High-Pressure Shock Compression of Condensed Matter

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Test Methods for Explosives

With 180 Illustrations
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It seems that there is no book that treats the measurement of the physical parameters of explosives as its only subject, although limited information is available in a number of books. Therefore, I have tried to bridge this gap in the literature with this book.

A large number of various physical parameters have to be determined experimentally in order to test or characterise an explosive. Various physical principles have been applied for such measurements. Accordingly, a large number of different experimental methods exist, as well as various testing apparatuses and procedures.

On the other hand, great progress has been made recently in the study of detonation phenomena. New measuring techniques can assess extremely short processes to below nanoseconds scale. They make it possible to determine important parameters in detonation physics.

I have made a great attempt to cover the available literature data on the subject. Because it would be a highly demanding task to include in a single volume all the methods that are in use by various testing agencies, I have tried to give primarily the principles for determination of individual physical parameters of explosives by different measuring methods as well as data treatment procedures.

It is known that many explosive parameters (e.g., sensitivity of explosive, working capacity, etc.) depend not only on the type of apparatus used for testing but also on the testing procedure applied. Many explosive properties also depend on the charge preparation procedure. Therefore, since 1958, attempts constantly have been made to standardise the methods for testing of explosives, first by the European Commission and later by the International Study Group.

In the five chapters of this book: General Concepts and Classification of Explosives, Sensitivity of Explosives, Combustion of Explosives, Detonation, and Working Capacity of Explosives, over 50 different testing methods are described.

The book is intended not only for newcomers to the field, graduate students, and practising engineers, but to be used also as a textbook for senior and postgraduate students, researchers, and scientists in the field of physics of explosives and explosion.
A number of people have helped in the preparation of this book. I thank the Brodarski institut—Marine Research and Special Technologies, Zagreb, Croatia, and the SUIS, Kumrovec, Croatia, for support during the preparation of the book. I thank Ms. Mira Horvatek for help with the translation of the manuscript, Mr. Vladimir Žeželj for preparation of the drawings, and Mr. Nikica Visković and Mr. Nikola Naranča for technical assistance. Special thanks are due to my colleagues Dr. Ines Batinic-Haberle of the Department of Chemistry, Duke University, Durham, NC (USA), for proofreading the manuscript and helpful suggestions, and Dr. Robert A. Graham of the Advanced Material Physics and Device Department 1153, Sandia National Laboratories, Albuquerque, NM (USA) for helpful suggestions that improved the manuscript.

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1 General Concepts and Classification of Explosives

An explosion can be generally defined as a process of the sudden expansion of matter to a volume much larger than the initial one. By this concept, the totalities of effects, including combustion, and detonation, as well as purely physical processes, such as sudden expansion of compressed gas, are understood.

Although explosions are usually associated with loud noise, clouds of black smoke, and scattering, they differ in nature, in particular in the physical nature of the energy of explosion and in the way it is released. One usually notices only the outward manifestation of the explosion.

The sources of the explosion energy are various: chemical, nuclear, thermal, electric, kinetic energy, energy of elastic compression, and the like. When a particular source of explosion energy is considered, three fundamental types of explosion can be distinguished: physical, chemical, and nuclear explosions.

Physical explosions (electrical discharges, steam explosion, volcanic explosion, meteor hitting Earth, and others) and nuclear explosions (thermonuclear reactions on the Sun’s surface) have always been present in the universe. According to some theories, explosions took part in the creation of the galaxies and Earth and also contribute to large and small scale qualitative changes that occurred on Earth’s surface.

Chemical explosions, that is, explosions of chemical substances, are the result of human activities. They are characterised by very high rates of propagation of chemical reactions through the explosive, accompanied by the release of a certain amount of thermal energy and by a large volume of warm gaseous products. These products are under a pressure much higher than the surrounding one. Thus, an explosion of a chemical explosive is essentially an irreversible process in which the explosive is converted into the final, mainly gaseous, products. The chemical reactions that are explosive in nature are characterised by

- high-rate propagation: the reaction can propagate through the explosive at a rate of nearly 10 km/s,
- the exothermic nature: the amount of released thermal energy is usually in the range between 3500 and 7000 kJ/kg,
the formation of a large amount of gaseous products; up to 1000 dm$^3$ per 1 kg of explosive, at standard conditions of temperature and pressure.

These reactions are also considered to be energetically self-sustaining. Chemical substances or mixtures of chemical substances that can, under the influence of some external energy (thermal, mechanical, etc.), undergo chemical reactions of the above-stated characteristics are called explosives or explosive substances. Depending on the initiation conditions of the chemical reactions, characteristics of explosives, physical state and mass of the explosive, existence and characteristics of confinement, etc., explosive processes can propagate at different rates and can have essentially different propagation mechanisms. With respect to these two factors, explosive processes may propagate in the form of combustion (or deflagration),$^1$ explosion, and detonation (Baum et al., 1959, 1975; Johansson and Persson, 1970).

All these processes have in common layer-by-layer propagation through the explosive substance in the form of a chemical reaction zone. Also, homogeneous explosion is possible. The basic difference among them is in the propagation mechanism and thus in the rate of propagation as well. During combustion, the energy is transferred from the warm gaseous products to the unreacted part of the explosive by heat conduction, diffusion, and radiation. These means of energy transfer are relatively slow, and therefore the combustion processes are relatively slow processes too. The theoretical upper limit of the combustion rate may be equal to the sound velocity through a given explosive. It is noteworthy that the external conditions, particularly pressure and temperature, significantly influence the rate of combustion.

Explosion and detonation are characterised by the same propagation mechanism based on the shock wave, i.e., on the dynamic compression of an explosive layer. However, the difference between them is in the stationarity of the propagation rate. Namely, explosion propagates at a non constant velocity, while detonation propagates at a constant velocity and is almost independent of the surrounding conditions. The velocity of the propagation of both explosion and detonation is always greater than the velocity of sound through a given explosive.

Explosive substances differ in a number of characteristics, such as chemical structure, sensitivity, and stability. They can be classified according to different criteria. However, the most satisfying classification seems to be

- initiating (primary) explosives,
- high (secondary) explosives,

$^1$Combustion denotes any oxidation reaction including those that introduce atmospheric oxygen. The term burning is also used for the same type of reaction. Deflagration denotes reactions that propagate without the introduction of atmospheric oxygen.
Primary explosives such as mercury fulminate, lead azide, lead styphnate, tetrazene, and diazodinitrophenol are characterised by a very high sensitivity to an external stimuli, which can cause the detonation of even very small quantities of primary explosives. Owing to this characteristic, they have been used primarily for the initiation of high explosives.

High explosives such as trinitrotoluene, pentrit, hexogen, octogen, nitroglycerine, nitroguanidine, and tetryl cannot be initiated as easily as primary explosives. In practice, they are usually initiated by means of primary explosives. Although detonation is their basic explosive process, high explosives can also, under certain conditions, burn steadily.

Propellants such as single base, double base, black powder, and composites are characterised by combustion, although some of them can even detonate under certain conditions.

Pyrotechnics can be separated as a particular group of explosive substances. They include flammable, smoke, illumination, flares, and other compositions and are characterised by combustion too.

1.1. Safety Precautions in Handling Explosives

All the activities related to the production, storage, maintenance, and use of explosives are extremely hazardous. Therefore, while performing these activities, special care should be exercised to create and maintain conditions that would eliminate any possibility of accidental explosion.

Safety measures in handling explosives include a system of co-ordinated technical, pyrotechnic, sanitary, education, and other activities directed towards the elimination of all possible causes of accidental explosions, and towards diminishing and removing the consequences of accidental explosions.

The analyses of some accidental explosions have shown that the most frequent causes of accidental explosions are subjective in nature, resulting from the disregard of necessary safety precautions.

Safety measures may be divided into

- preventive measures,
- limiting measures,
- special measures.

Preventive measures concern the elimination of all possible causes of accidental explosions. Limiting measures should be taken in order to diminish and bring under control the consequences of possible accidental explosions.
For performing the tests that are the subject of this book, it is necessary, among other things, to know well and to follow closely general safety instructions described elsewhere.

1.2. Initiating Devices

The initiation of high explosives in practice is performed by initiating devices, or initiators. The term *initiation* here denotes bringing an explosive into the state of deflagration or detonation.

Initiating devices are activated by external stimuli sources such as friction, spark, flame, and others. Depending on their application and external initiation mechanism, initiating devices can be classified into

- primers (or igniters),
- detonators,
- electric igniters and electric detonators,
- safety fuses,
- detonating cords.

*Primers* are used for the ignition of propellants and pyrotechnics and for the ignition of flash-type detonators, directly or indirectly, in the explosive train of a fuse. According to their external initiation mechanism, they are categorised into percussion primers that are mainly used for the ignition of propellants, stab primers used in the explosive train of fuses, and electric primers. These types of primers are given in Figure 1.1. With respect to the pyrotechnic mixture they are filled with, primers can be of sinoxid-mixture type and of mercury fulminate-based mixture type. A special type of percussion primer are so-called artillery primers. They are used for the ignition of large quantities of propellant charge in artillery ammunition. For this purpose, they are supplied with a tube filled with black powder.

*Detonators* (Figure 1.2) are used to detonate high explosives. They are classified according to their external initiation mechanism into stab and flash detonators. Stab detonators are initiated by a sharp firing pin and used in the explosive train of different types of fuses, while flash detonators are initiated by flame produced by a safety fuse, primer, delay elements, etc.

A special type of flash detonator ignited by the flame of a safety fuse is called the blasting cap. Other names such as standard detonator, nonelectric detonator, and ordinary detonator are in use as well. Blasting caps differ from each other according to the initiating strength and size. No. 8 and No. 6 blasting caps are the most frequently used types of such detonators. According to the type of pyrotechnic mixture they are filled with, detonators are mainly based on three types of mixtures: sinoxid-mixture, lead azide-based mixture, and mercury fulminate-based mixture.
Electric detonators (Figure 1.3) are used for the detonation of high explosive charges. They are similar in design to other types of detonators. The only difference lies in an electrical initiation achieved via a fusehead. An electric fusehead (Figure 1.1) consists of a bridgewire made of chromium/nickel wire. Bridgewire is covered by a heat-sensitive pyrotechnic mixture protected with varnish insulation. Standard types of electric fusehead have an electric resistance of 1.2–1.4 Ω. They are activated by electric current of 0.7 A.

![Diagram of fusehead](image)

Figure 1.1. Some types of primers: (a) percussion primers; (b) stab primer; (c) fusehead
Electric detonators are either of instantaneous or delay action. The electric detonators with delay action have a delay element between the electric fusehead and the initiating mixture. This element provides a half-second, quarter-second or millisecond delay time.

A safety fuse (Figure 1.4) is used for the direct ignition of propellants, pyrotechnics, and primary explosives. The safety fuse structure comprises a black-powder core, three either cotton or jute layers of yarn wound around it, a bitumen impregnation, and a plastic coating. The safety fuse burning time is usually $120 \pm 10$ s/m.

A detonating cord (Figure 1.5) is used for simultaneous detonation of a number of explosive charges. The detonating cord consists of a core, usually made of pentrit, cotton threads around it, and a plastic coating. When the core is made of pentrit, its detonation velocity is 6500 m/s. The detonating cord is initiated by means of a blasting cap.
Chapter 1. General Concepts and Classification of Explosives

Figure 1.3. Standard electric detonator

Figure 1.4. Safety fuse

Figure 1.5. Detonating cord
1.2.1. Initiation of High Explosive Charges

In practice, high explosive charge can be initiated

- by means of detonator and safety fuse (fuse detonator),
- electrically,
- by shock wave or by transmission of detonation.

The initiation of high explosive charge by means of a fuse detonator is performed using a safety fuse, a blasting cap, and, if necessary, a detonating cord. The simplest setup is shown in Figure 1.6.

It is not always possible to achieve a complete detonation of an explosive charge by means of blasting cap No. 8. This is the case, for example, if the charge is made of cast trinitrotoluene or is a mixture based on ammonium nitrate. In such cases, it is necessary to enhance the initiating impulse from the blasting cap using a booster (Figure 1.7). A booster is made of an explosive, usually tetryl, pentrit, or hexogen, which are more sensitive to blasting cap initiation than the explosive that is to be initiated.

In some cases, the initiation of the explosive charge by a plane shock wave is required. A plane wave may be produced by incorporating a lens of an inert material, a so-called wave shaper, such as polymethylmethacrylate (PMMA) in the explosive charge configuration. It may also be created by combining two explosives with different detonation velocities as shown in Figure 1.8.
The simultaneous detonation of several explosive charges, when they are at large distances from each other, can be realised by means of a detonating cord applying serial, parallel, or combined blasting networks. The combined blasting network is presented in Figure 1.9.

The electric initiation is a very effective way of simultaneous initiation of a number of explosive charges at a desired time. The devices for such an initiation include electric detonators, electric current sources, electric cables, lighting protective devices, and measuring instruments. Special blasting machines, dry batteries, storage batteries, power generators, etc. serve as electric current sources for the electric initiation of the explosive charges. Electric firing machines are the most frequently used since they produce direct current of a sufficiently high voltage and strength. According to the operating
principle, they can be divided into blasting machines with direct energy supply, such as self-induction or permanent magnet generator, and blasting machines with an indirect energy supply. In such machines, generated electrical energy is stored in a capacitor. These devices are also called capacitor blasting machines.
2
Sensitivity of Explosives

During production, storage, transport, and similar activities, explosives are frequently exposed to various external stimuli such as friction, impact, heat, etc. The ability of an explosive to react to these stimuli, resulting in either combustion or detonation, is defined as its sensitivity. This particular property of explosives might be a key factor in determining the practical applicability of a given explosive.

Due to the complexity of the initiation phenomenon, there is no absolute indicator of the sensitivity as expressed, for instance, by the minimum initiation energy. The energy required for the initiation of an explosive depends not only on the chemical nature of the explosive and on a number of physical parameters, but also on the kind of initial stimulus and the nature of energy transfer to the explosive. Thus, the total amount of the initiation energy may vary considerably. It could be generally stated that an even distribution of externally applied energy through the whole explosive volume is not suitable for a successful initiation. A high concentration of energy in time and in explosive volume is the necessary precondition for a successful initiation.

The energy required for the initiation of reactions of decomposition can be applied in the form of

- thermal impulses (flame, spark, heating, etc.),
- mechanical impulses (impact, friction, projectile impact, etc.),
- shock wave, etc.

2.1. Determination of the Heat Sensitivity of Explosives

The application of heat in the initiation of explosives can be realised in two ways

- by homogeneous heating of an explosive throughout its whole volume by means of a heat source but without exposing it to the open flame,
Chapter 2. Sensitivity of Explosives

- by local heating of an explosive by heat source in the form of flame, spark, etc.

In the former case, when a critical temperature is reached, the decomposition of the explosive follows according to the thermal explosion law. Namely, the initiation occurs after breaking down the heat balance between the energy generated by the external heating of the explosive and the heat dissipated into the surroundings. In the latter case, a localised thermal impulse creates a local zone in which reactions start to occur and then propagate through the rest of the explosive due to their self-sustaining character.

The comparative evaluation of the heat sensitivity of different explosives can be obtained by ignition temperature determination at a constant heating rate or isothermally. This temperature is also known as the deflagration point or deflagration temperature.

Principle of the Method

The ignition temperature can be experimentally determined by heating a sample of a given mass at a constant rate of temperature increase until the ignition occurs. The temperature at which, under given conditions, ignition occurs is assigned as ignition temperature.

Description of the Method

The determination of the ignition temperature can be performed in the apparatus shown in Figure 2.1.

The test is performed with 0.2 g of a sample that is previously dried and ground to a suitable particle size. The sample, placed in a test tube, is immersed in a liquid metal bath (usually Wood’s alloy) when the temperature in the bath reaches 100 °C. Three samples are tested simultaneously. An electric motor connected with a Beckman thermometer provides the heating rate of either 5 °C/min or 20 °C/min. When the ignition of the sample occurs, accompanied by a crack or whistle, the temperature is read out from the control thermometer.

A heating rate of 5 °C/min is typical for all types of explosives. The exception is the ignition temperature determination of black powder when a heating rate of 20 °C/min is applied.

Using the same apparatus, it is possible to determine the induction period, i.e., the time needed for the ignition of the sample at a given constant temperature (isothermally). The experiment is conducted as follows.

A Beckman thermometer is used to ensure a desired temperature. When the temperature stabilises, a test tube with the sample is immersed in a liquid alloy bath. A stop-watch is used to register the time interval between the immersion of the sample in the alloy and the ignition. This time period is the induction period.
Once the induction period is known, it is possible to calculate the activation energy of the ignition process, thus obtaining a more complete picture concerning the heat sensitivity of the explosives.

**Evaluation of Results**

The ignition temperature is determined as the lowest temperature of the three parallel tested samples. However, it should be noted that the ignition temperature value is influenced by several parameters, mostly by the mass of the sample, its physical state, and the heating rate. Therefore, when reporting test data, testing conditions also must be reported.

The energy of activation can be calculated on the basis of the experimentally obtained relation between temperature \( T \) and induction period \( \tau \) when testing is conducted isothermally, as shown in Figure 2.2. This relation can be expressed by the Arrhenius type of equation:

\[
\tau = B e^{E_a/(RT)} ,
\]  

(2.1)

where \( E_a \) is the energy of activation, \( R \) is the gas constant, and \( B \) is an experimental constant dependent on the explosive type.
From the logarithmic form of Eq. (2.1):

\[ \ln \tau = \ln B + \frac{E_a}{R} \frac{1}{T}, \]

it is evident that \( \ln \tau \) vs. \((1/T)\) is a linear function whose slope is \( E_a/R \). Thus, the energy of activation is

\[ E_a = R \tan \alpha. \quad (2.2) \]

It is to be pointed out that the ignition temperature should be distinguished from the autoignition temperature. Autoignition temperature is determined by the separate tests where the sample is heated at an automatically controlled oven temperature until exothermic decomposition reactions begin to occur. After this point is reached, the oven temperature is maintained constant. No additional heat is allowed to be transferred from the oven to the sample. The reactions in the sample continue due to their exothermic character. Thus, the autoignition temperature is a minimum temperature above which spontaneous ignition may occur.

The determination of autoignition temperature ("Autoignition Temperature," 1987), ignition temperature, and ignition activation energy, as well as the study of complete thermal behaviour of explosives as a function of temperature, are now mainly performed by means of thermal analysis. Most frequently used methods of thermal analysis are differential scanning calorimetry (DSC), differential thermal analysis (DTA), and thermogravimetry (TGA).

DSC (Figure 2.3) operates on the principle of heating a sample of a few milligrams in mass, at a controlled heating rate within the imposed temperature
range, followed by the simultaneous monitoring of the physical and chemical processes that are accompanied by the evolution or the absorption of heat. Such processes are dehydration, decomposition-ignition, phase transitions, melting, boiling, vaporisation, oxidation, etc.

A typical DSC thermogram is shown in Figure 2.4.

2.2. Determination of the Sensitivity of Explosives to Electric Spark

**Principle of the Method**

The electric spark sensitivity or electrostatic sensitivity test determines the minimum amount of energy of an electric spark discharge that will cause initiation of the tested sample.
Chapter 2. Sensitivity of Explosives

Figure 2.5. Schematic of an electric spark sensitivity test setup

**Description of the Method**

Somewhat different types of testing apparatus are used by different testing agencies ("Approaching-Electrode Electrostatic Sensitivity Test," 1987; McIntyre, 1980; "Safety and Performance Tests," 1972; "Sensibilite aux décharges électriques," 1982). A typical setup for the electric spark sensitivity testing is shown schematically in Figure 2.5. Whatever equipment is used, the principle of testing is as follows. A small amount of the powdered explosive is placed in a thin layer on a grounded metal plate-anode. The mass of the sample should not exceed 50 mg for high explosives and 15 mg for primary explosives. When a liquid explosive is tested, a couple of drops of a total mass below 25 mg are placed on the anode by means of a dropper.

The metal plate with the sample is placed on the holder in the apparatus, and the desired amount of energy of an electric spark is selected by the capacitor. Some values of electric spark energy vs. capacitance that are given in Table 2.1 are valid for a US ABL-Modified Bureau of Mines electrostatic discharge machine. An electric discharge is performed between the anode with the sample and the discharge needle-electrode using the cam actuating device. Electric discharge is realised by slowly lowering the electrode until the arc is formed between the anode and the electrode.

The test starts at the maximum energy level. It is then gradually decreased until the minimum energy level of electric spark that produces the initiation of the sample, is achieved. Initiation is considered to have occurred if either smoke, flame, flash, crackle, or characteristic smell of the reaction products is observed.

**Evaluation of Results**

The minimum energy level of electric spark that produces the initiation of the sample is considered to be measure of explosive sensitivity to the electric spark.
Table 2.1. The dependence of the energy of an electric spark on the capacitance value at a voltage of 5 kW

<table>
<thead>
<tr>
<th>Energy of spark, a J</th>
<th>Capacitance, µF</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.250</td>
<td>0.5</td>
</tr>
<tr>
<td>1.250</td>
<td>0.1</td>
</tr>
<tr>
<td>0.625</td>
<td>0.05</td>
</tr>
<tr>
<td>0.250</td>
<td>0.02</td>
</tr>
<tr>
<td>0.012</td>
<td>0.001</td>
</tr>
<tr>
<td>0.006</td>
<td>0.0005</td>
</tr>
<tr>
<td>0.001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

aEnergy of electric spark = \( \frac{CV^2}{2} \)


Since different types of testing apparatus are in use, it is necessary to standardise testing procedure, sample size, electrode to anode energy transfer, and the size of the electrodes. Despite differences in equipment, there seems to be a rather good correlation between different test data.

However, care should be exercised in the interpretation of the test results because at very high energy levels the arc can cause the dispersal of the sample. In some instances, this may cause the initiation of a dust cloud rather than a layer of the sample on the anode.

2.3. Determination of the Adiabatic Sensitivity of Explosives

Principle of the Method

The adiabatic sensitivity of an explosive is determined by allowing a test weight to fall from a predetermined height onto the air-compressing piston. This causes the compression of the air between the compressing piston and the sample of the explosive. Its adiabatic heating may consequently lead to the initiation of the sample.

Description of the Method

Adiabatic sensitivity testing can be conducted by means of the apparatus whose operating principle is illustrated in Figure 2.6. This test was developed in the US Naval Weapon Station—Yorktown (“Safety and Performance Tests,” 1972). The test is conducted in the following manner:
A sample, approximately 1 g, is placed into the sample holder. If the sample is granular, a special loading tool is used to press the sample in the holder to ensure that the height of the sample is 9.525 mm. The mass of the sample is adjusted to give a required loading density. The explosive can also be filled into the sample holder by casting, extruding, or applying other loading procedures, always maintaining, however, the height of the sample at 9.525 mm.

When the sample is prepared for testing, the drop weight is raised to the selected height \( H \). Then the loaded sample holder is installed into the machine. Between the compressing piston and the sample, a desired gap is adjusted, depending on the adiabatic sensitivity of the explosive. If an explosive of an unknown adiabatic sensitivity is being tested, it is the best to start from the minimum gap of 1.587 mm and the maximum drop height of 320 cm. If after the impact of the weight onto the compressing piston, the initiation does not occur, the gap is increased in increments of 1.587 mm. The increasing of the gap proceeds until a drop height with the smallest gap that permits the initiation is obtained.

**Evaluation of Results**

The adiabatic sensitivity value is the height of the drop weight at which 50% of trials result in the initiation of the explosive.

One possible way of finding out this particular drop height is to start from the maximum height. Then, if the initiation of the sample occurs in the first trial, the height is lowered for the increment for which the logarithmic value, if expressed in cm, is 0.05 (Table 2.2). For each subsequent trial, if the initiation
occurs, the drop height is lowered for the same increment. If no initiation occurs, the drop height is increased for the same increment. In this manner, 25 trials are performed, the results are recorded in a table, and then the 50% sensitivity drop height ($H_{50}$) is calculated. The $H_{50}$ calculation procedure, based on the statistical processing of the data, is illustrated by the example given in Tables 2.3 and 2.4.

The data from Table 2.3 are summarised in Table 2.4.

If the total number of initiations is lower than the number of noninitiations, the height of the drop weight at which 50% of initiations occur is calculated according to the equation

$$\log H_{50} = \log H_o + \log \Delta H \left( \frac{\sum AE}{\sum N} - \log \Delta H \right),$$

(2.3)

where $H_o$ is the lowest height of drop weight in the series and $\log \Delta H$ is the logarithmic increment of the drop height.

### Table 2.2. The height levels of the drop weight in the adiabatic sensitivity test

<table>
<thead>
<tr>
<th>Height level</th>
<th>Height ($H$), cm</th>
<th>log($H$)</th>
<th>Height level</th>
<th>Height ($H$), cm</th>
<th>log($H$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.0</td>
<td>0.6051</td>
<td>19</td>
<td>40.5</td>
<td>1.6051</td>
</tr>
<tr>
<td>0.5</td>
<td>4.5</td>
<td>0.6551</td>
<td>20</td>
<td>45.0</td>
<td>1.6551</td>
</tr>
<tr>
<td>1</td>
<td>5.0</td>
<td>0.7051</td>
<td>21</td>
<td>50.5</td>
<td>1.7051</td>
</tr>
<tr>
<td>2</td>
<td>6.0</td>
<td>0.7551</td>
<td>22</td>
<td>57.0</td>
<td>1.7551</td>
</tr>
<tr>
<td>3</td>
<td>6.5</td>
<td>0.8051</td>
<td>23</td>
<td>64.0</td>
<td>1.8051</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>0.8551</td>
<td>24</td>
<td>71.5</td>
<td>1.8551</td>
</tr>
<tr>
<td>5</td>
<td>8.0</td>
<td>0.9051</td>
<td>25</td>
<td>80.5</td>
<td>1.9051</td>
</tr>
<tr>
<td>6</td>
<td>9.0</td>
<td>0.9551</td>
<td>26</td>
<td>90.0</td>
<td>1.9551</td>
</tr>
<tr>
<td>7</td>
<td>10.0</td>
<td>1.0051</td>
<td>27</td>
<td>101.0</td>
<td>2.0051</td>
</tr>
<tr>
<td>8</td>
<td>11.5</td>
<td>1.0551</td>
<td>28</td>
<td>113.5</td>
<td>2.0551</td>
</tr>
<tr>
<td>9</td>
<td>12.5</td>
<td>1.1051</td>
<td>29</td>
<td>127.5</td>
<td>2.1051</td>
</tr>
<tr>
<td>10</td>
<td>14.5</td>
<td>1.1551</td>
<td>30</td>
<td>143.0</td>
<td>2.1551</td>
</tr>
<tr>
<td>11</td>
<td>16.0</td>
<td>1.2051</td>
<td>31</td>
<td>160.5</td>
<td>2.2051</td>
</tr>
<tr>
<td>12</td>
<td>18.0</td>
<td>1.2551</td>
<td>32</td>
<td>180.0</td>
<td>2.2551</td>
</tr>
<tr>
<td>13</td>
<td>20.0</td>
<td>1.3051</td>
<td>33</td>
<td>202.0</td>
<td>2.3051</td>
</tr>
<tr>
<td>14</td>
<td>22.5</td>
<td>1.3551</td>
<td>34</td>
<td>226.5</td>
<td>2.3551</td>
</tr>
<tr>
<td>15</td>
<td>25.5</td>
<td>1.4051</td>
<td>35</td>
<td>254.0</td>
<td>2.4051</td>
</tr>
<tr>
<td>16</td>
<td>28.5</td>
<td>1.4551</td>
<td>36</td>
<td>285.0</td>
<td>2.4551</td>
</tr>
<tr>
<td>17</td>
<td>32.0</td>
<td>1.5051</td>
<td>37</td>
<td>320.0</td>
<td>2.5051</td>
</tr>
<tr>
<td>18</td>
<td>36.0</td>
<td>1.5551</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2.3. An example of the test data

<table>
<thead>
<tr>
<th>Height level</th>
<th>Height, cm</th>
<th>log(H)</th>
<th>Reaction</th>
<th>Height level</th>
<th>Height, cm</th>
<th>log(H)</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>45.0</td>
<td>1.6551</td>
<td>E</td>
<td>19</td>
<td>40.5</td>
<td>1.6051</td>
<td>E</td>
</tr>
<tr>
<td>19</td>
<td>40.5</td>
<td>1.6051</td>
<td>N</td>
<td>18</td>
<td>36.0</td>
<td>1.5551</td>
<td>N</td>
</tr>
<tr>
<td>20</td>
<td>45.0</td>
<td>1.6551</td>
<td>N</td>
<td>19</td>
<td>0.5</td>
<td>1.6051</td>
<td>N</td>
</tr>
<tr>
<td>21</td>
<td>50.5</td>
<td>1.7051</td>
<td>E</td>
<td>20</td>
<td>45.0</td>
<td>1.6051</td>
<td>E</td>
</tr>
<tr>
<td>20</td>
<td>45.0</td>
<td>1.6551</td>
<td>E</td>
<td>19</td>
<td>40.5</td>
<td>1.6051</td>
<td>N</td>
</tr>
<tr>
<td>19</td>
<td>40.5</td>
<td>1.6051</td>
<td>N</td>
<td>20</td>
<td>45.0</td>
<td>1.6051</td>
<td>N</td>
</tr>
<tr>
<td>20</td>
<td>45.0</td>
<td>1.6551</td>
<td>N</td>
<td>21</td>
<td>50.5</td>
<td>1.7051</td>
<td>E</td>
</tr>
<tr>
<td>21</td>
<td>50.5</td>
<td>1.7051</td>
<td>N</td>
<td>20</td>
<td>45.0</td>
<td>1.6051</td>
<td>N</td>
</tr>
<tr>
<td>22</td>
<td>57.0</td>
<td>1.7551</td>
<td>E</td>
<td>21</td>
<td>50.5</td>
<td>1.7051</td>
<td>N</td>
</tr>
<tr>
<td>21</td>
<td>50.5</td>
<td>1.7051</td>
<td>E</td>
<td>22</td>
<td>57.0</td>
<td>1.7551</td>
<td>N</td>
</tr>
<tr>
<td>20</td>
<td>45.0</td>
<td>1.6551</td>
<td>E</td>
<td>23</td>
<td>64.0</td>
<td>1.8051</td>
<td>E</td>
</tr>
<tr>
<td>19</td>
<td>40.5</td>
<td>1.6051</td>
<td>E</td>
<td>22</td>
<td>57.0</td>
<td>1.7551</td>
<td>E</td>
</tr>
<tr>
<td>20</td>
<td>45.0</td>
<td>1.6551</td>
<td>N</td>
<td>21</td>
<td>50.5</td>
<td>1.7051</td>
<td>N</td>
</tr>
<tr>
<td>23</td>
<td>64.0</td>
<td>1.8051</td>
<td>E</td>
<td>22</td>
<td>57.0</td>
<td>1.7551</td>
<td>E</td>
</tr>
</tbody>
</table>

Legend: E initiation; N noninitiation.


### Table 2.4. Summarised data presentation

<table>
<thead>
<tr>
<th>Height level</th>
<th>Height, cm</th>
<th>Number of initiations, $\sum E$</th>
<th>Number of non-initiations, $\sum N$</th>
<th>$A^a$ (or $AN$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>36.0</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>40.5</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>45.0</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>21</td>
<td>50.5</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>22</td>
<td>57.0</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>23</td>
<td>64.0</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Totally:</td>
<td>12</td>
<td>13</td>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Level of the step height (the lowest step height in the series is assigned as level zero, next upward is assigned as level 1, etc.)

When the total number of initiations is greater than the number of noninitiations, the 50% sensitivity height is obtained by the equation

$$
\log H_{50} = \log H_0 + \log \Delta H \left( \frac{\Sigma AN}{\Sigma N} + \log \Delta H \right).
$$

In the given example $\Sigma N > \Sigma E$, thus $H_{50}$ value is calculated using Eq. (2.3):
\[ \log H_{50} = 1.556 + 0.05 \left( \frac{32}{12} - 0.05 \right), \]

i.e. \( H_{50} = 48.6 \) cm.

Besides reporting the \( H_{50} \) value, the gap value between the compressing piston and the tested sample, the mass of the drop weight, the way of loading the sample material into the holder, and the sample density should be considered in the data analysis.

### 2.4. Sensitivity of Explosives to Mechanical Stimuli

The initiation mechanism of an explosive when different mechanical stimuli such as impact, friction, firing pin impact or puncture, projectile or fragment impact, etc. are applied is similar and rather complex. The most acceptable theory that explains the initiation mechanism by mechanical stimuli is the so-called “hot spots” theory.

The initial mechanical stimuli are dynamic in nature. Therefore, under the dynamic action, strain and stress appear locally in the explosive, resulting in its local heating. The places of local heating, called “hot spots,” are the most probable causes of the initiation of an explosive.

It is generally accepted that, in order to achieve successful initiation of the majority of explosives, hot spots should have the following characteristics:

- temperature above 700 K,
- temperature duration above 300 \( \mu s \),
- diameter above 10 \( \mu m \).

#### 2.4.1. Determination of Impact Sensitivity


All these apparatuses operate on the same principle: a sample of the tested explosive is subjected to the action of a drop weight. The parameter to be determined is the mass of the drop weight and the drop height at which the initiation of the sample may occur. The main difference between the apparatuses
is related to their design and manner in which the sample is subjected to the drop weight impact via different types of plungers. For example, in the BoE Apparatus, a 10 mg sample is placed in a test cup; in the BoM Apparatus, it is placed between two parallel flat steel surfaces; whereas in the case of the PA Apparatus, the sample is placed in a die cup.

The BAM Impact Apparatus, which seems to give reasonably reproducible results, is described below.

**Principle of the Method**

A sample placed between two flat, parallel, hardened steel surfaces is subjected to the drop weight impact. Depending on the characteristics of the tested explosive, the drop weight mass, and the drop height (i.e., impact energy), the initiation of the sample may or may not occur. The drop height that enables the initiation of the tested explosive is the measure of its impact sensitivity.

**Description of the Method**

The BAM Impact Apparatus is presented in Figure 2.7.

A sample of the tested explosive is placed in the piston device, which consists of two steel rollers and a hollow cylinder (Figure 2.8). The sample is taken by a special 30 mm$^3$ measuring cup. Cast or pressed explosives should be previously grounded. The measured sample is placed into the open piston device (without the upper roller). The roller is then carefully placed back onto the piston device and slightly pushed until it touches the sample. The centering ring and the intermediate anvil are used to place the piston device with the sample on the anvil, and the protective wooden case of the apparatus is closed. The drop weight is then positioned to the desired height by means of the locking and unlocking device.

Pressing the locking and unlocking device lever arm, the drop weight is unlocked, consequently impacting the upper roller of the piston device. The sample response is observed.

For the impact sensitivity testing, drop weights having a mass of 1, 2, 5, or 10 kg are used. The weights have the grooves for frictionless guiding along sliding roads, parts for marking drop height, parts for locking in the locking–unlocking device, and mechanism for stopping the weight after rebounding from the anvil.

**Presentation of Result**

The impact of the drop weight, via the piston device, onto the sample may result in either its initiation or noninitiation, depending on the sensitivity of the explosive, the weight mass, and its drop height. The initiation is observed by sound, light effects, or smoke, or by inspecting the piston device. If none of these effects are noticed, initiation failure (noninitiation) is registered.
It is important to note that the piston device can be used only once. Every new test is conducted with a new piston device and a new sample.

The test can be conducted and the test results reported in the following ways:

a) A percentage of initiations \((I)\) under defined testing conditions and with a definite number of trials \((N)\): In the usual testing procedure of 25 trials, the drop height of the weight is held constant at 25 cm while the mass of the weight is changed. The experiment starts with the maximum mass of the weight. If after 25 trials the percentage of initiations is higher than 96% in the next testing series the mass of the weight is reduced. The percentage of initiations is calculated according to the equation:

\[
I = \left( \frac{N}{25} \right) \times 100
\]
The data on impact sensitivity of some explosives obtained in this manner are given in Table 2.5.

b) The impact sensitivity curve for a given explosive, i.e., the relation between the percentage of initiations and the drop height of the weight having constant mass: The experiment is conducted using a weight of a constant mass and by changing the drop height. For each drop height, six consecutive trials are performed and the corresponding percentage of initiations is calculated. The test results obtained can be tabulated or graphically presented, as shown in Figure 2.9.

