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TECHNICAL TRANSLATION 9

CONTRIBUTION TO THE STUDY OF THE INITIATION OF DETONATION PRODUCED BY IMPACT ON AN EXPLOSIVE

HENRI BERNIER

FEBRUARY 1966

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by

Henri Bernier

February 1966

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THESES

SUBMITTED TO THE FACULTY OF SCIENCES OF THE UNIVERSITY OF PARIS FOR THE DEGREE OF DOCTOR OF PHYSICAL SCIENCES

by

HENRI BERNIER

First Thesis

CONTRIBUTION TO THE STUDY OF THE INITIATION OF DETONATION PRODUCED BY IMPACT ON AN EXPLOSIVE

Second Thesis

TOPICS ASSIGNED BY THE FACULTY

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Messrs Rocard, President

Lafitte, Delloque) Examiners

Nuclear Research Center,

Saclay

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"Even if one hardly knows more about the subject than at the start, at least one has gained something by having lost the illusion of knowledge in many areas."

Jean Rostand

PREFACE

The study of detonation waves has been the object, for twenty years or so, of numerous theoretical as well as experimental investigations.

Of all the as yet unsettled problems in this vast field, we have examined the initiation of detonation by shock wave in a solid granular explosive. Whereas at the time when this study was begun the behavior of homogeneous explosives was quite well explained, there had been only a few experimental studies dealing with the behavior of granular explosives. In order to express these results -- which are sharply different from those furnished by the homogeneous explosives -- theoretically, we have worked out a mathematical scheme of the mechanism of initiation of the detonation by shock wave.

I would like, on the occasion of editing this work, to pay homage to the memory of Professor Ribaud, who died last autumn, and to thank Professor Rocard for agreeing to devote his attention to this quite special problem of fluid mechanics, despite his numerous responsibilities. I also thank M. Robert, Director of the Atomic Energy Commission, for authorizing me to carry out this work in his laboratories, as well as M. Barguillet, Director of the Research Center at Vajours, for all the facilities which he has placed at my disposal.

I want to express my profound gratitude to M. Berger, Chief Explosives Engineer, for his enlightened comments, his constructive criticism and the equipment which he was so kind to make available to me.

Finally, I must express my thanks to M. Vidart and Mme Prouteau for the programming and treatment of the mathematical scheme on the computer, and to M. Lezaud and his team for their constant devotion during the preparation and execution of the experiments.

INTRODUCTION

Historically, it seems that the initiation of detonation by impact in an explosive was discovered accidentally. It was probably the accidents which were unexplainable at that time that drew the attention of researchers to this phenomenon.

At the present time the procedure is quite frequently employed by laboratories specializing in the study of explosives, and also of certain detonators where the effect of impact is added to the thermal and shock phenomena. To this end, the impact is brought about by a metallic plate generally projected by means of a sheet of explosive.

Though frequently used, the phenomenon itself has been studied only to a limited extent. One has been content with verifying that it was indeed the impact which brings about the detonation, and with roughly determining the characteristics to be used: the velocity threshold for a given projectile and explosive. Nevertheless it should be pointed out that these studies had an essentially practical objective -- testing of safety -- and were not oriented toward basic research.

It was only in 1961 (Whitbread, Brown*) that certain parameters specific to this type of initiation of detonation were stated precisely.

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*S. M. Brown, E. G. Whitbread. Les Ondes de Détonation (Detonation Waves), 1962, Publications of the CNRS (Centre National de Recherche Scientifique; National Center for Scientific Research), No 109.

While the problem of detonation produced by impact has received only limited experimental treatment, we have numerous results relating to a very similar phenomenon, that of detonation produced by shock (with barrier). In both cases it is the induced shock wave which leads to the detonation of the explosive.

These two studies have many points in common with the phenomenon of transition from deflagration to detonation.

During detonation produced by impact, the physical phenomena involved seem to differ according to the intensity of this impact. In the case of a very weak induced shock, e.g. that generated by impact in sensitivity tests of explosives (fall of a mass weighing a few kilos from a height of approximately one meter), the detonation seems to be of thermal origin. In particular, the "hot spots" hypothesis seems to have received a clear experimental confirmation by the work of Bowden and his collaborators. Likewise, when the detonation is brought about by heat or by light, the explosive is subjected to a physical-chemical evolution in which the thermal phenomena seem to play a large role.

This is not the case when a shock wave is generated. Taken as a whole, the phenomenon is so fast (a few microseconds) that in order to explain the behavior of the explosive, one must call upon considerations other than those of thermal conduction and convection.

In the present study we shall deal only with the behavior of explosives subjected to high-intensity shocks (several kilobars).

