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Kwame Awuah-Offei *Editor*

Energy Efficiency in the Minerals Industry

Best Practices and Research Directions

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Contents

Part I Ground Fragmentation

Part II Material Handling

Part III Mineral Processing and Extractive Metallurgy

Part IV Renewable Energy and Miscellaneous Topics

Chapter 1
Introduction

Kwame Awuah-Offei

Abstract The goal of this book is to present the current knowledge regarding energy efficiency implications of mining processes and future research directions. This introductory chapter explains the purpose and motivation for this book, provides highlights of the book, provides strategies that a reader can use to read the book, and identifies the key unanswered questions that require further research. It is my hope that this book will be a valuable resource for industry professionals and researchers and stimulate further discussions on energy efficiency in mining.

Keywords Energy efficiency · Energy · Mining · Minerals industry

1.1 Introduction

Total energy costs are high for most mines because mining is an energy intensive activity. Energy cost is a key consideration for mining professionals and researchers that drive decisions on research and initiatives on energy efficiency. As pointed out by Levesque and co [1], the prevalence of energy efficiency initiatives in the minerals sector is closely correlated with energy prices. In recent years, however, concerns about climate change, the carbon footprint of products, and the related internalizing of associated costs are also driving decisions related to energy consumption and efficiency in the minerals sector. Finally, energy costs are important to mining professionals because the overall energy efficiency of mining is affected by the efficiency of all parts of a mineral project. Energy is consumed by all the processes in the mineral life cycle.

A volume like this one that discusses best practices and provides research directions for the future is long overdue. As energy consumption, the associated climate change impacts, and costs have become increasingly important, mineral

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industry professionals and researchers have had to look at a variety of sources to gather information about best practices and ongoing and future research initiatives. To the best my knowledge, no volume like this exists in the English literature that collates contributions from various experts into one resource for industry professionals and researchers.

This volume presents the current state of the art regarding energy efficiency implications of mining processes. The book is divided into four main sections: ground fragmentation; material handling; mineral processing and extractive metallurgy; and miscellaneous topics. The main sections follow, to a large extent, the unit processes of mining so that the reader can instinctively know where to find things. Besides attempting to explain the purpose and motivation for this volume, this introductory chapter tries to summarize the highlights of the chapters contained in this book, provide strategies that a researcher or an industry professional can use to read the book and identify the key unanswered questions that require further research.

1.2 Highlights

The first section of this book includes five chapters that discuss energy efficiency implications of blasting and ground fragmentation in mining [2–6]. The section starts with an overview of the energy distribution during ground fragmentation by blasting [2]. This chapter provides a basic introduction to the basic theories on the energy content of explosives, how that energy is released to the surrounding rock mass during detonation, and the different forms that energy is transformed into during explosives. By itself, the discussions in this chapter can inform a mining engineer's decisions on explosive selection, blast design, and execution. However, the chapter also serves as a useful introduction to the next four chapters in this section.

The last of these chapters experimentally examines the energy efficiency of rock fragmentation using blasting [6]. The researchers determined the proportion of the explosive energy transformed into seismic wave energy, kinetic energy, and fracture energy transferred during the blasting process. They conducted experiments at two quarries to determine the energy proportions using the seismic field from seismograph records, initial velocity of the blasted rock face obtained from high-speed video footage, and fragment size distributions from image analysis of the muckpile material, respectively. Their work shows that the maximum total energy measured, in these experiments, accounts for at most 26% of the available explosive energy, indicating that the energy efficiency of blasting is rather low.

One of the remaining three chapters deals with the energy efficiency of drilling, which is the method for creating a means of loading explosives into rock for fragmentation [5]. The remaining two chapters deal with the effect of hole stemming and detonation wave collision on fragmentation results and energy efficiency of blasting [3, 4].

The second section of the book, which covers material handling, contains four chapters that deal with the energy efficiency of material handling operations [7–10]. The section opens with an overview of energy efficiency implications of loading and hauling equipment [7]. The next two chapters deal, respectively, with shovels and trucks, which together constitute the most common loading and hauling method [8, 9]. The first of the two provides a review of the current literature on cable shovel energy efficiency while the second deals with approaches for benchmarking energy efficiency of trucks.