Table 2.5. Impact sensitivity of some explosives

<table>
<thead>
<tr>
<th>Sensitivity level</th>
<th>Explosive</th>
<th>Percentage of initiations with 10 kg weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>High sensitivity</td>
<td>Nitroglycerine, Pentrit</td>
<td>100</td>
</tr>
<tr>
<td>Increased sensitivity</td>
<td>Hexogen, Octogen</td>
<td>72–80</td>
</tr>
<tr>
<td>Medium sensitivity</td>
<td>Tetryl</td>
<td>44–52</td>
</tr>
<tr>
<td>Low sensitivity</td>
<td>Trinitrotoluene</td>
<td>4–8</td>
</tr>
<tr>
<td>Nonsensitivity</td>
<td>Ammonium nitrate</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: After Baum et al., 1975.
Chapter 2. Sensitivity of Explosives

Figure 2.9. Impact sensitivity curve

On the basis of the results obtained, the impact sensitivity can be expressed as the drop height at which 50% initiations occurred ($H_{50}$), the minimum drop height at which 100 initiations occurred ($H_{100}$), and the maximum drop height at which lack of initiation is observed ($H_{0}$).

Also, the test results can be expressed by the impact energy ($E_i$), at which a certain percentage of initiations occurred (usually 50%). The impact energy is calculated according to the equation:

$$E_i = M_w H g,$$

where $E_i$ is the impact energy, $M_w$ is the mass of the weight, $H$ is the drop height, and $g$ is the acceleration due to gravity.

c) The relative impact sensitivity ($O_R$) with respect to the impact sensitivity of a referent explosive, usually trinitrotoluene: The relative impact sensitivity of an explosive compared to that of trinitrotoluene is calculated by Eq. (2.7):

$$O_R = \frac{E_i(X)}{E_i(TNT)} \times 100,$$

where $O_R$ is the relative impact sensitivity, $E_i(X)$ is the impact energy of the tested explosive, and $E_i(TNT)$ is the impact energy of trinitrotoluene.

Some impact testing methods take the minimum drop height at which at least one of ten consecutive trials results in initiation of the sample as a measure of the impact sensitivity.

The results obtained may vary due to differences in the way the experiments
are conducted and reported, and with respect to the type of impact sensitivity apparatus being used. However, when all influencing factors are considered, it appears that there is similarity between the results obtained by different testing apparatuses.

The impact sensitivity of the primary explosives can be determined in a small BAM apparatus of the same design as the large one. There are modifications of the impact sensitivity test arrangements where the sample of a primary explosive is placed in a metal cup. For example, according to Weller (cited in Baum et al., 1975) impact impulse from the drop weight is transmitted to the sample via a striker ending in a truncated cone (Figure 2.10). A 0.02 g sample is placed into the metal cup and a weight that has mass between 0.5 and 1.8 kg is allowed to drop upon the sample via the striker.

Some data regarding the impact sensitivity of primary explosives obtained using the Weller method are shown in Table 2.6.

Table 2.6. Impact sensitivity of some primary explosives obtained by the Weller method

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Mass of the weight, kg</th>
<th>Drop height ((H_0)), cm</th>
<th>Drop height ((H_{100})), cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury fulminate</td>
<td>0.6</td>
<td>5.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Tetrazene</td>
<td>0.6</td>
<td>4.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Lead azide</td>
<td>0.6</td>
<td>–</td>
<td>25.0</td>
</tr>
<tr>
<td>Lead stypnate</td>
<td>0.6</td>
<td>–</td>
<td>50.0</td>
</tr>
</tbody>
</table>

\(H_0\), the drop height below which no initiation occurs;

\(H_{100}\), the drop height above which 100% initiations occur.

Source: After Baum et. al., 1975.

Figure 2.10. Schematic presentation of the impact sensitivity determination for the primary explosives according to Weller
2.4.2. Determination of Friction Sensitivity

During their life cycle, explosives are very often subjected to friction either between explosive particles or between explosive particles and various types of working surfaces. Under appropriate conditions, friction can cause the initiation of an explosive.

Between the surface of two materials in relative motion, sliding frictional force \( F_{xy} \) exists. It is proportional to the normal force \( F \) pressing the two materials together:

\[
F_{xy} = \mu_F F,
\]

where \( F_{xy} \) is the sliding frictional force, \( F \) is the normal force, and \( \mu_F \) is the friction coefficient.

The energy used to overcome the frictional force is spent either in the form of mechanical work or as heat. As a result of the heat, two bodies in relative motion become warmed. As the contact areas of two bodies in relative motion are not smooth on a microscopic scale, the dissipation of mechanical energy in the form of heat will mainly be localised. The points of local heating, called hot spots, are initiators of explosive chemical reactions. The temperature of the hot spots depends upon

- relative velocity between friction areas,
- normal force pressing two materials together,
- thermal conductivity coefficient,
- friction coefficient.

When the friction sensitivity is determined, the relative velocity of the bodies in motion, the friction coefficient, and the thermal conductivity coefficient are kept constant, whereas the normal force between contacting areas is changed.

The determination of the friction sensitivity can be performed using different types of apparatus including the Picatinny Friction Pendulum, where a 0.7 g sample is exposed to the action of a steel shoe swinging as a pendulum at the end of a long steel road; the Rotary Friction Apparatus, which determines the maximum frictional energy that will not initiate the sample when it is exposed to the friction generated between a stationary wheel and a sliding anvil surface; German Bundesanstalt für Materialprüfung (BAM) Apparatus (Andersen, 1981; Baum et al., 1959; “Friction Sensitivity Test,” 1987; Koenen et al., 1961; McIntyre, 1980; “Safety and Performance Tests,” 1972; “Senzibilité à la Friction Lineaire,” 1977; Suceska, 1987).

The testing procedure using the BAM Friction Apparatus is described below.
Principle of the Method

Friction is electromechanically generated between a small, stationary, cylindrically shaped porcelain pistil having a rough spherical end surface and a rough porcelain plate bearing a sample. The normal force between the porcelain pistil and the plate is changed. The normal force at which 50% of initiations occur is usually reported as the friction sensitivity measure.

Description of the Method

The BAM Friction Sensitivity Apparatus is shown in Figure 2.11. The operation mode of the apparatus is as follows. Friction is created electromechanically between the cylindrical porcelain pistil and the plate bearing the sample. The pistil and the plate are of definite roughness. The size and the shape of the plate and the pistil are shown in Figure 2.12.

Approximately 10 mg of dry explosive is placed on the rough porcelain plate which is attached to the sliding carriage of the apparatus. The cylindrical porcelain pistil, which is clamped in its carriage, is then lowered to the top of the sample by means of the loading arm. The loading arm is loaded by a
selected weight. The mass of the weight and its position on the loading arm determine the loading on the pistil, i.e., the normal force between the porcelain plate and the pistil. The force may vary from 4.9 to 353.2 N, as given in Table 2.7. The movement of the porcelain plate bearing the sample is provided by means of an electric motor. The stroke length is 10 mm forward and backward in the initial position.

The initiation occurrence depends upon the friction sensitivity of the tested explosive and the selected force. The occurrence of the initiation may be observed through the sound effects (crackling), appearance of smoke, or by the characteristic smell of the decomposition products.

The porcelain plate and the pistil must be replaced for each new testing.

**Evaluation of Results**

The test is conducted in such a way that the loading on the pistil is varied and the percentage of initiations under constant loading conditions is determined. Six consecutive trials are performed for each loading, and a friction sensitivity curve is established (Figure 2.13).

The characteristic points on the friction sensitivity curve $F_0$, $F_{50}$, and $F_{100}$, are reported as the friction sensitivity test results. Alternatively, the smallest loading of the pistil at which initiation is observed at least once in six trials may be reported as the test result.

**2.4.3. Determination of the Sensitivity to Fragment Impact**

High-velocity fragments, bullets, or projectiles impacting the explosive charges can cause their detonation. The determination of the sensitivity level of a given explosive to such mechanical stimuli is of considerable practical interest.
Figure 2.13. Dependence of the percentage of initiations on the normal force between the pistil and the plate bearing the sample

Table 2.7. The dependence of the normal force between the porcelain plate and the pistil upon the mass of the weight and its position on the loading arm in the BAM Friction Apparatus

<table>
<thead>
<tr>
<th>Weight number</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.9</td>
<td>5.9</td>
<td>6.9</td>
<td>7.8</td>
<td>8.8</td>
<td>9.8</td>
</tr>
<tr>
<td>2</td>
<td>9.8</td>
<td>11.8</td>
<td>13.7</td>
<td>15.7</td>
<td>17.7</td>
<td>19.6</td>
</tr>
<tr>
<td>3</td>
<td>19.6</td>
<td>23.5</td>
<td>27.5</td>
<td>31.4</td>
<td>35.3</td>
<td>39.2</td>
</tr>
<tr>
<td>4</td>
<td>29.4</td>
<td>35.3</td>
<td>41.2</td>
<td>47.1</td>
<td>52.9</td>
<td>58.9</td>
</tr>
<tr>
<td>5</td>
<td>39.2</td>
<td>47.1</td>
<td>54.9</td>
<td>62.8</td>
<td>70.6</td>
<td>78.5</td>
</tr>
<tr>
<td>6</td>
<td>58.9</td>
<td>70.6</td>
<td>82.4</td>
<td>94.2</td>
<td>105.9</td>
<td>117.7</td>
</tr>
<tr>
<td>7</td>
<td>78.5</td>
<td>94.2</td>
<td>109.8</td>
<td>125.6</td>
<td>141.3</td>
<td>156.9</td>
</tr>
<tr>
<td>8</td>
<td>117.7</td>
<td>141.3</td>
<td>164.8</td>
<td>188.4</td>
<td>211.9</td>
<td>235.4</td>
</tr>
<tr>
<td>9</td>
<td>176.6</td>
<td>211.9</td>
<td>247.2</td>
<td>282.5</td>
<td>317.8</td>
<td>353.2</td>
</tr>
</tbody>
</table>

The methods for the experimental determination of the fragment (or projectile) impact sensitivity of an explosive differ in details such as

- the shape and the size of the projectile impacting into the explosive charge tested,
- the shape and the size of the explosive charge and the way it is exposed to the projectile impact (kind of confinement, if any),
- the bore calibre from which the projectile is fired,
- the way of registering the effects of the projectile impact into the explosive charge.

However, it should be pointed out that all of the methods are intended to simulate real circumstances as adequately as possible (Barker et al., 1985; James, 1988; Köhler and Meyer, 1993; Ljungberger, 1973).
A testing method developed in Great Britain (RARDE Fragment Attack Test) (Barker et al., 1985) will be described here.

**Principle of the Method**

A cylindrical steel projectile is fired using a smooth bore having a calibre of 12.7 mm, impacting into a tested explosive filled into a cylindrical holder, the impact test vehicle. On the basis of the test vehicle damage caused by the projectile impact, the response of the tested explosive is determined.

When the projectile velocity is varied, the relationship between the degree of explosive response and the projectile velocity is obtained.

**Description of the Method**

The RARDE fragment attack test arrangement is shown in Figure 2.14. The explosive charge is contained in a mild-steel vehicle (Figure 2.15). The density of the explosive charge and the loading procedure applied are such that they correspond to the density employed in normal service use. After the test vehicle is filled with the explosive, the vehicle is closed with a mild-steel or aluminum end cap, which provides a 3.2 mm thickness of a front septum.

A cylindrical steel projectile, 12.7 mm in diameter and 12.7 mm long, is used in testing. The projectile is fired using a smooth-bore gun 12.7 mm in calibre such as a modified Browning gun. The projectile velocity varies within the limits of 400–2000 m/s by changing the propellant charge mass. The projectile velocity is measured for each firing. Thin foil screens connected to a microsecond counter may be used for the projectile velocity measurements. The projectile velocity and the explosive response can also be monitored using a high-speed camera.

![Figure 2.14. Fragment attack test arrangement](image)
Evaluation of Results

When different projectile velocities are applied, the relation between the explosive response and the projectile velocity is determined. The kind of induced explosive response to the projectile impact can be determined on the basis of the damage of the test vehicle. The following categories are possible (Barker et al., 1985):

- **Degree 0**: No visible sign of reaction after penetration of the septum by the projectile.
- **Degree 1**: Hint of burning reaction, which has faded rapidly, no obvious consumption of explosive.
- **Degree 2**: Detachment of the septum, up to 20% of explosive consumed.
- **Degree 3**: Septum detached, vehicle intact or broken into large fragments, more than 20% of explosive consumed.
- **Degree 4**: 100% of explosive consumed in a very violent reaction characterised by breaking up the vehicle into a large number of small fragments.

Although the division into these categories is rather rough, degree 4 may indicate full explosion of the explosive charge, while degrees 0, 1, and 2 imply rather mild explosive responses.

The test results are generally reported in the form of graphs (Figure 2.16) showing the degree of response over the range of velocities.

The minimum projectile velocity at which the complete detonation of the explosive charge occurs also can be reported as the test result. In this case, particular care should be exercised in the identification of the completion of detonation.
2.4.4. Determination of Impact Vulnerability

Principle of the Method

This method determines the capability of a tested explosive, filled in an aluminum tube, to withstand the impact of a driving metal plate having a velocity of 122 ± 7 m/s. Such a velocity of the metal plate is obtained using a special propulsion charge made of low-bulk-density nitroguanidine.

Description of the Method

The explosive is filled in an aluminum tube 25.4 mm in internal diameter, 25.4 mm high and 1.6 mm in wall thickness (Figure 2.17). If the explosive is granular, it is filled into the aluminum tube by direct pressing at 1115 kp/cm² (McIntyre, 1980). Other types of explosives such as cast, molded, and extruded are previously prepared in the form of a cylinder 22.2 mm in diameter and 25.4 mm high and then are filled into the aluminum tube. The density of the explosive is calculated from its volume and its mass.

The steel plate that impacts the explosive charge is made of steel of a defined quality. It is heat treated to a hardness of 28-31 Rockwell C, is 50.8 mm in diameter, and 19.05 mm high.

The propulsion charge should be sufficient to propel the steel plate at a velocity of 122 ± 7 m/s. It is made of nitroguanidine, whose density is 0.685 g/cm³.
The nitroguanidine is filled into the cardboard tube in four portions, each portion having a mass of 70.5 g. Such a mass should ensure the required velocity of the steel plate. However, by means of previously performed measurements, the plate velocity and the amount of nitroguanidine necessary to give the specified plate velocity have to be established.

Nitroguanidine is initiated by a booster 50.8 mm in diameter and 12.7 mm in height. The booster is made of tetryl pressed at 1115 kp/cm².

**Evaluation of Results**

After the initiation of the nitroguanidine propulsion charge, the steel plate is propelled at a velocity of 122 m/s. Depending on the sensitivity of the explosive, the impact of the steel plate can cause its initiation. Whether or not the initiation has occurred may be concluded on the basis of dent depth or other detectable damage in the steel witness plate.

An explosive is considered to have satisfied the impact vulnerability test if no initiations of the tested explosive are caused in 20 consecutive trials.
2.5. Determination of the Initiating Strength of Primary Explosives

**Principle of the Method**

The determination of the initiating strength or priming ability of primary explosives is very important for the correct solution of tasks related to the service application of the primary explosives in initial devices, explosive trains, etc.

The principle of the initiating strength determination is based upon the determination of the minimum mass of a primary explosive that is, under defined conditions, capable of causing complete detonation of a certain high-explosive charge (Baum et al., 1975; “Mesure du pouvoir d’amorçage méthode de la charge limite,” 1979; “Safety and Performance Tests,” 1972). This mass serves as the measure of the priming ability of the given explosive.

**Description of the Method and Evaluation of Results**

One of the possible methods for testing the initiation strength of the primary explosives is illustrated in Figure 2.18. The test is conducted as follows.

One gram of selected high explosive is press-loaded at 1000 kp/cm² in a copper tube 45 mm high, 7 mm in external diameter, and 0.3 mm in wall thickness. Above it, the primary explosive is also press-loaded at 500 kp/cm². The mass of the primary explosive is varied.

By means of a plastic or wooden holder, the copper tube is placed in a vertical position on a lead plate 35 mm in diameter and 5 mm thick. The initiation of the primary explosive is performed by means of a safety fuse. If a clear hole is cut in the witness lead plate, a complete detonation of the high explosive has occurred. By reducing or increasing the mass of the primary explosive, the minimum mass necessary to cause a complete detonation of the selected high explosive is determined. Six consecutive trials have to be performed for each applied mass. The data related to the minimum mass of the primary explosives that may cause a complete detonation of given high explosives are presented in Table 2.8.

The initiating strength of primary explosives can also be determined by the method illustrated in Figure 2.19. It differs from the previous method in a way that shock effects, caused by the complete or incomplete detonation of a high-explosive charge, are registered on the basis of the dent depth produced in the witness steel plate.

The test is conducted in the following manner: 200 mg of hexogen are press-loaded at 1115 kp/cm² in a polymethylmetacrylate (PMMA) holder. Above it, a primary explosive is filled in the state at which its initiating strength is to be tested: freely poured or pressed to a desired density. The initiation of the primary explosive is performed by means of a safety fuse. If the depth of the dent produced after initiation in the steel witness plate of 70-90 Rockwell B hardness is greater than 0.76 mm, the complete detonation of hexogen is
Chapter 2. Sensitivity of Explosives

The test starts with 100 mg of a primary explosive. Then, depending on the test result, the mass is reduced or increased at 15 mg increments until the mass at which 50% of initiations of hexogen occur is determined.

The comparative initiating strength of different types of primary explosives may be obtained in a similar way—on the basis of the dent depth produced in the steel witness plate after the detonation of the primary explosive alone. For this, 300 mg of primary explosive alone is press-loaded at 1115 kp/cm² into a PMMA sample holder, which is then placed on the steel witness plate. The initiation of the primary explosive is performed by means of the safety fuse. The depth of the dent produced in the steel witness plate after the detonation of the primary explosive is connected with its initiating performance and serves for the comparative evaluation of the initiating strength of different types of primary explosives.

It should be pointed out that the initiating strength of primary explosives depends on several factors, such as explosive purity, loading density, confinement conditions, etc. Thus, the results obtained by different testing methods are not directly comparable.

Table 2.8. Minimum mass of the primary explosives required for the complete detonation of high explosives

<table>
<thead>
<tr>
<th>High explosive</th>
<th>Mercury fulminate</th>
<th>Lead azide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trinitrotoluene</td>
<td>0.36</td>
<td>0.090</td>
</tr>
<tr>
<td>Tetryl</td>
<td>0.29</td>
<td>0.025</td>
</tr>
<tr>
<td>Hexogen</td>
<td>0.19</td>
<td>0.050</td>
</tr>
<tr>
<td>Pentrit</td>
<td>0.17</td>
<td>0.01–0.02</td>
</tr>
</tbody>
</table>

Source: After Baum et al., 1975.
2.6. Determination of the Sensitivity of High Explosives to Detonators

The sensitivity of high explosives to the initiation by a given detonator depends primarily on their characteristics, density, and confinement conditions, as well as on the type of detonator being used. Detonators differ from each other in their size, weight, and the type of the explosive they are filled with. Consequently, their capabilities to detonate different types of high-explosive charges are different too.

The experimentally determined ability of a detonator to detonate a high explosive can be applied to determine the comparative sensitivity of different types of high explosives. The results obtained may be used to classify the explosives with respect to hazard too.

The methods described below are primarily intended for sensitivity testing of an explosive to the standard detonator, the blasting cap. The tests are also known as cap sensitivity tests.


Chapter 2. Sensitivity of Explosives

Principle of the Method

The cap sensitivity tests described here are based on the initiation of a high explosive charge by the standard detonator. The effects of the detonation of the explosive charge on a lead cylinder, steel plate, or steel tube are observed. On the basis of these effects, the conclusion about the completion of the detonation of the high explosive is made.

Description of the Methods and Evaluation of Results

The determination of the sensitivity of high explosives to the detonator may be performed using the testing equipment shown in Figure 2.20.

The sample material is filled in a 200 mm long steel tube with a 22 mm inside diameter and a 2.8 mm wall thickness. The sample mass is adjusted to give a desired density of the explosive charge. In the modifications of the test, steel tubes of different dimensions and tubes of different materials are also used.

The charge is initiated by means of the standard detonator, No. 8, No. 6, or equivalent, either electric or nonelectric. After detonation, the steel tube is either damaged or destroyed, depending on the completion of the detonation of the high explosive. According to Fukuyama (1980), depending on the tube damage, the explosive can be classified according to the sensitivity degrees given in Table 2.9.

The sensitivity of the high explosive to the detonator may also be determined by the method illustrated in Figure 2.21.

Figure 2.20. Steel tube cap sensitivity test (Reprinted with permission from Fukuyama, 1980)
Table 2.9. The degree of the cap sensitivity of the explosives according to Fukuyama

<table>
<thead>
<tr>
<th>Degree of sensitivity</th>
<th>Steel tube state after explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Detonation: steel tube destroyed into small pieces.</td>
</tr>
<tr>
<td>2</td>
<td>Detonation: steel tube destroyed into medium-sized pieces.</td>
</tr>
<tr>
<td>3</td>
<td>Incomplete detonation: half of steel tube destroyed.</td>
</tr>
<tr>
<td>4</td>
<td>Incomplete detonation: only the part of steel tube in the vicinity of detonation destroyed, the rest of tube undamaged.</td>
</tr>
<tr>
<td>5</td>
<td>Nondetonation: steel tube undamaged.</td>
</tr>
</tbody>
</table>

Source: Reprinted with permission from Fukuyama, 1980.

A 50.8 mm cube sample is placed on the top of a perpendicular lead cylinder, 38 mm in diameter and 101.6 mm high. The cylinder is placed onto a steel plate. By means of a wooden or plastic holder, the detonator is put on the top surface of the sample. The detonator is initiated in an adequate manner, and the state of the lead cylinder after the detonation is examined. On the basis of the compression of the lead cylinder, i.e., reduction of its initial height, the conclusion about the completion of the detonation is made.
Another cap sensitivity test was developed in Germany (cited in Köhler and Meyer, 1993). According to this test, a high explosive is filled into a 200 mm long cardboard tube having an inside diameter of 80 mm. The determination of completion of the detonation is accomplished on the basis of the clean hole cutting in the 1 mm thick steel witness plate.

2.7. Shock Wave Initiation of Detonation

A shock wave, which can be generated in various ways in an explosive, frequently serves as a tool for the initiation of explosives. The shock wave initiation mechanism is based on the formation of a dynamic compression zone immediately behind the shock wave front. In the zone due to the temperature rise, exothermic reactions begin to occur.

The initiation mechanism of heterogeneous explosives (e.g., mixture-type of explosives) is somewhat different compared to the initiation mechanism of the homogeneous explosives.

The initiation mechanism of heterogeneous explosives is mainly the result of the local heating of an explosive, leading to the formation of hot spots due to

- friction between the solid particles of the explosive,
- viscous heating produced by the rapid flow,
- friction caused by the shear stress at the sliding surface,
- adiabatic compression of air inclusions.

The critical values of the shock wave pressure that may cause the initiation of heterogeneous explosives are 1–5 GPa, while the hot spot temperature is 700–800 K.

The initiation of homogeneous explosives, for example, liquid explosives, may occur as a result of homogeneous heating in the dynamic compression zone. However, for successful initiation, the shock wave pressure should exceed 10 GPa, causing the hot spot temperature to rise up to 1000 K.

Accordingly, the possibility of initiation of an explosive by shock wave depends basically on the shock wave pressure, but it also depends on the shock wave time profile (Figure 2.22), i.e., the shock wave positive phase duration.

The experimental study of the shock wave initiation process is primarily directed to the determination of the pressure of the shock wave front, which may cause initiation, and to the determination of the relation between the shock wave pressure and the distance (or time) that the shock wave passes through the explosive before being transformed into a full detonation wave. This distance is known as run-to-detonation distance.

Particularly interesting, from the practical point of view, is the study of the phenomenon of transmission of detonation from one to another neighbouring explosive charge, and the investigation of all factors that influence this phenomenon. This phenomenon is known as a sympathetic detonation.
2.7.1. *Wedge Test for Determination of the Shock Wave Initiation Sensitivity*

**Principle of the Method**

As already stated, when a high explosive is subjected to the action of the shock wave whose pressure is somewhat below its detonating wave pressure, the shock wave will travel a run-to-detonation distance through the explosive before being transformed into a full detonation wave. The lower the pressure of the shock wave, the longer the distance (or time) to the full detonation. The sensitivity of a given explosive to shock wave initiation is indicated by run-to-detonation distance.

The wedge test principle consists in monitoring the propagation of the shock wave front of a known initial pressure through the tested explosive that has a wedge form, followed by the verification of distance at which the shock wave transforms into a full detonation wave (Gibbs and Popolato, 1981; "Safety and Performance Tests," 1972).

**Description of the Method**

The determination of the sensitivity of an explosive to the initiations by the shock wave applying the wedge test is schematically illustrated in Figure 2.23.

The explosive being tested is formed by pressing, or casting (or some other technique) into a square-based triangular wedge. The inclination angle of the wedge is small enough to minimise rarefaction effects as the shock wave exits the upper wedge surface. For explosives with a narrow chemical reaction zone, the inclination angle is 30–35 degrees. A shock wave of known pressure is generated by means of the plane wave generator, booster, and attenuator. The shock wave generated acts on the base of the wedge. At the wedge toe, it
immediately begins to emerge from the wedge through its top surface. The locus of the shock wave front exit on the top surface is recorded by a high-speed streak camera owing to a distinct change in the reflectivity at this locus. The record in the form of a shock wave travelling distance vs. time relation is obtained. The illumination of the wedge top surface is provided by means of an Argon flash bomb or some other similar technique.

The exit of the shock wave on the top wedge surface can also be viewed by optical fibre/streak camera technique (see Subsection 4.1.2). The successive exit of the shock wave on the upper wedge surface is transmitted by optical fibres as a light signal, which is recorded with a streak camera. If more optical fibres are aligned at known distances along the upper wedge surface (Figure 2.24), again the travelling distance vs. pressure curvature may be established.

In practice, boosters of various sizes with a diameter even above 200 mm are used for testing purposes. This enables the use of an explosive charge wedge having a base length above 100 mm. The plane wave generator, the booster, the attenuator, and the wedge are bonded together by thin layers of binder. Diluted polyurethane elastomer may be used for that purpose.

The desired shock wave pressure may be obtained using different combinations of boosters and attenuators. Some examples are given in Table 2.10.

**Evaluation of Results**

A typical record of the shock wave exit on the wedge upper surface as obtained by a streak camera is shown in Figure 2.25.
Figure 2.24. Wedge test setup with optical fibres/streak camera recording technique

Table 2.10. The possibility of obtaining shock waves of different pressure

<table>
<thead>
<tr>
<th>Booster (25.4 mm thick)</th>
<th>Attenuator</th>
<th>Shock wave pressure, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material</td>
<td>Thickness, mm</td>
</tr>
<tr>
<td>TNT</td>
<td>Al 2024</td>
<td>12.7</td>
</tr>
<tr>
<td>LX-04</td>
<td>Brass</td>
<td>25.4</td>
</tr>
<tr>
<td>Baratol</td>
<td>Brass</td>
<td>12.7</td>
</tr>
<tr>
<td>Baratol</td>
<td>Brass</td>
<td>12.7</td>
</tr>
<tr>
<td>Baratol</td>
<td>Brass</td>
<td>19.1</td>
</tr>
<tr>
<td>Baratol</td>
<td>Brass</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Note: Baratol—mixture of Ba(NO₃)₂ and TNT at different mass ratios.

Figure 2.25. A typical record of the shock wave propagation through a tested explosive
A curvature of the same shape, but in a series of discontinuous points representing the shock wave travelling through an explosive, is obtained when the optical fibres/streak camera technique is used.

The transition of the shock wave into the detonation wave is visible on the travelling distance-time curve as a point at which the slope has rapidly changed. The distance that the shock wave passes through the explosive until the transition point occurs can be calculated from the upper surface distance \( Y_t \) that is actually recorded on the streak camera film (see Figure 2.26):

\[
Y = Y_t \sin \alpha,
\]

(2.9)

where \( Y \) is the run-to-detonation distance and \( \alpha \) is the inclination angle of the wedge.

The distance \( Y \) is seen on the film as trace \( R \):

\[
R = f Y_t \cos(\beta - \alpha),
\]

(2.10)

where \( f \) is the magnification on the film.

Consequently, the run-to-detonation distance \( Y \) can be calculated according to the equation

\[
Y = \frac{R \sin \alpha}{f \cos(\beta - \alpha)}.
\]

(2.11)

The shock wave velocity \( (U_m) \) may be calculated from the test data by Eq. (2.12).
where $\Omega$ is the camera writing speed and $dR/dt$ is the slope of trace on the film.

On the basis of the test data, the relation between the shock wave pressure and run-to-detonation distance is finally obtained. The length of the run distances in different types of explosives at the same shock wave pressure is the measure of the explosive sensitivity to the shock wave initiation.

It should be mentioned that it is necessary to find out the relationship between the attenuator thickness and the transmitted shock wave pressure by prior tests. Some of the tests described in Section 5.9 may be applied for this kind of measurement.

### 2.7.2. Gap Test for Determination of the Shock Wave Initiation Sensitivity

#### Principle of the Method

The gap test enables the determination of the minimum shock wave pressure that can cause complete detonation of the tested explosive. The explosive to be tested is subjected to the action of the shock wave of a known pressure. Such wave is generated by means of a booster and a shock wave pressure attenuator. Whether or not the shock wave caused the complete detonation of the explosive can be concluded on the basis of the mechanical effects produced after the detonation of the explosive: hole cutting in a steel plate, dent depth in a witness steel block, or compression of a copper cylinder.

In this kind of test, the gap medium stops flying particles and direct heat transmission completely, thus serving as a heat filter. Consequently, the shock wave is the only energy transmitted to the explosive.

#### Description of the Method

There are several variants of the gap test (Aubert et al., 1989; Foan and Coley, 1981; Foster et al., 1985; Grief et al., 1985; Hollenberg, 1986; Keefe, 1981; "Large Scale Gap Test," 1987; "Mesure du pouvoir d'amorcage méthode du gap test," 1975; Sanchidián, 1993). The main difference among them is in the size of the donor (booster) and acceptor (tested explosive) charges. This difference arises because the tests must be performed with shock waves not only of different pressures but also of different duration of the shock wave positive phase. Thus, for example, when increasing the donor and acceptor diameters from 50 to 200 mm, the shock wave positive phase duration may increase from a few to nearly 50 milliseconds.
The US Naval Ordnance Laboratory’s (NOL) large-scale gap test is illustrated in Figure 2.27.

The explosive is filled into a 139.7 mm long steel tube having an inside diameter of 36.5 mm. The explosive mass is adjusted to give a desired loading density.

A booster made of tetryl, pentolite, or phlegmatised hexogen (depending on the desired pressure of the initial shock wave) serves as a shock wave generator. Between the booster and the tested explosive charge, an attenuator of the pressure of the shock wave is inserted. The material of which the attenuator is made and its thickness depend on the desired pressure of the shock wave, which is to be achieved at its exit from the attenuator. Generally, the attenuators are made of material whose adiabatic shock is well known such as duralumin, PMMA, polyamide, and the like.

By selecting the appropriate booster and thickness of the attenuator, the desired pressure of the shock wave can be obtained. If, for example, the booster is made of phlegmatised hexogen with 5% wax and 1.60 g/cm³ density, and the attenuator of Polyamide-6, then the dependence of the pressure of the shock wave upon the thickness of the attenuator shown in Figure 2.28 is obtained.
The level of damage to the steel wetness plate after the detonation may serve as a criterion for the estimation of the completion of detonation. The complete detonation of the explosive (acceptor) is indicated when a clean hole is cut in the steel witness plate that is 9.53 mm thick.

Alternatively, the dent depth in a steel witness plate that is 76.2 mm in diameter and 50.8 mm thick may be taken as a criterion of the completion of the detonation. In that case, a PMMA ring spacer with an 11.1 mm inside diameter and 12.7 mm height is placed between the explosive and the witness block.

### Evaluation of Results

The test result may be given as the minimum pressure of the shock wave that may cause the complete detonation of the explosive (acceptor charge) or as the pressure of the shock wave at which 50% of complete detonations occur.

### 2.7.3. Determination of the Transmission of Detonation in Open Air

The term transmission of detonation or sympathetic detonation denotes the phenomenon of initiation of an explosive charge by the detonation of a neighbouring charge. The maximum distance between two charges in a line at which transmission of detonation may occur depends on many factors: mass of the charge and its density, detonation properties of charges, physical and chemical characteristics of charges, existence and characteristics of acceptor charge confinement, existence and characteristics of the medium between the
Chapter 2. Sensitivity of Explosives

charges, etc. The distance at which transmission of detonation may occur is also influenced by the shape of the donor charge and the position of its initiation.

If other relevant factors are constant, the possibility of the transmission of detonation is determined mostly by both the sensitivity of the acceptor charge and by the initiating strength of the donor charge.

It should be mentioned that the transmission mechanism is rather complex and somewhat different if compared to that of a gap test. It includes the initiation of the acceptor charge by a shock wave, by flying particles from the charge casing or from the surroundings, by hot detonation products, and the like.

**Principle of the Method**

The method is based on the determination of the distance between the donor and the acceptor charge of given masses at which transmission or failure of detonation occurs. On the basis of the test data, the coefficient of the transmission of detonation is calculated.

More detailed study of the transmission of detonation through the air also includes the determination of the functional relationship between the key parameters in the transmission of detonation: the performance and the mass of the donor charge and the distance at which detonation transmission occurs under defined testing conditions. The influence of other parameters such as donor shape, existence, and kind of donor confinement can also be included into the study.

**Description of the Method**

One possible way of testing transmission of detonation through the air, recommended by the International Study Group for the Standardisation of the Methods of Testing Explosives (Ahrens, 1977), is illustrated in Figure 2.29.

Prior to the test, the explosive charge whose mass is 100 g (or another mass used in normal industrial cartridges), is kept for 20–40 hours in a room at a constant temperature ranging from 20 to 25 °C. Fluctuations are allowed to be within one degree. The climatisation period may vary depending on the type of explosive.

Two charges, donor and acceptor, separated from each other by a desired distance equal to a whole number of centimetres, are attached by means of metal wires or an adhesive tape along the same axis to a rigid rod, 4 mm in diameter and at least 500 mm in length. The whole setup is suspended at a distance of at least 500 mm from the walls of the chamber where the test is being conducted. When the charges are attached, a standard detonator is inserted into the previously made 12 mm deep cavity in the donor charge. After the distance alignment is done and the distance between the charges is checked, the initiation of the donor charge is performed.
Depending on the test result—transmission of detonation or its failure—the distance between the donor and the acceptor charge is decreased or increased in the next trial according to the following distance scale:

- from 0 cm to 9 cm in steps of 1 cm
- from 10 cm to 20 cm in steps of 2 cm
- beyond 20 cm in steps of 5 cm

**Evaluation of Results**

By decreasing or increasing the distance between the donor and the acceptor charge, the greatest distance at which in three consecutive trials complete detonation of the acceptor charge is observed ($d_{100}$) is determined. In addition, the distance at which in three consecutive trials no transmission of detonation to the acceptor charge ($d_0$) occurs is determined. On the basis of these characteristic distances, the coefficient of transmission of detonation ($C.T.D.$) is calculated:

$$C.T.D. = \frac{d_{100} + d_0}{2}$$

(2.13)

One can also study the influence of the mass of the donor charge on the distance at which complete transmission of detonation to a given acceptor charge may occur. Then the tests are conducted in such a manner that the distances $d_{50}$ or $d_{100}$ at which transmission of detonation occurs in 50% or 100% cases, respectively, are determined for each mass of the donor charge. On the basis of the data, the dependence of the distance ($d_{50}$ or $d_{100}$) upon the mass of the explosive charge ($M_d$) as shown in Figure 2.30 may be obtained.
It has been experimentally shown that the functional dependence of the distance $d_{50}$ upon the mass of the donor charge may be expressed by Eq. (2.14) (Baum et al., 1959):

$$d_{50} = kM_d^n,$$

(2.14)

where constants $k$ and $n$ may be obtained by the fitting of the experimental data $d_{50} - M_d$.