To bring about such shocks, various devices may be employed. The most common shock generators are the explosives themselves. However, in that case, the shock is a reactive one and in order to transform it into inert shock, it is necessary to proceed through the intermediary of a barrier. This procedure has been tried out in numerous laboratories. It has made it possible to obtain valuable data regarding this phenomenon of detonation initiation, but has the serious defect that it introduces a pressure signal into the explosive which is not too well known. Hence the interpretation of the results is a difficult undertaking.

The other method of initiation by shock wave is the impact of a projectile launched at a high speed, the explosive

serving as target. This procedure presents the advantage of assuring a shock of constant characteristics during a certain period of time. However, few experimental results have been published.

The explosives subjected to shock do not behave in an identical manner. The homogeneous explosives (liquids, single crystals) exhibit a period of "incubation" prior to the initiation of the detonation, while the heterogeneous explosives (granular solids) do not exhibit such a period. The detailed examination of these differences is completed by a study of the various physical mechanisms which must be called upon to explain the initiation of the detonation; this forms the object of Chapter 2.

The next chapter is devoted to the experimental apparatus used by us, both for the realization of a correct impact of known characteristics, and for the study of the shock-detonation transition in the explosive serving as target.

These devices have the peculiarity of assuring an almost one-dimensional phenomenon in the entire zone of measurement. This makes it possible to obtain results that may be directly compared with those furnished by calculation.

Next, the theoretical aspect of the problem is approached Strictly speaking, if we want to take into account that the explosive is not a homogeneous body but is made up of essentiall spherical granules in contact with each other, then the hydrodynamic phenomenon alone is nonstationary tridimensional. Moreover, the medium is reactive. Hence it is necessary to make use of chemical kinetics and the various equations of state of the constituent substances (solids) or of those formed in the course of the reaction (generally gases).

Hence a simplifying scheme is necessary. Its only purpose is to account fully for the overall phenomenon.

While the presently available schemes do give a good explanation of the behavior of homogeneous explosives, they do not make it possible to explain the characteristic behavior of granular explosives. In our opinion this seems to be due to two reasons: first, the solid and gaseous phases cannot be at the same temperature for the same pressure; and second, the Arrhenius-type law of chemical kinetics is much too violent to initiate the reaction. A mathematical model which takes into

account these two remarks -- differentiation of the temperatures of the solid and gaseous phases during the reaction; a law of chemical kinetics that is more progressive than Arrhenius' exponential law -- was constructed. It furnishes a rather satisfactory agreement with the various known experimental results.

Chapter 1

STUDY OF THE SHOCK WAVE RESPONSIBLE FOR THE INITIATION OF DETONATION

1.1. RECAPITULATION OF THE HYDRODYNAMIC EQUATIONS OF SHOCK. APPLICATION TO SOLIDS.

Let us consider a fluid initially in state (0) traversed by a shock wave of absolute velocity U, downstream of which the state of the fluid is denoted by (1).

In a one-dimensional flow, the equation of the conservation of mass is written as

$$\rho_0(U - u_0) = \rho_1(U - u_1)$$

The momentum theory furnishes the equation

$$p_1 - p_0 = \rho_0(U - u_0)(u_1 - u_0)$$

and the conservation of energy:

$$p_1 u_1 - p_0 u_0 = \rho_0(U - u_0)\left[E_1 - E_0 + \tfrac{1}{2}(u_1^2 - u_0^2)\right]$$

In the following applications, p_0 is negligible compared with p, and u_0 may be taken as zero.

After rearrangement, the above system of equations may be written in the following form which can be used more directly:

$$\rho_0 U = \rho_1(U - u)$$

$$p = \rho_0 U u$$

$$E_1 - E_0 = \tfrac{1}{2} p_1\left(\frac{1}{\rho_0} - \frac{1}{\rho_1}\right)$$

For a variable shock intensity, we obtain in the p, v plane ($v = \frac{1}{\rho}$) the dynamic adiabatic, and in the p, u plane the shock polar of the body, while the equations of state and of internal energy furnish the two complementary equations necessary for the complete determination of the various variables of the shock as a function of one of them chosen as parameter.

The equation of state of a solid may be written as:

$$p = p_i + \varepsilon (T - T_o)$$

In this way the equation of isothermal compressibility is stated in a clear manner.

More precisely, we have chosen for all subsequent calculations the term p_i given by the equation of Pack, Evans and James [14]:

$$p_i = a \left(\frac{v}{v_o}\right)^{-\frac{1}{3}} \left[\exp\left\{\beta\left[1 - \left(\frac{v}{v_o}\right)^{\frac{1}{3}}\right]\right\} - 1\right]$$

and taken the coefficient $\varepsilon = \left(\frac{\partial p}{\partial T}\right)_v$ as constant.