The final chapter in this section presents a framework for assessing dragline energy efficiency using equipment monitoring data [10]. The authors present a three-step approach involving: (1) assess energy efficiency using data from dragline monitoring systems to estimate an overall performance indicator; (2) quantify the relationship between different operating parameters and the energy efficiency indicator; and (3) improve the energy efficiency performance of operators by using the results to optimize operator training.

The third section deals with energy efficiency implications of mineral processing and extractive metallurgy and contains four chapters [11–14]. Given the significance of comminution energy in any discussion of energy efficiency in mining, it is perhaps befitting that this section begins with a chapter on the best practices and future research needs for energy efficient comminution [11]. The next chapter discusses electrical energy consumption in electrowinning of metals from solution [12]. The chapter shows that to achieve energy efficient electrowinning a plant has to maximize current efficiency and optimize electrolysis parameters. The chapter also concludes that significant energy savings can only be achieved by changing one of the underlying electrochemical reactions or reducing the anode overpotential. The next chapter deals with plant process control and real-time optimization approaches that are used to achieve lower specific energy requirements by lowering variability in key process variables and determining more appropriate operating points [13]. The chapter also presents case studies to illustrate the current state of the art in process plant automation for energy efficiency. The final chapter in this section presents the case of the Atlantic Copper in Huelva, Spain, which was the first copper smelter in the world to receive ISO 50001 energy management certification [14]. The chapter presents Atlantic Copper's experience, process, and results in energy management.

The final section, which includes three chapters, deals with renewable energy in mining and other miscellaneous topics [15–17]. The use of renewable energy in mining is one of the major energy innovations in the last decade. The first chapter in this section discusses the integration of solar energy in mines' energy supply to enable them address energy and sustainability challenges [15]. The chapter discusses recent developments in solar energy in the mining industry and presents case studies where this framework has been successfully applied to incorporate solar energy into the mining energy supply mix. The second chapter in this section deals with energy efficient practices in mine ventilation [16]. Mine ventilation is an ancillary operation in underground mining that can have significant energy efficiency implications. The second chapter of this section discusses the energy efficiency implications of this important aspect of underground mining systems.

The final chapter of the section investigates the technical and economic feasibility of installing an energy recovery system (ERS) on diesel electric drive mine haul trucks [17]. On a mine haul truck, an ERS saves energy by recovering energy when the truck brakes during descent into the pit and puts that energy back into the system during ascent out of the pit. The chapter evaluates the technical and economic viability of various ERS technology using simulation. The work shows that lithium-ion batteries are infeasible because of poor charging rate while electrolytic double-layer capacitors are infeasible because of its low cycle life. Electromechanical flywheels are judged the most cost-effective option.

1.3 How to Use This Book

This book intended to be a resource for mine managers and engineers who want to improve the energy efficiency of their operations and, thereby, increase production efficiency and sustainability. It is also intended to be a resource for researchers looking for a comprehensive review of the literature on energy efficiency in the minerals industry. Each chapter is written by subject-matter experts who have contributed to the literature on the topics they have written in this book and are familiar with the current knowledge and outstanding questions that need further research. I anticipate that there will be two kinds of users for this book: industry practitioners and researchers.

For industry professionals, I suggest they start with this introduction. They can take note of the description of the various sections of the book as outlined in Sect. 1.2. The professional can then refer to the particular section of the book or the particular chapter that is of interest. It is my hope that each chapter provides an adequate overview of the energy efficiency consideration in the particular area for an industry professional. However, in case further reading on the subject is required, the list of references in the chapters is a good starting point for any professional.

For researchers, this volume is a good starting place for research on various energy efficiency topics in mining. Each of these chapters is a good review paper that summarizes the state of the art and provides citations to the relevant literature in the area. For the beginning graduate student or the seasoned researcher, the chapters in this book represent a valuable resource for energy efficiency research in the minerals sector. In some cases, complimentary chapters (especially, those in the same section) can provide additional resources that will be useful for any energy efficiency research endeavor.

1.4 Future Research Directions

This volume provides many suggestions for industrial best practices that managers and engineers across the mine life cycle can use to improve the energy efficiency of the mines. Each of these suggestions is backed by sound research. However, many other areas still require further research so we can bridge the gap between theoretical benchmarks and actual energy efficiency performance.