Belyaev (cited in Baum et al., 1975) has found out that for the majority of high explosives $n$ has a value between 0.33 and 0.50, whereas the value of $k$ is between 0.2 and 0.55 if $M_d$ is expressed in kg and $d_{50}$ in cm.

2.7.4. Determination of the Transmission of Detonation in Confinement

Principle of the Method

This test is designed to simulate the real circumstances of the possible industrial use of ion exchange (permitted) explosives.

The donor and acceptor charges, separated by an air gap, are placed in a coal-cement tube stemmed at both ends. By decreasing or increasing the distance between the charges, one can determine the maximum distance at which in three consecutive trials the complete transmission of detonation is achieved.

Description of the Method and Evaluation of Results

Explosive charges 30 mm in diameter and up to 150 mm in length are placed in a 500 mm long coal-cement tube. The tube has an inside diameter of 40 mm and an outside diameter of 140 mm (Figure 2.31).
The donor charge is initiated by a standard detonator. The detonator is completely inserted into the donor charge in order to allow the contact between the charge and the stemming. A desired distance between the charges is adjusted, usually in the range from 0 to 20 cm, according to the same distance scale given in Subsection 2.7.3, where testing of the transmission of detonation in the open air is presented. Then both tube ends are closed by 30 mm long clay stemming and initiation is performed.

The tube is made of low-rank semibituminous coal and Portland cement: 2 parts coal + 1 part cement + 1 part water. Instead of a coal-cement tube, either a steel tube or a rigid PVC tube without stemming can be used as a resistant confinement. The steel tube is 40 mm in inside diameter, 76 mm in outside diameter, and 500 mm in length, while the PVC tube is 42 mm in inside diameter, 50 mm in outside diameter, and 500–1000 mm long.

The test result is given by the greatest distance between the charges at which three consecutive trials lead to a complete detonation of the acceptor charge.

2.7.5. Determination of the Transmission of Detonation on a Free Surface

Principle of the Method

The method is based on the determination of the maximum distance between the donor and the acceptor charge, placed on a flat steel plate, at which complete transmission of detonation from the donor to the acceptor charge is obtained in three consecutive trials.
Description of the Method and Evaluation of Results

Donor, acceptor, and control charges are placed along the same axis on a 700x700x100 mm steel plate (Figure 2.32). When the distance between the donor and the acceptor charge is adjusted, the initiation of the donor charge is performed by a standard detonator.

The efficacy of transmission of detonation can be estimated on the basis of the completion of detonation of the control charge placed immediately after the acceptor charge and on the basis of the traces left on the steel plate. When the complete detonation of the acceptor charge occurs, the control charge is detonating too. In the absence of detonation, it is only thrown away or damaged.

The maximum distance at which the complete transmission of detonation is observed in three consecutive trials is reported as a test result.

2.8. Determination of Blasting and Technical Characteristics of Detonators

Apart from the requirements regarding the safe handling of detonators and their size, some other requirements concerning their blasting and technical characteristics have to be met. Only those detonators that fulfill all the imposed requirements may be used as a reliable device for the initiation of high explosive charges.

The testing of blasting and technical characteristics of different types of detonators—first, their sensitivity to the external stimuli and their initiating strength—is performed using various methods (Ahrens, 1973, 1977; Eitz, 1973; Giltaire, 1973; Gurton, 1972; Moreau and Grosborne, 1973; Prior, 1973; Sinabell, 1973; Wenstöp, 1973). The most frequently used testing methods are:

- flash detonator sensitivity testing to the open flame,
– stab detonator sensitivity testing to the action of the firing pin,
– initiating strength testing by the lead block test,
– initiating strength testing by the lead plate test,
– initiating strength testing by the compression of a copper crusher,
– initiating strength testing by the Sevran method,
– initiating strength testing by the Haid method.

2.8.1. Determination of the Sensitivity of Flash Detonators to Open Flame

Principle of the Method

Flash detonators, which are initiated by a flame (e.g., safety fuse flame), should to be tested to the action of the open flame.

The test is based on the determination of the maximum distance between the detonator and the flame source at which the initiation of the detonator is achieved. A standard percussion primer or a specially prepared ignition charge made of black powder is used as a flame source.

Description of the Method

Devices used for the determination of the flash detonator’s sensitivity to the open flame may be of different design. The basic difference refers to the flame source used for the initiation of flash detonators. The flame may be originated by a

– standard percussion primer,
– black powder ignition charge.

The black powder ignition charge, used in the former Soviet Union, is made by pressing black powder and has the shape and size shown in Figure 2.33. The mass of the charge is between 0.095 and 0.102 g, and its density is between 1.74 and 1.81 g/cm³. The charge is ignited electrically by an electrically resistant wire. The wire is coiled at the site that is in contact with the ignition charge.

A typical device for the determination of the flash detonator sensitivity to the flame of the black powder ignition charge is presented in Figure 2.34.

The detonator is placed on a lead witness plate, 35 mm in diameter and 1.5–5 mm thick, in order to test simultaneously its initiating strength. Depending on the type of detonator, a clean hole will be cut through a lead witness plate of a definite thickness, see Subsection 2.8.4.
The distance between the ignition charge and the detonator can be adjusted by lowering and raising the holder of the lead plate. After the desired distance is obtained, the protecting door of the casing is closed, and the initiation of the ignition charge is performed.
If a percussion primer is used as a source of the flame, the test may be conducted in the apparatus shown in Figure 2.35. A percussion primer, usually a Boxer type, 5.5 mm in diameter, is placed in the plastic holder. It is initiated through an impact of a firing pin achieved by the drop weight. The weight may be locked and unlocked at a desired drop height in different manners. Mainly, the electromagnetic way of locking-unlocking is used. A 45 mm long steel firing pin, 4 mm in diameter, is used. The firing pin has a blunt end in the form of a truncated cone with an inclination angle of 15 degrees and a flat end 0.38 mm in diameter. The mass of the weight and the drop height at which the initiation of the percussion primer occurs in 100% of cases are determined by the preliminary tests.

Figure 2.35. Test arrangement for the determination of flash detonator sensitivity to flame using a percussion primer as a flame source
Evaluation of Results

By changing the distance between the flame source and the flash detonator, one can establish the maximum distance at which 100% of initiations of the detonator occur. The number of consecutive trials for the same distance may vary from at least 6 up to 50.

Throughout the testing procedure, the initiating strength of the detonator is also simultaneously determined on the basis of the hole punched through the lead witness plate of defined thickness.

2.8.2. Determination of the Sensitivity of Stab Detonators to the Firing Pin

Principle of the Method

The test applies to the stab detonators that are initiated by firing pin action.

The test is based on the action of a firing pin, impacted by a weight dropping from a selected height onto a stab detonator. The mass of the weight and the drop height at which initiation of the detonator occurs are reported as test results.

Description of the Method

The arrangement for the testing of the sensitivity of the stab detonator to the action of the firing pin is illustrated in Figure 2.36.

A 45 mm long steel firing pin, 4 mm in diameter, is used in testing. The firing pin has a blunt end, the shape of a truncated cone with an inclination angle of 15 degrees and a flat end 0.38 mm in diameter. The stab detonator, inserted into a plastic cylindrical holder, is centered on a lead plate. The diameter of the plate is 30–35 mm, and its thickness is 1.5–5 mm, depending on the detonator type, i.e., its initiating strength. Then a plastic holder of the firing pin, which also serves for centering and guiding of the pin, is placed above the lead plate. Finally, the firing pin is slowly lowered to touch the detonator.

Weights of different masses can be used for testing. The most frequently used weight has a mass of 52 ± 0.5 g. The mechanism of the locking and unlocking of the weight at the desired drop height can be operated differently, however, most often electromagnetically.

Evaluation of Results

The experiment is conducted so that the drop height of the weight is changed, and the percentage of initiation is determined for each drop height of the
weight. Six consecutive trials are performed for each drop height. On the basis of the test results, the impact sensitivity curve is constructed as shown in Figure 2.37.

The test result may be given by the characteristic points on the impact sensitivity curve. They are the drop height above which 100% of initiations occur ($H_{100}$), the drop height below which no initiation occurs ($H_0$), and the drop height at which initiation is achieved in 50% of trials ($H_{50}$).

The method enables simultaneous determination of the initiating strength of the detonators on the basis of the hole that is punched through the witness lead plate of a defined thickness.

Figure 2.36. The arrangement for the testing of the sensitivity of stab detonators to action of the firing pin
2.8.3. Lead Block Test for Determination of the Initiating Strength of Detonators

Principle of the Method

The initiating strength of detonators is determined on the basis of the expansion of a lead block (Sinabell, 1973). The expansion is produced when a tested detonator is initiated in the cavity of the lead block.

Description of the Method and Evaluation of Results

As already stated, the detonator is placed into the cavity of the lead block (Figure 2.38). The block should be made of lead having precisely defined quality. It should be cast from soft lead at 390–400 °C. No tin or antimony impurities are allowed.

Dry sand passed through a sieve of 144 meshes is used, if necessary, for stemming the cavity after the insertion of a detonator. The initiation of the detonator is performed by a suitable manner—by safety fuse or electrically.

After the initiation of the detonator, the volume of the cavity of the lead block will be increased due to the action of the detonation products. The expansion of the cavity is measured by pouring into it the required volume of water. The net expansion value is obtained as the difference of the cavity volume after and before detonation (initial volume of cavity).

Throughout the testing procedure, the block temperature is maintained at 15 °C. If temperature differs from 15 °C, the correction in the cavity volume due to the temperature expansion of the lead should be applied (see Section 5.1).
2.8.4. Lead Plate Test for Determination of the Initiating Strength of Detonators

**Principle of the Method**

The lead plate test is conducted in order to determine the initiating strength of the detonators on the basis of its ability to punch a clean hole through a lead plate of defined thickness and quality. The method may be applied to various types of detonators.

**Description of the Method and Evaluation of Results**

The lead plate test setup is presented in Figure 2.39. The plates used in the experiment are made of unalloyed lead, 30–40 mm in diameter and 1.5–5 mm thick, as required for a given detonator type. For example, the No. 8 standard detonator should cut a clean hole through a 5 mm thick lead plate.
The plate is placed in its carriage, and the detonator is placed perpendicularly to the top surface of the plate. A detonator holder is used to center the detonator in the middle of the lead plate. When varying the plate thickness, the particular thickness through which a detonator can punch a clean hole, can be established. The diameter of the hole should be equal to or greater than the diameter of the detonator. The defined thickness that a given detonator can “puncture” is a measure of the detonator strength. According to the criteria imposed on the thickness of the lead plate, the test also may serve for verifying the validity of the given detonator.

2.8.5. Copper Crusher Compression Test for Determination of the Initiating Strength of Detonators

Principle of the Method

A specially prepared test explosive charge is initiated by a detonator whose initiating strength is to be determined. Depending on the initiating strength of the detonator, the test explosive charge is either partially or completely detonated. The completion of the detonation is established on the basis of the degree of compression of a standard copper crusher.

The degree of the compression of the copper crusher, i.e., the decrease of its initial height, expressed in the “crushing units,” is the measure of the initiating strength of the detonator.

The method is mainly applied for the testing of both electric and nonelectric detonators.

Description of the Method

The arrangement of the copper crusher compression test is shown in Figure 2.40.

A mixture of the pure crystalline trinitrotoluene with 2% of paraffin oil is used as the test explosive (Ahrens, 1977). The test explosive is prepared in the following way.

In a 50 L vessel that has double shells, 15.8 kg of trinitrotoluene is dissolved in a solution made of 14 L of acetone and 18 L of ethanol. The mixture is then stirred and heated at 50 °C until trinitrotoluene is completely dissolved. The solution is then cooled at 25 °C and stirred for three hours, followed by the vacuum filtration. Afterwards, the filtrate is washed with alcohol and dried at room temperature. The dry trinitrotoluene is passed through a 1 mm sieve. Approximately 92% of the particles in the final product should range in size from 30 to 60 μm. On the laboratory scale, 1/10 of the stated quantities could be sufficient.

Then 200 g of trinitrotoluene, prepared as described, are placed in a long pan, 250 mm in diameter, and diluted in a solution of 4 g of paraffin oil in 100
ml of ether. The mixture is stirred for 10–15 minutes. At the end, the mixture obtained is put into a fume cupboard and is left there until the ether has evaporated completely.

The test explosive is pressed by an annular press ram into the casing (Figure 2.41) made of Al/Mn alloy. The height of the casing is 50.8 mm, its inside diameter is 14.9 mm, and the thickness of the wall is 0.7 mm. The filling and the pressing of the test explosive into the metal casing is done in three portions—each of approximately 1.25 g of the explosive pressed at 375 bar.

A cardboard cylinder is used to center the metal casing with the test explosive on a steel roller. The roller is 15 mm in diameter and 15 mm high, and it lays on a copper crusher. Finally, the detonator is placed into the test explosive, and it is initiated.

**Evaluation of Results**

Before the detonator is tested, the compression characteristics of the test explosive must be verified. At least three series, ten trials of each, have to
be performed for verifying. The test explosive is considered valid if the compression of the copper crusher corresponds to certain previously established values, depending on the type of the detonator. Thus, for example, the mean value of the crusher compression when a standard nonelectric detonator (having 0.6 g pentrit charge) is used should be equal to $2.5 \pm 0.1$ mm.

For testing, ten consecutive trials are performed, and the compression of the crusher is measured for each trial with a micrometer that is accurate to 1/100 mm. The mean value of the compression of the copper crusher and the deviation are reported as test results.

The measured compression value may be converted into the so-called “units of crushing” according to Table 2.11. The units of crushing correspond to the load that acts on the crusher.

2.8.6. *The Sevran Method for Determination of the Initiating Strength of Detonators*

**Principle of the Method**

A specially prepared test explosive charge that is placed perpendicularly to a witness lead plate is initiated by a detonator. The depth of the dent created in the lead witness plate after complete or incomplete detonation of the test explosive charge serves as the measure of the initiating strength of a given detonator (Ahrens, 1977; Giltaire, 1973).

**Description of the Method**

The Sevran test arrangement is illustrated in Figure 2.42.

The test explosive used in the experiment has the following composition (Ahrens, 1977):
Table 2.11. Table for converting the deformation into the units of crushing for a copper crusher 7 mm in diameter and 10.5 mm high (according to Haid and Selle)

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<th>Deformation, mm</th>
<th>Units of crushing</th>
<th>Difference</th>
<th>Deformation, mm</th>
<th>Units of crushing</th>
<th>Difference</th>
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</table>

Figure 2.42. Test arrangement for the determination of the initiating strength of the
detonator by the Sevran method

- pentrit 43%
- potassium perchlorate 37%
- plasticizer 20%

The composition of the plasticizer is

- polyvinylacetate 19%
- dinitroethylbenzene 25%
- dinitrotoluene 50%
- trinitrotoluene 6%

The substances used for the preparation of the test explosive should have the
following characteristics:
- Pentrit should have a melting point of 140.4 °C, and a particle size such
  that 100% of the particles should pass through a 1 mm sieve, over 75% through
  a 0.5 mm sieve, and less than 5% through a 0.125 mm sieve.
- Potassium perchlorate should have a purity above 99%. The potassium
  chlorate content must be below 0.5%. The size of the particles must ensure that
  100% pass through a 1 mm sieve and more than 90% through a 0.2 mm sieve.
- Polyvinylacetate should be of such a degree of polymerisation that the
  solution of 2 g of polyvinylacetate in 100 ml of nitrobenzene has a viscosity of
  0.0035 ± 0.0005 Pa·s at 20 °C.
- Dinitroethylbenzene produced by nitration of ethylbenzene should have a
  density of 1.29 g/cm³ at 18 °C.
- Dinitrotoluene, which is actually a mixture of isomers, contains 1/3
  mononitrotoluene. Therefore, it is liquid above 2 °C and has a density of 1.34
  g/cm³ at 18 °C.
- Trinitrotoluene should have a melting point in a range of 78–80 °C.

The test explosive is filled into a cardboard tube 25 mm in inside diameter. The cardboard tube is formed by winding a piece of cardboard (17 cm x 15 mm) around a special piston to obtain the required inside diameter of the tube. The mass of the test explosive is 60 g and the overall height 69.3 mm. The explosive is filled into the tube in two portions of 30 g each and is pressed to a height of 34.65 mm. In the upper portion of the test explosive charge, a 20 mm deep cylindrical cavity is made to insert the detonator to be tested.

The test explosive charge should not be used earlier than 48 hours after preparation.

The witness plate (150x150x30 mm) is made of >99.98% pure lead by casting at a temperature of 360 °C.

**Evaluation of Results**

The initiation of the tested detonator results in the complete or incomplete detonation of test explosive charge, depending on the detonator initiating strength. On the basis of a volume of a dent produced in the witness plate, the conclusion upon the initiating strength of different types of detonators can be made.

In one test, three to six detonators are examined. The volume of the dent produced in the lead witness plate is measured by pouring in water from a graduated burette or by means of fine sand. The mean value of the dent volume is reported as a test result.

Several factors may influence the test results:

- the lead plate temperature; the temperature increase from 15 to 20 °C results in the dent volume change for ~ 1 cm³ due to the thermal expansion of the lead,
- the mass of the test explosive; when the mass is decreased from 60 to 55 g, a dent volume is decreased for 5 cm³,
- the test explosive “age”; when the accelerated aging is performed at 40 °C during 160 hours, the dent volume decreases about 6%.

**2.8.7. Haid’s Method for Determination of the Initiating Strength of Detonators**

**Principle of the Method**

A specially prepared test explosive charge placed perpendicularly to the lead plate is initiated by a detonator. The test explosive charge is made from the mixture of trinitrotoluene and talcum as a phlegmatizer at different ratio. The
maximum amount of the talcum at which the detonator is still capable of causing the complete detonation of the test explosive charge is reported as the test result.

The degree of the completion of detonation of the test explosive charge has been evaluated on the basis of the dent depth in the lead witness plate.

**Description of the Method**

Haid's test setup is illustrated in Figure 2.43. The explosive charge, 25 mm in diameter and 41 mm high, is formed by pressing the mixture of trinitrotoluene having a particle size between 0.15 and 0.50 mm and fine grounded talcum at 1225 kp/cm². The talcum content in the test explosive can reach 70% by mass.

A cavity for the detonator is made on the upper end of the test explosive charge. The explosive charge is placed on the lead witness plate. The plate has a 100 mm diameter and a 30 mm thickness. After the insertion of the detonator into the cavity, the initiation occurs.

**Evaluation of Results**

The experiment starts with a certain content of talcum in the test explosive. If the complete detonation of the test explosive charge occurs, as observed on the basis of the depth of the dent in the lead witness plate, a new trial is performed with an increased amount of talcum content. The testing proceeds until determination of the talcum content at which the given detonator is no longer capable of causing the complete detonation of the test explosive charge.

The maximum talcum content at which a given detonator may cause the complete detonation of the test explosive charge serves as the measure of the detonator initiating strength. The number of consecutive trials under the same testing conditions may even exceed 20.

![Figure 2.43. Haid's test setup](image-url)
2.9. Determination of the Initiating Strength of Boosters

The initiation to detonation of a high-explosive charge with a booster is closely related to the pressure of the shock wave generated by a booster. If a steady detonation wave in an explosive charge is to be reached at the shortest possible distance from the initiating point (i.e., in the shortest time interval), the pressure of the initiating shock wave must be greater than the detonation pressure of the explosive that is to be initiated. Thus, in the manufacturing of the boosters, high explosives of sufficiently high sensitivity to initiation by shock wave (i.e., initiation by detonator) as well as of a sufficiently high detonation pressure are used.

The determination of the initiating capability (or the initiating strength) of a booster is done in order to find out to what extent it is suitable for application in individual cases. The type of the explosive, its size, density, and some other factors influence the booster efficacy.

Two principles can be applied in the experimental determination of the initiating strength of boosters. One relates to the determination of the damage effect caused in the witness plate by the detonation of the booster, whereas the other concerns the determination of the capability of a booster to detonate a test explosive charge, which in addition to the explosive, also contains an inert component. The possible variant of the latter principle implies the determination of the so-called failure of detonation distance, i.e., the distance at which the detonation process is broken down. The failure of detonation distance can be determined on the basis of the traces that are left on a copper or brass plate after the detonation took place. The setup for the determination of the failure of the detonation distance is shown in Figure 2.44.

Later in the text, the determination of the initiating strength of boosters by Johansson and Alfredsson's method (1964).

Principle of the Method

The method for the determination of the initiating strength of boosters is based on the determination of the completion of detonation of the test explosive. The

![Figure 2.44. Setup for the determination of the failure of detonation distance](image)
test explosive is a mixture of trinitrotoluene and glycerine in different mass ratios. The conclusion upon the degree of the completion of the detonation is made on the basis of the degree of compression of the lead cylinder that was in contact with the test explosive.

**Description of the Method**

This method has been widely used since it somehow incorporates the principles on which other methods for the determination of the initiating strength of the booster are based and at the same time is very reliable. The test setup is shown in Figure 2.45.

The test explosive is a mixture of different trinitrotoluene to glycerine ratios by mass. It is prepared by mixing manually finely ground trinitrotoluene, that has particle sizes below 10 µm and glycerine until a high degree of homogeneity is achieved. The test explosive prepared is filled into a tin-walled PVC tube of 30 mm inside diameter. Prior to filling, a lead cylinder 30 mm in diameter and 30 mm high is placed into the tube. The tube is encircled with brass rings to ensure a regular cylindrical form of the explosive charge. The height of the explosive charge prepared in this manner is 50 mm, while its mass depends on its composition.

The initiation of the booster is performed by the standard detonator.

**Evaluation of Results**

The detonation of the test explosive results in the compression of the lead cylinder. The degree of compression of the cylinder depends on the degree of completion of the detonation, which is in turn related to the initiating strength of the booster.

![Figure 2.45. Johansson and Alfredsson test setup for the determination of the initiating strength of the booster](image-url)
The degree of the completion of the detonation of the test explosive charge is
determined on the basis of the relative decrease in the height ($H_C$). $H_C$ is the
quotient of decrease of the cylinder height after the detonation ($\Delta H$) and its
initial height ($H_0$); $H_C = \Delta H / H_0$. When $H_C$ is determined for different content of
the glycerine in the test explosive ($C_{NGI}$), the curve shown in Figure 2.46 is
obtained. On the basis of the curve, it is possible to define the influence of the
type of the explosive and its density on the initiating strength of the booster.

The dependence of the initiating strength of the booster upon its diameter
can be determined on the basis of the experimentally obtained relation between
the glycerine content in the test explosive at which $H_C = 0.5$ and the booster
diameter (Figure 2.47).

![Figure 2.46. Dependence of the relative decrease of height of the lead cylinder on the
glycerine content](image)

![Figure 2.47. Dependence of the initiating strength of the booster on its diameter](image)
Figure 2.48. Dependence of the initiating strength of the booster on its height

The influence of the height of the booster on its initiating strength can be determined from dependence $H_C$ upon the height of the booster, as given in Figure 2.48. The glycerine content in the test explosive in such tests is kept constant.
3
Combustion of Explosives

The term *combustion* denotes any oxidation reaction including those that introduce atmospheric oxygen. Here this term relates to the exothermal oxidation reactions that propagate layer-by-layer through the explosive without introducing atmospheric oxygen. The terms *burning* and *deflagration* are also used for this process.

The propagation of the combustion through an explosive is illustrated schematically in Figure 3.1.

The main characteristics that make a combustion process different from a detonation one, are:

- The energy transfer from the chemical reaction zone to the unreacted part of the explosive is performed by heat conduction, diffusion, and radiation.
- The combustion rate through the explosive is considerably lower than the detonation velocity and is always lower than the sound velocity through the given explosive.
- The nature and the rate of propagation of the chemical reactions taking place in the combustion process are both considerably dependent on the external conditions, mostly on the external pressure and on the temperature.
- The combustion products that are immediately behind the flame front move in the direction opposite to the flame front.

![Figure 3.1](image-url)
The first investigations of the combustion phenomenon in the middle of the last century were accomplished upon gaseous mixtures. Significant advances were achieved in the field of combustion of gaseous and solid explosives in the middle of the 20th century, while only recently the investigation of the combustion and combustion-to-detonation transition process of solid explosives has been developed to a greater extent.

The combustion-to-detonation transition process is of special importance. Namely, it has been found that the combustion of primary explosives is unstable and easily transformed into the detonation. In the case of propellants, combustion is very stable and the transition to detonation may be reached only under very extreme conditions. In practice these conditions are rarely realised.

The possibility of the combustion-to-detonation transition in the case of high explosives is somewhere between the former two cases.

For the majority of solid explosives, the combustion process occurs in the solid and gas phases. Therefore, the external pressure has a considerable influence on the rate of this process. Under sufficiently high pressures, such combustion may be transformed into the detonation.

During the combustion of solid explosives, the existence and the creation of the shock waves and the matter flow in front of the flame front are excluded. The formation of the shock wave is possible only behind the flame front in hot gaseous products. The characteristic of the solid explosive combustion is a rapid increase of the volume in the flame zone due to the transformation of the reacted part of the explosive into gaseous products. If the withdrawal of the originated gaseous products is not sufficiently rapid, the pressure in the flame zone and, consequently, the combustion rate constantly grow. When the combustion rate reaches a limiting value, a stable combustion becomes impossible, and the combustion transforms into detonation. This process is greatly influenced by the characteristics of the explosive, its initial temperature, the ratio between the explosive mass and the volume of the combustion chamber, and the existence of the explosive confinement and its characteristics.

The combustion of the propellants is a stable process that proceeds in parallel layers on the surface of a propellant even at very high values of external pressure, up to a few thousand bars. The investigation of the influence of the external pressure on the combustion rate is especially important in the field of internal ballistics of weapons and solid-propellant rocket motors. It has been shown experimentally that the dependence of the combustion rate \( r \) on the external pressure \( P \) may be expressed by the following equation:

\[
r = a + bp^n,
\]

where \( a, b, \) and \( n \) are experimental constants dependent on the propellant characteristics; constant \( n \) is called the combustion index.

If the pressure is below 200 bar, which is typical for rocket motors, the dependence of the combustion rate upon the pressure may be satisfactorily
expressed by Paul Vielle's law (Barrere et al., 1960):

\[ r = bp^n. \]  

(3.2)

In the field of internal ballistics of artillery weapons, where pressures exceed a few thousand bars, Muraour's law is often applied:

\[ r = a + bp. \]  

(3.3)

The methods for the experimental determination of the individual parameters of the combustion process have long been in existence. They enable precise determination of the parameters of the combustion process. These parameters are the heat of combustion, the composition and the volume of the combustion products, the pressure, and the combustion rate at constant volume conditions. In addition, these methods enable the study of the external factors' influence on the parameters of combustion.

Some parameters, such as combustion temperature and the combustion-to-detonation transition process, may be determined using the same principles that are described for methods applied for the determination of the detonation parameters (see Chapter 4).

### 3.1. Determination of the Combustion Pressure at Constant Volume Conditions

If combustion proceeds at constant volume conditions, then the hot gaseous products that are formed exert pressure on the walls of a combustion chamber. In addition to the characteristics of the explosive, the magnitude of the pressure inside the chamber depends on the ratio between the mass of the explosive and chamber volume (loading density), composition and volume of the gaseous products, combustion temperature, and combustion rate: the higher the combustion rate, the less the dissipation of the heat and accordingly the higher temperature of the gaseous products and the higher pressure are achieved.

**Principle of the Method**

The determination of the combustion pressure of propellants (or pyrotechnic compositions) at constant volume conditions is performed in a specially designed closed vessel. The vessel has a combustion chamber with a volume up to 2.5 dm³, and it can withstand the dynamic pressure of as much as 5000 bar. Such vessels are so-called closed bombs, ballistic bombs, or manometric bombs.

The pressure inside a combustion chamber is measured as a function of combustion time using suitable pressure gauges. The treatment of the pressure
time dependence so-obtained yields the values of the maximum pressure, pressure gradient, and other important parameters of the combustion process.

**Description of the Method**

Manometric bombs are cylindrical vessels with a heavy steel casing, closed by a screw cap. Their volume is from 0.05 to 2.5 dm$^3$. The pressure developed inside the combustion chamber reaches 5000 bar. The maximum amount of the propellant that can be tested depends on the chamber volume. Usually, it is below 0.3 kg of propellant per dm$^3$ of the chamber volume.

The bombs may be of different design. One of the most frequently used is illustrated in Figure 3.2. The main parts of the closed bomb are the combustion chamber, chamber closing elements, elements for the electric ignition of the sample, pressure discharge valve, and temperature and pressure gauges.

The prepared sample of a given mass is placed in the combustion chamber. The electric ignition system, with black powder as the ignition charge, is prepared, and the vessel is closed by the screw cap and the sealing rings. After that, the air from the combustion chamber is evacuated by a vacuum pump up to 0.1 bar. Then the liquid for the maintenance of constant temperature is allowed to circulate. When the temperature stabilises, the sample may be ignited.

The pressure in the combustion chamber can be determined as follows:

- on the basis of the copper crusher compression,
- by the pressure gauges (transducers), that dynamic pressure transform into the corresponding electric signal; e.g., piezoelectric and semiconductor pressure transducers.

![Figure 3.2. Cross section of the closed bomb](image-url)
The determination of the pressure on the basis of the compression of the copper crusher is an older method based on the assumption that the degree of the crusher compression is a function of the acting pressure. The method enables determination of the maximum pressure developed in the combustion chamber using calibration tables or curves. The test is accomplished as shown in Figure 3.3.

It should be mentioned that in the case of static compression of the crusher, the relation between the deformation of the crusher and the measured pressure is linear. Meanwhile, if the compression of the crusher is dynamic, this relation is more complex, and thus, the possibility of an accurate calibration is accordingly lower.

Determination of the pressure as a function of the combustion time is now mainly performed by means of piezoelectric pressure transducers. They operate such that the measured pressure that acts on their quartz-crystal measuring element via a diaphragm is transformed into a corresponding electric charge. After the electric charge is amplified, it is recorded by suitable measuring equipment. Quartz-crystal, barium titanate, and lithium sulphide can be used as the measuring elements in piezoelectric transducers.

The pressure acting on the measuring element creates the electrostatic charge \( q_E \) on its poles, which may be calculated by Eq. (3.4):

\[
q_E = N_e F, \tag{3.4}
\]

where \( N_e \) is the piezoelectric modulus and \( F \) is the force acting on the measuring element.

The relationship between the voltage \( U \) at the charge amplifier input and the pressure \( p \) is given by Eq. (3.5):
\[ U = \frac{q_E}{C_M + C_P} = \frac{N_e F}{C_M + C_P} = \frac{N_e p S}{C_M + C_P}, \]  

where \( S \) is the area of the measuring element, \( C_M \) is the capacitance at the charge amplifier input, and \( C_P \) is the capacitance of the piezoelement.

The piezoelectric pressure transducers may differ with respect to their design. However, most commonly in use are the piezoelectric transducers with a diaphragm, as shown in Figure 3.4a.

The quartz-crystal as a measuring element can withstand pressures up to 1000 bar, i.e., 2000–3000 bar under static and dynamic conditions, respectively. Pressures even higher than that may be measured applying the compensation pressure method. The method implies decreasing the area of either the diaphragm or the piston relating to the measuring elements area.

Pressure transducers that can measure dynamic pressures above 10 kbar and pressure gradients up to 300 bar/ms have been developed.

Pressure transducers based on the semiconductor materials on the basis of germanium, gallium antimonide, solid solutions of aluminum, and gallium arsenide have come into use lately. This type of pressure transducer, given in Figure 3.5, is sensitive to bulk compression and is characterised by low electric resistance, high sensitivity to pressure, and linear dependence of the electric resistance upon the pressure. Nonlinearity less than 1.5% is observed in the range up to 1000 bar.

![Figure 3.4](image-url)  

Figure 3.4. Two types of piezoelectric pressure transducers; (a) with diaphragm, (b) with piston
The operating principle of the semiconductor pressure transducer is the following. The pressure that acts on the diaphragm makes it sag compressing. Consequently, the silicone liquid filled inside the transducer’s body causes the compression of the semiconductor active element. The pressure acting on the semiconductor element causes the change of its electric resistance. By suitable measuring equipment, the corresponding voltage change in the electrical circuit is registered. When the action of the pressure stops, the diaphragm returns to its initial position.

**Evaluation of Results**

The data acquisition and processing systems for the pressure measurement in the closed bombs may differ. However, they should always enable the amplification of the low-voltage signal produced at the transducer poles due to the action of the pressure, recording of the output voltage as a function of the combustion time, and treatment of the recorded data. A calibration curve (or equation) is used to transform the voltage-time curve into the pressure-time curve. This curve offers a lot of useful information necessary for the internal ballistics calculations.

In its simplest version, the data acquisition and processing system consists of a charge amplifier and a storage oscilloscope. However, a complete system usually includes a charge amplifier, a transient recorder, and a storage oscilloscope. The output signal from the charge amplifier may be fed via an A/D converter to a personal computer, which enables direct treatment of the pressure-time curve, necessary calculations, and printout of results. The schematic representation of the possible data acquisition and processing system for the pressure measurement in the closed bomb is given in Figure 3.6.
Figure 3.6. Data acquisition and the processing system for the pressure measurement in a closed vessel by the piezoelectric pressure transducer

From the pressure-time curve obtained (Figure 3.7), the pressure gradient-time curve, maximum pressure, and maximum pressure gradient are calculated.

Figure 3.7. Output results from the pressure measurement in a closed vessel
It is noteworthy to point out that the closed vessel is the “main tool" in the field of internal ballistics of weapons since it enables the experimental determination of the majority of parameters necessary for the ballistic calculations. These parameters are combustion rate, specific energy of the propellants, covolume of the combustion products, etc.

3.2. Determination of the Composition and the Volume of Combustion Products

The experimental determination of the composition and the volume of combustion products is a rather complex task due to the fact that both of the parameters depend not only upon the composition of a given explosive but also upon the conditions at which the combustion process takes place: at constant volume or constant pressure conditions. If combustion takes place at constant volume conditions, the composition of the combustion products, and thus their total volume, depends mostly on the loading density. When the combustion occurs under constant pressure condition, the composition and the volume of the combustion products depend upon the pressure at which combustion takes place.

From a practical point of view, it is important to know the composition of combustion products, i.e., the chemical equation that describes the transformation of the explosive into its final products. This in turn enables the calculation of the thermochemical parameters of the combustion process and the estimation of some other parameters that can be related to the explosive strength.

The determination of the composition of the combustion products is actually performed after cooling the combustion products, i.e., at a moment of “freezing” the chemical equilibrium. This does not equal the moment when reactions are finished. The composition and the volume of the combustion products of the propellants may be determined using the closed bomb or the calorimetric bomb. For the determination of the composition of the detonation products, specially designed closed bombs of 20 dm³ chamber volume are used. Such is the Bichel bomb.

**Principle of the Method**

The determination of the volume and the composition of the combustion products of propellants under constant volume conditions is performed through the ignition of a sample that is placed in a specially equipped closed or calorimetric bomb. After the bomb is cooled down to room temperature, the qualitative and quantitative analysis of the combustion products is accomplished.
Description of the Method

The closed bomb used for such measurements is shown in Figure 3.2. It must be equipped with a pressure gauge, a temperature gauge, a firing electrode, and a gas release valve. Additionally, a gasometer, tubes filled with appropriate absorbers, and an explosion pipette are elements of the equipment.

The prepared sample is placed into the combustion chamber, which is then closed with the cap. The air inside the bomb is evacuated by a vacuum-pump, and the chamber is then tempered to operating temperature. The sample is ignited electrically.

After combustion, the closed bomb is cooled down to room temperature. Then, the pressure inside the chamber is registered by a suitable gauge. At the end, the combustion products are taken for analysis through the gas release valve.

Evaluation of Results

During the combustion process, the propellants are transformed mainly into gaseous products, accompanied by the formation of water vapor. Occasionally, the formation of solid carbon may occur. The chemical reaction that describes the combustion process may be written:

$$C_7H_{11}N_3O_3 \rightarrow n_1H_2O + n_2CO_2 + n_3CO + n_4H_2 + n_5N_2 + n_6CH_4 + n_7NH_3 + n_8C + n_9O_2 + n_{10}OH + n_{11}H + ...$$

where $n_1 - n_n$ represents the number of moles of individual combustion products.