With this equation of state, an isentropic defined by

$$dE + p\, dv = 0$$

with

$$dE = c_v\, dT + \left(T \frac{\partial p}{\partial T} - p\right) dv$$

where c_v is assumed to be constant, leads to

$$p = p_i - \varepsilon T_o + \varepsilon T_1 \exp\left[\frac{\varepsilon}{c_v}(v_1 - v)\right]$$

with subscript 1 indicating the pole of this isentropic.

The temperature is given by

$$T = T_1 \exp\left[\frac{\varepsilon}{c_v}(v_1 - v)\right]$$

and the velocity of sound, defined as follows:

$$a^2 = \left(\frac{dp}{d\rho}\right)_{s=\text{const}}$$

is then given by the expression:

$$a^2 = \frac{\gamma v_0}{3}\left(\frac{v}{v_0}\right)^{\frac{1}{3}} \left\{\left[\exp \beta\left(1 - \left(\frac{v}{v_0}\right)^{\frac{1}{3}}\right)\right]\left[2 + \beta\left(\frac{v}{v_0}\right)^{\frac{1}{3}}\right] - 2\right\} + \frac{g^2 v^2}{c_v} T_1 \exp\left[\frac{g}{c_v}(v_1 - v)\right]$$

The equations of the shock furnish the dynamic adiabatic p(v):

$$p = \frac{\frac{p_1 c_v}{g} - g T_0 (v - v_0) + \int_{v_0}^{v} p_1 \, dv}{\frac{c_v}{g} - \frac{1}{2}(v_0 - v)}$$

This has, for pole, the point p = 0, v = v_0 of Clapeyron's diagram.

The velocity of propagation of the shock, U, and the material velocity, u, are then given by

$$U^2 = \frac{p}{\rho_0\left(1 - \frac{v}{v_0}\right)} \qquad u = \frac{p}{\rho_0 U}$$

The temperature is immediately deduced from p, by means of the equation

$$T = T_0 + \frac{p - p_1}{g}$$

In the subsequent numerical applications, we have used, for the sake of simplifying the calculations, linear relationships between the various parameters.

In particular, we know ([3], p 261) that there exists, in a very good approximation and in a relatively large zone, a linear relationship between the velocity of the shock (U) and the material velocity (u): U = A + Bu.

A second approximation was employed for determining the velocity of sound as a function of the ratio ρ/ρ_0,

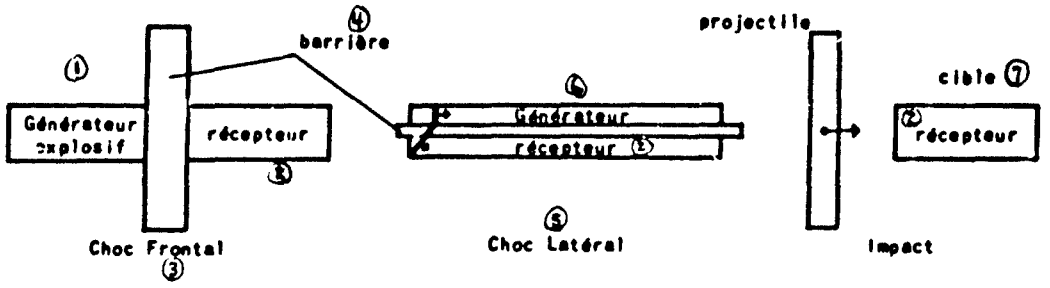
$$a = a_1 \frac{\rho}{\rho_0} + a_2$$

This last law, which is the linearization of the preceding theoretical results, has been experimentally proved in a quite satisfactory manner [2].

These two simplifications have permitted us to reduce considerably the time of calculation and to preserve the possibility of varying the different parameters while insuring a satisfactory accuracy.

1.2. PRESENTATION OF THE DIFFERENT MODES OF INITIATION OF THE SHOCK

The procedure most commonly used for obtaining shocks of high intensity employs an explosive. This explosive induces in a barrier an inert shock which is subsequently transmitted to the receiving explosive. Two procedures of initiation may be considered: frontal shock and lateral shock.



(1) Generating explosive; (2) Receptor; (3) Frontal shock; (4) Barrier; (5) Lateral shock; (6) Generator; (7) Target.

For obvious reasons of convenience of interpretation, only the frontal shock is employed in these studies. Some tests have, indeed, been carried out by lateral shock [6], but to our knowledge no theoretical study has been subsequently undertaken of the two-dimensional nonstationary character of the phenomenon (three variables: two of space and one of time). By contrast, the frontal shock may be one-dimensional nonstationary (only two variables: one of space, the other of time) if one adheres to certain experimental conditions. Hence its physical interpretation and its being put into an equation form are a priori easier.

Another procedure for the initiation of shock consists in the impact of a projectile on a target. This method has

made it possible to bring about the most intense shocks up to now (up to 10 megabars) [1] [13]. If certain experimental precautions similar to those employed in the case of frontal shock are taken, it can lead to a one-dimensional nonstationary phenomenon.

