total quantity of energy (and thus cost) required to take material from in situ conditions to saleable product.

Many operations are utilizing fragment size distributions to analyze blasting needs with reference to the downstream processes. Mines perform fragmentation analysis utilizing mostly photographic analysis of the muckpile resulting from the blast. Other studies measure the efficiency of the blast according to resulting crusher throughput or energy consumption of primary, secondary, and/or tertiary crushing processes. In each case, very little attention is paid to the fundamental partitioned use of explosive energy. In general, the process is evaluated based on energy in (drill and blast cost) and energy out (efficiency of downstream processes). This optimization exercise generally results in efficient mining processes; however, significant advances could be made with a deeper understanding of the complex processes involved with explosive energy utilized in the fragmentation of a rock mass. For this reason, research continues to quantify the energy partition further.

2.5 Summary

The availability, utilization, and distribution of energy from the detonation of explosives require a detailed understanding of the detonation process. This introductory chapter discussed several concepts and the current state of the art theories. Due to the difficulty in measuring some of the processes that occur during detonation including extremely high pressures and temperatures, the process still remains somewhat ambiguous even to experienced researchers. Nevertheless, many theories add to the understanding of the overall process and distribution of energy from detonation to perform useful work like breaking and moving rock. While some of these studies are based on empirical data and experience, others are based on numerical analysis of the basics of physics and chemistry. The basic information presented in this chapter can be utilized to inform decisions on explosive selection, blast design, and execution.

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