In practice, the combustion products accounted in the above equation are usually reduced to the main ones, i.e., the products present in considerable quantities.

As mentioned earlier, the final composition of the combustion products depends on many factors and changes during the cooling. Therefore, such tests determine the composition of the combustion products after they are completely cooled down. In order to obtain the composition of the combustion products that would correspond as closely as possible to the composition at the very moment the combustion ended, specially designed closed bombs have been developed. They enable fast cooling, i.e., “freezing” of the chemical equilibrium, thus retaining as truly as possible the initial composition of the combustion products.

The qualitative and quantitative analysis of the combustion products can be performed using modern instrumental methods in analytical chemistry, such as gas chromatography and mass spectrometry. However, the method based on the classical chemical analysis of gases will be described here.
The initial step in the evaluation of the test results is determination of the total volume of the gaseous combustion products (by gasometer) and its reduction to the referent conditions, i.e., temperature of 298.15 K and pressure of 1 bar, not taking into account the formation of water. The calculation of the volume of gaseous products at referent conditions \( V_0 \) is based on the equation of the state of ideal gas, assuming that the number of moles of the gaseous products at the moment of the very end of combustion equals those determined after the cooling process is finished. Thus, it is valid:

\[
\frac{p_0 V_0}{RT_0} = \frac{p_1 V_1}{RT_1},
\]

i.e., \( V_0 \), expressed in dm\(^3\) per kg of propellant, is

\[
V_0 = \frac{V_B (p_B - p_{H_2O}) 1000}{p_0 T_B M_B}, \tag{3.6}
\]

where \( V_B \) is the volume of the combustion chamber, \( p_B \) is the pressure inside the combustion chamber after cooling, \( p_{H_2O} \) is the unsaturated vapor pressure, \( T_B \) is the temperature of the combustion chamber after being cooled down, \( M_B \) is the mass of the propellant (expressed in grams), and \( p_0, T_0 \) are the referent pressure and temperature.

The amount of the individual gaseous products is determined by the method of classical chemical analysis of gases. The method is based on the successive quantitative absorption of the individual products by the different absorbers. The following absorbers may be used:

- for CO\(_2\), KOH aqueous solution,
- for O\(_2\), base solution of pyrogallol (1,2,2-C\(_6\)H\(_3\)(OH)\(_3\)),
- for CO, ammonium CuCl\(_2\) solution,
- for NO, saturated FeSO\(_4\) solution,
- for NH\(_3\), diluted sulphuric or hydrochloric acid,
- for H\(_2\), N\(_2\), and CH\(_4\), there are no suitable absorbers.

From the resulting mass increase of the individual tube filled with the suitable absorber, the mass of the individual gaseous products and their volume fraction \( (c_i) \) in the total volume of the gaseous products are calculated. On the basis of the volume fraction, the number of moles of the individual products \( (n_i) \) per 1 kg of propellant is calculated:

\[
n_i = \frac{c_i V_0}{V_m}, \tag{3.7}
\]
where $V_m$ is the molar volume; at 273.15 K its value is 22.414 dm$^3$/mol, and at 298.15 K it is 24.789 dm$^3$/mol.

The determination of H$_2$ and CH$_4$ is performed after the absorption of other gaseous products: CO$_2$, O$_2$, CO, NO, and NH$_3$. What is left after the absorption is led into the explosion pipette. There, the gases are mixed with a known amount of oxygen and ignited by electric spark. When the combustion is finished, the decrease in the volume is observed as the result of the following chemical reactions:

$$2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$$

$$\text{CH}_4 + 2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{CO}_2$$

Since the combustion of 2 mol of H$_2$ results in the volume decrease in the amount of 3 mol, then the combustion of $x$ mol of H$_2$ results in the volume decrease ($\Delta V_1$) in the amount of $(3/2)x$:

$$\Delta V_1 = \frac{3}{2}x.$$  

Combustion of $y$ mol of methane decreases the gas volume for 2$y$:

$$\Delta V_2 = 2y.$$  

The total volume decrease ($\Delta V_T$) will then be:

$$\Delta V_T = \Delta V_1 + \Delta V_2 = \frac{3}{2}x + 2y.$$  

$\Delta V_T$ is determined by the direct measurement, the value of $y$ is equal to the volume of produced CO$_2$ (it is determined by the absorption in the aqueous solution of KOH), and thus the amount of H$_2$ is calculated.

The amount of the water can be accurately determined using a closed bomb with an inlet and outlet valve. The gases are released over the gasometer through the tube filled with calcium chloride. The mass of the tube has been previously weighted. Afterwards, dry air is introduced through the inlet valve and blown through the combustion chamber and the tube. From the resulting increase in the mass of the tube, the amount of water, expressed in grams per 1 kg of propellant, is calculated:

$$n_{\text{H}_2\text{O}} = \frac{M_{\text{H}_2\text{O}}}{18.01M_B} 1000,$$  \hspace{1cm} (3.8)

where $M_{\text{H}_2\text{O}}$ is the mass of the water.
When no solids are observed in the combustion products, the amount of the water can be determined from the difference in the mass of the sample and sum of the masses of all gaseous products.

The amount of nitrogen is determined on the basis of the difference in the volume of the mixture taken for the gas analysis and the sum of volumes of all gaseous components present.

If there are solid particles in the combustion products, they are mechanically collected, and identified, and their amount is determined by suitable analytical methods.

### 3.3. Determination of the Combustion Rate of Propellants at Constant Pressure Conditions

A very important parameter of the propellants is their combustion rate. A linear combustion rate is defined as the distance traveled per second by the flame front, perpendicularly to the surface of the propellant grain. The combustion rate depends upon the propellant composition and the pressure and temperature at which it occurs. The dependence is shown in Figure 3.8.

The dependence of the combustion rate upon the pressure may be expressed by Eqs. (3.1) through (3.3). The parameters $a$, $b$, and $n$ in these equations can be determined if the combustion rate at different pressures is measured. Such experiments are carried out in a specially designed vessel, the so-called constant pressure bomb or Crawford bomb.

#### Principle of the Method

In order to determine the propellant combustion rate at constant pressure, the neutral atmosphere is pressurised into the combustion chamber, followed by the ignition of the tested sample. The movement of the flame front as a function of combustion time is viewed by suitable equipment. On the basis of the flame front distance-time dependency, the combustion rate is calculated.

The moving of the flame front may be followed using the ionisation probes (or other types of velocity probes)/electronic counter (or oscilloscope) technique. Optical and electrooptical methods may be used as well.

#### Description of the Method

A constant pressure bomb is a steel, thick-walled tube cylinder. It is equipped with

- the device for the pressure measurement in the combustion chamber,
the equipment for the chamber temperature measurement,
the equipment that enables the measurement of the combustion time (time intervals needed for the flame front to travel a known distance along the sample),
the equipment that ensures the attainment of high pressures inside the bomb combustion chamber.

The design and the size of the closed bombs differ. One possible design is shown in Figure 3.9. The volume of the combustion chamber may range up to 5 dm³. Throughout the testing procedure, the combustion chamber is locked with a locking cap. The chambers can withstand pressures of several hundred bars. In more recent designs, the inside wall of the combustion chamber is coated with ceramics to avoid the corrosive attack of the acid salts formed during the combustion, which holds true especially when the combustion of the composite propellant is carried out.

The pressure at which the combustion rate is to be determined is achieved by pressurising an inert gas, usually nitrogen, into the combustion chamber until the desired pressure is reached. This is made possible by a high-pressure compressor and an electromagnetic valve, which enables remote control. The pressure inside the chamber is measured by a suitable pressure gauge.

The constant-pressure bombs may also have a system for cooling or heating of the combustion chamber.

The sample of the propellant (or pyrotechnic mixture) is of the form of a long, thin strand, which is inhibited laterally in order to burn like a cigarette. The strand diameter is usually from 3 to 10 mm. During the test, the strand is attached to the holder, which is fixed to the locking cap. After the desired pressure inside the combustion chamber and the desired temperature of the chamber are achieved, the sample is electrically ignited.

Figure 3.8. Dependence of the combustion rate of propellants on the pressure and temperature
The determination of the combustion rate is based on the measurement of the time interval needed for the flame front to travel a known distance along the sample. For this purpose, suitable velocity probes capable of registering the flame front arrival are embedded in the strand. Velocity probes of ionisation type (see Subsection 4.1.5) may be used since in the flame zone the combustion products are greatly ionised and are thus capable of conducting the electric current. Thus, when the flame front arrives at the ionisation probe, the electric current circuit is closed via it. This moment may be registered as the voltage signal (jump) on an oscilloscope, or it may be transformed into the voltage pulse that starts or stops the counting assembly of the electronic counter.

The determination of the combustion rate using ionisation probes and an electronic counter resembles the determination of the detonation velocity. The same principle is applied in both cases. The main difference lies in the different values of the measured time interval: In the detonation, the time interval is on the microsecond scale, while in combustion the time interval is of seconds or tenths of seconds.

The determination of the combustion rate with two ionisation probes and an electronic counter is schematically represented in Figure 3.10.
Moreover, applying a special kind of velocity probe and an oscilloscope technique (Subsection 4.1.5) or an optical technique (Subsection 4.1.2), it is possible to obtain continuous viewing of the flame front when it travels through the sample. That in turn enables the combustion rate in any part of the sample or at any moment during the combustion process to be obtained.

The continuous viewing of the flame front that travels through the sample can be carried out by an optical technique using high-speed streak cameras. In order to apply such a method for the determination of the combustion rate, it is necessary to supply the combustion chamber with a window made of optically transparent and mechanically resistant material. Through such materials, the combustion process may be recorded by a high-speed streak camera.

**Evaluation of Results**

If the time interval \( t \) needed for the flame front to travel the known distance \( L \) through the sample is measured, the combustion rate \( r \) can be calculated by the equation

\[
    r = \frac{L}{t}.
\]

If the combustion rate is determined at several different pressures, the parameters \( a, b, \) and \( n \) in Eqs. (3.1) through (3.3) can be found out by a fitting procedure. Thus, an analytical expression describing the relation between the
It should be emphasised that the pressure inside the combustion chamber may be kept constant by means of the regulating valve. If a chamber without a regulating valve is used, then, strictly speaking, the pressure inside the combustion chamber is not constant. Namely, during combustion, the pressure inside the chamber is somewhat increased. However, the increase in the pressure can be minimised by the choice of an adequate sample size and the volume of the combustion chamber.

The constant-pressure bomb is a very suitable tool for the determination and the comparison of the combustion rates of different propellants. However, the combustion rate as a function of the pressure may also be determined using a small test rocket motor. The motor’s diameter may be between 50 and 100 mm. The combustion pressure is varied inside the motor by varying a nozzle throat area. The influence of the geometry of the propellant grain occasionally may be significant, resulting in no good correlation between the combustion rate determined in a constant-pressure bomb and that in a test rocket motor.

3.4. Determination of the Heat of Combustion of Explosives

Principle of the Method

The measurement of the heat of combustion is analogous to the determination of the heat exchange in various chemical or physical processes.

The experiment is performed in an adiabatic calorimeter assembly. It is based on the observation of the temperature increase in the calorimetric vessel during the combustion. If the relation between the amount of the heat evolved within the calorimetric bomb and the consequent temperature increase in the calorimetric vessel (i.e., the heat capacity of the assembly comprising the calorimetric bomb, calorimetric vessel, and the water in the vessel) is known, the heat of combustion may be calculated.

Description of the Method

The adiabatic calorimeter assembly shown in Figure 3.11 consists of a calorimetric bomb (Figure 3.12), a calorimetric vessel filled with water, a stirrer, and a thermometer.

Calorimetric bombs are devices made from stainless steel. They can be of different size, with an inside volume ranging from 50 to 300 cm³. The bombs are closed with a screw cap bearing two valves. One valve is used for evacuating the air from the bomb before testing, while the other enables the
release of the combustion products. The electric connectors for the electric ignition of the sample are also inserted in the bomb cap.

During testing, the calorimetric bomb is immersed into the inner calorimetric vessel equipped with a stirrer and a thermometer. The vessel is filled with water to the precisely defined level, and it is placed in the water-jacketed cylindrical outer calorimetric vessel, which ensures the maintenance of a constant temperature inside the inner vessel.

The other parts of the adiabatic calorimeter are
Chapter 3. Combustion of Explosives

- the electric parts for the sample ignition and the adjustment of the stirrer speed,
- a wire of known calorific value for the electric ignition of the sample,
- a Beckman thermometer which has a 5 °C scale with 1/100 of one degree Celsius subdivision.

The mass of the sample is usually chosen to obtain the loading density of about 0.01 g/cm³. This value ensures that during combustion the pressure inside the bomb does not exceed the pressure that the bomb can withstand.

The weighted sample is placed into the sample vessel, which is attached to the screw cap by means of the holders. The holders also serve as the electric conductors.

The sample may be freely poured into the sample vessel or pressed in the form of a pastille using a special hand-operated press. The wire for the electric ignition is inserted through the middle of the sample. To ensure successful ignition, the middle part of the wire is coiled. Finally, the bomb is closed with the screw cap, and the air is evacuated by the vacuum pump until a vacuum of only a few millibars is attained. The calorimetric bomb is now placed into the inner calorimetric vessel. The electric conductors for the sample ignition are connected with the connectors on the cap of the bomb. A previously measured volume of water at operating temperature is poured into the inner calorimetric vessel. The cover of the calorimetric vessel is then closed, followed by the ignition via the electric switch. The temperature increase in the inner calorimetric vessel is followed by the Beckman thermometer.

In the course of an experiment, it is important to keep the operating room temperature constant. The water temperature in the outer vessel should be 1–2 °C lower than room temperature, whereas the temperature inside the inner calorimetric vessel should be 0.5–0.7 °C lower than the temperature in the outer vessel. In that way, errors due to heat transfer may be minimised.

**Evaluation of Results**

Prior to the main experiment, the relationship between the heat evolved in the calorimetric bomb (Q) and the consequent increase of the water temperature (ΔT) inside the inner calorimetric vessel should be established. It has been shown that this correlation is linear and can be written in the following form:

$$Q = K_w \Delta T,$$

where $K_w$ is the heat capacity of the calorimeter (water value of the calorimeter).
The determination of the constant $K_w$ is carried out by burning a material of known heat of combustion. These are benzoic acid, naphthalene, and the like. If the temperature increase in the inner vessel accompanying the combustion of a sample of a known mass is measured, assuming the known value $K_w$, the heat of the combustion ($Q_s$) may be calculated according to the equation

$$Q_s = \frac{K_w \Delta T - L_p Q_p}{M_s},$$

(3.10)

where $M_s$ is the mass of the sample, $L_p$ is the length of the ignition wire, and $Q_p$ is the heat of combustion of ignition wire, expressed per unit length.

The value obtained so far refers to the heat of combustion at constant volume conditions. It should be pointed out that the heat of combustion value depends, among other things, on the loading density of the sample.

Occasionally, the heat of combustion in the vacuum or inert atmosphere is assigned as the "heat of reaction," while the term "heat of combustion" refers to the combustion in the atmosphere of oxygen. If the heat of combustion in the atmosphere of oxygen is to be determined, the air is evacuated from the bomb, and then it is filled with oxygen until a desired pressure of ~ 30 bar is reached. Finally, the sample is ignited. In this way, the heat of "complete combustion" is determined. The term complete combustion here refers to the oxidation of the whole carbon to CO$_2$ and whole hydrogen to H$_2$O.

Once the heat of the total combustion is known, it is possible to calculate the heat of formation of an explosive. The latter is given as a difference between the sum of heats of formation of products (CO$_2$ and H$_2$O) and the heat of total combustion of an explosive.
4
Detonation

Detonation is a process of layer-by-layer, supersonic propagation of chemical reactions through an explosive (Figure 4.1). According to the generally accepted Zeldovich-von Neumann-Doering (ZND) model of detonation, chemical reactions occur at a definite rate in the chemical reaction zone, under the action of a shock wave (Baum et al., 1975; Berger and Viard, 1962; Chéret, 1979, 1993; Cook, 1958, 1974; Fickett and Davis, 1979; Johansson and Persson, 1970; Mader, 1979; Thévenin, 1978).

Under the influence of the dynamic action of the shock wave, a thin layer of the explosive is compressed from the initial density \( \rho_0 \) to the density \( \rho_1 \) in accordance with the shock (or Hugoniot) adiabatic curve for a given explosive. The equation defines the relationship between the density (or volume) and the pressure during the dynamic compression of the explosive. As a consequence of dynamic compression, the increase of the pressure to the value \( p_1 \) occurs, resulting in a significant temperature increase in the compressed explosive layer where consequently the initiation of the chemical reactions takes place. When the chemical reactions are at their end, the density and the pressure of the reaction products reach the \( \rho_1 \) and \( p_2 \) values (Figure 4.2). That state corresponds to

![Figure 4.1. Schematic representation of the detonation process](image)
the point lying on the shock adiabatic curve for the detonation products. From that state, the products expand isentropically into the surrounding medium.

According to the steady-state model of detonation, the points \((\rho_0, p_0), (\rho_1, p_1)\) and \((\rho_2, p_2)\) lie on one line. It is called the Rayleigh or Michelson line. The slope of the Rayleigh line is determined by the detonation velocity of a given explosive. According to the Chapman and Jouguet postulate, the Rayleigh line is a tangent to the adiabatic shock of the detonation products at the point that corresponds to the end of the chemical reactions. That point is assigned as the Chapman-Jouguet point (CJ point).

The detonation process may be described mathematically applying thermodynamic and hydrodynamic laws. The state and the motion of the matter in the detonation wave may be expressed by means of the laws of conservation of mass, momentum, and energy. These laws can be written in the form

\[
\rho_0 D = \rho (D - W), \tag{4.1}
\]

\[
p = \rho_0 DW, \tag{4.2}
\]

\[
e - e_0 = \frac{1}{2} (p + p_b)(V_0 - V) + q, \tag{4.3}
\]

where \(D\) is the detonation velocity, \(W\) is the mass velocity, \(q\) is the heat of detonation, \(e\) is the internal energy, and \(V\) is the specific volume \((V = 1/\rho)\) (subscript "0" refers to the unreacted explosive).
Combining the above equations and considering the equation resulting from the Chapman-Jouguet postulate

\[ \gamma = \frac{\partial \ln p}{\partial \ln V_s} = \frac{\partial p}{p \partial V} = \frac{V}{p} \left( \frac{p - p_0}{V - V_0} \right), \tag{4.4} \]

where \( \gamma \) is the polytropic exponent, it is possible to find out the relationship between the most important detonation parameters.

It is difficult to achieve an entirely reliable experimental determination of the detonation parameters due to their extreme values: detonation velocity reaches 10 mm/\( \mu \)s, detonation pressure goes as far as 400 kbar, detonation temperature ranges from 2000 to 5000 K, duration time of the chemical reactions in the reaction zone is in a microsecond region, and the width of the chemical reaction zone ranges from tenths of a micrometer to several millimetres.

However, experimental methods for a quite accurate determination of the detonation velocity (errors less than 1%), mass velocity, and the detonation pressure (errors less than 3%) have been developed. For the last fifteen years, efforts have been directed towards the study of detonation wave structure, i.e., the chemical spike and chemical reaction zone. Unfortunately, the time resolution slightly below 10\(^{-9}\) seconds, achievable by the most recent measuring techniques, is still insufficient for a reliable study of the processes in the chemical spike and occasionally in the chemical reaction zone.

### 4.1. Determination of the Detonation Velocity

Detonation velocity is the velocity at which the chemical reaction zone propagates through a given explosive. It is one of the most important detonation parameters. Bearing in mind the fact that detonation velocities of known high explosives may reach nearly 10 mm/\( \mu \)s, the experimental determination of the detonation velocity is not easily achieved. However, when compared to the other detonation parameters, its accomplishment represents the least complicated task.

The determination of the detonation velocity is based upon the measurement of the time interval needed for the detonation wave to travel a known distance through the explosive being tested. The measuring equipment used for the determination of the detonation velocity should provide

- the detection of the arrival of the detonation wave using suitable velocity probes,
the measuring of the very short time-intervals (on a microsecond scale) needed for the detonation wave to travel a known distance through the sample between two velocity probes.

Depending on the measuring equipment selected, the methods for the detonation velocity determination can be divided into

- the optical methods, which are based on the use of different types of high-speed cameras,
- the electrical methods, which are based on the use of different types of velocity probes combined with an electronic counter or an oscilloscope.

For the rough estimation of the detonation velocity, simpler methods can be applied. One such method is the Dautriche method, which is described below.

4.1.1. The Dautriche Method for Determination of the Detonation Velocity

Principle of the Method

This simple method does not require the use of any special and costly instruments. The determination of the detonation velocity is based on the fact that processes that propagate at different linear velocities travel different distances in the same time interval. The difference in the length of the distance traveled is a simple function of the velocities of these two processes.

Although this method is mainly used for the determination of the detonation velocity of commercial explosives, the same principle can be applied in order to determine the detonation velocities of high explosives. The accuracy of the method may be less than 4.5%.

Description of the Method

The Dautriche method for the determination of the detonation velocity (Persson, 1978, 1980; "Rate of Detonation,” 1970; Sučeska, 1987) is illustrated in Figure 4.3.

The explosive to be tested is filled into a 500 mm long steel tube, of a 30 mm inside diameter. A thickness of the tube wall is 3 mm. A cardboard tube of the same length and the same inside diameter but of a 2 mm wall thickness can be also used.

Two holes are made in the previously prepared cylindrical explosive charge, given as points A and B in Figure 4.3, where the ends of the detonating cord are inserted. The ends may be capped with standard detonators before being inserted into the explosive charge. The distance between point A and point B equals 300, mm and it is actually the length at which the detonation velocity
is to be determined. Between point A and the position of the initiation of the explosive charge, the distance should be 100 mm or greater.

The detonating cord length is usually 900 mm. The middle part of the detonating cord passes over a lead or aluminum plate, as illustrated in Figure 4.3.

After the initiation of the explosive, traces will be left on the lead plate, indicating the point of collision of two detonation waves that are travelling from point A and from point B, respectively.

On the basis of the traces left on the lead plate after detonation, and assuming the detonation velocity, the length of the detonating cord, and the distance between points A and B are known, the calculation of the detonation velocity of the explosive is performed.

**Evaluation of Results**

After the initiation of the explosive charge, a detonation wave begins to propagate through it at an unknown velocity, $D_x$. Also, from point A and point B, two detonation waves start to propagate through the detonating cord at the same known velocities, $D_F$. These two waves meet at a point assigned as S or at a point assigned as $S_1$, depending on the relation between detonation velocities $D_x$ and $D_F$. At the meeting point in the lead plate, the trace of collision will be sharply marked.

If the detonation velocity of the explosive equals the detonation velocity of the detonating cord, the detonation waves that travel through the detonating cord will meet at the point that lies in the middle of the lead plate, assigned as M. If the length of the detonating cord is 900 mm and the length of the
measuring distance through the explosive between points A and B is 300 mm, the meeting point will be 600 mm from point A in the detonating cord. However, two other cases are usually met in practice:

- the detonation velocity of the explosive is lower than the detonation velocity of the detonating cord,
- the detonation velocity of the tested explosive is higher than the detonation velocity of the detonating cord.

In the former case, since the time intervals needed for the detonation waves to pass the distance A-M-S₁ and the distance A-B-S₁ are the same, the detonation velocity is calculated using Eq. (4.6):

\[ D_F = \frac{D_F}{D_X} = \frac{L_1 + h}{L + \frac{L_2 - h}{D_F}} \]

\[ D_X = \frac{D_F L}{L_1 - L_2 + 2h} \]

where \(L\) is the distance between points A and B, \(L_1\) is the length of the detonating cord between points A and M, \(L_2\) is the length of the detonating cord between points B and M, and \(h\) is the distance between the detonation waves meeting point (S₁) and point M.

In the latter case, the detonation velocity is obtained using the following equations:

\[ D_F = \frac{L_1 - h_1}{D_X} = \frac{L}{D_X} + \frac{L_2 + h_1}{D_F} \]

\[ D_X = \frac{D_F L}{L_1 - L_2 - 2h_1} \]

The accuracy of this method depends upon the accuracy of the measurement of the distances \(L_1, L_2, L_1,\) and \(h\) (or \(h_1\)), and upon the variation of the detonation velocity of the detonating cord. In the presentation of the test results, the type of confinement, the charge diameter, and the charge density also have to be reported.
4.1.2. Determination of the Detonation Velocity by Optical Methods

Principle of the Methods

The detonation processes, as well as the combustion processes, are accompanied by the emission of light. This makes it possible to view the propagation of both of these processes through the explosive using optical methods and consequently to calculate their velocities (Berger and Viard, 1962; Cook, 1958, 1974; Früngel 1958; Johansson and Persson, 1970; Schriever, 1961; Thévenin, 1978).

To obtain information about the velocity of the process being viewed the camera film should move perpendicularly to the direction of the process propagation, i.e., to the light emission propagation direction. Thus, the image of the process, which is projected on the film by the objective lens, is transformed into a laterally moved luminous trace from which the distance-time curve is obtained. By additional treatment of the distance-time curve, the velocity of the process at any instant of its propagation may be calculated applying an appropriate numerical procedure.

Description of the Method

Different types of high-speed cameras that are in use may be classified into the following groups with respect to their operating principle:

- rotating-drum cameras,
- rotating-mirror (or prism) streak cameras,
- rotating-mirror (or prism) framing cameras,
- electronic cameras.

The rotating-drum camera is an older type of camera that is suitable for the estimation of the combustion processes of propellants and explosives. A schematic illustration of the operating principle of the rotating-drum camera and the way the distance-time curve is formed is similar to other types of cameras and is given in Figure 4.4.

The main parts of the rotating-drum camera are a hollow drum, an electric motor, an electronic synchronising system, and a time pulse generator.

Two types of rotating-drum cameras exist:

- cameras in which the film track is mounted on the external drum surface; they have a maximum writing speed of about 0.1 mm/μs,
- cameras in which the film track is mounted on the inside drum surface; they have a maximum writing speed of about 0.2 mm/μs.

The principle of the formation of the distance-time curve when using a rotating-drum camera is as follows.
If, at a given moment, the detonation wave has traveled the distance from point A to point B through the explosive, and assuming for simplicity that the detonation wave front is represented by a point, then in the case where the film track does not move, the luminous point on the film will outline A'B'' line, which is parallel with the longitudinal drum axis. However, if the track moves at a linear velocity in the direction perpendicular to the direction of the detonation front, the A'B' curve will be obtained on the film track. When the film and detonation velocities are constant, instead of the A'B' curve, a line will be obtained. The slope of this line gives the detonation velocity.

When using *rotating-mirror* (or *rotating prism*) streak cameras, the distance-time curve is obtained by rotating a mirror that reflects an image on a stationary film track as shown in Figure 4.5. The way the distance-time curve is obtained is basically the same as in the previous case. However, it is technically realised in a different way.

In addition to its optical part, streak cameras also have an electronic part, which has to provide

- the initiation of an explosive charge at a definite time, which will correspond to a fixed point with respect to the sweep of an image from the mirror along the film track,
- an accurate determination and regulation of the camera mirror velocity.

The rotating-mirror streak cameras have a writing speed of a few mm/μs, which is some ten times greater if compared to the rotating-drum cameras.

The operating principle of the *rotating-mirror framing cameras* is illustrated in Figure 4.6.
Figure 4.5. The operating principle of the rotating-mirror streak camera

The optical part of the framing camera includes an objective lens, a field lens, a rotating mirror, and relay lenses (a bank of a few dozens in a set). The objective and field lenses enable a real image of the object to be formed on the rotating mirror surface. After the reflection, it is imaged on the film track by one of the sets of relay lenses, depending on the angular position of the mirror in that moment. Thus, as the mirror rotates, the image of the event is in turn recorded on the film track by each relay lens, yielding a sequence of pictures. The number of pictures on the film track may equal the number of relay lenses.

The rate at which the pictures on the film track are taken depends upon the angular velocity of the mirror and upon the location of the relay lens stations (usually several frames/μs).

Figure 4.6. The operating principle of the rotating-mirror framing camera
The operating principle of an electronic camera is shown in Figure 4.7. The image of the event is formed on the photocathode via the objective lens. By means of the focusing electrode and the anode, the optical image is converted into an electron beam, which forms a sharp image of the event on the phosphorus screen. The image from the screen is photographed on a Polaroid film or a high-speed negative film.

Electronic cameras can operate in streak or framing mode. When the framing mode operates, after the completion of every framing sequence, the electron beam is deflected by shift plates horizontally on the screen where a new image is formed. By compensating plates, the beam is deflected vertically, thus yielding two vertical pictures at every framing sequence.

When the streak mode operates, the electron beam is continuously deflected by shift plates horizontally across the screen, yielding a continuous record of the event.

**Evaluation of Results**

When the propagation of the detonation through an explosive charge is recorded by means of a streak camera, the detonation wave front distance-time curve is obtained. A typical record is shown schematically in Figure 4.8.

The left boundary bright line on the film record represents the detonation wave front path in the distance-time coordinates, whereas on the right, secondary processes are outlined.

The detonation velocity along the explosive charge is obtained by the differentiation of the distance-time curve:

\[
D(t) = \frac{dL}{dt},
\]  

(4.9)
where \( L \) is the distance traveled by the detonation wave front and \( t \) is the time corresponding to the distance traveled.

As can be seen from Figure 4.4, the projection of a part of the distance-time curve on the ordinate that corresponds to the distance \( L \) traveled by a detonation wave through the explosive charge is equal to \( A'B'' \) length. Accordingly, if the magnification of the image is \( f \), then the vertical distance \( y \) on the film equals:

\[
y = fL,
\]

thus yielding \( dL \):

\[
dl = d(y / f).
\]

At the same time, the film track, which moves at a linear velocity \( \Omega \), will travel a distance \( x \):

\[
x = \Omega t,
\]

yielding

\[
dt = d(x / \Omega).
\]

Substituting Eqs. (4.11) and (4.13) into Eq. (4.9), the expression for the calculation of detonation velocity at any instant of time (i.e., distance) is obtained:

\[
\frac{dL}{dt} = \frac{d(y)}{d(x / \Omega)}.
\]
where \( dy/dx \) is the slope of the distance-time curve.

When the detonation velocity along the observed part of the explosive charge is constant, the \( dy/dx \) is constant too. If the detonation velocity is not constant along the whole measuring distance, then on the basis of the data from the film, one can find out the mathematical expression that describes distance-time dependence, applying the fitting procedure. Its differentiation yields the detonation velocity value at any instant of time, according to Eq. (4.9).

The processing of the data obtained by framing cameras is somewhat different if compared to streak cameras. When framing cameras are used, then the detonation velocity is calculated as a ratio between the distance traveled by the detonation wave between two successive frames and the time interval between these two frames from the film track.

### 4.1.3. Determination of the Detonation Velocity Using Electronic Counter and Velocity Probes Technique

#### Principle of the Method

A short time interval needed by the detonation wave to travel a known distance between two velocity probes (or pins) through the explosive is determined by an electronic counter. Thus, the detonation velocity is obtained as a ratio between the distance traveled and the corresponding time interval.

The electronic counter operates on the principle of continuous generation of pulses from an oscillator, which are consequently registered by a counting assembly. An electronic switch enables the passage of the pulses to the counting assembly during the measuring interval only, which is limited with the signals for starting and stopping of the counting assembly. The oscillation frequency usually ranges from 10 to 100 MHz, which corresponds to a time resolution of 100 to 10 ns.

#### Description of the Method

The measuring system that uses an electronic counter/velocity probes technique is schematically represented in Figure 4.9.

Two holes that are limiting the measured distance are made in the explosive charge. The velocity probes capable of detecting detonation wave arrival are inserted into the holes. Velocity probes may be of various types, but depending on their operating principle they are divided into
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Figure 4.9. Functional diagram of the system for the determination of the detonation velocity using the electronic counter/velocity probes technique

- ionisation type,
- electrocontact type.

Ionisation probes. The operating principle of the ionisation probes is based on the fact that detonation products behind the detonation front are highly ionised, which makes them capable of conducting electric current. Thus, the arrival of the detonation wave at an ionisation probe (which is actually an electrical switch) enables the closure of the electric circuit. That allows a capacitor to discharge, and the associated voltage signal is used to start/stop the counting assembly of the electric counter.

An ionisation probe of the simplest design is illustrated in Figure 4.10. The probe is made of two twisted copper wires, one of them with, and the other one without, insulation. During testing, the twisted part of the probe is inserted into the explosive charge, perpendicularly to its longitudinal axis, to a depth of 2/3 of the charge diameter or through the whole charge depth.

Figure 4.10. Ionisation probe made of two twisted copper wires
This type of probe is frequently used for the determination of the detonation velocity. However, when explosives of very low detonation velocity (below 2000 m/s) are tested, the probability of the detonation wave detection is considerably decreased because of the decreased ionising effect in such detonation waves.

The frequently used ionisation probe is the so-called pin ionisation probe (Figure 4.11). The electric conductor inserted into the explosive charge parallel with the charge's longitudinal axis serves as a common electrode. It is actually a noninsulated copper wire (or strip) 1 mm in diameter. The other two electrodes are steel pins placed perpendicularly to the common electrode at a distance 0.5–3.0 mm from it. When the detonation wave arrives at the pin, the electric contact between the common electrode and the pin is restored, due to the ionisation effect in the detonation wave.

Stripped ionisation probes shown in Figure 4.12 are suitable for the velocity determination of explosive charges consisting of several segments. Both electrodes are thin copper foils, 40 μm thick and 3 mm wide. They are placed into the explosive charge at a distance of 1–3 mm between them. The explosive charge segments are put as close together as possible and are fixed together by
an adhesive substance such as adhesive tape. The principle of the detection of the detonation wave arrival is the same as in the other ionisation probes.

**Electrocontact probes.** The electrocontact, or mechanical, probes are of a more complex design and are mainly used for the determination of low detonation velocities. Closure or breakage of the electrical circuit by means of these probes is accomplished mechanically due to a detonation wave pressure action.

The electrocontact type of probe according to Amster and Beguregad (cited in Anastasijevich, 1970) is illustrated in Figure 4.13. The probe consists of a 40 mm long insulated copper wire, 0.5 mm in diameter. The insulation is removed from 10 mm of the middle part of a wire. The wire is then placed into a copper tube 0.8–1.1 mm in internal diameter. The wire insulation prevents the electric contact between the wire and the tube. During the experiment, the probe is placed into a hole made in the explosive charge. The middle part of the copper wire that lacks the insulation should reach the middle of the explosive charge. By the arrival of a detonation wave, the copper wire will be squeezed under the action of the detonation wave pressure, and the electric contact between the copper wire and the copper tube will be realised.

When the electrocontact probes are used, the arrival of the detonation wave is registered with a certain delay on the microsecond scale. This has, however, no effect on the accuracy of detonation velocity determination since delay is the same in all electrocontact probes that are emplaced in explosive charges.

The electrocontact type of probe according to Campbell (cited in Anastasijevich, 1970) is shown in Figure 4.14. This probe consists of two conductive rectangular metal foils between which a thin insulation foil made of nylon, mica, etc. is placed. The electric contact between the two metal foils is realised by the action of the arriving detonation wave. The wave action causes the first foil to start moving, consequently crushing the insulation foil and closing an electric circuit.
Irrespective of the probe type used for determination of the detonation velocity when an electronic counter/velocity probes technique is applied, the way the initial signal produced by the closure of an electric circuit is transformed into the corresponding signal that starts or stops the counting assembly of the electronic counter is the same: the probe leads are connected to a resistance-capacitance (RC) assembly that produces sufficient voltage signal to start/stop the counting assembly of the electronic counter (Figure 4.9).

**Evaluation of Results**

If two probes are inserted into an explosive charge at a known distance from each other \( (L) \), the arrival of the detonation wave at the first probe will start the counting assembly while its arrival at the second probe will stop it. The time interval registered by the counting assembly \( (t) \) is the time needed by the detonation wave to pass the distance \( L \). The detonation velocity is then calculated as the quotient of distance and time:

\[
D = \frac{L}{t}
\]

When performing the test, care should be taken that

- the distance between the initiation position and the first probe is large enough so that a stable detonation wave can be established,
- the distance between the probes is large enough to diminish the possible influence of an inaccurate measurement of the distance length.
4.1.4. Determination of the Detonation Velocity Using Oscilloscope and Velocity Probes Technique

Principle of the Method

The time interval needed by the detonation wave to travel a known distance between two probes placed at a known distance from each other in an explosive charge is determined using a fast storage oscilloscope.