1.3. DETERMINATION OF THE PARAMETERS OF THE SHOCK INDUCED IN AN INERT RECEPTOR

After recalling the methods used in this determination when the tested body is an inert solid, we shall discuss the validity of these procedures when the receptor is an explosive substance.

1.3.1. Experimental Methods

The intensity of the shock induced in the receptor is determined by the equality of the pressures (p) and of the material velocities (u) on both sides of the interface (barrier-receptor in the case of frontal shock; projectile-target in the case of impact). Hence it is advantageous to employ the (p, u) plane for graphical representation. In this plane the shock polar p(u) of the barrier (or the projectile) is assumed known. Furthermore, it may be determined previously by means of analogous experiments, provided that the receptor is made of the same material as the barrier (or the projectile)

Experimentally it is sufficient to determine two parameters of the shock. The hydrodynamic equations permit calculating the other variables. The speed of propagation of the shock is determined by measuring the time elapsed during the passage of the shock between two points situated at a known distance from each other. The other parameter measured is the free surface velocity $u_{s\ell}$ (velocity acquired by the mass after expansion to atmospheric pressure). The latter, in a good approximation, is equal to twice the material velocity [3, p 263].

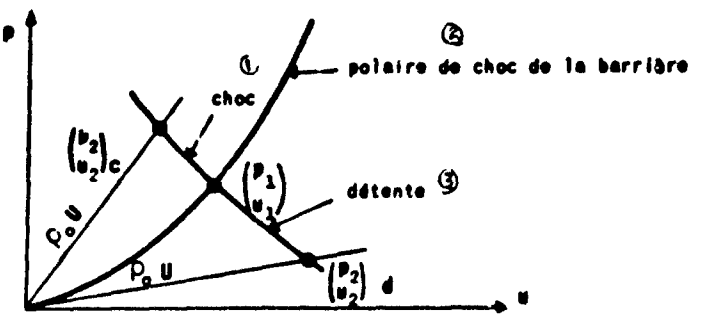
Various methods are employed for carrying out these measurements:

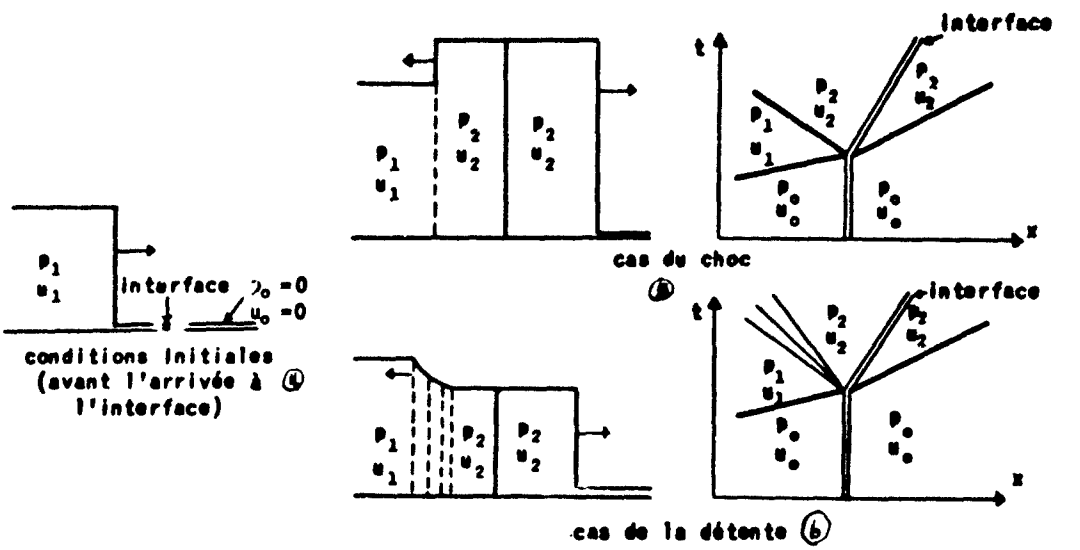
The optical method of chambers filled with argon (or xenon) [3, p 267] employs the intense luminosity of this gas under impact. By means of the slit camera the instant of closure of these chambers is recorded.

The method of electric probes is based on the short circuit which may be obtained by the movement of the material as

soon as the shock passes. The moment of closing of this circuit breaker placed into an electronic circuit is registered by means of a oscilloscope.

The wire- (or luminous slits) method consists in measuring the rate of displacement of a reflecting surface by means of the apparent rate of displacement of the image of a fixed wire (or a luminous slit) [5] [15].





(1) Shock; (2) Shock polar of the barrier; (3) Expansion;
(4) Initial conditions (before arrival at the interface);
(5) Case of shock; (6) Case of expansion.