Comminution and material handling are still the main areas that show the most potential for energy efficiency improvement. The gap between theoretical benchmarks and current best practice is still wide. For example, as I have pointed out earlier, Sanchidrián and colleagues estimate that the maximum total energy measured during a blast does not exceed 26% of the available explosive energy [6]. We will need to reimagine how we remove in situ material and reduce its fragment sizes to the sizes required to liberate valuable minerals from gangue in order to bridge this gap.

Certainly, research that uses holistic, systems-based approaches (e.g., mine-to-mill techniques) that lead to globally optimal systems should be encouraged over approaches that optimize subsystems alone [4, 11, 18, 19]. At a minimum, any energy efficiency improvement initiative should evaluate the effect of improving a subsystem along the mining energy chain on the global energy efficiency of the mine. Management should not pursue any energy improvement initiative that improves a subsystem but does not result in overall energy improvement. Hence, future research that aims to improve mining energy efficiency should always consider the system-wide effects of any efforts to optimize energy efficiency.

Specific areas that can provide the necessary improvement in energy efficiency of comminution and material handling include research that helps us improve our understanding of energy transformations during blasting so that we can direct more of the explosives energy toward useful work. Also, we need better understanding of how operators affect energy efficiency of material handling machines. This is necessary to clarify the relationship between specific operator practices and energy efficiency. Finally, to facilitate more energy efficient comminution, we need to better understand fracture mechanics in rocks.

In addition to comminution and material handling, especially in light of climate change and its implications for mining, there is a need for research that facilitates optimal integration of renewable energy sources into mines. We need more research that provides means for determining optimal hybrid systems for different operating and economic conditions [20]. This is particularly important for mines in remote areas where there is little to no energy infrastructure.

Finally, as I have argued elsewhere [21], we need research that properly articulates the return on investment for public policy that facilitates energy efficiency in the minerals industry. Typically, manufacturing and residential energy consumers get the bulk of the policy attention when it comes to energy efficiency. However, mining is very energy intensive and a significant energy consumer in many economies. In particular, electricity consumption by the mining industry makes up a significant portion of the energy use in developing countries with significant extractive industries [22]. Hence, it will be of public interest to increase the energy efficiency of mines in order to improve the energy efficiency of the entire economy.

1.5 Conclusions

It is my hope that this volume will be a valuable resource for industry professionals and researchers. The work in this volume represents the state of the art regarding key topics in energy efficiency in the minerals sector. The breadth of coverage and the depth in each of the chapters make it a useful resource for all managers and engineers interested in energy consumption and efficiency at the mine site. Above all, I hope that this volume will spur on further discussions on all aspects of energy efficiency in mining.

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Part I
Ground Fragmentation

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.

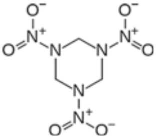
2.2.1 Reaction Product Hierarchy

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 NOx (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:

$C_3H_6N_6O_6 \rightarrow$



1. All nitrogen becomes N_2:

$$6N \rightarrow 3N_2$$

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

$$6H + 3O \rightarrow 3H_2O\,(3O\ \text{remaining})$$

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

$$3C + 3O \rightarrow 3CO\,(\text{all O was consumedat this point})$$

4. Leftover oxygen from step (3) converts CO to CO_2.
   There is no O, so no CO_2 is formed

So the overall reaction of RDX is:

$$C_3H_6N_6O_6 \rightarrow 3N_2 + 3H_2O + 3CO$$

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:

$$C_xH_yN_wO_z \tag{2.1}$$

Assuming that all the carbon could be oxidized to carbon dioxide (CO_2) and all hydrogen is transformed into water (H_2O), then Eq. 2.2 gives the number of oxygen atoms required for exact balance after explosion.

$$\mathrm{OB} = z - 2x - \frac{y}{2} \tag{2.2}$$

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:

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

where $\mathrm{MW}_{\mathrm{expl}}$ is the molecular weight of the explosive.