When the oscilloscope/velocity probes technique is applied, more than two probes can be placed into the explosive charge. Moreover, with special types of probes, it is possible to achieve continuous determination of the detonation velocity along the whole explosive charge.

Description of the Method

Determination of the detonation velocity using an oscilloscope/velocity probes technique is schematically presented in Figure 4.15.

Two or more probes of ionisation or electrocontact type, limiting the measured distance, are inserted into the test explosive charge. The arrival of the detonation wave at the probe causes closure of the electric circuit, capacitor discharge, and the voltage jump on the resistor, which is recorded by a fast storage oscilloscope. The time base of the oscilloscope is started shortly before the detonation wave’s arrival to the first probe by a triggering probe. The triggering probe is also of either ionisation or electrocontact type and is inserted into the explosive charge between the place of initiation and the first probe.

![Schematic of the measuring system for the determination of the detonation velocity using the oscilloscope/velocity probes technique](image)

Figure 4.15. Schematic of the measuring system for the determination of the detonation velocity using the oscilloscope/velocity probes technique
The oscilloscope used for these experiments is of the two-beam type. The horizontal beam is used for time recording, and the vertical one for voltage recording. The oscilloscope is combined with a charge amplifier for the vertical deflection of the beam.

A time pulse generator generates time pulses, which are recorded on the oscilloscope horizontal (time) axis with a repetition period even up to 1/100 µs.

**Evaluation of Results**

A typical oscillogram obtained when detonation velocity is determined using two velocity probes is shown in Figure 4.16.

The peaks on the oscillogram correspond to the arrival of the detonation wave at the probes. The time interval needed for the detonation wave to travel the distance between the two probes is calculated knowing the time scale \( b \) and the distance between two voltage jumps—assigned as \( l_0 \) in the oscillogram. The time scale, which is expressed in µm/cm, is calculated according to the equation

\[
b = \frac{n_i \Delta t}{d},
\]

where \( d \) is the distance between several time pulses, \( n_i \) is the number of time pulses at distance \( d \), and \( \Delta t \) is the time pulse repetition period.

Thus, the time interval between two peaks (probes) will be

\[
t = bl_0,
\]
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The detonation velocity is then calculated as a quotient of the distance between two probes and the corresponding time interval.

4.1.5. Determination of the Detonation Velocity Using Probe for Continuous Determination of the Detonation Velocity and Oscilloscope Technique

For viewing the initiation path of high explosives, combustion-to-detonation transition, determination of the failure diameter of the explosive charge, transmission of the detonation process, and for studying the establishment of stable detonation, a special types of probes combined with a fast oscilloscope are used.

Principle of the Method

The principle of the continuous determination of detonation velocity is based on the continuous oscilloscopic recording of an electric resistance change of special types of probes through which constant current flows, caused by the detonation wave propagation through the test explosive charge.

The probe is placed into the explosive charge parallel with its longitudinal axis. Under the action of the detonation wave, the probe is continuously shortened, and thus its electric resistance is changed. The electric resistance change causes the voltage change in the electric circuit, which is recorded on the oscillogram as a function of time. From the oscillogram obtained the detonation velocity at any part of the explosive charge can be calculated.

Description of the Method

For the continuous determination of the detonation velocity, specially designed types of probes and accompanying measuring equipment are required. A constant current source is of greatest importance. The type of probe used determines the possibilities of its application in individual cases.

As the detonation velocity and the detonation pressure of different explosives may vary, various types of probes should be applied. According to their operating principle, all are of the ionisation type.

The Amster and Gibson probe (Figure 4.17) can be used for the determination of the unstable detonation velocity, e.g., during the initiation process of high explosives by booster. It also may be used for the determination of the explosive charge failure diameter. A steel tube containing a tested explosive serves as one conductor. A resistant chromium/nickel wire (approx. 80 μm in diameter), placed into the explosive charge parallel with its longitudinal axis, is used as the second conductor. The distance between the two conductors is about 3 mm. The detonation wave propagating through the explosive charge shortens the chromium/nickel wire length and closes the electric circuit at the wire free
end due to the ionisation effect in the detonation wave. The resultant change of the resistance in the probe connected to a constant current source results in a voltage drop in the electric circuit, which is continuously recorded by a fast oscilloscope.

Jaffe and Price have used velocity probes shown in Figure 4.18 for the determination of the critical diameter of an explosive charge of conical shape.

For the study of the unstable detonation, Galyparin and Svedov have used the probe illustrated in Figure 4.19. The operating principle of this probe is based on the change of the probe resistance, as previously described. However, the specific feature of the probe is its pulse supply from a constant current source.

Figure 4.18. The velocity probes according to Jaffe and Price for continuous determination of detonation velocity (After Jaffe and Price, 1962)
The probe shown in Figure 4.19 consists of a resistant chromium/nickel wire, 0.1 mm in diameter, densely wound around a copper wire, 1.1 mm in diameter.

For the determination of the detonation velocity of high explosives and the combustion rate of pyrotechnic mixtures, Pitts used a probe of the so-called sandwich type as shown in Figure 4.20.
In addition, the closed-type probe shown in Figure 4.21 for the determination of the detonation velocity and combustion rate is frequently used. One conductor of the probe is a copper wire, ~ 1 mm in diameter, with varnish insulation, and the other is an uninsulated resistant wire, 30 μm in diameter and of 1.6 Ω/mm resistance. The resistant wire is placed on the copper wire and attached to it with several coils of a thin uninsulated copper wire, 0.1 mm in diameter. It is then soldered to one end of the copper wire from which the insulation was previously taken. There the electric contact between the copper wire and the resistant wire should exist. The other end of the resistant wire is also attached to the copper wire with several coils of a thin copper wire, but the insulation is left. Therefore, no electric contact exists at that place. As the current circuit is closed by the probe before the measurement starts, this type of velocity probe is called closed-type.

The measuring equipment needed for the determination of the detonation velocity using the above described type of probes and oscilloscope is illustrated in Figure 4.22.

A source of constant direct current (25–250 mA) must be provided from a stabilised voltage source to supply the probe. The instruments for the fine adjustment and measurement of the current are needed as well.

Once the detonation wave arrives at the probe, the electric circuit will be closed via the probe due to the strong ionisation (Figure 4.23). As the detonation wave travels through the explosive charge, the length of the probe through which current flows is continuously shortened. Since the electric resistance of the probe per unit of length \( r_p \) is constant, the probe resistance \( r_t \) at a certain instant of time, i.e., the resistance in the part of the explosive charge that is not yet detonated, will be

![Figure 4.22. Schematic presentation of the measuring equipment for continuous determination of detonation velocity](image-url)
Chapter 4. Detonation

Figure 4.23. Schematic representation of the operating principle of the probe

\[ r(t) = L(t)r_p', \]  
\[ (4.17) \]

where \( L(t) \) is the length of the undetonated part of the explosive charge.

Since a current of constant strength \( (I_s) \) flows through the probe, the voltage \( U(t) \) at the probe output in the moment \( t \) will be

\[ U(t) = L(t)r_p'I_s. \]  
\[ (4.18) \]

As the detonation wave travels through the explosive charge, i.e., through the probe, the voltage at the probe output is being changed, which is recorded on the oscilloscope as the vertical beam deflection. Simultaneously, via a time pulse generator, the time units are recorded on the horizontal axis. By further treatment of the so-obtained voltage-time curve, the detonation velocity at any moment of time, i.e., at any distance along the explosive charge, may be calculated.

**Evaluation of Results**

A typical oscillogram obtained when continuous determination of the detonation velocity is performed is given in Figure 4.24.

It follows from Eq. (4.18) that the change of the voltage with time is proportional to the distance traveled by the detonation wave:

\[ L(t) = \frac{U(t)}{r_p'I_s}. \]  
\[ (4.19) \]

Accordingly, detonation velocity can be obtained by differentiation of the above expression with respect to time:
Figure 4.24. Typical oscillogram obtained for stable detonation

\[ D(t) = \frac{dL(t)}{dt} = \frac{1}{r_p I_x} \frac{dU(t)}{dt}. \] (4.20)

If the oscillogram is represented in \( x - y \) coordinates, then the voltage and the time for any point of the curve can be calculated using the following equations:

\[ U(t) = ay(t), \] (4.21a)

\[ t = bx(t), \] (4.21b)

where \( a \) is the voltage scale on the vertical axis (V/cm) and \( b \) is the time scale on the horizontal axis (\( \mu \)s/cm).

The time scale on the horizontal axis is calculated as described in Subsection 4.1.4, whereas the voltage scale is obtained on the basis of the maximum deflection value on the vertical axis (\( h \)) for the total voltage drop from the initial value \( (r_u I_a) \) to zero, where \( r_u \) represents the sum of the probe resistance \( (r_d) \) and the conductor resistance \( (r_v) \):

\[ a = \frac{I_s (r_d + r_v)}{h}, \] (4.22)

where \( r_d = L_m r_p \), and \( L_m \) is the maximum length of the probe.

Introducing Eqs. (4.21a) and (4.21b) into Eqs. (4.19) and (4.20), the following equations are obtained:
\[ L(t) = \frac{a}{r_p I_s} y(t) , \quad (4.23) \]

\[ D(t) = \frac{(a/b) dy}{r_p I_s \ dx} . \quad (4.24) \]

Using Eq. (4.24), the detonation velocity at any instant may be obtained. The slope of the curve \((dy/dx)\) can be determined either graphically or as a derivation of an analytical expression for \(y = f(x)\) dependence. This dependency can be found by fitting of experimental data.

Such continuous determination of detonation velocity enables the study of unstable detonation processes, including the deflagration-to-detonation transition. Some examples of the application of this method are illustrated in Figures 4.25–4.27.

### 4.1.6. Determination of the Detonation Velocity Using Optical Fibres as Velocity Probes

In the past 15 years, the fibreoptic technique has been widely used for the determination of different detonation parameters such as detonation velocity, detonation wave shape, detonation temperature, etc. (Lu et al., 1985; Xianchu et al., 1985; Xinghai, 1985).

Figures 4.25. The estimation of the initiation process of an explosive charge by booster
Figure 4.26. The estimation of the transmission of detonation in the air

Figure 4.27. The determination of the critical diameter of the explosive charge

Using the optical fibre/high-speed camera technique, it is possible to overcome some difficulties that are present while applying the ionisation probes method. For example, if more than one signal arrives at the same time, a separate recording channel must be provided for each one—otherwise, confusion can arise from improper matching of signal–probe.
Principle of the Method

The determination of the detonation velocity is based on the ability of the optical fibre to accept a light signal when the detonation wave arrives, and to transmit that signal to the suitable measuring equipment, which enables precise recording of the time interval between two signals. From the measured time interval and the corresponding distance traveled by the detonation wave, the detonation velocity is calculated.

The detonation wave’s arrival at the optical fibre, i.e., the light signal accompanying the detonation process, can be either recorded by the optical technique using a high-speed streak camera, or it can be transformed into an electric signal that may be recorded by a fast-storage oscilloscope or a multichannel analyser.

Description of the Method

For the measurements in the field of detonation, optoelectronic single-grade monofilament optical fibres of a relatively low attenuation factor, 1 mm core diameter and 2.2 mm outside diameter of the black plastic jacket, may be used.

If the explosive charge is unconfined, then the optical fibre is placed directly into the explosive charge to a depth of 2/3 of the charge diameter. When the explosive charge is confined, the fibre is placed as illustrated in Figure 4.28.

The other end of the optical fibre is led to the measuring equipment, which will record detonation wave arrival. The length of the optical fibre may go above 20 m. The experiment configuration when the optical fibre/streak camera technique is applied looks like the one shown in Figure 4.29. The optical fibre ends are fixed using a holder. The moment of the arrival of the detonation wave on the optical fibre is recorded as a light point-trace by a streak camera whose writing speed is $\sim 10 \text{ mm/\mu s}$.

Another possible way of registering the arrival of the detonation wave on the optical fibres is to transform the light signal from the fibre by a fast photodiode that has a rising time of about 10 ns into an electric signal that may be recorded either by a fast oscilloscope or a multichannel analyser (Figure 4.30).

Figure 4.28. The position of an optical fibre in the case of a confined explosive charge
Evaluation of Results

When using the optical fibres/streak camera technique, a discontinuous series of light points-traces is obtained. The number of points corresponds to the number of optical fibres placed into the explosive charge. On the basis of the known distances between individual optical fibres (measuring distances through the explosive charge) and the corresponding time intervals between traces on the film (obtained from the camera writing speed), the detonation velocity is calculated.

If the optical fibres/fast photodiode/oscilloscope technique is used, an oscillogram similar to the one in Figure 4.16 is obtained. By further treatment of the oscillogram, the detonation velocity is obtained as a ratio of distance traveled and corresponding time interval.
4.2. Determination of the Detonation Wave Parameters

According to the ZND model of detonation, detonation wave structure (Figure 4.31) includes

- the shock front followed by the chemical reaction zone (chemical spike or von Neumann spike),
- the steady chemical reaction zone,
- the Chapman-Jouguet plane,
- the Taylor wave of isentropic expansion of detonation products.

Various dynamic methods based on different physical principles are used for the experimental determination of the pressure at the CJ point and the duration of the chemical reactions in the chemical reaction zone. A large number of these methods, especially for the determination of the pressure at the CJ point—detonation pressure, were independently developed in the USA and the former USSR in the 1950s. In the years to follow, the detonation parameters of the solid explosives, equation of state, and adiabatic shock (or Hugoniot) equation of detonation products were the subject of numerous experimental and theoretical investigations. But it should be mentioned that different interpretations of the experimental results were frequent.

The experimental methods for the determination of the detonation wave parameters can be classified into two groups. The first, the so-called internal methods group, includes the methods by which detonation parameters are directly determined. These are the determination of the mass velocity of the detonation products by the electromagnetic particle velocity gauge method, direct determination of the detonation pressure by a manganin pressure gauge, determination of the mass velocity of the detonation products by the flash X-ray technique, etc. The time resolution of these methods can be on a nanoseconds scale, which is still not sufficient for fully reliable study of a very narrow chemical reactions zone, and in particular, of a shock wave front.

![Figure 4.31. The structure of the detonation wave](image-url)
The other group of methods includes those that are based on the registration of the state originated after the shock wave reflection from a barrier. For instance, the detonation pressure may be determined on the basis of the measurement of a thin metal plate free-surface velocity. The plate free-surface velocity can be determined using optical methods or the electrocontact type of probes and oscilloscope technique. The methods based on the determination of the shock wave velocity through an inert material, e.g., the Aquarium test, are also included in this group. The time resolution of these methods may be on a nanoseconds scale, and even less than a nanosecond, e.g., when laser interferometry technique is used. Since the processes in the shock front occur on a nanosecond scale, the present-day techniques are still inadequate to study the detonation wave shock front.

4.2.1. Flying Plate Test for Determination of the Detonation Parameters

Principle of the Method

The determination of the detonation pressure of an explosive on the basis of the metal plate free-surface velocity was first suggested by Goranson in 1945. The method was later improved by Al'tshuler, Krupnikov, and Deal (cited in Deal, 1957; Gibbs and Popolato, 1981). A modern summary is given by Mader et al., (1987).

The calculation of the detonation pressure is based on the fact that the pressure and the rate of the material flow behind the passing and the reflected waves are equal on both sides of the contact surface. The impulse conservation law and the known metal plate adiabatic shock equation are applied.

The metal plate free-surface velocity may be determined by different optical methods or by the electrocontact type probes and oscilloscope technique.

Description of the Method

According to the ZND model of detonation, a steady-state plane detonation wave has the pressure-time profile shown in Figure 4.32.

When a detonation wave impacts on a metal plate that is in contact with an explosive charge, a complex interaction occurs. This may be illustrated by the distance-time curve given in Figure 4.33.

Due to the explosive/metal plate interaction, the plot of shock wave pressure in the metal plate versus the plate thickness has the shape shown in Figure 4.34.

Each point on this plot may be related to a certain point on the pressure-time curve (Figure 4.32). Thus, for instance, the region of the sharp drop of the detonation pressure at low values of the plate thickness corresponds to the influence of the chemical reaction zone on the shock wave parameters in the metal plate. When the metal plate thickness equals zero, the pressure
corresponds to von Neumann’s spike pressure, while the pressure assigned as $p^*$ corresponds to the pressure at the CJ point, i.e. the detonation pressure.

Figure 4.32. Pressure-time profile for the steady-state detonation wave

Figure 4.33. Time-distance curve of shock waves in explosive/metal plate configuration

Figure 4.34. Dependence of the shock wave pressure in the metal plate on the plate thickness
In order to obtain the plot of shock wave versus plate thickness, it is necessary first to determine the plate free-surface velocity as a function of plate thickness. Then, the corresponding pressure value should be calculated as a function of plate thickness on the basis of the relationship between detonation wave parameters (Eqs. (4.1)-(4.4)).

As already stated, the metal plate free-surface velocity can be experimentally determined by electrocontact type or velocity probes/oscilloscope technique, and by optical methods.

Determination of the metal plate free-surface velocity using electrocontact probes is illustrated in Figure 4.35.

The plate, the ring, and the screens are made of the same material, and they fit tightly to each other. For testing, three pairs of probes are used. The first pair of probes touches the surface of the first screen and closes the electric circuit at the moment when the shock wave exits to the screen surface. The second pair of probes touches the metal plate free surface and closes the electric circuit at the moment when the shock wave leaves the free surface of the plate. The metal plate thickness serves as the measuring distance for the determination of the shock wave velocity in the plate. The third pair of probes is placed to touch the external surface of the second screen. It closes the electric circuit at the moment when the moving metal plate impacts the screen. The height of the ring serves as the measuring distance for the free-surface velocity calculation.

The signals, produced by the electric circuit closure by electrocontact probes, are led and then recorded by oscilloscope. When the oscillogram thus obtained is treated, as described in Subsection 4.1.4, the shock wave velocity \( U_m \) in the metal plate may be obtained.
The shock wave velocity in the metal plate and the metal plate free-surface velocity ($v_{sp}$) can be calculated as follows.

The shock wave velocity is calculated according to the equation

$$U_m = \frac{d}{t_m},$$

(4.25)

where $d$ is the metal plate thickness and $t_m$ is the time interval between the first and the second pair of probes.

The metal plate free-surface velocity ($v_{sp}$) is calculated on the basis of the time interval between the second and third pairs of probes. This time interval includes the time of the motion of the plate free surface ($t_s$) and the time of the shock wave motion through the second screen ($t_2$). The height of the ring ($h$) is so taken that the time of the motion of the plate free surface is less than the time of the shock wave motion ($t_m$) through the plate:

$$t_s < t_m,$$

i.e.,

$$\frac{h}{v_{sp}} < \frac{d}{U_m}.$$  
(4.26)

Otherwise, the metal plate will be accelerated.

As the second screen is ten times thinner than the ring, the shock wave retardation through the screen can be neglected. Thus, $t_s$ is calculated according to Eq. (4.27):

$$t_s = \frac{h}{v_{sp}},$$

(4.27)

and accordingly, the metal plate free-surface velocity:

$$v_{sp} = \frac{h}{t_s}.$$  
(4.28)

The Goranson postulate states that the plate free-surface velocity at the moment the shock wave leaves the plate surface is equal to two times the power of mass velocity behind the shock front. This follows from the relationship
between the shock wave parameters at the explosive/inert material contact surface. Accordingly, the mass velocity \( W_m \) may be calculated from Eq. (4.29):

\[
W_m = \frac{v_{sp}}{2} = \frac{h}{2t_s}.
\]  

(4.29)

The determination of the metal plate free-surface velocity using a high-speed camera is illustrated in Figure 4.36.

One face of a tested explosive charge is initiated by a plane wave generator. At the opposite face of the charge, the metal plate is placed. On the top surface of the metal plate to be studied, a Plexiglas block assembly is placed. Argon gaps, approximately 90 μm deep and covered by a tin steel shim, are made in the Plexiglas block. The metal plate motion is viewed through the Plexiglas block by a streak camera through a slit and is swept on the film trace in a direction perpendicular to the slit image.

When the metal plate driven by the explosive begins to move, the argon gaps near the plate surface get closed, which yields a brilliant flash of light of short duration, recorded on the film. After the free surface passes the known distance \( d \), it closes the central gap and yields another flash of light. The time interval between these two flashes corresponds to the time of the plate free-surface motion, and it is used for the calculation of the plate free-surface velocity.
Evaluation of Results

If considering the interaction at the explosive charge/metal plate contact interface, represented in Figure 4.37 as a shock wave pressure vs. mass velocity, then one can write

\[ p_m = p + \rho_0 U_r (W - W_m), \quad (4.30) \]

where subscript \( r \) refers to the reflected wave parameters, \( m \) to the metal plate parameters, and parameters \( p \) and \( W \) without subscripts relate to the CJ point.

Using the impulse conservation equation (4.2):

\[ p = \rho_0 DW, \]
\[ p_m = \rho_m U_m W_m, \]

one obtains

\[ \frac{p_m}{p} = \frac{\rho_0 U_m}{\rho_0 D} \frac{(\rho_0 D + \rho_0 U_r)}{(\rho_0 U_m + \rho_0 U_r)}. \quad (4.31) \]

Applying acoustic approximation \((\rho_0 U_r = \rho_0 D)\), Eq. (4.31) can be simplified
to the form

\[ p = \frac{p_m}{2 \rho_{om} U_m} \left( \rho_o D + \rho_{om} U_m \right) \]  

(4.32)

Since from the momentum conservation law (Eq. (4.2)) follows:

\[ W_m = \frac{p_m}{\rho_{om} U_m} \]

Eq. (4.32) (known as Goranson equation) may be written in the form

\[ p = \frac{1}{2} W_m (\rho_o D + \rho_{om} U_m) \]  

(4.33)

With respect to the experimentally obtained dependence between the metal plate free-surface velocity and the plate thickness, which is related to the characteristics of the tested explosive and the applied plate thickness, two cases are possible, as shown in Figure 4.38:

- the CJ point is clearly seen as a point at which the curve slope is sharply changed,
- the CJ is not obtained on the curve, i.e., there is a linear dependency of the plate free-surface velocity and the plate thickness.

The first case is characteristic for explosives having a broad chemical reaction zone. It may be obtained if very thin plates, of a thickness less than or equal to the chemical reaction zone width, are used. The detonation pressure may then be calculated as follows:

![The plate free-surface velocity as a function of plate thickness](image)
Chapter 4. Detonation

Plate Thickness

Figure 4.39. Shock wave in time vs. plate thickness diagram

a) The parameters $\rho_0$, $\rho_{om}$, and $D$ are known; i.e., previously determined.
b) The plate free-surface velocity for the series of different plate thicknesses is determined experimentally.
c) Applying Goranson’s postulate, the mass velocity for the corresponding plate thickness is calculated (Eq. (4.29)).
d) The shock wave velocity for the corresponding thickness may be calculated from the adiabatic shock equation for the metal plate, which is usually done in the form of either

$$U_m = c + sW_m,$$

(4.34)

or

$$U_m = c + sW_m^2 + zW_m^2,$$

(4.35)

where $c$, $s$, and $z$ are experimental constants.

e) Applying Goranson’s equation (4.33), the pressure value as a function of plate thickness is calculated. The pressure value that corresponds to the zero plate thickness (obtained by extrapolation to zero plate thickness) corresponds to the chemical spike pressure, while the pressure value that corresponds to the transition point is detonation pressure, i.e. pressure at the CJ point.
f) Once the plate thickness that corresponds to the CJ point is known, the chemical reaction zone width ($\delta$) can be calculated.

If the shock wave is represented in the time vs. plate thickness diagram given in Figure 4.39, the expression for the calculation of
the chemical reaction zone width can be deduced:

\[
\delta = \frac{b(W_m + c_m - U_m)(D - W_m)}{D(W_m + c_m + v_c)},
\]

(4.36)

where \(v_c\) is the mean value of the explosive-metal plate interface velocity, \(c_m\) the mean value of the sound velocity at distance \(b\), and \(U_m\) the mean value of the shock wave velocity in the metal plate.

If the CJ point is not attained experimentally from the free-surface velocity vs. plate thickness diagram (as for example when explosives of narrow chemical reaction zone are tested or when the plates of greater thickness are used), the detonation pressure can be calculated as follows:

a) The parameters \(\rho_0\), \(\rho_{0m}\), and \(D\) are known, i.e., previously determined by applying a suitable method.

b) The plate free-surface velocity is determined for the series of different plate thicknesses.

c) By a fitting procedure, an adequate analytical expression of free-surface velocity dependence upon the plate thickness may be found. Then the plate free-surface velocity for the zero plate thickness is calculated. This value can also be determined graphically if one plots the free-surface velocity vs. plate thickness and then extrapolates to zero plate thickness.

d) On the basis of the free-surface velocity value for the zero plate thickness, the corresponding mass velocity is calculated (according to Eq. (4.29)). Since flow rates are equal on both sides of the contact surface, this mass velocity (at the beginning of the interaction) corresponds to the mass velocity of the detonation products.

e) On the basis of the known plate adiabatic shock equation, the shock wave velocity for zero plate thickness is calculated.

f) The detonation pressure value is then calculated according to Goranson's equation (4.33).

There is, however, an alternative method for the determination of the CJ point and the detonation pressure at this point. The method is based on the determination of free-surface velocities of a series of plates made of different materials and having different impedances \((r_{0m}U)\). The plates of thickness greater than the width of the chemical reaction zone are being used. In that case, the relationship between the free-surface velocity and the plate thickness is linear (Figure 4.38). Extrapolating the plate free-surface velocity to zero thickness, the velocity of the interface of the detonation products and the metal plate at the beginning of the interaction is obtained. Depending on the impedance ratio between the detonation products and the metal plate, the reflected wave (if plate impedance is greater) or rarefaction wave (if detonation
products impedance is greater) begins to travel through the detonation products.

If the curve, presenting the impedance ratios, is plotted for a series of plates made of different materials in \( p - W \) coordinates, then the intersection of this curve with the \( p = \rho_a D W \) line represents the CJ point (Figure 4.40). At that point, the impedance of the metal plate is equal to the impedance of the detonation products. This means that there is neither rarefaction nor slowing down of the detonation products, i.e., the detonation and the shock wave parameters at the explosive/plate interface are equal to the shock wave parameters. The technique described is known as the impedance match technique.

For example, for trinitrotoluene of density 1.637 g/cm\(^3\) and detonation velocity 6.942 km/s, Deal (1957) found that the dependence of the free-surface velocity of the aluminum plate on the plate thickness \((d)\) is

\[
v_{sp} = 2.468 - 0.00642 \cdot d.
\]

Since the plates of 2.3 to 51 mm thickness have been used in the experiment, the CJ point has not been achieved. Thus, the free-surface velocity for the zero plate thickness \((d=0)\) will be

\[
v_{sp} = 2.468 \text{ km/s}.
\]

From Eq. (4.29), it follows that the corresponding mass velocity is

\[
W_m = \frac{v_{sp}}{2} = \frac{2.468}{2} = 1.234 \text{ km/s}.
\]

If the aluminum adiabatic shock equation is given in the form

\[
U_m = 5.15 + 1.37 W_m,
\]

![Figure 4.40. The determination of the CJ point in a p-W diagram](image)
it follows that the zero shock wave velocity is

\[ U_m = 5.15 + 1.37 \cdot 1.234 = 6.84 \text{ km/s}. \]

Finally, substituting \( U_m, W_m, \rho_0, \) and \( \rho_m (\rho_m = 2.79 \text{ g/cm}^3) \) into the Goranson equation, the detonation pressure of 18.78 GPa is obtained.

4.2.2. The Aquarium Test for Determination of the Detonation Parameters

Principle of the Method

The aquarium test is essentially a modification of the flying plate test in which the metal plate is replaced by a layer of water or some other optically transparent material, such as Plexiglas. Instead of the determination of the plate free-surface velocity, the traveling of the shock wave through an inert and optically transparent material is viewed as a function of time. When having the shock wave velocity vs. distance dependence, and knowing the adiabatic shock equation of the inert material used, the mass velocity behind the shock wave front and the detonation pressure of a tested explosive may be calculated.

Description of the Method

An explosive charge to be tested, 72 mm in diameter and 144 mm long (Rigdon and Akst, 1970), is immersed into a glass container filled with destilled water as shown in Figure 4.41.

Following the detonation of the explosive charge, a shock wave begins to travel through the water causing a change in the optical transparency of the water. A high-speed streak camera, with its streak slot along the axis of the

![Figure 4.41. Schematic of the aquarium test](image-url)
Figure 4.42. Aquarium test arrangement with a Plexiglas block as a transparent material charge, is used to record the position of the shock wave front as a function of time. The container is illuminated from the background with an impulse high source such as an Argon flash bomb.

If the shock wave velocity is to be determined in the Plexiglas as an optically transparent material, the test arrangement similar to the one shown in Figure 4.42 may be used.

Evaluation of Results

Several methods of calculating the detonation pressure based on aquarium test data are cited in the literature. One method uses the Goranson equation. This calculation is described below:

a) From the film track record, which gives a time-dependent position of the shock wave front, the dependence of the shock wave velocity in an inert material upon the distance from the explosive charge surface \( R_m \) is calculated. By analytical or graphical extrapolation of the dependence obtained, the shock wave velocity in the inert material at \( R_m=0 \) (i.e., initial shock wave velocity) is determined.

For the analytical solution of this task, an adequate analytical expression that expresses the \( R_m=f(t) \) dependence in the best possible way is chosen. Two exponential expressions are frequently used (Hornberg and Volk, 1989):

\[
R_m = a_1 + a_2 t - a_3 e^{-a_4 t},
\]  

or

\[
R_m = a_1 t + 4a_2 a_3 \arctan \left( \frac{t}{2a_2} \right).
\]

\( \text{Equation } 4.37 \)

\( \text{Equation } 4.38 \)
When Eqs. (4.37) and (4.38) are differentiated with respect to time, the shock wave velocity is obtained. At $t=0$, the initial shock wave velocity, corresponding to distance $R_m=0$, is obtained:

$$U_m(0) = a_2 + a_3a_4,$$  

(4.39)  

$$U_m(0) = a_1 + 2a_3.$$  

(4.40)

Equations (4.39) and (4.40) are obtained by differentiation of Eqs. (4.37) and (4.38), respectively. Coefficients $a_1$ through $a_4$ are found by the fitting procedure.

b) From the adiabatic shock equation of the inert material and $U_m(0)$ value, the mass velocity value at the contact interface, i.e., at the time $t=0$ (or $R_m=0$), is calculated. For the calculation, one may use the inverse form of the adiabatic shock equation for water (Homberg and Yolk, 1989):

$$W_m = -0.607 + 0.372 \ U_m + 0.0283 \ U_m^2,$$  

(4.41)

($U_m$ and $W_m$ are expressed in mm/μs).

c) Finally, from the mass velocities obtained and known densities of the explosive and the inert material, it is possible to calculate the detonation pressure by applying the Goranson equation.

4.2.3. Determination of the Detonation Parameters Using the Laser Technique

Principle of the Method

The determination of the detonation wave parameters and its structure on the basis of the determination of the shock wave velocity in an inert and optically transparent material using a laser follows the same principles as in the case of the aquarium test. However, if compared to the standard aquarium test, it is characterised by a better time resolution, on a nanosecond scale. Thus, this technique allows the study of the detonation wave structure, i.e., the chemical reaction zone width and the duration time (Ashaev et al., 1988).

Shock wave velocity in an inert material as a function of the distance from the explosive charge/inert material interface is determined on the basis of viewing a laser beam that is reflected from the optical barriers in the inert material by a photomultiplier and an oscilloscope. From the plot of the shock wave velocity vs. distance (shock wave attenuation curve) obtained for an inert
material whose adiabatic shock wave is known, the shock wave velocity at the explosive/inert material interface, and the corresponding mass velocity are calculated. Then, the detonation pressure is calculated applying the Goranson equation, while the width and duration time of the chemical reaction zone are calculated on the basis of the shock wave attenuation curve.

**Description of the Method**

The detonation wave structure proposed by the ZND model of detonation was proven by numerous experimental works. Also, those experiments have proven the existence of the chemical spike steady zone, which does not depend on the length of the explosive charge and ends in the CJ point. In addition, the existence of the unsteady zone of the expansion of the detonation products where the pressure decrease depends on the length of the explosive charge (see Figure 4.45) has been proven.

The development and the application of the laser-based measuring methods in the field of physics of explosives have enabled a significant increase in the time resolution when studying the detonation processes.

Analyses have shown that most information about the structure of the detonation wave may be obtained by the methods that determine the dependence of the shock wave velocity in an inert material on the distance from the explosive/inert material interface. Such dependence contains information about the state and the values of the parameters at the explosive/inert material interface, i.e., at the moment the detonation wave exits the explosive surface.

If it is possible to determine the shock wave velocity in an inert material at the distance of 0.1 mm from the explosive charge/inert material interface, then the information about the parameters of the state at the explosive/inert material interface will be obtained in 2–5 ns after the detonation begins, i.e., after the shock front. The laser measuring technique allows such measurement.

Immediately at the explosive charge surface, opposite the initiation point, the PMMA discs are placed (Figure 4.43). Their thickness is 0.5–1.0 mm. The pulverisation procedure is used to cover the discs with a thin (about 1 μm) aluminum layer. A special device is used to clamp discs into one set. The device ensures a fixed (several micrometers) clearance between the discs. The clearance between the discs represents an optical barrier for the laser beam.

The shock wave travels through the PMMA discs and successively closes the optical barriers, thus changing the total intensity of the reflected laser beam. The reflected laser beam is then directed to the photomultiplier by a system of mirrors and lenses. The output signal from the photomultiplier is recorded by a fast oscilloscope that has a time resolution on the nanosecond scale.

**Evaluation of Results**

A typical oscillogram is shown in Figure 4.44. It represents the shock wave position as a function of time.
Figure 4.43. Test setup for the determination of the shock wave velocity in an inert material using the laser technique

Figure 4.44. The shock wave position as a function of time as obtained on an oscillogram

When the oscillogram is treated applying an appropriate numerical procedure, the shock wave velocity-distance curve is obtained (Figure 4.45). The CJ point corresponds to the position where the slope of the curve is markedly changed. The shock wave velocity corresponding to the CJ point is then read from the curve.

The duration time of chemical reactions ($\tau$) in the reaction zone may be calculated according to the equation (Ashaev et al., 1987):

$$
\tau = \frac{R_{CJ}}{D} \left( \frac{W_m + c_m - U_m}{c_m} \right)
$$

(4.42)

where $R_{CJ}$ is the distance corresponding to the CJ point (values of $W_m$, $c_m$, and $U_m$ refer to the CJ point).
The mass velocity is calculated from the known shock wave velocity and known adiabatic shock equation for PMMA. The latter can be written in the form (Ashaev et al., 1987):

\[ W_m = -1.692 + 0.656 U_m \]  \hspace{1cm} (for \( 3.34 < U_m < 6.59 \))

\[ W_m = -2.418 + 0.766 U_m \]  \hspace{1cm} (for \( U_m > 6.59 \)).

The width of the chemical reaction zone is estimated from the equation

\[ \delta \approx (D - W) \tau , \]  \hspace{1cm} (4.43)

while the detonation pressure is calculated using the Goranson equation.

If the CJ point is not reached, i.e., there is no marked change in the slope of the curve, then the calculation of the detonation parameters is based on the extrapolation of the shock wave velocity to the zero distance (initial shock wave velocity) and consequent calculation of the corresponding mass velocity and pressure, applying the adiabatic shock equation and Goranson equation (the calculation procedure is similar to the one used in the flying plate test).

### 4.2.4. Determination of the Detonation Parameters Using the Electromagnetic Particle Velocity Gauge Technique

#### Principle of the Method

The electromagnetic particle velocity gauge (EPVG) method is based upon the fact that an electric conductor when moving in a fixed homogeneous magnetic field generates an electromotive force. The intensity of the electromotive force
so-induced will be proportional to the conductor velocity, its size, and the magnitude of the magnetic field.