1.3.2. Case of the Frontal Shock

The measurement of the free surface velocity of the barrier makes it possible to place, in plane (p, u), the representative point (p_1, u_1) on the shock polar of this body, while the measurement of the shock velocity U in the receptor medium permits drawing the straight line having the slope $\rho_0 U$ (where ρ_0 is the initial specific mass of the receptor). Depending on the position of this straight line with respect to point (p_1, u_1), a shock or a beam of expansion waves rises in the barrier, while a shock is propagated in the receptor.

This method, known as the "graphic" method, has been used for determining the dynamic adiabatic of the majority of common metals.

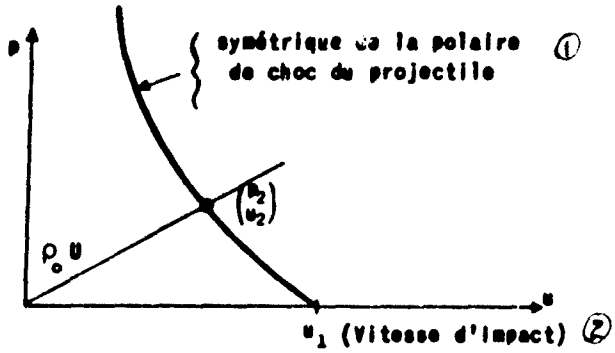
It should be noted that, strictly speaking, the point representative of the shock $(p_2, u_2)_c$ which rises in the barrier is situated on the curve symmetrical with respect to straight line $u = u_1$ of the shock polar having p_1, u_1 for pole, and not on the symmetric of the shock polar having $p = 0$, $u = 0$ for pole. The case is the same when we go from (p_1, u_1) to $(p_2, u_2)_d$ via an expansion; strictly speaking, the latter is isentropic. However, in the case of solids it may be estimated that these curves coincide in a large pressure range.

1.3.3. Case of Impact

The measurements carried out are: the impact velocity of the projectile and the shock velocity in the receptor.

The conditions of equal pressure and mass velocity at the interface are given, in plane (p, u), by the intersection of the shock polar of the projectile and the straight line having the slope $\rho_0 U$ (U = the shock velocity in the receptor of initial specific mass ρ_0).

In contrast to the frontal shock method, the point representative of the shock in the receptor is situated strictly on the curve which is symmetrical with respect to the straight line $u = u_1/2$ of the shock polar of the projectile of pole $p = 0$, $u = 0$).



(1) Symmetric of the shock polar of the projectile; (2) Impact velocity.

1.3.4. Shape of Pressure Signal Induced in the Receptor

The shock induced in the barrier, and consequently in the receptor, is not strictly constant. In effect, in addition to the uncertainty with respect to the reaction zone and the shape of the pressure signal in this zone, the expansion of detonation products constantly perturbs the induced shock. Hence the intensity, shape and decay in time of the pressure signal induced in the receptor cannot at the present time be determined accurately: they depend, for the same generating explosive, on the nature and thickness of the barrier.

Hence this generator is not too satisfactory since by its very design it makes one feel certain that it induces in the receptor an essentially variable pressure signal; this signal decays in space and time independently of any dissipating phenomenon. Hence it is indispensable to calibrate the generator by studying the decay of the shock in space and time as a function of the barrier thickness; then it is possible to determine the initial intensity of the shock for a given barrier thickness, roughly estimate the shape of the pressure signal and represent it, at a given instant, by an exponential law or by a linear law (signal of triangular shape).

In the case of impact the phenomenon is different. In effect, the shocks induced in the projectile and in the target are of constant intensity except for the effect of any dissipation phenomena, as long as a free surface has not been attained by one of them. Hence, since the receptor may be chosen to be of a sufficient length to rule out this inconvenience, it is the thickness of the projectile which determines

the time during which the shock induced in the explosive remains constant.

This nevertheless supposes that at the moment of impact the pressure is zero and the velocity is equal to a constant at all points of the projectile.

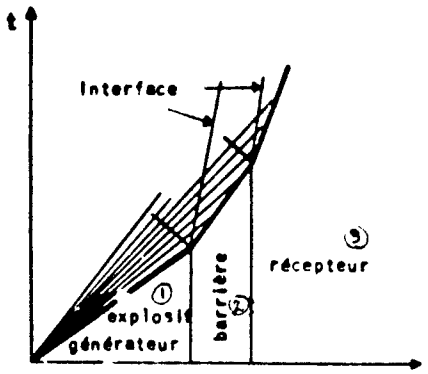
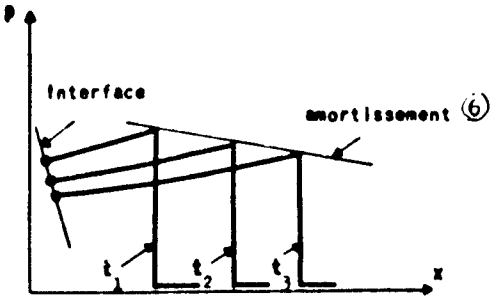