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

$$C_3H_6N_6O_6: \ x = 3; \quad y = 6; \quad w = 6; \quad z = 6$$

and

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

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:

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

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:

$$\rho_{\mathrm{TMD}} = a_i - k_i H, \tag{2.4}$$

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 Mettegang 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:

$$\mathrm{VOD} = a + b\rho, \tag{2.5}$$

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:

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

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

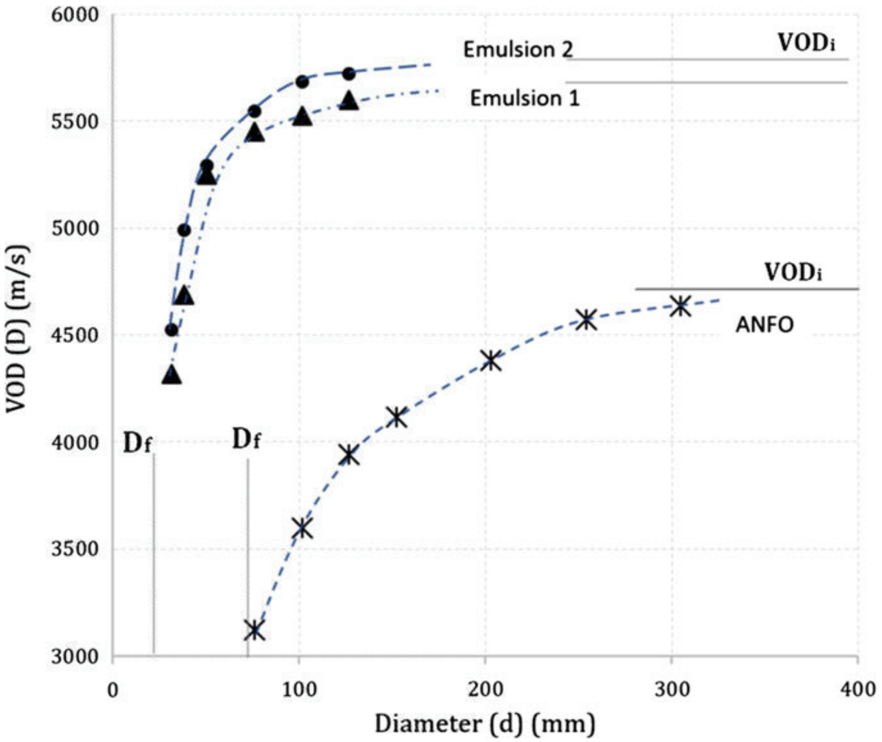


Fig. 2.1 VOD versus charge diameter. (Adapted from [3])

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.

$$\mathrm{VOD} = \mathrm{VOD}_{\mathrm{ideal}} * e^{\frac{b}{d^2}}, \tag{2.7}$$

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

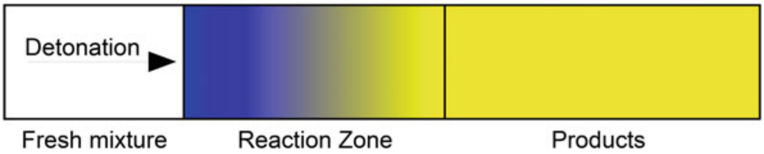


Fig. 2.2 Detonation process

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.

$$P_{\mathrm{CJ}} = \frac{\rho * \mathrm{VOD}^2}{\gamma + 1}, \tag{2.8}$$

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:

$$P_{\mathrm{CJ}} = \frac{\rho * \mathrm{VOD}^2}{4} \tag{2.9}$$

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.

$$\Delta H = \Delta U + P\Delta V, \tag{2.10}$$

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:

$$\Delta H = \Delta U + \Delta nRT, \tag{2.11}$$

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:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{2.12}$$

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).

$$\Delta H_r^o = \sum \Delta H^o_{f(\text{products})} - \sum \Delta H^o_{f(\text{reactants})}, \tag{2.13}$$

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 ($NO_{2(g)}$) is formed from the combination of nitrogen oxide ($NO_{(g)}$) and one molecule of oxygen [2O atoms, ($O_{2(g)}$)] all in gaseous state.

$$2NO_{(g)} + O_{2(g)} \rightarrow 2NO_{2(g)}$$

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

$O_{2(g)}$	0 kJ/mol, reactant
$NO_{(g)}$	90.25 kJ/mol, reactant
$NO_{2(g)}$	33.18 kJ/mol product

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

$$\Delta H_r^o = 2\text{ mol} * \frac{33.18\text{ kJ}}{\text{mol}} - \left\{ 2\text{mol} * \frac{90.25\text{ kJ}}{\text{mol}} + 1\text{ mol} * 0\frac{\text{kJ}}{\text{mol}} \right\}$$
$$\Delta H_r^o = -114.1\text{ kJ}$$