The detonation parameters are determined by recording the electromotive force generated by the motion of a thin metal foil gauge placed in an explosive charge, carried together with the detonation products behind the detonation wave front through a homogeneous magnetic field.

The explosive charge, with the gauge placed in it, is placed in the middle of a fixed homogeneous magnetic field. A fast oscilloscope is used to register the intensity of the electromotive force as a function of time behind the detonation wave front. The oscillogram obtained is used to calculate the mass velocity of the detonation products as a function of time.

**Description of the Method**

The EPVG measuring equipment may differ with respect to the source of the homogeneous magnetic field, the gauge shape and size, the way of recording the data, etc. (Cowpertwhite and Rosenberg, 1985; Erickson et al., 1981; Leiper et al., 1985; Philippart, 1985; Seitz et al., 1985).

The gauge used in this technique is a thin metal foil (Figure 4.46) placed into the explosive charge. It is made of aluminum or copper foil and has a thickness of 50–150 μm. If aluminum foil is used, then it is anodised in order to form an external protective oxide coating (Al₂O₃) 10–15 μm thick. The oxide coating insulates the gauge from the reacting explosive and enhances the structural rigidity of the assembly, facilitating the handling and placement of the gauge into an explosive charge. The width and the thickness of the gauge have no influence on the intensity of the electromotive force.

The explosive charge with the emplaced gauge is placed into the middle of a homogeneous magnetic field as illustrated in Figure 4.47.

When the detonation wave reaches the gauge, the gauge will be moved forward at the surrounding particles' velocity, cutting the magnetic field.

![Figure 4.46. Shape of the particle velocity gauge](image-url)
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Figure 4.47. Placement of the explosive charge with the gauge into the magnetic field

Consequently, at the gauge's active surface, an electromotive force \( E_s \) is generated:

\[
E_s = BWl,
\]  
(4.44)

where \( B \) is the magnetic induction, \( l \) is the length of the active surface of the gauge, and \( W \) is the gauge velocity.

Since \( B \) and \( l \) are constant for a given measuring system, the intensity of the electromotive force generated will be directly proportional to the gauge velocity

\[
E_s = KW,
\]  
(4.45)

where \( K \) is the proportionality constant for a given measuring system.

The change of the intensity of the electromotive force versus time is followed by a fast oscilloscope, and then the mass velocity is calculated according to Eq. (4.45). An EPVG measuring system is illustrated in Figure 4.48.

A generator of the homogeneous magnetic field is the essential part of the measuring system. There are several different ways of generating a homogeneous magnetic field: by electromagnets, cylindrical coils, Helmholtz coils, Maxwell coils, quadratic shape coils, etc. However, Helmholtz coils, given in Figure 4.49, proved very suitable for the generation of the homogeneous magnetic field.

Helmholtz coils consist of two identical rings made of nonmagnetic material, which are placed parallel to each other. The coils may have several hundred turns of enameled copper wire. When direct current is allowed to pass through the coils, a homogeneous magnetic field is produced. The greatest
homogeneity is produced in the middle of two coils. Thus, for instance, coils that are 500 mm in diameter and consist of 210 turns of enameled copper wire with a cross-section area of 4 mm$^2$ give a magnetic field of 0.05 T at a distance of 250 mm, when a direct current of 100 A is applied (Leiper et al., 1985). During testing, the explosive charge is placed at the position of the greatest magnetic field homogeneity.

The purpose of the calibrating system is to match the vertical deflection of the oscilloscope beam to the electromotive force and the horizontal one to the time. The vertical deflection is calibrated by a precise potentiometer, and the horizontal one by a time pulse generator.
The mass of the tested explosive charge depends upon the size of the coils and the type of its protection from the blast damage. Thus, for instance, when the diameter of the coils is 500 mm, and 10 mm thick nonmagnetic stainless steel casing is used for protection of the coil assembly, then up to 200 g of explosive can be detonated.

**Evaluation of Results**

When the detonation wave reaches the particle velocity gauge, the gauge moves forward at a velocity equal to the velocity of detonation product particles behind the detonation wave front. It is considered that, due to the small size of the gauge, its velocity becomes equal to the velocity of the detonation products in less than 0.1 μs. This means that the method enables registration of the state of the detonation wave in 0.1 μs behind the shock front. Therefore, it is to be expected that the method might be used in the study of detonation wave structure.

From the oscillogram (Figure 4.50), the plot of the mass velocity vs. time may be obtained according to Eq. (4.44).

For the explosives that exhibit a narrow chemical reaction zone, the CJ point is not clearly marked (Figure 4.51). In such a case, the CJ point may be obtained by the extrapolation of the Taylor wave, whereas for the explosives that exhibit a broad chemical reaction zone, the CJ point may be easily obtained as the point of marked change of curve slope (Figure 4.52).

When the mass velocity at the CJ point is determined and the density of the explosive and its detonation velocity are known, the detonation pressure can be calculated according to Eq. (4.2).

If the CJ point is clearly marked on curve $W=f(t)$, it is possible to determine the duration time ($\tau$) of the chemical reactions directly from the curve. On the basis of the duration time, the width of the chemical reaction zone ($\delta$) may be calculated:

![Figure 4.50. A typical oscillogram obtained by the EPVG method](image)
\[ \delta = (D - \overline{W}) \tau, \quad (4.46) \]

where \( \overline{W} = (W_{\text{max}} + W_{\text{CJ}})/2 \) is the mass velocity mean value within the chemical reaction zone.

Using the equation...
which follows from the relationships between detonation parameters, the polytropic exponent \( \gamma \) at the CJ point may be calculated.

4.2.5. Determination of the Detonation Wave Parameters Using Flash X-Ray Photography

Principle of the Method

The flash X-ray radiographic technique used for the determination of the detonation wave parameters is based on time-dependent tracing of the position of thin metal foils moving together with detonation products behind the detonation wave front at the same velocity. Therefore, viewing the movement of the foils, one obtains the velocity of detonation products behind the detonation wave front, i.e., their mass velocity (Chick et al., 1985; Dorokhin et al., 1988; Huiling et al., 1985; Trimble et al., 1981). On the basis of that velocity, other detonation parameters can be calculated.

The foils are made of metal that is a good absorber of X-rays.

Description of the Method

The X-ray radiographic experimental setup for viewing the flow of the detonation products is shown in Figure 4.53.

The explosive charge consists of 5–10 discs, 120 mm in diameter, having an individual thickness of 10 mm (Dorokhin et al., 1988). Between the discs, thin metal foils are embedded. The foils are usually made of lead since lead is a good X-ray absorber. The foils are 50 mm in diameter and 20 \( \mu \text{m} \) thick.

![Figure 4.53. X-ray radiographic test setup](image-url)
The pulse X-ray machine produces a radiation pulse having a length of about 0.1 µs (at the half-height). The length of the radiation pulse is recorded by a fast oscilloscope via a photoelement. Simultaneously, detonation velocity may be determined by applying the velocity probe/oscilloscope technique.

A cassette with a photographic film track is placed at a minimum safe distance from the explosive charge. The X-ray machine is placed perpendicularly to the longitudinal axis of the explosive charge in such a way that the longitudinal cross section of the explosive charge is viewed. During the movement of the metal foils and the detonation products, the transparency of X-rays is changed at some points through the explosive charge. These points actually indicate the instantaneous position of the metal foils.

A typical photographic record of the metal foil motion is shown in Figure 4.54. Analysing the photographic record and expressing the data in the reduced dimensionless coordinates $X$-$Y$:

\[ X = \frac{X_0}{L_D}, \]
\[ Y = \frac{Y_0}{L_D}, \]

where $X_0$ is the distance between the initiation plane and the metal foil before the arrival of the detonation wave, $Y_0$ is the distance between the initiation plane and the position of the metal foil at the moment of arrival of the
detonation wave, and \( L_0 \) is the distance traveled by the detonation wave at a given moment, a diagram shown in Figure 4.55 is obtained.

Since all the parameters of the flow are functions of displacement gradient \( dY/dX \), this method of data treatment is known as the displacement gradient method.

The detonation products that flow behind the detonation wave front can be recorded by flash X-ray radiography in a different way as well. Namely, instead of several metal foils embedded at different distances along the explosive charge, it is possible to use a single metal foil embedded into the explosive charge in the manner illustrated in Figure 4.56.

Figure 4.55. Test results in dimensionless coordinates

Figure 4.56. The shape of the explosive charge and position of the metal foil in flash X-ray radiographic viewing of the flow of the detonation products
The explosive charge consists of four parts, 120 mm in diameter and 100 mm in overall length. Between the two slanting discs of the explosive charge, a 20 μm thick and 30 mm wide metal foil is embedded. Followed by the arrival of the detonation wave, this metal foil will be successively carried by the detonation products (Figure 4.57).

Analysing the test data illustrated in Figure 4.57, one can find out the relationship between the initial position of the $i$th element of the metal foil ($X_0$) and the position of the same element at the moment of its recording ($Y_0$). If the test data obtained in this way are presented in reduced dimensionless coordinates, a curve corresponding to the one given in Figure 4.56 will be obtained.

The advantage of such continuous viewing of the flow of the detonation products lies in the possibility of observing the positions of the whole metal foil as a function of time. The smaller mass of a single foil (compared with several foils in the case of the previously described test) and the possibility of recording the detonation products flow vs. the time profile behind the detonation wave front enable the study of the structure of the detonation wave.

**Evaluation of Results**

On the basis of the data obtained from X-ray photography, represented in dimensionless coordinates (Figure 4.55), the mass velocity of the detonation products can be calculated and used further for the calculation of other detonation parameters.

One possible way of treating the experimental data is to start from an analytical expression of $Y=f(X)$ dependence. Dorokhin and co-workers (1988a, 1988b) suggested that this dependency could be best expressed by the equation

![Figure 4.57. Metal foil position before (a) and at the moment after the arrival of the detonation wave (b): (1a) metal foil position before the arrival of the detonation wave; (1b) metal foil position at the moment after the arrival of the detonation wave; A-A detonation wave front position at a moment of time]
\[
Y = 1 + \frac{1}{A} \ln \left( \frac{AX + B}{A + B} \right). \quad (4.48)
\]

Coefficients \(A\) and \(B\) from the above equation are found by the fitting proce­
dure.

The density of the detonation products is calculated from the obtained data
using the mass conservation law in the form

\[
\rho \, dY = \rho_0 \, dX,
\]

\[
\rho = \frac{\rho_0}{(dY/dX)}.
\quad (4.49)
\]

The \(dY/dX\) in the above equation is obtained by differentiation of Eq. (4.48).
The density of the detonation products at the CJ point is calculated via \(dY/dX\)
value for \(X=1\), using Eq. (4.49). Finally, other detonation parameters at the CJ
point are calculated knowing \(\rho\) at the CJ point and applying well-known
relationships between the detonation parameters:

\[
W = D \frac{\rho - \rho_0}{\rho},
\]

\[
p = \rho_0 D W,
\]

\[
\gamma = \frac{\rho_0}{\rho - \rho_0} = \frac{D - W}{W} = \frac{\rho_0 D^2}{p} - 1.
\]

If an assumed \(\gamma\)-law equation of state of the detonation products is used

\[
p = A_1 \rho^\gamma,
\quad (4.50)
\]

then if \(\rho\), \(\gamma\), and \(\rho\) at the CJ point are known, the constant \(A_1\) may be calculated.
Consequently, the equation of the expansion isentrope is defined.

The expansion isentrope for hexogen/trinitrotoluene composition (50/50)
obtained by the above method is shown in Figure 4.58.

4.2.6. Determination of the Detonation Pressure Using a
Manganin Pressure Gauge

Manganin pressure foil gauges began to be used for the determination of the
detonation and shock wave pressure in the 1960s. Manganin, an alloy of
copper, manganese, nickel, iron, and silica, is characterised by a significant
change of electrical resistance under the action of dynamic pressure. Manganin oil gauges have a low coefficient of sensitivity to pressure and are therefore suitable for the determination of higher pressures, i.e., above several hundreds of MPa. The relationship between the change of the electric resistance and the measured pressure is almost linear. Manganin gauges are also characterised by an exceptionally low resistance change with the temperature and by a low hysteresis (Graham and Asay, 1978; Song and Lee, 1989; Urtiew et al., 1986).

**Principle of the Method**

The principle of the determination of the detonation pressure by a manganin pressure gauge is based on the fact that under dynamic action of detonation pressure the electrical resistance of the gauge is changed. The resistance change is directly related to the measured detonation pressure.

The gauge is placed into the explosive charge perpendicular to the traveling direction of the detonation wave, and the resistance change of the gauge is detected by a modified Wheatstone bridge circuit.

**Description of the Method**

The manganin gauge consists of an active element made of copper, manganese, iron, and silica alloy, Teflon insulation or insulation made of an epoxy resin, and electric contacts (Figure 4.59). The upper and the lower Teflon insulating sheets between which an active element is placed are bound together with epoxy resin by vacuum pressing during the cure process.
Manganin gauges may be different with respect to design and manganin alloy composition. The characteristics of some manganin gauges are given in Table 4.1. A more complete summary is given in Graham and Asay (1978).

A manganin gauge can be placed into the explosive charge in the manner illustrated in Figure 4.60.
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The manganin pressure gauge is supplied by a constant voltage source that gives a rectangular voltage pulse. The pulse has an amplitude of 30–300 V, a duration time of 100 μs, and a current of 3–30 A.

A schematic of the measuring system for the determination of detonation pressure is shown in Figure 4.61.

**Evaluation of Results**

Power supply and measurement of the change of the manganin pressure gauge resistance, induced by the detonation wave action, are realised via a modified Wheatstone bridge circuit (Figure 4.62), which, also enables calibration of the measuring system.
The relationship between the resistance change of the gauge and the corresponding voltage change is determined through calibration, as follows. At the selected value of the supply voltage, the measuring system with the manganin gauge is set to zero. Then, instead of the gauge, resistors of lower or greater resistance than the gauge are coupled into the current circuit.

The change of a relative resistance \( \Delta r/r_0 \) in the Wheatstone bridge circuit is related to the voltage change \( \Delta U \) and the current \( I \) by the expression

\[
\left( \frac{\Delta r}{r_0} \right) = \left( \frac{U_0 + \Delta U}{Ir_0} \right) - 1,
\]

(4.51)

where \( r_0 \) is the initial gauge resistance and \( U_0 \) is the bridge circuit input voltage.

If for a defined measuring system \( U_0, I, \) and \( r_0 \) are known, the above equation may be written in the form

\[
\left( \frac{\Delta r}{r_0} \right) = \left( \frac{A\Delta U}{B - \Delta U} \right).
\]

(4.52)

Constants \( A \) and \( B \) are obtained by fitting the experimental data \( \Delta r/r_0 \) vs. \( \Delta U \), obtained by the calibration of the measuring system, to Eq. (4.52).

Since the change of relative resistance is proportional to the pressure acting on the gauge, it is possible to determine the measured pressure from the voltage change:

\[
\left( \frac{\Delta r}{r_0} \right) = K \cdot p = \left( \frac{A\Delta U}{B - \Delta U} \right),
\]

(4.53)
where $K$ is the piezoresistive coefficient, which can sometimes be considered constant for a wide range of pressure.

The voltage change as a function of time is recorded by a fast oscilloscope. An example of a typical output voltage profile is given in Figure 4.63.

In order to define the relationship between the change of the relative gauge resistance and the measured pressure, the pressure gauge has to be calibrated. The calibration is performed using an explosive whose detonation pressure is known. If the calibration is performed with several different explosives, i.e., with different detonation pressures, a calibrating diagram similar to the one shown in Figure 4.64 will be obtained. Alternately controlled impact loading can be employed for more precise calibrations.

Since the relationship between the change of the gauge relative resistance and the measured pressure is given by Eq. (4.53), then the slope of the calibrating diagram represents the piezoresistive coefficient $K$.

Figure 4.63. Typical output voltage profile (After Song and Lee, 1989)

Figure 4.64. A calibrating diagram of the manganin pressure gauge
Figure 4.65. A detonation pressure profile obtained by the manganin pressure gauge

From the output voltage signal and Eq. (4.53), the detonation pressure as a function of time behind the detonation wave front is calculated (Figure 4.65).

From the pressure-time curve, the CJ point is determined as the point at which the curve has a marked change in slope or by extrapolation of the Taylor wave. The detonation pressure value is then read directly from the curve. Knowing the detonation velocity and detonation pressure and applying the relationships that connect detonation parameters, one can also calculate other detonation parameters at the CJ point. Typical use is shown by Wantine et al., (1980).

4.2.7. Determination of the Detonation Pressure Using a Polyvinylfluoride-Based Pressure Gauge

Principle of the Method

Polyvinylfluoride-based pressure gauges have been in use for dynamic pressure determination since the 1980s (Graham et al., 1992; Urtiew et al., 1986).

The main features of these gauges are a simple operation principle and no need for an energy supply source. These gauges have their own accumulated energy, which is liberated under their dynamic compression. The operating principle of the gauge is based on the fact that semicrystalline polyvinylfluoride, when treated mechanically and electrically, possesses piezoelectric properties. Therefore, upon the action of a dynamic pressure, an electric charge is created at the poles. The pressure is determined using a calibration curve, which expresses the relationship between the change of the gauge electric charge and pressure.
Description of the Method

Polyvinylfluoride is a semicrystalline polymer. Its monomer units (CH₂–CF₂) are about 50% crystalline and 50% amorphous. It has been proven that this material has pronounced piezoelectric properties if mechanically treated (elongated) and then polarised under the action of a strong variable electric field.

The polyvinylfluoride pressure gauge consists of a thin polyvinylfluoride film placed between two copper or gold platines (Figure 4.66). The gauges can be of different thickness. The thinner gauges are more sensitive, however, they are more complicated for the operation. Gauges having a thickness of 23 μm and an active element of a circular shape 3.75 mm in diameter are commercially available.

The electric charge produced at the gauge poles under the dynamic action of a pressure is recorded in a suitable manner as a function of time. The usual manner is to lead the signal from the gauge poles first to the resistance electrical circuit and then to the resistance-capacitance electrical circuit. In the first circuit, the current strength \( I \) is registered:

\[
I(t) = \frac{U(t)}{r},
\]

and in the second circuit, the integration and calculation of the electric charge \( q_E \) are performed:

\[
q_E = \int \frac{U(t)}{r} dt.
\]

Alternately, the measured current can be integrated numerically.

![Polyvinylfluoride-based pressure gauge diagram](image)
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Evaluation of Results

Prior to measurement, the polyvinylfluoride-based pressure gauge has to be calibrated; i.e., the relation between the measured electric charge and corresponding pressure has to be established. In the calibration procedure, the gauge is exposed to the action of dynamic pressure of known magnitude, usually generated by explosive detonation. The resultant corresponding electrical charge produced is recorded. The $q_E = f(p)$ calibration curve obtained is illustrated in Figure 4.67.

The calibration curve or a corresponding analytical expression for the $q_E = f(p)$ relationship is used to obtain the $p = f(t)$ curve from the experimental data. Then the CJ point as well as the detonation pressure may be determined.

4.2.8. Determination of the Detonation Parameters by the Laser Interferometry Technique

Principle of the Method

The laser interferometry technique is widely used for the study of the detonation wave time profile and structure due to its exceptionally good time resolution. The laser interferometry operating principle is based on the Doppler effect. The technique records the position and time dependence of the interferometric fields obtained due to the Doppler shift in wavelength of the reflected laser beam, resulting from the thin metal shim motion. The metal shim, 15–25 μm thick, is placed between the explosive charge and “windows” that are made of an inert optically transparent material, such as water, lithium fluoride, or polymethylmethacrylate. On the basis of the velocity of the explosive/metal shim interface as a function of time, it is possible to calculate the values of detonation parameters of the explosive (Gimenez et al., 1985, 1989; Hemsing, 1985; Lee et al., 1985).
Description of the Method

There are several types of velocity interferometers, such as ORVIS, FABRY-PEROT, VISAR, and others. They differ from each other in time resolution; that is, from about 0.3 nanoseconds to a few nanoseconds.

Determination of the velocity of a metal shim moved by the explosive charge detonation using the Fabry-Perot interferometer is illustrated in Figure 4.68.

The measuring system consists of cylindrical and spherical lenses, a Fabry-Perot interferometer (velocity meter), and a high-speed streak camera. It enables recording of the position of interferometric fields obtained due to Doppler shift in wavelength of the reflected laser beam from a moving metal shim. The interferometric fields are generated as the interferometer lets the beam pass through only at the angles defined by the distance between the Fabry-Perot mirrors and the beam wavelength. The recording intensity gain is attained by the cylindrical lens, which concentrates the interferometric image in two dot pairs at the position of every interferometric ring. The dot pairs are formed at the high-speed camera objective plane.

When the target velocity is to be determined, the laser beam is sent to the moving target. The target surface is prepared to produce a diffuse reflected beam. Mirrors and lenses are used to direct the reflected beam as a parallel one to the Fabry-Perot interferometer.

In spite of the Doppler shift, the laser beam reflected from the target moving at a constant velocity gives a static image. However, if the velocity of the
moving target slows down, the reflected beam frequency will be decreased due to the Doppler shift. As a result, the vertical narrowing of the image on the film will be obtained. Rather than the usual rings produced by Fabry-Perot interferometry, the reflected beam may be converted in only one direction, producing interference fringes as dot pairs at the camera objective plane.

By viewing the motion of the thin metal shim in contact with the explosive charge by the interferometric technique, an interferogram (streak record of fringes) is obtained. The shape of the interferogram is directly related to the detonation propagation through the explosive charge.

An argon laser is used as a laser beam source. A maximum output power of 4 W and a beam wavelength of 514.5 nm are applied.

A typical test configuration of the explosive charge with a metal shim and optically transparent window is illustrated in Figure 4.69.

**Evaluation of Results**

The Doppler shift of the reflected laser beam wavelength produces a corresponding shift in fringe (or dot pairs) spacing. In the case of a very thin shim, the fringe spacing on the interferogram is related to the explosive charge/metal shim interface velocity. A typical interferogram–streak record obtained by the test is schematically shown in Figure 4.70.

The target velocity \( (v) \) is calculated from the fringe spacing on the interferogram using the equation
Figure 4.70. Schematic of typical interferogram obtained for the metal shim velocity determination

\[ v(t) = \frac{2c}{4L} \left( \frac{d_{n+m}^2 - d_n^2}{d_{n+1}^2 - d_n^2} + m \right), \]  

(4.56)

where \( \lambda \) is the initial laser beam wavelength, \( c \) the is sound velocity, \( d_n \) and \( d_{n+1} \) are the distances between dot pairs for \( n \) and \( (n+1) \) static fringes, \( d_{n+m} \) is the dynamic fringe spacing for \( (n+m) \) fringe, \( m \) is the number of fringes shifted at shock arrival time, and \( L \) is the Fabry-Perot mirror spacing.

The interferometer time resolution is defined by the distance between interferometric fields, i.e., by the \( \lambda c/4L \) value. When the velocities observed are on the mm/\( \mu s \) scale, time resolution of several nanoseconds and an accuracy of about 1% are obtained.

If the impedance of the inert material equals the impedance of the tested explosive, the velocity of the explosive charge/inert material interface will be related to the detonation products' adiabatic shock. Consequently, the mass velocity of the detonation products at the CJ point might be determined directly, as given for instance in Figure 4.71. However, most frequently, the explosive/inert material interface velocity could be assigned neither to the velocity corresponding to the chemical spike state nor to the CJ point state, i.e., to the mass velocity of the detonation products. In such cases, the calculation of the detonation parameters at the CJ point is much more complex and requires knowing the adiabatic shock for the unreacted explosive, detonation products, and inert material, i.e., application of the extended impedance match solution method.
4.3. Determination of the Detonation Temperature

Detonation temperature is an extremely important detonation parameter, especially with respect to the study of the kinetics of chemical reactions in the reaction zone and the thermodynamic state of the detonation products. However, the detonation temperature is a parameter that is still difficult to accurately determine experimentally.

The first attempts to determine the detonation temperature of high explosives were made by Gibson, et al., (1958) applying electro-optical methods. Afterwards, a number of other researchers studied the emission spectrum of the detonation front. Dremin, Savrov, and others used a photoelectric scanning spectrometer in their studies. Later, thanks to the rapid advances in optoelectronics, significant contributions to the determination of the detonation temperature were made by Urtiew, Burton, Kato, and others (Barton et al., 1981; Kato et al., 1981, 1985; Xianchu et al., 1985).

However, the majority of the studies relating to the determination of the detonation temperature conducted so far are restricted to transparent liquid explosives. Actually, in these studies it is the temperature of the detonation wave front that is determined. This temperature is frequently assigned as the detonation temperature, i.e., the temperature at the CJ point.

The temperature at the detonation wave front and the temperature of the detonation products can be determined only by optical methods. The choice of the optical method is limited by the pressure and temperature of the detonation wave and by their duration time.
The radiation nature during the detonation is rather complex. The intensity of radiation depends not only on the explosive characteristics but also on the air temperature in the shock wave front resulting from the interaction between the air and the detonation products. Some researchers tried to eliminate the shock wave radiation by immersing the explosive charge into water. However, those investigations as well as the determinations of the detonation temperature of pressed and cast solid explosives containing a considerable amount of air inclusions have shown that it is difficult to obtain reliable results concerning detonation temperature of the solid explosives.

The temperature of a radiant can be calculated by applying Planck’s or Wien’s law. These laws interrelate the intensity of the radiation and the radiant temperature. The temperature of the radiant can be calculated in several ways:

- by determination of the total radiant energy,
- by comparing a selected monochromatic radiation of a tested radiant and a reference radiant,
- by determination of the radiation energy distribution through the spectral range; in its simplest version, this principle is reduced to the comparison of monochromatic radiation for two selected wavelengths.

The last principle is the one most frequently used for the determination of the detonation temperature. It is illustrated in Figure 4.72.

The radiation of the explosive charge is viewed through an unreacted part of the explosive charge perpendicular to the detonation wave front plane. Using a high-quality reflective optical system, the radiation is focused onto the spectrograph, passing through a very narrow entrance slit. In the spectrograph, the light radiated is split into several (minimum two) narrow wavelengths within the 390–770 nm spectral range. Then, the light signal is sent to the photomultiplier–detector, where it is transformed into a corresponding electrical signal that is recorded by an oscilloscope.

Figure 4.72. Schematic of the principle of detonation temperature determination
Presently, numerous different measuring systems for the determination of detonation temperature exist. They differ mainly with respect to the optical system used. Here a method developed by He Xianchu and co-workers (1985) will be described. The method enables the determination of the detonation temperature of solid and liquid explosives.

4.3.1. Determination of Detonation Temperature Using a Two-Colour Optical Fibre Pyrometer

**Principle of the Method**

The method is based on the determination of the radiation energy of two wavelengths of the monochromatic radiation. Wien’s law is applied for the temperature calculation. In this method, the optical system is replaced by an optical fibre that receives detonation light and transmits it to a spectrometer. The light signal is, by means of a photomultiplier, transformed into a corresponding electrical signal recorded by a wideband oscilloscope.

**Description of the Method**

The determination of the detonation temperature by an optical electric two-colour pyrometer combined with an optical fibre is schematically represented in Figure 4.73. With its one end, the optical fibre is pulled through the explosive charge along its longitudinal axis in order to receive the light signal and then transmit it to the spectrometer, where the signal is split into two narrow bands within the visible spectral range.

![Figure 4.73. Measuring system for the determination of detonation temperature by optical-electronic two-colour pyrometer](image)
The methods for determining the detonation temperature of solid and liquid explosives differ somewhat. In the case of liquid and optically transparent explosives, the optical fibre is placed directly into the explosive charge (Figure 4.74a). In the case of solid explosives, due to their nontransparency and in order to eliminate the shock wave radiation originating from the interaction of the detonation products and the surrounding air, the configuration of the explosive charge is different, as shown in Figure 4.74b.

It can be pointed out that the detonation temperature of solid explosives may not be determined before the moment of the exit of the detonation wave to the surface of the explosive charge. Between the explosive charge and the optical fibre a transparent material is placed in order to eliminate the influence of the shock wave radiation. However, it should be pointed out that in this case a shock wave reflected from the explosive charge/inert material interface is produced. That causes the change of the pressure of the detonation products, and thus the change of the detonation temperature too. This effect can be decreased using a transparent inert material whose impedance matches the impedance of the explosive. Such a material can rarely be found in practice. Therefore, liquids such as water, glycerine, and boroform are used.

**Evaluation of Results**

The detonation temperature is calculated on the basis of experimentally obtained voltage signals, recorded by the oscilloscope, for two wavelengths of the radiated light. The calculation is carried out applying the relationship between temperature and intensity of radiation.
The intensity of radiation \( L(\lambda, T) \) of a black body is directly related to its temperature and can be expressed by the Planck equation:

\[
L(\lambda, T) = \frac{\varepsilon(\lambda, T)C_1\lambda^5}{e^{C_1\lambda T} - 1},
\]

(4.57)

where \( \lambda \) is the wavelength of the radiated light, \( h \) is Planck's constant, \( k \) is Boltzmann's constant, \( C_1 = c^2h \), \( C_2 = ch/k \), \( \varepsilon \) is the emissivity, and \( T \) is the radiant temperature.

If \( (C_2/\lambda T) \gg 1 \), then the intensity of the radiation can be rather accurately expressed by Wien's approximate radiation law:

\[
L(\lambda, T) = \frac{\varepsilon(\lambda, T)C_1\lambda^5}{e^{C_1\lambda T}}.
\]

(4.58)

In the course of the determination of detonation temperature following this method, radiated light is led to the photomultipliers through the optical system composed of an optical fibre and a spectrometer. The effective power of the radiated light \( P \) that arrives on the photocathodes of the photomultipliers is

\[
P = A\Omega\beta PL(\lambda, T),
\]

(4.59)

where \( A \) is the area of the optical fibre core, \( \Omega \) is the light receiving angle of the fibre, and \( \beta \) is the effective transmissivity.

The voltage recorded on the oscilloscope is:

\[
U = PSG,
\]

(4.60)

where \( S \) is the photomultiplier spectral response sensitivity and \( G \) is the amplifier gain.

The detonation temperature is determined through the measurement of the voltage signal ratio of radiated light coming from two spectral bands. If the spectral-band channels of two spectral bands are marked with subscripts \( i \) and \( j \), respectively, then the ratio of the two voltage signals is

\[
\frac{U_i}{U_j} = \frac{\beta_i S_i G_i}{\beta_j S_j G_j} \frac{L(\lambda_i, \Delta T)}{L(\lambda_j, \Delta T)},
\]

(4.61)

where \( \Delta \lambda \) is the spectral band width (which is usually 10–20 nm).
For a defined measuring system and test conditions, parameters \( \beta, \lambda, \Delta \lambda, S, \) and \( G \) may be determined, and thus, Eq. (4.61) may be written in the form

\[
\frac{U_i}{U_j} = K \left( \frac{\varepsilon_i}{\varepsilon_j} \right) \exp \left( -\frac{C_2}{T} \left( \frac{1}{\lambda_i} - \frac{1}{\lambda_j} \right) \right),
\]

where \( K \) is a constant.

By logarithmic transformation of the expression above, the following is obtained:

\[
\ln \left( \frac{U_i}{U_j} \right) - \ln \left( \frac{\varepsilon_i}{\varepsilon_j} \right) = a + b \left( \frac{1}{T} \right),
\]

(4.63)

where \( a \) and \( b \) are experimental constants.

For a black or grey body, Eq. (4.63) is converted into

\[
\ln \left( \frac{U_i}{U_j} \right) = a + b \left( \frac{1}{T} \right).
\]

(4.64)

To obtain experimental constants \( a \) and \( b \), the measuring system is calibrated with a tungsten ribbon lamp on 2500 K. If calibration at temperatures higher than 2500 K is required, a carbon arc produced between defined carbon electrodes may be used. The arc temperature is 3811 K. Then from the voltage signals obtained for two spectral bands of radiated light and applying Eqs. (4.63) and (4.64), detonation temperature is calculated.

According to literature sources, the errors in the determination of the detonation temperature may be as high as \( \pm 150 \) K for solid explosives and up to \( \pm 300 \) K in the case of liquid explosives.

It should be pointed out that the methods for the determination of the detonation temperature need improvement. Among other things, it is necessary to define precisely what is meant by the term detonation temperature whose values are obtained experimentally. It should be made clear whether the detonation temperature is the temperature of the detonation wave front or the temperature of the detonation products.
4.4. Determination of the Composition of Detonation Products

The methods for the determination of the composition of detonation products are mainly based on the determination of the composition after the products are cooled to room temperature at constant volume conditions. There were many attempts to "freeze" the state of the chemical equilibrium and to obtain the composition that would correspond as closely as possible to the composition at the end of the chemical reactions, i.e., at the CJ state. The composition of the detonation products changes with cooling. Therefore, the results obtained correspond only roughly to the real composition at the CJ state.

The methods which enable a more realistic analysis of the composition of the detonation products have been developed only lately by Blais and Valentini (1985; Blais, 1989). This method enables the analysis of the composition of the detonation products shortly after the end of chemical reactions in the reaction zone. The interval between the very end of the chemical reactions and the analysis of the composition is the time needed by the detonation products molecules to pass, adiabatically expanding, a short distance of about 50 cm through a high vacuum to the mass spectrometer detector.

**Principle of the Method**

The explosive sample is initiated in a high-vacuum reaction chamber. Simultaneously, the analysis of the composition of the detonation products is performed using a mass spectrometer connected to the chamber.

After detonation, molecules of the detonation products formed expand freely into the vacuum. Moving at a high velocity, they first arrive at the collimating aperture of the mass spectrometer, which is at a distance of about 50 cm. Since the time interval between the end of the chemical reactions in the reaction zone and the moment of analysis is very short, it is reasonable to assume that the method, when compared to some others, gives more realistic results.

**Description of the Method and Evaluation of Results**

The measuring system used for the determination of detonation product composition is shown in Figure 4.75.

The explosive sample is initiated in a 119x48x48 cm high-vacuum chamber. The detonation products that are formed expand adiabatically, arriving at the first collimating aperture. By the time the molecules arrive at this aperture, their density has decreased sufficiently so that very few collisions occur, and thus the molecular state distribution ceases. Almost all of the molecules
that pass through the aperture reach the electron impact ioniser. After being ionised they are mass analysed by the quadropole mass filter.

Before the initiation of the sample, the pressure in the reaction chamber is $10^{-6}$ torr. It may be subsequently raised to a maximum of $10^{-3}$ torr. The sample, 20–100 mg in mass, has a form of pallet that is 4 mm in diameter and 3 mm high. It is initiated using an electrically driven Kapton slapper, 1.5 mm in diameter and 25 μm thick.

Different data acquisition systems can be applied. One possibility is to send the output signal from the electron multiplier to a fast pulse preamplifier-discriminator and a multichannel scalar.

When the multichannel scalar output data are processed, the mass spectrum of the detonation products is obtained. An example of mass spectrum of the detonation products of pentrit obtained by Blais is shown in Figure 4.76.

Although the composition of the detonation products obtained in this way is not the composition at the very end of the chemical reactions, i.e., at the CJ point, or the composition immediately before the detonation product expansion, the composition obtained relates much more closely to the real ones than the results obtained by some other methods.
Figure 4.76. Mass spectrum of PETN detonation products (After Blais and Valentini, 1985)
5
Working Capacity of Explosives

The energy liberated during explosive processes can be used for performing mechanical work. The sum of all forms of mechanical work performed is assigned as the total work done on account of the energy of an explosive.

Since the mechanical work on the surroundings is performed by gaseous products on account of the thermal energy liberated during the explosive process, the total thermal energy liberated can be taken approximately as the measure of working capacity-performance potential of an explosive:

\[ Q = qM_0 = qV\rho_0, \]  

where \( q \) is the heat liberated per unit of an explosive mass, \( M_0 \) is the mass of the explosive, \( V \) is the volume of the explosive, and \( \rho_0 \) is the density of the explosive.