Diagramme de marche (4)



Forme du signal de pression dans la barrière, au cours du temps. (7)

Cas du choc induit avec barrière (5)

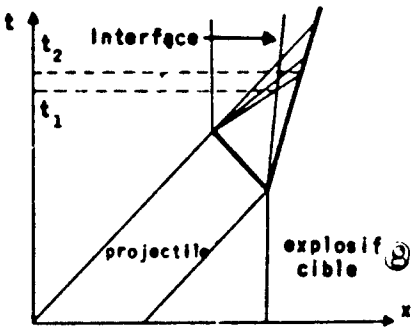
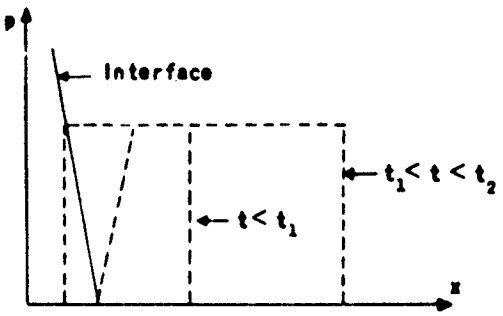


Diagramme de marche



Forme du signal de pression dans la cible, au cours du temps (9)

Cas de l'impact (10)

(1) Generating explosive; (2) Barrier; (3) Receptor; (4) Progress diagram; (5) Case of shock induced with barrier; (6) Decay; (7) Form of pressure signal in barrier in the course of time; (8) Target explosive; (9) Form of pressure signal in target in the course of time; (10) Case of impact.

Hence this mode of shock generation presents two important advantages compared with frontal shock: the shock induced in the receptor is initially uniform, and the time during which this signal is permanent depends on the thickness of the projectile.

1.3.5. Generators of Shock by Impact

Now we are in a position to discuss the choice of the various experimental devices for realizing the impact.

The simplest solution consists in employing a cannon whose projectile exhibits a plane face in the front so as to achieve a correct impact on a sufficiently large surface area. The phenomenon brought about in the target is thus one-dimensional if care is taken that the expansions originating from the edges of the generator or the receptor do not intervene in the zone where the measurements are carried out.

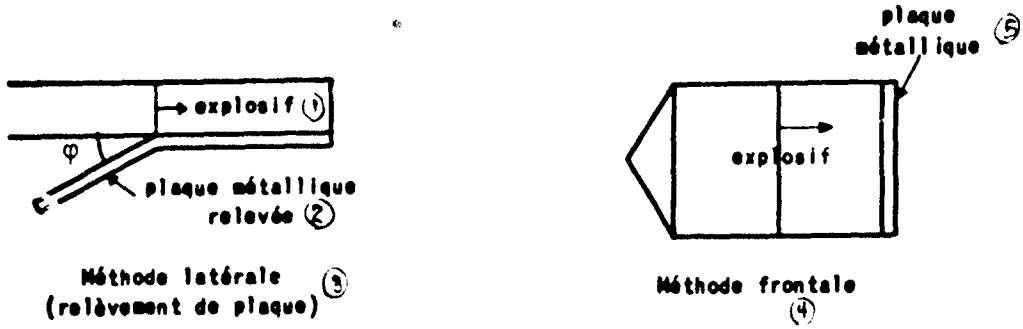
Nevertheless the classic projectiles have a rather complicated shape and it is difficult to define their "useful" thickness. On the other hand, their use does not permit the variation of this thickness in a simple manner. The use of guide shoes considerably complicates the mounting and makes it necessary that one make sure that they do not modify the phenomenon after impact. This method has been successfully used by Brown and Whitbread, enabling them to obtain the only results specific to this mode of generation of detonation published to date, even though the one-dimensional character of the phenomenon was probably not respected [4].

It nevertheless seems preferable to look for a method of projection which would make it possible to choose from among a large variety of projectiles, impact velocities (these two parameters determining the intensity of the induced shock) and projectile thicknesses (which defines the duration of application of the shock).

The procedure known as the "plate lifting" meets these requirements rather well. It consists of laterally projecting a thin metallic plate (a few millimeters thick) by means of an explosive whose detonation is initiated in such a way that it propagates parallel to the plane of the plate. It is noted experimentally that the latter, after a zone of acceleration, becomes essentially plane and assumes a position which makes a constant angle φ with its original direction. Moreover, this device makes it possible to select for the projectile the three fundamental parameters which determine the shock induced

in the target. In view of the diversity of possibilities which it offers, we have preferred this device to all others.

Another method of projection of the plate is the frontal method, and the velocities realized in this manner are greater than those furnished by the lateral method. In addition to presenting the same advantages as the preceding method, it makes it possible to explore a higher velocity range. We shall see that this advantage is hard to make use of in this study, since then the steady state of detonation is attained too fast in the target.