In this example, ΔH_r^o 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

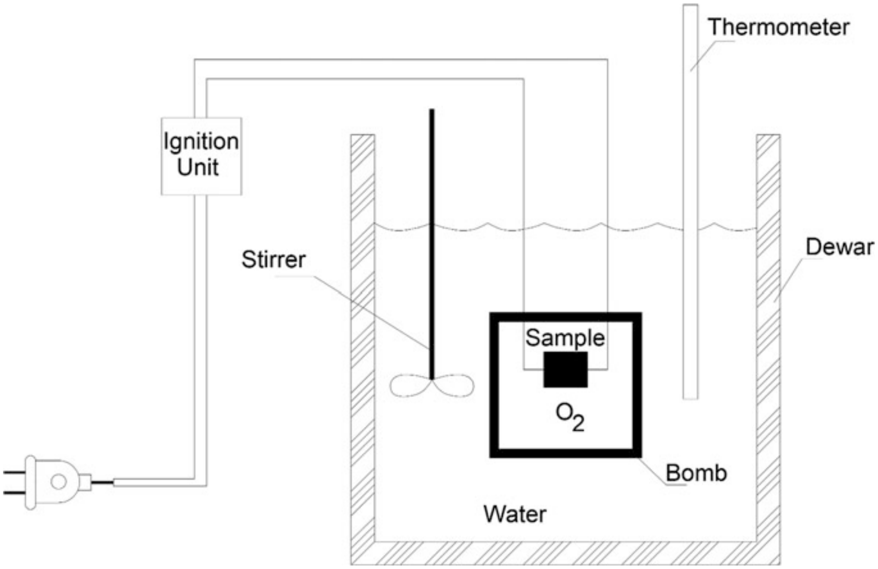


Fig. 2.3 Bomb calorimeter device

(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:

$$C_3H_6N_6O_6 \rightarrow 3N_2 + 3H_2O + 3CO$$

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.

$$E_{\mathrm{w}} = \int_{v_1}^{v} p\,\mathrm{d}v - \frac{u^2}{2}, \tag{2.14}$$

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:

$$E_{\mathrm{w}} = \frac{P_{\mathrm{CJ}}}{2\rho_{\mathrm{CJ}}}, \tag{2.15}$$

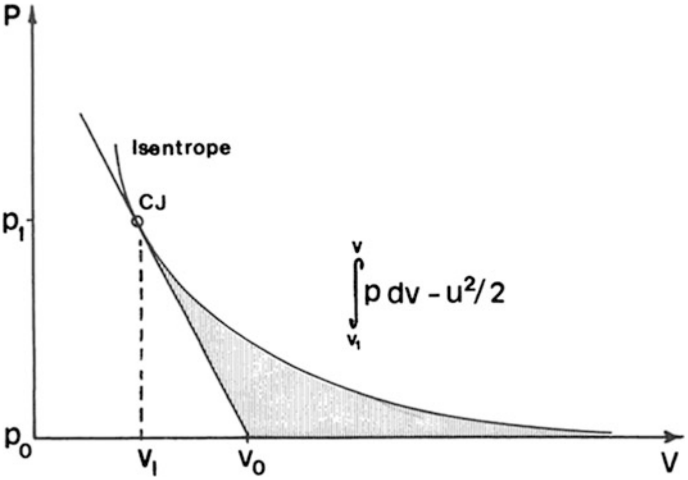


Fig. 2.4 p-v Hugoniot plane

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:

$$\rho_{\mathrm{CJ}} = \frac{1+\gamma}{\gamma}\rho_o, \tag{2.16}$$

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:

$$E_{\mathrm{w}} = \frac{\gamma}{2(1+\gamma)^2}\mathrm{VOD}_{\mathrm{ideal}}^2 * e^{\frac{2b}{d^2}} \tag{2.17}$$

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 by expressed by [10]:

$$E_{\mathrm{AEE}} = E_{\mathrm{F}} + E_{\mathrm{S}} + E_{\mathrm{K}} + E_{\mathrm{R}} + E_{\mathrm{NM}}, \tag{2.18}$$

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]:

$$E_{\mathrm{F}} = A_{\mathrm{F}} \gamma_{\mathrm{F}}, \tag{2.19}$$

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