If one makes a rough approximation that the gaseous products behave as an ideal gas, then the change of their internal energy (\( dE \)) is equal to the sum of the heat exchanged with the surroundings (\( dQ \)) and the performed mechanical work (\( dA \)):

\[ dE = dQ + dA. \]  

Further, if one considers the explosive process as an adiabatic process in which there is no heat exchange with the surroundings, i.e., \( dQ = 0 \), then the above equation becomes

\[ dE = dA = c_p dT, \]  

i.e., the total work, without losses, will be

\[ A_{\text{max}} = \int c_p dT. \]  

The total work is the maximum work that may be performed by the gaseous products if their internal energy is completely transformed into the mechanical
work. The maximum work is also known as explosive potential. However, in practice, different forms of losses are always present. Therefore, the true mechanical work performed on account of the explosive energy is always less than the explosive potential.

When explaining possible forms of explosive action on the surroundings, one has to bear in mind conditions under which the explosive process takes place as well as characteristics of the given explosive.

For example, when a propellant (or high explosive) burns under semiclosed and closed conditions, then hot gaseous products that are formed during the burning exert a pressure on the surroundings, thus performing different kinds of mechanical work. But, in the case of detonation, interaction between the detonation products and the surroundings is quite different and thus ability of an explosive to perform some kinds of mechanical work is different as well. Namely, on the arrival of a detonation wave to the explosive surface, gaseous products exert a strong dynamic impact on the surrounding medium. Due to the impact, a shock wave originates and begins to travel through the surrounding medium such as the air, water, or solids. Depending on the density of the medium compared to the density of the detonation products at the beginning of their expansion, they will either continue to move (in the air, for instance) or will be stopped and reflected. The latter will happen when the products impact into a rigid barrier.

When detonation occurs in the air, the gaseous products having a much greater initial density than the density of the air suddenly press back the surrounding air. Consequently, the air starts to move in the form of a spherical cloud (Figure 5.1). Its anterior border is the front of a so-created shock wave. The gaseous products move behind the shock wave front. After a distance of 2–2.5 radii of the explosive charge, the products already begin to lag behind the

![Figure 5.1. Shock wave formation in the air and its pressure profile](image-url)
shock wave front. At a distance of 10–15 radii, they completely remain behind and expand to the atmospheric pressure.

Accordingly, the main form of an explosive action as a result of detonation is a strong impact of the detonation products and shock wave on the surrounding medium at small distances from the explosive charge surface and the shock wave at the larger distances exclusively.

However, the working potential of an explosive cannot possibly be expressed by means of a single thermochemical or detonation parameter of given explosive, such as heat liberated in chemical reactions or detonation velocity. The ability of a certain explosive to perform a defined kind of mechanical work is determined by several parameters: the amount of gases formed in the reactions, the liberated heat, and the detonation velocity. Which one of these parameters will be the most important for a defined kind of work depends primarily on the condition under which the explosive process takes place.

If, for example, an explosive detonates (or burns) under closed or semiclosed conditions (e.g. in a borehole), the most important parameters for a working potential of an explosive are the amount of the gaseous products formed and heat liberated. The detonation velocity does not play too important a role in this case. The working potential of an explosive, i.e., its strength, may be predicted theoretically by means of internal energy of gaseous products (Eq. (5.3)) or by means of specific energy ($f$) as the most relevant thermodynamically calculable parameter (Köhler and Meyer, 1993; Schmidt, 1962):

$$f = pV = nRT.$$  \hspace{1cm} (5.5)

If the ability of an explosive to create a strong shattering effect in the nearest vicinity of the explosive charge is considered, then the most important parameter for explosive working potential will be detonation velocity. The ability of an explosive to perform such mechanical work is called brisance ability. The word comes from briser, which in French means “to shatter,” “to fragment.” Brisance ability is mainly a result of the strong dynamic impact of the detonation products and shock wave into the surrounding medium. Therefore, it is fully of dynamic-impulse nature.

Attempts have been made to make theoretical calculations of explosive brisance ability. It can be noted that some authors have even started from different physical assumptions. Thus, for instance, Kast and Hess (cited in Baum et al., 1959) consider that brisance should be defined by the strength of explosive, i.e., by the energy liberated per unit of time. However, Hess neglects the influence of density of explosive. He takes a strength per unit of an explosive mass, while Kast gives greater importance to the explosive density. He thinks that brisance should be defined as strength per unit of an explosive volume. Kast proposes the following expression to be used for the calculation of the brisance:

$$B = \frac{A_{\text{max}} P_0}{r},$$ \hspace{1cm} (5.6)
where $B$ is the brisance and $\tau$ is the work duration time.

Taking further that $\tau$ is inversely proportional to the detonation velocity and $A_{\text{max}}$ is proportional to the specific energy, Kast's expression becomes

$$B = f \rho_0 D.$$  \hfill (5.7)

Becker and Schmidt (cited in Baum et al., 1975) start from a hydrodynamically correct assumption concerning the detonation process and think that brisance can be defined by means of overpressure ($\Delta p$) at the detonation wave front:

$$\Delta p = p_{\text{CJ}} - p_0 = p_0 D W.$$ \hfill (5.8)

Starting from the correct assumption that at the moment of collision with a barrier the density of the detonation products increases, and thus also the pressure acting on the barrier, Rudenberg suggests that brisance may be defined by the summarised quantity

$$p_{\text{imp}} = \Delta p + \rho_1 W^2,$$ \hfill (5.9)

where $\rho_1 W^2$ is the momentum in the detonation wave zone.

The author calls $p_{\text{imp}}$ the impulsive force, and for strong detonation waves proposes the expression

$$p_{\text{imp}} = \frac{\gamma + 1}{\gamma} p_{\text{CJ}}.$$ \hfill (5.10)

According to Zeldovich and Stanyukovich (Baum et al., 1959, 1975), brisance does not depend only on overpressure at the detonation wave front but on its duration too. Thus, the authors propose that brisance should be defined by pressure impulse acting on a unit of the barrier area, i.e., by specific impulse.

Specific impulse value may be approximately calculated if the pressure-time dependence is known, assuming that there is no lateral scattering of detonation products. Assuming that the expansion isentrope equation for the detonation products has the form (Eq. (4.50))

$$p = A \rho^\gamma,$$

and that the polytropic exponent has the value of 3 (which is approximately correct for the strong detonation waves and for the detonation product densities close to the density at the CJ point), as well as that the sound velocity in the CJ
point is given by the equation

\[ e_{CJ} = \frac{3}{4} D, \quad (5.11) \]

then the equation for the calculation of the pressure acting on the barrier, as a function of time, is obtained:

\[ p = \left( \frac{64}{27} \right) p_{CJ} \left( \frac{l}{tD} \right)^3. \quad (5.12) \]

Integration of the above equation leads to the total impulse \( I \) of the reflected shock wave:

\[ I = \int_{l/D}^{\infty} p dt = \left( \frac{32}{27} \right) p_{CJ} S \left( \frac{l}{D} \right), \quad (5.13) \]

where \( S \) is the cross section of the explosive charge and \( l \) is the length of the charge.

Taking that

\[ p_{CJ} \approx \frac{1}{4} \rho_0 D^3, \quad (5.14) \]

then the equation for the impulse becomes

\[ I = \left( \frac{8}{27} \right) S \rho_0 D l = \left( \frac{8}{27} \right) M_{\text{E}} D, \quad (5.15) \]

where \( M_{\text{E}} = S \rho_0 l \) is the explosive charge mass.

For experimental determination of blasting capacity (called also energy of the detonation products, the strength of explosives, etc.) and brisance, a number of different methods are proposed. What the majority have in common is the fact that working capacity is not expressed in work units but most frequently via some other parameters: degree of compression of metal cylinders, volume increase after explosion within the lead block, depth dent formed in the steel plate after explosion, etc.

For determination of the blasting and brisance capacity of explosives, the following methods are used:

- lead block test (or Trauzl test),
5.1. Lead Block Test for Determination of the Strength of Explosives

**Principle of the Method**

Determination of the strength of explosives by the lead block (or Trauzl) test consists in the determination of the expansion, or volume increase, that is produced by the detonation of a tested explosive charge in the cavity of a lead block of a defined quality and size.

The volume increase produced by the detonation serves as a measure of the strength of a tested explosive (Ahrens, 1973, 1977; Bigourd, 1972, 1973a, 1973b; Lingens, 1972; Srinivasan and Mahadevan, 1973). The strength of the tested explosive also may be expressed as a relative strength with respect to a selected reference explosive.

**Description of the Method**

The lead block used for the determination of the strength of explosives should be made of soft lead, cast at a temperature 390–400 °C. The lead block test configuration is given in Figure 5.2.
The differences in the test procedure are attributed to the way the amount of explosive is measured: either constant mass or constant volume. Some authors always weigh out the explosive charge as a 10 g mass. According to others and to the European Commission for the Standardisation of the Tests of Explosives (Ahrens, 1977), tested charges always have a constant volume of 10 cm$^3$. In the latter case, the density of the test charge may vary.

If the explosive charge is taken by a mass of 10 g, it is prepared in a 70 mm high, 120x150 mm trapezoidal piece of tinfoil as follows. A cylindrical tube 25 mm in diameter is formed from a piece of tinfoil by winding it around a piston of defined size. Then 10 g of the explosive is placed into the tube. At one end of the prepared explosive charge, a cavity for the insertion of a detonator is made.

If the explosive charge is taken by a volume of 10 cm$^3$, it is to be prepared in a special device illustrated in Figure 5.3 as follows. A trapezoidal piece of 10 μm thick tinfoil (Figure 5.4) is wound around the piston, and the projecting part of the tinfoil is folded down onto the end of the piston, forming a tube. Then the end of the piston is inserted into the matrix together with the so-formed tinfoil tube. The matrix is clamped by means of the frame, and the piston is withdrawn slowly from the tinfoil tube. At the bottom of the tube, a hole is pierced by means of a wooden rod, and a standard detonator is inserted so that it projects 12 mm from the base piece of the device.
After that, the explosive charge is put into the tinfoil tube and is lightly compressed by means of a wooden rod. Finally, the projected part of the tinfoil is folded down inwardly, and the piston is inserted into the matrix. The test explosive charge is so formed, and the piston may be withdrawn from the matrix.

If necessary, because of the safety requirements, during the charge preparation procedure, the detonator may be replaced by a metal cylinder of the same size as a standard detonator. The detonator is inserted into the explosive charge shortly before the testing.

Liquid explosive substances are tested in thin-walled glass cylinders or by pouring 10 cm$^3$ of a liquid explosive into the lead block cavity. Before testing, it should be found out in separate experiments whether or not the liquid explosive is compatible with the lead.

The explosive charge prepared is inserted into the lead block cavity together with the detonator, and then the cavity is stemmed by dry sand. The sand has a density of 1.35 g/cm$^3$ and has a particle size below 500 μm. During the testing, the lead block is placed on a 100x100x5 cm steel plate. The explosive charge is initiated by the standard electric or nonelectric detonator.

**Evaluation of Results**

The expansion of the cavity produced by the detonation of the explosive charge is measured by the volume of water poured from a graduated measuring cylinder. The net-expansion value is obtained when the volume of the initial lead block cavity (63 cm$^3$) and the expansion produced by the detonator alone are subtracted from the total expansion after the detonation of the charge. The temperature of the lead block is measured in the depth of the cavity. It should be in the range of 10–20 °C before inserting the charge. If the temperature is not in this range, then the corrections given in Table 5.1 should be applied.
Table 5.1. Correction table for temperatures other than those in the range of 10–20 °C

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Correction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>+6.25</td>
</tr>
<tr>
<td>-5</td>
<td>+5.00</td>
</tr>
<tr>
<td>0</td>
<td>+3.75</td>
</tr>
<tr>
<td>+5</td>
<td>+2.50</td>
</tr>
<tr>
<td>+10</td>
<td>+1.25</td>
</tr>
<tr>
<td>+15°</td>
<td>0.00°</td>
</tr>
<tr>
<td>+20</td>
<td>-1.25</td>
</tr>
<tr>
<td>+25</td>
<td>-2.50</td>
</tr>
<tr>
<td>+30</td>
<td>-3.75</td>
</tr>
<tr>
<td>+35</td>
<td>-5.00</td>
</tr>
<tr>
<td>+40</td>
<td>-6.25</td>
</tr>
</tbody>
</table>


Before conducting the test, the lead block of the same casting should be calibrated. The calibration is performed with a pure picric acid whose density is 1 g/cm³ and charge volume is 10 cm³. The net-expansion value of such an explosive charge, obtained in three shots, should amount to between 287 and 300 cm³. However, the values between 280 and 310 cm³ can also be accepted. In that case, conversion of the net-expansion values obtained should be made. The conversion is obtained by multiplication of the calibration net-expansion value by the quotient of the mean value of the admissible calibration interval (294 cm³) and the obtained value.

The net-expansion value for the explosive can also be given in the form of the so-called pentrit equivalent. The pentrit equivalent represents the ratio between the net-expansion value produced by a pentrit/potassium chloride mixture and the net-expansion value produced by pure pentrit, whose density is 1.40 g/cm³. The charge volume in the tests is always 10 cm³. The pentrit equivalent is given in percent. A reference curve representing the relationship between the net-expansion value of the lead block and the pentrit equivalent (and pentrit content in the mixture) is given in Figure 5.5. Such a curve may be used for the conversion of the net-expansion value to the pentrit equivalent.

Due to some shortcomings, such as the influence of the charge volume when charges of constant mass are tested, the quality and the price of the lead block, and the lack of the strict proportionality between the true strength of an explosive and the lead block expansion, Belyaev (cited in Baum et al., 1975) has proposed the use of the so-called equivalent charge to express the strength of explosives.

In that case, the determination of the strength of an explosive is based on the determination of the mass of the reference explosive charge Ammonit-6, that produces the same expansion value as a explosive tested under the same testing conditions. Since equal lead block expansion values should be the result of equal works done, it can be written:
Chapter 5. Working Capacity of Explosives

Figure 5.5. The reference curve for pentrit/potassium chloride for the transformation of the expansion value of the lead block (Modified from Ahrens, 1977)

\[
\frac{A_X}{A_{\text{Ammonit}-6}} = \frac{M_{\text{Ammonit}-6}}{M_X},
\]  
(5.16)

where \( A_X \) and \( M_X \) are the work done by the tested explosive and its mass, respectively, and \( A_{\text{Ammonit}-6}, M_{\text{Ammonit}-6} \) are the work done by the reference explosive and its mass, respectively.

The mass of the reference explosive charge that corresponds to the definite net-expansion value, i.e., the definite mass of a tested explosive, is determined using a calibration curve. The curve represents the relationship between the expansion value and the reference explosive charge mass (Figure 5.6).

Figure 5.6. Lead block expansion value dependence on the Ammonit-6 charge mass
5.2. Determination of Explosive Strength Using the Ballistic Mortar

Principle of the Method

A massive steel mortar enclosed by a "projectile" (weight) is suspended from the pendulum axis by a long pendulum arm. The explosive charge of a given mass is initiated in the mortar cavity. Under the action of the detonation products, the projectile is ejected out of the mortar, whereas due to the counteracting force, the mortar is swung from its position. The maximum swing of the mortar is recorded, and it serves for the calculation of the strength of the explosive tested.

Apart from being used for the determination of the strength of explosives (Ahrens, 1977; Srinivasan and Mahadevan, 1973), the ballistic mortar also proved to be a very suitable device for the determination of an impulse of the force at the explosive charge surface (Baum et al., 1959, 1975).

Description of the Method

Ballistic mortars of different design exist, but the one most frequently used is illustrated in Figure 5.7. The mortar, 311 kg in mass, is suspended from knife-edges. Two cylindrical cavities are made in the mortar. One cavity is designed to contain the projectile and the other one to hold the explosive charge (Figure 5.8). The steel projectile has a cylindrical shape and is 16 kg in mass. The maximum play between the projectile and the mortar is 0.2 mm.

The ballistic mortar suitable for the determination of the impulse of force at the explosive surface, applied in the former Soviet Union, is shown in Figure 5.9.

Figure 5.7. Ballistic mortar
When the ballistic mortar illustrated in Figure 5.7 is used in strength determination, explosive charges of 10 g mass are used. The explosive charges are prepared in a cylindrical tube. A tube is made of a trapezoidal piece of tinfoil that is 127x152 mm wide, 66.6 mm high, and 12 μm thick. After the tested explosive is inserted into the tube, the projected part of the tube is folded...
down onto the explosive. Then the cavity for the detonator is pierced by a wooden rod.

The explosive charge may be detonated by an electric or nonelectric standard detonator. When an electric detonator is used, the wires of the detonator are passed from the firing chamber through the axial opening in the mortar, as shown in Figure 5.8. When a nonelectric detonator and a safety fuse are used, the free end of the safety fuse is passed through the axial hole in the projectile. In that case, another projectile, having an axial hole of φ7 mm, made through the whole length of the projectile, is used.

The explosive charge is placed into the firing chamber of the mortar. The projectile is placed into the mortar too. The rider on the graduated scale that records the maximum swing is adjusted to zero position. Finally, the initiation of the explosive charge is performed.

After the detonation, the projectile is ejected out from the mortar. It stops at the protecting barrier located at a distance of about 6 m in front of the mortar. Due to the counteracting force, the mortar is swung from its equilibrium position. The angle of the maximum swing is recorded on the graduated scale by means of the rider.

The strength of an explosive is usually expressed relative to the strength of the reference explosive. Therefore, it is necessary to test the reference explosive at the beginning of the experiment. Blasting gelatin is used as the reference explosive. It has the following composition:

- nitroglycerine/nitroglycol 90.7%
- dry nitrocotton 8.2%
- milled borax 0.5%
- ground chalk 0.6%

The preparation of the reference explosive is as follows.

- The nitroglycerine/nitroglycol mixture is obtained by nitration of the mixture that contains 20% ethylene glycol and 80% glycerine. The moisture content of nitroglycerine should not exceed 0.3% by mass, and alkalinity calculated as sodium carbonate should not exceed 0.005%.
- Nitrocotton has a nitrogen content of 12.1% and a viscosity between 100 and 200 centipoises as a 3% solution (by volume) in 95% acetone. The acidity of the nitrocotton calculated as sulphuric acid should not be greater than 0.05%.
- Chalk should be pure calcium carbonate of more than 98% purity with a moisture content below 0.5%.
- Borax (sodium borate) must be chemically pure; the moisture content including water of crystallisation should be between 45% and 47.5%; it should not contain any heavy metal salts.

The required quantities of borax, chalk, and nitrocotton are introduced into a plastic gelatinisation box. The nitroglycerine is then, with continual stirring,
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poured into the box. The stirring is continued for five minutes. After that, the mixture is allowed to stand for one hour at a temperature not lower than 15 °C to allow the gelatinisation process to produce a fairly stiff gel. The gel is then added in small portions into the mixer provided with a water jacket. It is mixed for the next 15 minutes at a temperature of 30 °C. The preparation of the reference explosive is completed in that way. The mixer is emptied, and the preparation of the explosive charge may follow.

Instead of blasting gelatin, one can use another explosive as an intermediate standard such as trinitrotoluene, picric acid, etc. In that case, the results have to be converted by means of a correction factor in order to relate them to the blasting gelatin.

Evaluation of Results

After the detonation of the explosive charge, a part of the energy released is spent to give a certain momentum to the projectile, while the other part is spent to raise the mortar to a certain height. Thus, the total work \( A \) done on account of the energy of the explosive charge may be written

\[
A = A_1 + A_2, \tag{5.17}
\]

where \( A_1 \) is the work done for raising the mortar to a certain height and \( A_2 \) is the work done to give a certain momentum to the projectile.

The work \( A_1 \) and \( A_2 \) are calculated using the following equation:

\[
A_1 = M_M H = M_M L (1 - \cos \alpha), \tag{5.18}
\]

\[
A_2 = \frac{M_p v_p^2}{2g}, \tag{5.19}
\]

where \( M_M \) is the mass of the mortar, \( M_p \) is the mass of the projectile, \( H \) is the height to which the mortar is being raised, \( v_p \) is the velocity of the projectile, \( \alpha \) is the angle of the mortar swing, and \( L \) is the distance from the centre of mass to the suspension axis.

The projectile velocity can be calculated from the equilibrium condition of the mortar and the projectile momentum:

\[
M_M v_M = M_p v_p. \tag{5.20}
\]

The mortar swing velocity \( (v_M) \) is calculated from the equation
Introducing the expressions for $A_1$ and $A_2$ into Eq. (5.17), the equation for the calculation of total work is obtained:

$$A = M_M L (1 - \cos \alpha) \left(1 + \frac{M_M}{M_p}\right)$$  \hspace{1cm} (5.22)

From Eq. (5.22) it is obvious that the total work does not depend on the charge density. This is consistent with some theories of the explosive strength calculation.

In practice, the strength of the tested explosive is usually reported relative to the strength of a reference explosive—blasting gelatin. The relative strength of the tested explosive ($WS$) is obtained as a ratio between the strengths, i.e., work done by the tested ($Ax$) and reference explosive ($AR$) under the same testing conditions, and is expressed in percentages:

$$WS = \frac{Ax}{AR} = \frac{1 - \cos \alpha}{1 - \cos \alpha_0} \times 100$$  \hspace{1cm} (5.23)

where $\alpha_0$ is the angle of the mortar swing for the reference explosive and $\alpha$ is the angle of the mortar swing for the tested explosive.

The determination of the impulse of the force at the explosive charge surface using the ballistic mortar illustrated in Figure 5.9 is performed by placing a metal plate on the base of a cylindrical explosive charge, opposite the initiation position. As a result of the detonation of the charge, the plate will be driven out, impacting the projectile and giving it a certain momentum. In order to transfer the whole impulse from the explosive to the projectile, the plate should not be destroyed by the detonation.

The calculation of the impulse is based on the application of the laws of conservation of angular momentum and energy. These laws can be written in the form

$$M_m v_m r = (M_m r^2 + K) \omega_0$$  \hspace{1cm} (5.24)

$$\frac{1}{2} (M_m r^2 + K) \omega_0^2 = g (M_p L + M_m r) (1 - \cos \alpha)$$  \hspace{1cm} (5.25)

where $M_m$ is the mass of the metal plate, $v_m$ is the velocity of the metal plate, $r$ is the impact radius of the metal plate in relation to the suspension axis, $K$ is
the moment of inertia of the ballistic mortar, and $\omega_0$ is the angular velocity of the projectile.

Assuming that

\[(1 - \cos \alpha) = 2 \sin^2 (\alpha / 2),\]  

(5.26)

and solving Eqs. (5.24) and (5.25), the following equation is obtained:

\[\frac{M_m^2 v_m r^2}{M_m r^2 + K} = 4(M_p + M_m) g L \sin^2 (\alpha / 2),\]  

(5.27)

i.e.,

\[M_m v_m = \sqrt{(M_p + M_m) g L \left(\frac{2 \sin (\alpha / 2)}{M_m r}\right)}.\]  

(5.28)

Since $M_m r^2$ and $M_m$ are negligible compared to $K$ and $M_p$, respectively, Eq. (5.28) may be written in the form

\[M_m v_m = \left(\frac{2 \sin (\alpha / 2)}{r}\right) \sqrt{M_p g L K}.\]  

(5.29)

If $K$ is extracted from the equation for the calculation of the period ($T$) of oscillations of physical pendulum,

\[T = 2\pi \sqrt{\frac{K}{M_p g L}},\]  

(5.30)

and inserted into Eq. (5.29), the equation for the calculation of the impulse ($I$) is obtained:

\[I = M_m v_m = \frac{TM_p g L}{\pi r} \sin (\alpha / 2).\]  

(5.31)

The $(TM_p g L / \pi r)$ is called the constant of ballistic mortar. It may be determined when the period of oscillations and the static moment of the ballistic mortar ($M_p g L$) are obtained experimentally.

The impulse can also be obtained experimentally when no metal plate is used and the explosive charge is in direct contact with the projectile. In that case, $L = r$, while the mass and velocity of the metal plate are replaced by the mass and velocity of the detonation products.
5.3. Determination of Explosive Strength by Underwater Detonation

Since the 1970s, the underwater detonation test increasingly has been applied for the determination of the strength of explosives, especially those that are not cap sensitive (Barnes et al., 1988; Bjarnholt, 1978; Persson, 1978, 1980; Satyavratan and Vedam, 1980; Wollert-Johansen, 1980). The test is of particular importance because it enables the determination of the strength of explosives that cannot detonate completely when a charge mass is less than 10 g (that means that they could not be tested by ballistic mortar or lead block test). By this method, the strength of an explosive is determined on the basis of measurable forms of energy released by underwater detonation—shock wave energy and bubble energy.

**Principle of the Method**

The method is based on the detonation of an explosive charge by means of a detonator or via a booster at a defined depth under the water surface and on recording the shock wave time profile and the bubble pulse period at a given distance from the explosive charge. From the shock wave-time profile, the shock wave energy is calculated, whereas from the bubble pulse period, the bubble energy is calculated. The sum of the shock wave energy and the bubble energy gives the total energy of the explosive.

**Description of the Method**

The testing conditions for the underwater detonation test for the determination of explosive strength have not yet been standardised. Namely, the test is performed somewhere on natural lakes or seas (e.g., Engene's underwater shooting station near Oslo), but water-filled tanks of different sizes are sometimes used as well. The natural seas or lakes are advantageous since they enable the testing of explosive charges of greater mass. This is important since the charge mass may influence the test results.

The principle of the underwater detonation test is illustrated in Figure 5.10. The size of the water-filled tank in Figure 5.10 is after Satyavratan and Vedam (1980).

A suitable tool is used for fixing the explosive charge at a defined depth under the water surface. The charge mass is limited by the tank size.

A gauge for the shock wave pressure measurement is fixed at a known distance from the explosive charge. The pressure gauge is connected to a charge amplifier and oscilloscope. Right in front of the pressure gauge a triggering gauge is fixed. Piezoelectric pressure gauges are usually used for the shock wave pressure measurements and as a triggering gauge. The explosive charge is initiated by a standard electric detonator, with or without use of a booster.
Efforts have been made in order to standardise testing conditions. Following these efforts, the International Study Group for the Standardisation of the Methods of Testing Explosives (Persson, 1980) has suggested that standard underwater detonation tests should be made in two size ranges—one with 1 kg charges and the other with 8 kg charges. The suggested testing conditions are given in Table 5.2.

### Evaluation of Results

The energy released by the detonation of the explosive charge under water appears in two measurable forms: shock wave energy and bubble energy.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mass 1 kg</th>
<th>Mass 8 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test charge mass, kg</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Test charge size, L/d</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Initiation</td>
<td>Standard</td>
<td>Standard detonator and 10 g PETN/Wax booster</td>
</tr>
<tr>
<td>Charge depth, m</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Pond depth, m</td>
<td>&gt; 6</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>No boundary of water closer to the charge or gauge, m</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: After Persson, 1980.
The shock wave energy is calculated from the experimentally obtained shock wave pressure-time dependency. The shock wave energy \( E_S \) at a certain distance from the explosive charge \( R \) is proportional to the integral of the second power of the square of the shock wave pressure, with respect to time:

\[
E_S \approx \int p^2 dt,
\]  
(5.32)

i.e.,

\[
E_S = \frac{4\pi R^2}{M_E v_w \rho_w} k_1 k_c \int p^2 dt,
\]  
(5.33)

where \( v_w \) is the sound velocity in water, \( \rho_w \) is the density of water, \( M_E \) is the mass of the explosive charge, \( k_1 \) is the amplification factor, and \( k_c \) is the integrator constant.

Following the detonation, the gaseous detonation products expand and then contract, i.e., pulsate. The pulsing period \( T \) is dependent on the third root of the bubble energy \( E_B \):

\[
E_B \approx T^3.
\]  
(5.34)

For the calculation of the bubble energy, expressed in MJ/kg, from the experimentally determined bubble pulsing period, one may use the equation originated from the US Army Engineer Nuclear Creation Group (cited in Wollert-Johansen, 1980):

\[
E_B = 2.5 \frac{T^3}{M_E} (3.28 H + 33.95)^{2.5},
\]  
(5.35)

where \( T \) is the bubble pulse period, i.e., the period between the detonation and the first bubble collapse (expressed in seconds), and \( H \) is the depth of the explosive charge (expressed in meters).

The total energy of the explosive \( E_T \) is obtained as a sum of the shock wave energy and the bubble energy. If corrections for the energy dissipated to the water and the correction factor for the explosive charge shape are taken into account, then the equation for the calculation of the total energy of an explosive may be written in the form

\[
E_T = E_f [(1.542 + 6.655 \cdot 10^{-9} \rho_0 D^2) E_S + E_B],
\]  
(5.36)

where \( E_f \) is the correction factor for the charge shape.
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Figure 5.11. Influence of the charge mass on the total energy of the explosive (Reprinted with permission from Wollert-Johansen, 1980)

It should be mentioned that several factors may influence the test data; primarily, it is the mass of the explosive charge (Figure 5.11), the charge depth, and the manner of charge initiation. The energy value obtained by the underwater detonation test is comparable with the energy value obtained by the theoretical thermodynamic calculations.

Some investigations have shown that there is a good linear correlation between the underwater and lead block test results. The best correlation is between the total energy of the explosive and the lead block expansion. This indicates that both shock wave and gas energy affect the lead block test, but its final value manifests as a composite effect of both of them.

5.4. Determination of Explosive Performances by the Double Pipe Test

The double pipe test is a simple method that may be applied for the determination of the performances of commercial explosives, especially those used in a borehole (du Plessis and Lownds, 1985; Lownds and du Plessis, 1984). The testing conditions are similar to those in practice, which proves to be an important advantage of this method.

More generally, the method may also be classified among the methods for the determination of explosive sensitivity to initiation. However, both the run-to-detonation process when an explosive charge is initiated in the borehole and the strength of an explosive are extremely important parameters for commercial explosives from the practical point of view.
Figure 5.12. Double pipe test arrangement (Reprinted with permission from Lownds and du Plessis, 1984)

Principle of the Method

Explosive charges in the form of standard cartridges of different length are placed in a pipe that simulates a borehole. Together with the charge, the pipe is placed on the top of a witness steel pipe, which rests on a heavy anvil. After the detonation of the explosive charge, the witness pipe will be dented. The depth of the dent depends on several parameters: characteristics of explosive charge, charge diameter, charge density, loading density, characteristics of pipe material, etc. Under the same testing conditions, the deformation of the witness pipe is related only to the performance of the explosive charge. Therefore, from the test, one may obtain comparative information about performances of different explosives.

Description of the Method and Evaluation of Results

The double pipe test arrangement is illustrated in Figure 5.12.

The pipe size and material of which it is made may differ. The top pipe with the inserted charge is put on the witness pipe, and the two pipes are then fixed together by adhesive tape. Both pipes are then fixed to a mild steel anvil. Afterwards, the explosive charge may be initiated.

The testing conditions may differ. For example, Lownds and du Plessis (1984) have used several variants of the method. The differences in testing condition are as follows:

- charge length from 0.6 m to 4 m,
- initiation by means of standard detonator, booster, or detonating cord,
- top pipe internal diameter from 25 to 80 mm,
- top pipe material: plastic (PVC), plastic-lined steel and steel,
- witness pipe made of manganese steel hollow bar of outside diameter from 32 to 50 mm and wall thickness from 5 to 9 mm,
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- anvil made of mild steel bar of 80 mm square cross section and up to 2 m long.

After detonation of an explosive charge, the witness pipe will be dented in the form shown in Figure 5.13.

When the testing conditions are maintained constant and witness pipes of the same quality are used, the pipe denting will be reproducible and may be related to the tested explosive performances.

The depth of the witness pipe dent is measured at intervals along the entire pipe length to get the full information regarding the charge performances along its entire length. A typical test result thus obtained is given in Figure 5.14.

However, besides the characteristics of the explosive charge, the channel effect and the way the initiation of the charge is performed may have a significant influence on the test results. The channel effect manifests in decreasing the dent depth as the distance from the initiation point is increased. It may be diminished if the ratio between the volume of the explosive charge and the internal volume of the pipe is increased, i.e., if the charge is consolidated. The way the charge is initiated has a greater influence at the distances closer to the initiation point.

Figure 5.13. Cross section of the witness pipe before and after detonation (Reprinted with permission from Lownds and du Plessis, 1984)

Figure 5.14. Dent profile for an ANFO explosive poured into a 35 mm internal diameter top pipe (Reprinted with permission from Lownds and du Plessis, 1984)
The test results for emulsion commercial explosives have shown that there is a correlation between the depth of the wetness pipe dent and the relative energy calculated theoretically. The test results are very useful, especially when used together with results obtained by underwater detonation and by ballistic mortar tests.

5.5. Determination of the Parameters of Explosive Effects From the Cylinder Expansion Test

The most complete information necessary for the correct solving of certain problems such as optimum transfer of the energy from an explosive charge to the warhead can be obtained experimentally by viewing the expansion of the detonation products inside a metal tube (Feng Lan et al., 1993; Gibbs and Popolato, 1981; Hornberg, 1986; Hornberg and Volk, 1989; Miller and Carlson, 1989; “Safety and Performance Tests,” 1972). Such a test is called a cylinder test.

It is known that the definition of the brisance is a highly arbitrary parameter because there is no defined absolute value of brisance as a characteristic of an explosive independent of the method by which it is determined. So brisance may be defined as a ratio between the potential of explosive and the duration of the detonation. However, it is possible to find out, with a good approximation, a direct relationship between the brisance and the detonation wave pressure. If one wants to predict the explosive effects on a certain surrounding medium, then it is preferable to use the Gurney energy instead of the brisance. The Gurney energy is composed from the kinetic energy of the expanding detonation products and the kinetic energy of the displaced material, e.g., the walls of the metal tube if detonation is performed inside the tube.

If an explosive charge detonates in a metal cylinder, and assuming that the density of detonation products is constant, the Gurney energy \( E_G \) can be expressed by the equation

\[
2E_G = \mu v_m^2 + \frac{1}{2} \int v_g \, dv',
\]

(5.37)

where \( v_m \) is the velocity of the wall material, \( v_g \) is the velocity of the detonation products, and \( \mu \) is the ratio between the masses of the cylinder and the explosive.

Assuming that the velocity of the detonation products is linearly increased in the expansion direction, and taking that for the cylindrical geometry of the metal casing \( v_g = v_m r/r_m \) (where \( r_m \) is cylinder radius), the above equation can be integrated yielding
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\[ 2E_G = \left( \mu + \frac{1}{2} \right) v_m^2. \]  

(5.38)

From the above equation, the cylinder wall velocity is

\[ v_m = \sqrt{\frac{2E_G}{\mu + 1/2}}. \]  

(5.39)

The conditions of the charge detonation in metal cylinders, i.e., warheads, are well described by Eq. (5.39). From this equation, it can be seen that the wall velocity during expansion depends on the ratio between the masses of the cylinder and the explosive. The quantity \( \sqrt{2E_G} \) is called the Gurney constant.

The maximum wall velocity can be calculated theoretically if the detonation velocity of an explosive is known and assuming that the total energy of an explosive \( (M_Eq) \) is spent on the velocity of the wall material (which means that all kinds of energy losses are neglected):

\[ M_Eq = \frac{M_m v_m^2}{2}, \]  

(5.40)

where \( M_E \) is the mass of the explosive, \( q \) is the heat of detonation, and \( M_m \) is the mass of the metal cylinder.

If the detonation velocity is expressed via the heat of detonation by the equation

\[ D = \sqrt{2(\gamma^2 - 1)q}, \]  

(5.41)

and if the polytropic constant \( (\gamma) \) is taken to be 3 (that is a valid approximation for the explosives of higher densities), one obtains

\[ D = 4\sqrt{q}, \]

i.e.,

\[ q = \frac{D^2}{16}. \]  

(5.42)

If the above equation is substituted into Eq. (5.40), the maximum wall velocity may be calculated as
Considering the losses of the kinetic energy of the detonation products and also the heat losses, one can deduce in the analogous way the following equation for the calculation of the wall velocity:

\[ v_m = \frac{D}{2} \sqrt{\frac{1}{2\mu + 1}}. \]  

(5.44)

The Gurney energy is most frequently obtained experimentally from cylinder test data. Additionally, on the basis of more detailed theoretical consideration of the detonation products and the wall material expansion process, the cylinder test makes it possible to calculate the detonation pressure and the heat of the detonation of an explosive.

**Principle of the Method**

In the course of the test procedure, one measures the time progression of the radial expansion of a copper cylinder as the result of an expansion of the detonation products after the detonation of an explosive charge within the cylinder.