(1) Explosive; (2) Lifted metal plate; (4) Lateral method (lifting of plate); (4) Frontal method; (5) Metal plate.

It should be noted, however, that the stress undergone by the metal during its being set in motion, especially in the device for the lifting of the plate, may influence its subsequent behavior by allowing the survival, within the metal, of pressure and velocity gradients. However after a trajectory of a few centimeters in the case of a plate having a thickness of the order of one mm or a few mm, it can be assumed that these gradients are too small to be able to modify the behavior of the plate upon impact. The theoretical study of the following chapter will make it possible to affirm this hypothesis in a more concrete manner.

1.4. APPLICATION TO THE CASE WHERE THE RECEPTOR IS AN EXPLOSIVE

The preceding study on the determination of the parameters of the shock induced in a receptor implies two hypotheses:

-- The media in contact with each other are homogeneous;

-- No process other than that of hydrodynamics perturbs the phenomenon.

Let us now see how valid these hypotheses are in the case where the receptor is an explosive.

1.4.1. Are the Media in Contact Homogeneous?

This hypothesis is not verified when the receptor is a solid body constituted of grains of variable size and of different chemical composition having a greater or lesser number of gaseous inclusions, depending on the density of the charge. The behavior of such a mixture under shock cannot be calculated theoretically. Hence it is questionable whether the hydrodynamic equations of shock are applicable.

Then the problem arises as to whether it is legitimate to speak, in the case of this mixture of substances, of a dynamic adiabatic when the experimentally determined values (shock velocity, free surface velocity, and even charge density) are but averages of the values of each of the constituents. We know, for example, that when the charge density is low, the dynamic adiabatic which is determined experimentally is practically that of the gas contained in the explosive.

Recent studies on porous substances [10][11] have revealed notable deviations of behavior from that of homogeneous solids.

This heterogeneous character of the receptor confers on the front of the wave which propagates in the receptor a sinusoid form in perpetual evolution. Its propagation is no longer one-dimensional and related phenomena (for example wave convergence) may become dominant during the initiation of the detonation.

1.4.2. Is the Phenomenon Solely a Hydrodynamic One?

Here we have to do with a body which, under the effect of the shock, is capable of "reacting." As a result a chemical phenomenon is superposed on the hydrodynamic phenomenon. Now, the laws of chemical kinetics are not known sufficiently well under these special conditions to permit us to estimate the time after which the behavior of the explosive can no longer be considered governed by the laws of hydrodynamics alone.

We shall see that in the case of homogeneous explosives there exists an "incubation" time, a time during which the

chemical reaction seems negligible; consequently it seems reasonable in this case to treat the explosive as an inert substance during this period; it may be considered that the measurements carried out in this way depend solely on hydrodynamic phenomena.

However, in the case of heterogeneous explosives the process seems to be sharply different. The reaction is initiated almost immediately -- which we shall see later on, -- hence the chemical phenomenon can no longer be neglected. Nevertheless the values obtained for very weak shocks are generally considered valid. Still, one is never sure if the shock has been an inert one, and the result which has been obtained solely on the basis of hydrodynamics should be accepted with the greatest caution.

1.4.3. Shock Characteristics of the Explosive

For reasons indicated above, the shock characteristics of solid granular explosives have been studied only to a limited extent. Nevertheless, for certain special explosives, the methods used for the determination of the dynamic adiabatic of solid inert substances -- summarized above -- have been used by some researchers [8] [9] [12] [16].

Another method, based on the loss of transparence of plexiglas (or glass) when subjected to a shock also permits, after previous calibration under pressure, the measurement of the shock velocity in an explosive sample of known thickness placed between two blocks of this substance [7].

To be exact, these various methods do not lend themselves to a measurement of velocity but to a measurement of time. In order that the average velocity inferred from them represent the physical phenomenon, it is necessary that the propagation of the shock be constant during the measurement. Now we know that it is nothing of the kind, but it is impossible to verify directly by these techniques if the shock is reactive (acceleration) or inert (decay).

Hence a more delicate method is preferable. We shall see later on how it is possible to obtain a continuous diagram of the course of the shock in the explosive. Nevertheless the obtainment of such a diagram does not make it possible to draw any conclusions except in the case where the recorded curve is nearly linear. In the other case we can simply say that the equations of hydrodynamics do not suffice for explaining the behavior of the explosive.

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Chapter 2

STUDY OF THE INITIATION OF DETONATION BY SHOCK WAVE

The preceding study of shock generators has shown us that the difference between the device with barrier and the impact device consists essentially in the form of the pressure signal induced in the receptor. Hence we have the right to think that the process which leads to detonation is the same in both cases. While a large number of researchers have used the barrier arrangement, few publications are available which mention the results obtained by impact. Hence the results mentioned below have, for the most part, been obtained by means of experiments with barrier.