The increase of the cylinder external radius is viewed at a constant section of the cylinder, opposite to the cylinder axis. The optical methods are most frequently applied. The cylinder external radius vs. time curve, the so-called expansion curve, is thus obtained. The treatment of the curve yields the wall velocity and the Gurney energy.

Besides, on the basis of the cylinder test data, if the detonation parameters at the CJ point as the initial point of the products' expansion are known, it is possible to deduce constants in the Jones-Wilkins-Lee equation (known as JWL equation of state) of the detonation products' isentropic expansion.

**Description of the Method**

The cylinder test principle is illustrated in Figure 5.15.

The tested explosive is filled into a copper cylinder. The internal diameter of the cylinder is 25.4 mm, its length is 305 mm, and its wall thickness is 2.6 mm. The initiation of the so-prepared explosive charge is performed at the end of the cylinder front by a detonator and a booster. The cylinder expansion, i.e., the increase of its external radius, is viewed by suitable equipment. For example, a high-speed streak camera may be used. It is positioned to cover a constant section of the cylinder. A background illumination ought to be applied.

Simultaneously, the detonation velocity of the explosive charge may be accomplished by one of the methods described in Section 4.1.
Evaluation of Results

Although the cylinder test appears to be a simple method, the treatment of the data provides a lot of important information regarding the tested explosive. It gives us the Gurney energy (from cylinder wall velocity) and the equation of the detonation products' isentropic expansion.

The direct experimental output of the cylinder test is the increase of the cylinder external radius as a function of time, i.e., the cylinder expansion curve (Figure 5.16).

Calculation of the Cylinder Wall Velocity. By simple graphical or analytical treatment of the cylinder expansion curve, one can obtain cylinder wall velocity: as a tangent to the curve, if determined graphically, or as a derivation of an analytical expression, if determined analytically. Consequently, the Gurney energy may be calculated according to Eq. (5.38).

The unsteady flow of the wall material is shown to exist at the initial stage of the expansion. Therefore, in the treatment of the test data, it is better to start from the increase of the radial expansion value equal to 5 mm \([r_a-r_{a0}=5 \text{ mm}]\). As a point of the maximum wall velocity, the velocity corresponding to the increase of the radial expansion value equal to 19 mm \([r_a-r_{a0}=19 \text{ mm}]\) should be taken.

Usually, the test data are treated in a slightly complex but, from the theoretical point of view, more correct way. The first step in such a treatment is an
analytical presentation of the cylinder expansion curve. Here the assumption may be made that the pressure of the detonation products behind the detonation wave front and the radial acceleration, have an exponential drop:

$$\frac{d^2 r_m}{dt^2} = \sum a_j b_j e^{-b_j t}.$$  \hspace{1cm} (5.45)

Subscript \( m \) denotes the cylinder radius, whose value is somewhere between its external \((r_o)\) and internal \((r_i)\) radius.

Since the initial conditions of the expansion are

\[ r_i = r_o, \]
\[ \frac{dr}{dt} = 0, \quad t = 0, \]
\[ r_m dr_m = r_i dr_i, \]

then, by means of double integration of Eq. (5.45) within the limits \( t=0 \) and \( t=t_i \), analytical expressions for the wall velocity-time curve \((dr_m/dt)\) and the increase of the external cylinder radius-time curve \((r_m-r_m0)\) are obtained:
\[
\frac{dr_m}{dt} = \sum a_j \left(1 - e^{-b_j t}ight),
\]
(5.46)

\[
(r_m - r_{m0}) = \sum a_j \left[ t - \frac{1}{b_j} \left(1 - e^{-b_j t}ight) \right].
\]
(5.47)

Parameters \(a_j\) and \(b_j\) are found in the fitting procedure of experimentally obtained data \((r_m - r_{m0})\) vs. \(t\). For a sufficiently accurate representation of the cylinder expansion curve, only two addends are sufficient.

Let us now consider the expansion process more carefully. From the point of impact of the detonation wave on the inner surface of the ring-shaped wall section, a shock wave propagates through the cylinder wall and reaches the outer cylinder surface only at a later point in time. Not earlier than that moment \(t_0\), the cylinder wall starts to move as a whole at a free surface velocity. Accordingly, it is

\[
t_i = t + t_0.
\]

Thus, instead of \(t_i=0\), the initial condition of the expansion is \(t_i=t_0\). Applying the new initial condition, the integration of Eq. (5.46) leads to the following equation for the calculation of the external cylinder radius increase:

\[
(r_m - r_{m0}) = \sum a_j \left[ t - \frac{e^{-b_j t}}{b_j} \left(1 - e^{-b_j t} \right) \right].
\]
(5.48)

From now on, Eq. (5.48) is applied instead of Eq. (5.47).

A nonlinear curve fitting procedure provides us with five parameters of Eq. (5.48): \(a_1, a_2, b_1, b_2,\) and \(t_0\), for \(j=2\). For the calculation of the radial wall velocity and acceleration, Eqs. (5.45) and (5.46) are used.

In order to obtain the genuine wall velocity, i.e., the velocity joined to a mass point and including both radial and axial components, one may start from the analysis of the expanding path of the individual cylinder particle (Figure 5.17).

A high-speed streak camera is used for viewing the cylinder expansion. It records the position of points Q and P at times \(t_1\) and \(t_2\). Their starting positions at the cylinder wall before the expansion are at the points \(Q'\) and \(P'\). After \(t_1\) and \(t_2\) periods, the detonation wave front occupies new positions \(D_1\) and \(D_2\). In fact, both points \(P\) and \(Q\) have already begun to expand before being recorded by the streak camera. Thus, the time of particle motion, assigned as \(\tau\), is greater than the time \(t\), which is measured by the camera (\(\tau > t\)).
If one observes the point $P$ of the cylinder's wall, which has the coordinates

$$g(\tau) = r_m(t) - r_{m0},$$  \hspace{1cm} \text{(5.49)}

$$f(\tau) = D(\tau - t),$$  \hspace{1cm} \text{(5.50)}

then, assuming that the wall material is incompressible and taking the fact that arc length $s(t)$ must be equal to the trajectory of the detonation wave (AP'), the differential connection can be obtained:

$$\frac{d\tau}{dt} = \sqrt{1 + \left(\frac{1}{D}\frac{dr_m}{dt}\right)^2} = \frac{1}{\cos\theta},$$  \hspace{1cm} \text{(5.51)}

where $\theta$ is the expansion angle, which can be calculated according to Eq. (5.52):

$$\frac{dr_m}{dt} = v_r = D\tan\theta,$$

i.e.,

$$\tan\theta = \frac{v_r}{D},$$  \hspace{1cm} \text{(5.52)}

where $v_r$ is the radial wall velocity.
By differentiation of Eqs. (5.49) and (5.50) with respect to time, the equation for the calculation of the cylinder wall genuine velocity is obtained:

\[ v_s = \sqrt{\left( \frac{dg}{d\tau} \right)^2 + \left( \frac{df}{d\tau} \right)^2}, \]  

(5.53)

where radial and axial components of the velocity are

\[ \frac{dg}{d\tau} = \left( \frac{dr_m}{dt} \right) \cos \theta, \]

\[ \frac{df}{d\tau} = D(1 - \cos \theta). \]

The centrifugal acceleration \( b_z \) is calculated according to the equation

\[ b_z = \sqrt{\left( \frac{d^2 g}{d\tau^2} \right)^2 + \left( \frac{d^2 f}{d\tau^2} \right)^2}, \]

(5.54)

where

\[ \frac{d^2 g}{d\tau^2} = \left( \frac{d^2 r_m}{dt^2} \right) \cos^4 \theta, \]

\[ \frac{d^2 f}{d\tau^2} = \sin \theta \cos^3 \theta \left( \frac{d^2 r_m}{dt^2} \right). \]

Finally, as the aim of the test, the Gurney energy may be calculated from the genuine wall velocity and acceleration.

However, in order to deduce the parameters in the JWL equation of the detonation products’ isentropic expansion, it is necessary to start from the analysis of the expansion of detonation products within the cylinder.

**Analytical Presentation of Expansion of Detonation Products.** For the detonation products behind the detonation wave front, the following equations of conservation (Eqs. (4.1) through (4.4)) are valid:

\[ \rho_0 D = \rho_1 (D - W_1), \]
For parameters at the CJ point, subscript 1 is replaced by CJ.

The detonation products' flow condition at the chemical reaction zone is preferentially viewed from a system permanently fixed in the detonation front where detonation products' flow and cylinder limits are completely stationary. From the reaction zone whose internal radius is \( r_{i0} \), the detonation products begin to expand at the velocity \( (D-W_{CJ}) \), reaching the velocity \( (D-W) \) at the radius \( r_i \), as shown in Figure 5.15. According to the conservation of mass law through cross section \( \pi r^2 \) and cross section \( \pi r^2 \), the same amount of the detonation products passes at the same time. This can be written

\[
\rho_0 D\pi r_{i0}^2 = \rho (D-W)r_i^2. \tag{5.55}
\]

Besides, the flow conditions in the funnelled cylinder are also defined by the Bernoulli equation. The equation predicts that in the stationary flow conditions, the sum of the enthalpy \( (h=e+pV) \) and kinetic energy \( [(D-W)^2/2] \) is constant along the flow path. For the isentropic expansion, on the other hand, it is valid that \( dh=Vdp \). Together with the equation of conservation of energy in the detonation wave (i.e., the adiabatic shock equation), this gives the equation for the energy conservation for the detonation products' flow conditions in the metal cylinder:

\[
e_0 + q + p_0 V_0 + \frac{D^2}{2} = e + pV + \frac{(D-W)^2}{2}. \tag{5.56}
\]

The cylinder wall material flows at the constant velocity \( D \) along the longitudinal section of the cylinder. As a result of that flow, the movement in the expansion area behind the detonation wave front takes place in a convexly bent curve. Accordingly, a centrifugal acceleration \( (b_z) \), directed towards the centre of the cylinder, and a centrifugal force \( (M_m b_z) \) exist. From the stationary condition it follows that the centrifugal force matches the pressure of the detonation products, i.e., the counteracting force:

\[
M_m b_z = p2\pi. \tag{5.57}
\]
From the above equation
\[
p = \frac{\text{force}}{\text{area}} = \frac{M_m b_s}{2r_1 \pi}.
\] (5.58)

Introducing the expressions for \( b_s \) and \( v_s \) in the equation of the momentum conservation, after mathematical recalculation, one obtains
\[
p \left( \frac{r_s}{r_{0s}} \right)^2 - p_0 - \frac{\mu}{2} \rho_0 v_s^2 = \rho_0 DW,
\] (5.59)

where \( \mu \) is the ratio between cylinder and explosive masses; for a copper cylinder having a size assigned in Figure 5.15 \((r_{0s}=12.7 \text{ mm}, \ r_{as}=15.306 \text{ mm}, \ L=304.8 \text{ mm}, \ \rho_m=8.939 \text{ g/cm}^3)\), \( \mu \) has a value 4.045/\( \rho_0 \).

For an analytical presentation of expansion of the detonation products, one starts with the second adiabatic exponent, known as the Gruneisen coefficient \( (\Gamma) \):
\[
\Gamma = - \left( \frac{\partial \ln T}{\partial \ln V_s} \right)_s = V \left( \frac{\partial p}{\partial E} \right)_V
\] (5.60)

where \( V=\rho_0/\rho=V/V_0 \) (relative volume).

According to the generally accepted relations that connect detonation velocity at one side and the explosive density and the heat of detonation at another, the Gruneisen coefficient depends only on the volume. By integrating Eq. (5.60), the Gruneisen equation of state is obtained:
\[
p = p_r(V) + \frac{\Gamma(V)}{V} \left( E - E_r(V) \right).
\] (5.61)

Despite the fact that the detonation products are gaseous (except solid carbon and metal oxides), Eq. (5.61) assigns certain solid properties of them. This may be understood if the detonation products are considered to be an ordered community of oscillating molecules. By this approach, the isentropic reference value of pressure \( (p_r) \) is composed of three summands: the intermolecular attraction, the repulsion forces, and the zero point portion of the grid oscillations. The intermolecular attraction and the repulsion forces can be among others expressed via exponential expressions, whereas the zero point portion with \( \Gamma = \text{const.} \) is obtained, because \( p = -\partial E/\partial V \) and \( pV = \Gamma E \) through the sequence of powers risen in \( CV^{\Gamma-1} \). Thus, the equation known as the JWL
Analytical presentation of cylinder expansion curve \((r_m-r_m0)=f(t)\):
- determination of parameters in Eq. (5.48) by nonlinear fitting procedure
- calculation of radial wall velocity (Eq. (5.46))
- calculation of acceleration (Eq. (5.45))

Calculation of expansion angle (Eq. (5.52))

Calculation of genuine cylinder wall velocity (Eq. (5.53)) and acceleration (Eq. (5.54))

Calculation of pressure (Eq. (5.58))

Calculation of mass velocity (Eq. (5.59))

Calculation of \(V=p_0/p\)

Nonlinear fitting procedure of dependency \(p=f(V)\), i.e., calculation of parameters in JWL equation of state (Eq. (5.62))

Figure 5.18. Flowchart of possible calculation procedure to obtain parameters in the JWL equation of state

equation of state for the isentropic expansion of the detonation products is obtained:

\[
p_r = Ae^{-B_1 V} + Be^{-B_2 V} + CV^{\Gamma-1},
\]  

(5.62)

where \(A, B, C, R_1, R_2,\) and \(\Gamma\) are parameters that can be determined by fitting the \(p-V\) data obtained to Eq. (5.62).
Using Eq. (5.62) the equations for the calculation of $E_r$ and polytropic exponent ($\gamma$) may be obtained:

$$E_r(V) = -\int p_r dV$$

$$= \frac{A}{R_1} e^{-R_1 V} + \frac{B}{R_2} e^{-R_2 V} + \frac{C}{\Gamma} V^{-\Gamma}, \quad (5.63)$$

$$\gamma(V) = -\frac{d \ln p_r}{d \ln V} = -\frac{V}{p_r} \frac{dp_r}{dV}$$

$$= \frac{V}{p_r} \left( A R_1 e^{-R_1 V} + B R_2 e^{-R_2 V} + C (\Gamma + 1) V^{-\Gamma-2} \right). \quad (5.64)$$

There are several ways described in the literature for the determination of the parameters in the JWL equation of state from the cylinder test data. One of the possible ways is given by the block diagram (Figure 5.18).

An example of the cylinder test data: cylinder expansion curve, wall velocity-time curve, acceleration-time curve, and JWL isentropic expansion curve for Comp B are given in Figures 5.19 and 5.20.

---

**Figure 5.19.** Cylinder wall velocity and acceleration vs. time for Comp B (Reprinted with permission from Homberg, 1986)
5.6. Determination of the Brisance by the Hess Test

**Principle of the Method**

The brisance of an explosive is determined on the basis of the compression of a lead cylinder under the action of the shock wave originated by the detonation of a tested explosive charge. The test was already proposed in 1876 by Hess (cited in Baum et al., 1959).

The determination of the brisance is based on the assumption that the lead cylinder compression is proportional to the brisance of an explosive charge. The brisance of an explosive may be expressed either directly via the deformation of the lead cylinder or as a relative brisance in relation to a reference explosive.

**Description of the Method**

The experimental setup for the determination of the brisance by the Hess test is shown in Figure 5.21.

A lead cylinder of a defined size (60 mm height and 40 mm diameter) and defined quality is placed on a massive steel base. A 10–30 mm thick and 41.5 mm in diameter steel disc is placed on the cylinder. The steel disc serves for the shock wave pressure attenuation. Its thickness depends on the brisance of the explosive. The 50 g of the tested explosive charge whose diameter is 40 mm is placed onto the steel disc. Afterwards, all the parts are fixed by means of adhesive tape.

The explosive charge is initiated by means of a standard electric or nonelectric detonator.
**Evaluation of Results**

After the detonation of the explosive charge, the lead cylinder will be pressed down in a mushroom shape as shown in Figure 5.22. The difference in the lead cylinder height before and after the detonation serves as a direct measure of the brisance of the tested explosive.

In the case of more brisant explosives or explosive charges of a higher density, the lead cylinder may be completely destroyed. To avoid that, the thickness of the steel disc is increased from 10 to 30 mm or the mass of the explosive charge is reduced to 25 g. When reporting the test data, the density of the explosive charge and the mass, as well as the steel disc thickness, are also reported.

The decrease of the lead cylinder height may be reported as the test result. For instance, trinitrotoluene having a density of 1.2 g/cm³ produces a decrease in the cylinder height of 18.8 mm via a 10 mm thick steel disc, while hexogen of the same density produces a decrease in the cylinder height of 17.2 mm via a 30 mm steel disc.
As stated, the brisance of the tested explosive may be expressed as relative brisance relating to a reference explosive, both treated under the same testing conditions. The relative brisance is obtained as a ratio between the decreases of the cylinder height produced by the detonation of the tested and reference explosives.

5.7. Determination of the Brisance by Kast’s Method

Principle of the Method

Determination of the brisance by this method is based on the measurement of the compression of the copper crusher produced by the detonation of a tested explosive charge. The copper crusher is placed in a special apparatus so that it is separated from the explosive charge by a steel piston. The piston enables the transmittance of the momentum from the explosive charge surface to the crusher.

The brisance of a tested explosive is expressed by means of "units of crushing" (according to Table 2.11) or as a relative brisance with respect to a reference explosive.

Description of the Method

The apparatus for the determination of the brisance according to Kast is illustrated in Figure 5.23.

The explosive charge of a constant volume is prepared by filling it at a normal charge density into a zinc tube. The tube is 80 mm high, 21 mm inside diameter and 0.3 mm walls and base thickness (Ahrens, 1977). The explosive charge is initiated by a standard detonator via an intermediate charge made of picric acid pressed to a density of 1.50 g/cm³. The intermediate charge is 21 mm in diameter and is 20 mm high. The copper crushers made of electrolytic copper 7 mm in diameter and 10.5 mm high are used.

During the testing, the Kast apparatus is placed onto a massive steel support (500x500x20 mm). For each trial, new 4 mm thick lead protection discs have to be used.

As a reference explosive, pure crystallinic picric acid is used. The charge is prepared by filling the zinc tube with 27.7 g of picric acid in four equal portions. After each quarter is added, it is slightly and evenly compressed by a wooden rod, 20.5 mm in diameter, to a density of 1.0 g/cm³. For this purpose, the rod has five annular marks at distances 100, 80, 60, 40, and 20 mm. In this way, the required density of the reference explosive charge of 1.0 g/cm³ is ensured.
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5.8. Determination of the Brisance by the Plate-Denting Test

**Principle of the Method**

The method is based on the measurement of the dent depth in a steel witness plate produced by the detonation of a cylindrical explosive charge positioned on the plate.
As the measure of the brisance, the depth of the hemispherical dent produced in the steel witness plate is taken. Also, a relative brisance as a ratio between the depths of the dents produced by tested and reference explosives can be taken.

**Description of the Method**

The experimental setup for the determination of the brisance of explosives by the plate-denting test is shown in Figure 5.24.

The cylindrical explosive charge, 41 mm in diameter and 200 mm high, is placed onto a 152x152x51 mm steel witness plate. The plate is made of steel having a Rockwell hardness in the range from B-74 to B-76. The explosive charge and the witness plate rest on a massive steel base. The initiation of the explosive charge is performed by means of a standard detonator and a booster.

After the detonation of the tested explosive charge, the witness plate is brushed off, and the depth of the produced dent is measured in the manner illustrated in Figure 5.25.

![Figure 5.24. Setup for determination of the brisance by plate-denting test](image)

![Figure 5.25. Arrangement for measurement of dent depth](image)
In order to avoid the effects of irregularities in the dent shape and the plate surface in the vicinity of the dent during the dent depth measurement, an outer ring, which provides support for the depth micrometer on the undamaged region of the plate, and a ball bearing placed into a dent are used. If the ball bearing diameter is equal to the ring height, the depth of the dent is obtained directly from the micrometer reading.

**Evaluation of Results**

Since the test results are influenced mostly by the quality of the steel witness plate, it is necessary to calibrate the plates for every batch. Trinitrotoluene of 1.60 g/cm\(^3\) density is usually taken as a standard explosive for the calibration. For pressed trinitrotoluene charges whose density ranges from 1.58 to 1.64 g/cm\(^3\), the linear dependency between the depth of the dent \((h)\) and the density has been determined by Smith (1967):

\[
h = 7.412 \rho_o - 5.375. \tag{5.65}
\]

The depth of the dent in Eq. (5.65) is expressed in millimetres.

For the determination of the relative value of the brisance (or percentage brisance), a trinitrotoluene having density of 1.63 g/cm\(^3\) is used as a reference explosive. In that case, the depth of the dent calculated according to Eq. (5.65) equals 6.706 mm.

The relative brisance \((B_r)\) of a tested explosive in relation to trinitrotoluene is calculated according to the equation

\[
B_r = \frac{\text{dent depth of tested explosive}}{\text{dent depth of trinitrotoluene}} \times 100,
\]

\[
B_r = \frac{h}{6.706} \times 100 = 14.912 \ h. \tag{5.66}
\]

The relative brisance obtained by this method is comparable to the relative brisance obtained by other methods. However, the test results obtained by this method may be advantageous in a different way as well. Namely, since the beginning of the 20th century, attempts have been made in order to relate the term brisance to some fundamental detonation parameter of explosives. Consequently, the assumption of Taffanel and Dautriche, and later of Becker (cited in Smith, 1967), was made that the detonation pressure is a predominant factor in the determination of the brisance of an explosive. This assumption was proved valid by further research. Becker even suggested that the term brisance had outlived its usefulness and should be therefore deleted from modern explosive terminology since it could be defined as the detonation pressure.
Table 5.3. Test results obtained by the plate-denting test

<table>
<thead>
<tr>
<th>Explosive</th>
<th>$\rho_0$ g/cm$^3$</th>
<th>$p_{CJ}$ kbar</th>
<th>$D_0$ m/s</th>
<th>$h_r$ mm</th>
<th>$B_r$ %</th>
<th>$p_{CJ}$ kbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trinitrotoluene</td>
<td>1.633</td>
<td>212</td>
<td>6945</td>
<td>6.731</td>
<td>100</td>
<td>225</td>
</tr>
<tr>
<td>Pentrit</td>
<td>1.670</td>
<td>310</td>
<td>7985</td>
<td>9.804</td>
<td>146</td>
<td>327</td>
</tr>
<tr>
<td>Hexogen</td>
<td>1.767</td>
<td>338</td>
<td>8640</td>
<td>10.516</td>
<td>157</td>
<td>351</td>
</tr>
<tr>
<td>Tetryl</td>
<td>1.681</td>
<td>--</td>
<td>--</td>
<td>8.103</td>
<td>121</td>
<td>270</td>
</tr>
<tr>
<td>Octogen</td>
<td>1.730</td>
<td>--</td>
<td>--</td>
<td>10.084</td>
<td>150</td>
<td>336</td>
</tr>
<tr>
<td>Comp B</td>
<td>1.730</td>
<td>304</td>
<td>7980</td>
<td>8.636</td>
<td>129</td>
<td>288</td>
</tr>
<tr>
<td>Baratol (76/24)</td>
<td>2.610</td>
<td>140</td>
<td>4925</td>
<td>3.226</td>
<td>48</td>
<td>108</td>
</tr>
<tr>
<td>Cyclotol (77/23)</td>
<td>1.754</td>
<td>320</td>
<td>8290</td>
<td>9.373</td>
<td>140</td>
<td>313</td>
</tr>
<tr>
<td>Octogen/VITON (88/15)</td>
<td>1.852</td>
<td>348</td>
<td>8430</td>
<td>10.211</td>
<td>152</td>
<td>341</td>
</tr>
<tr>
<td>Nitromethane</td>
<td>1.133</td>
<td>145</td>
<td>6245</td>
<td>4.140</td>
<td>62</td>
<td>138</td>
</tr>
</tbody>
</table>

Source: Modified from Smith, 1967.

In other words, the brisance and the detonation pressure describe the same property of explosives.

Accordingly, on the basis of the plate-denting test, the detonation pressure of the tested explosive may be calculated. In order to determine the absolute value of the detonation pressure, it is necessary to perform calibration, i.e., to define the relationship between the dent depth and the detonation pressure. The calibration may be performed using explosives of known detonation pressures. Smith (1967) has found the linear relationship between the dent depth and the detonation pressure:

$$p_{CJ} = 33.374 \times h_r,$$

(5.67)

where $p_{CJ}$ is expressed in kbar.

Some values of relative brisance and detonation pressures obtained by this method are given in Table 5.3.

The same test can also be used for the determination of the elastic/plastic behaviour of materials; for example, the yield strength. For this purpose, computer programs necessary to correlate the characteristics and behaviour of materials with the detonation parameters of explosives have been developed.

5.9. Determination of the Shock Wave Parameters

After the detonation wave reaches the explosive charge surface, a shock wave begins to travel through the surrounding medium. If the density of the surrounding medium is less than the density of the detonation products before
their expansion, the detonation products will move (expand) in the direction of the detonation wave. In the surrounding medium, a shock wave is produced. It will propagate faster than the detonation products. Consequently, at a definite distance from the explosive charge, the detonation products will be completely stopped when once expanded to the atmospheric pressure. Thus, at great distances, the shock wave is the main carrier of explosive energy.

A shock wave propagation, as well as a detonation wave propagation, is a hydrodynamical process that can be mathematically described by means of the conservation laws

\[ \rho_0 U_m = \rho(U_m - W), \quad (5.68) \]
\[ p = \rho_0 U_m W, \quad (5.69) \]
\[ \frac{W^2}{2} = \frac{1}{2} (p + p_0)(V_0 - V) = e - e_0. \quad (5.70) \]

If the above equations are combined, then different forms of relationships between shock wave parameters may be obtained. However, the most frequently used relationships are

\[ p = f(W), \]
\[ U_m = f(W). \]

These, as well as the relationship \( p = f(\rho) \), are the forms of adiabatic shock equations of the medium examined. A very often used relationship is \( U_m = f(W) \), since it is linear for the majority of media and for a wide range of \( W \) and \( U_m \) (Eq. (4.34)):

\[ U_m = c + sW_m. \]

It is evident from the above that, in order to establish the adiabatic shock equation for a given medium, at least two shock wave parameters have to be determined experimentally. Modern experimental methods enable direct determination of the shock wave pressure and shock wave front velocity with good accuracy. This proves to be sufficient for defining the adiabatic shock equation for a given medium. Once the adiabatic shock equation of a material is known, one may predict the behaviour of the material under dynamic pressure action.

On the other hand, the determination of the shock wave parameters has significant importance from the practical point of view. Thus, for instance, the study of the shock wave propagation through an explosive is important for the estimation of the initiation mechanism and the sensitivity of the explosives to...
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the shock wave action. Furthermore, on the basis of the parameters of shock waves in air and water, the performance potential of explosives can be estimated. Based on the study of shock waves in solids, it is possible to estimate the state and behaviour of the materials under the dynamic pressure action, i.e., their dynamic compressibility, dynamic strength, and the like.

For the determination of the shock wave parameters in different media, the methods identical to those used for the determination of detonation wave parameters can be applied to a large extent.

It should also be mentioned that there are a number of empirical expressions (Held, 1983, 1990; Lehmann, 1973) that one can use to calculate, with certain accuracy, the shock wave parameters such as shock wave pressure in different materials, shock wave velocity, pressure positive phase duration, and shock wave impulse.

5.9.1. Determination of the Shock Wave Pressure

For the determination of the shock wave pressure in different media (air, water and solids), different types of pressure gauges are used (Defourneaux, 1975; Urtiwe et al., 1986; Yadav and Kamath, 1986). The choice of the pressure gauge and the measuring equipment are related, among other things, to the kind of medium where the shock wave pressure is to be measured.

The shock wave pressure in air and water is determined by being terminated at a certain distance from the explosive charge, i.e., at a distance at which there is no more action of the detonation products.

For the very rough determination of the shock wave pressure in air, different kinds of mechanical pressure gauges with a diaphragm can be used. One such gauge is illustrated in Figure 5.26. The shock wave pressure determination by mechanical pressure gauges is based on the assumption that the measured shock wave pressure is proportional to the depth of the sagging of the metal diaphragm, made of copper or lead. With a previously obtained calibration, one can determine the value of the measured shock wave pressure.

Nowadays, piezoelectric pressure transducers are mainly used for the determination of the shock wave pressure in air and in water.

Figure 5.26. Mechanical pressure gauge with diaphragm
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Principle of the Shock Wave Pressure Determination in Air and in Water by Piezoelectric Pressure Transducer

The principle of the dynamic pressure determination by piezoelectric pressure transducer is described in Section 3.1. In its simplest version, the measuring equipment includes a charge amplifier and a storage oscilloscope. From the voltage signal recorded on the oscilloscope, the shock wave pressure as a function of time is obtained and the shock wave impulse as well.

Description of the Method and Evaluation of Results

The method of determining the shock wave pressure in air is illustrated in Figure 5.27. In a similar way, shock wave pressure in water is determined.

An oscilloscope of a high time resolution enables a pressure-time curve to be obtained (Figure 5.28):

When the curve \( p = f(t) \) is treated, the maximum shock wave pressure, the shock wave impulse \( (I = \int p\,dt) \), and the shock wave energy \( (E = \frac{1}{2}\int p^2\,dt) \) at a given distance from the explosive charge can be obtained.

![Figure 5.27. Determination of the shock wave pressure in air](image1)

![Figure 5.28. Pressure-time curve of the shock wave in air](image2)
Chapter 5. Working Capacity of Explosives

If the shock wave pressures at different distances \((R)\) from the explosive charge are determined, an analytical expression \(p=f(R)\) relating pressure to distance may be established.

According to some authors, it is possible to predict the explosive blasting potential on the basis of the determination of a shock wave in the air. The prediction of the explosive blasting potential by this method is based on the assumption that all energy of the explosive is transformed into the shock wave energy. For the prediction of the explosive blasting potential, a trinitrotoluene equivalent \((k_{\text{TNT}})\) is introduced. To determine the trinitrotoluene equivalent, one should first determine the shock wave pressure of the tested explosive \((P_x)\) having a mass \(M_x\) at a distance \(R\) from the explosive charge. Either experimentally or using an analytical expression that relates shock wave pressure to the distance for trinitrotoluene, one then determines the mass of trinitrotoluene \((M_{\text{TNT}})\) that will give the same shock wave pressure at the same distance as obtained for the explosive tested. Thus, trinitrotoluene equivalent is calculated from the mass ratio:

\[
k_{\text{TNT}} = \frac{M_x}{M_{\text{TNT}}}. \tag{5.71}
\]

Principle of the Method for Determining Shock Wave Pressure in Solids

The direct determination of the shock wave pressure in solids is based on registering the effects of dynamic action of the pressure on a specific property of some materials that are used as an active element in pressure gauges. Such gauges are, for example, the manganin pressure gauge and the carbon-resistant pressure gauge.

The operating principle of the manganin pressure gauge is based on the change of the gauge resistance under the dynamic action of pressure (see Subsection 4.2.6). The measured pressure is obtained from the calibrating diagrams.

Description of the Method and Evaluation of Results

The manganin pressure gauges as well as the complete measuring equipment used for the determination of the detonation pressure are identical to that used for the shock wave pressure measurement (see Figure 4.61).

The manganin pressure gauge is placed into the material where shock wave pressure is to be measured, as illustrated in Figure 5.29.

The shock wave is generated by the explosive charge. At a definite distance from the charge, its pressure is determined as a function of time (Figure 5.30).
When the shock wave pressure at several different distances from the explosive charge is measured, an analytical expression for the shock wave pressure-distance dependency may be obtained.

5.9.2. Determination of the Shock Wave Velocity

The measuring principle is similar to the principle of determination of the detonation velocity of explosives—the measurement of very short time intervals needed by the shock wave to travel a known distance.

The methods used for the determination of the shock wave velocity can be divided into optical or electrical.
The determination of the shock wave velocity in an inert and optically transparent material by optical methods is described in Subsections 4.2.2 and 4.2.3. The electrical methods used for the shock wave velocity determination are based on the detection of the arrival of the shock wave using

- Electrocontact probes,
- Probes in which the shock wave causes the change of a certain physical property; for instance, piezoelectric velocity probes.

**Principle of the Electrical Method for Determining Shock Wave Velocity in Air and Water**

The arrival of the shock wave is registered with suitable probes placed at a certain distance from each other and at a definite distance from the explosive charge. The time interval needed for the shock wave to pass the distance between two probes is registered by an electronic counter or an oscilloscope. The shock wave velocity at a measured distance from the explosive charge is calculated as a ratio of distance to time.

When several probes are used, or when the probe's distance from the explosive charge is changed in several consecutive tests, the dependence of the shock wave velocity upon the distance from the explosive charge can be established.

**Description of the Method and Evaluation of Results**

The determination of the shock wave velocity in air and in water is illustrated in Figure 5.31. At a known distance from the explosive charge, one pair or several pairs of probes are placed at a distance (assigned as $L$) from each other. This distance limits the measuring length at which the mean shock wave velocity is determined.

The shock wave arrival is registered by suitable probes. The probes at which the shock wave pressure causes the change of a certain physical property are mainly used since they enable simultaneous determination of the shock wave pressure. The piezoelectric pressure transducer is mostly used.

![Figure 5.31. Determination of the shock wave velocity in air and water](image-url)
An electric counter or oscilloscope can be used for measuring the time interval needed for the shock wave to pass a known distance between two probes. The advantage of the oscilloscope technique is that it enables simultaneous use of several probes. The same test thus enables determination of the dependence of the shock wave velocity upon the distance from the explosive charge.

The treatment of the data resembles the detonation velocity determination when ionisation probes and an electronic counter or an oscilloscope are used (Subsections 4.1.3 and 4.1.4).

Principle of the Electrical Method for Determining Shock Wave Velocity in Solids

The principle of the method is identical to that applied for the determination of shock wave velocity in air and water. However, for the determination of shock wave velocity in solids, electrocontact type of probes are mainly used.

Description of the Method and Evaluation of Results

Velocity probes are inserted into the material in the manner illustrated in Figure 5.32.

The measuring system used in the case of electrocontact velocity probes is the same as that described in Subsections 4.1.3 and 4.1.4.

The often used electrocontact probe in these experiments is the coaxial probe with a cap, as shown in Figure 5.33.

The probe operates on the principle of closing the electric contact between the external and internal probe conductors due to the copper cap motion under the action of the shock wave pressure.

One of the simplest electrocontact probes consists of a copper foil and a twined copper wire with varnish insulation. The probe is inserted into a solid as illustrated in Figure 5.34.

The probe consists of a thin copper wire ($\phi=0.3$ mm) having a varnish insulation. The wire is twined at a part that is in contact with a 70 $\mu$m thick copper foil. Two or more copper foils are placed at a known distance from each other.
other into the material whose shock wave velocity is to be determined. This distance limits the measuring length at which the shock wave mean velocity is to be determined. The twined ends of the copper wires are placed into the holes made in the material so that the tip of the wire touches the copper foils. Since the copper wires are insulated, there is no electric contact between the wires and the foils. As the shock wave arrives, the varnish insulation of the copper wire will be destroyed, and thus the electric contact between the wire and the foil will be established. As soon as the electric contact is established, a voltage signal will be produced. The signal will be recorded on the oscilloscope or will be used for the start/stop of the electronic counter counting assembly.
Evaluation of Results

The method enables determination of the mean value of shock wave velocity at a given distance from the explosive charge. By inserting several probes into the explosive charge at different distances from the explosive charge or changing the distance in several consecutive trials, the dependence of shock wave velocity upon the distance from the explosive charge can be established (Figure 5.35).

Once the shock wave pressure and the shock wave velocity in a material are determined experimentally, the adiabatic shock (Hugoniot) equation of this material may be defined in the form \( p = f(U_m) \). Also, if the mass velocity and the shock wave pressure (or shock wave velocity) are being determined experimentally in a tested material, the adiabatic shock equation may be defined in the form \( U_m = f(W_m) \) or \( p = f(W_m) \).

![Figure 5.35. Dependence of the shock wave velocity on distance from explosive charge (Modified from Anastasijevich, 1979)](image)
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