2.1. EXPERIMENTAL METHODS USED FOR THE STUDY OF THE GENERATION OF THE DETONATION WAVE IN THE EXPLOSIVE

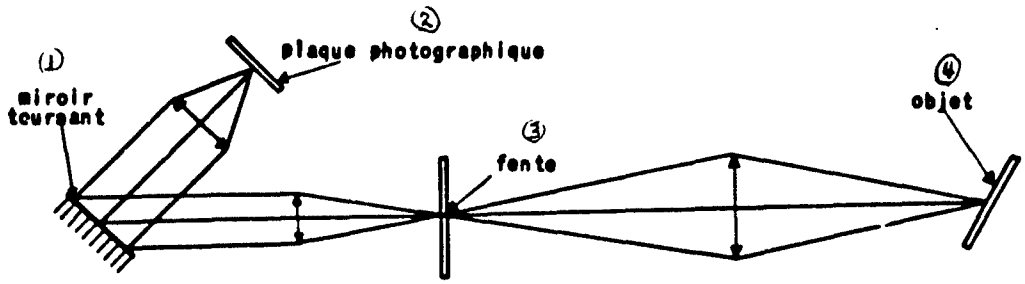
The techniques employed for the determination of the equations of state of the solids (dynamic method), summarized above, have been the first ones to be employed by the researchers; they have, nevertheless, been soon dethroned by methods which are better adapted to the nonstationary phenomenon to be studied.

In order to try to determine the behavior of the explosive, the most direct procedure consists in the continuous recording of the progress of the front of the shock wave by means of a slit camera.

Let us recall briefly the operation of this type of camera in the version which we have employed (rotating mirror - Brixner variant).

The image of the phenomenon to be studied is formed, by means of an objective, on a slit placed in the focus of a

second objective. The parallel beam issuing from the latter is reflected on a rotating mirror. A third objective forms the image of the slit on a photographic plate arranged in such a way that on this plate space and time correspond to two perpendicular directions.



Slit camera (rotating mirror).

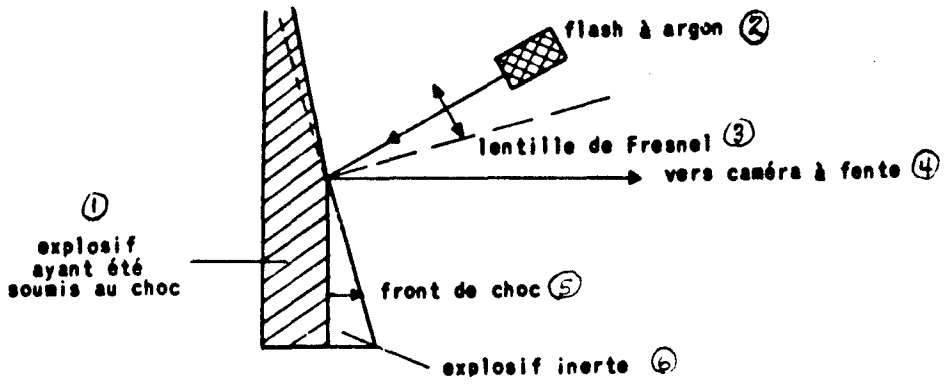
(1) Rotating mirror; (2) Photographic plate; (3) Slit; (4) Object.

Experimentally, one operates as follows: When the initially transparent substance (the case of certain explosive liquids) becomes opaque as a result of shock, the progressive darkening of a light beam furnished by an argon flash placed in the camera axis is registered as a function of time (recording by shadow) [8, 17, 31]. This method assumes that the darkening immediately follows the shock front, which cannot always be the case. It nevertheless makes it possible to isolate the phenomenon from the edge effects, if the latter do not mask the phenomenon along the axis of the assembly.

When this procedure cannot be used, and if the phenomenon is luminous (the case of a detonation wave), its evolution is chronologically recorded along a side parallel to the axis of the cartridge. However, the one-dimensional character is no longer respected, and it is no longer possible to neglect the edge effects. In effect, the compatibility of pressure and deflection on the faces of the cartridge with the contacting medium involves a lateral expansion of the medium which has undergone shock. This perturbs the thermodynamic conditions behind the shock front which becomes curved at the vicinity of the interface. Then the phenomenon is two-dimensional [7, 12, 13, 14, 15, 17, 19, 27, 30].

To remedy this disadvantage, another method is used. The receptor is cut in the shape of a wedge and the progress of the

shock is recorded by means of the abrupt variation which it brings about in the reflection of a light beam of a judiciously placed argon flash (the reflecting power of the surface of the wedge is generally obtained by means of a metallic tinsel a few tens of microns thick).

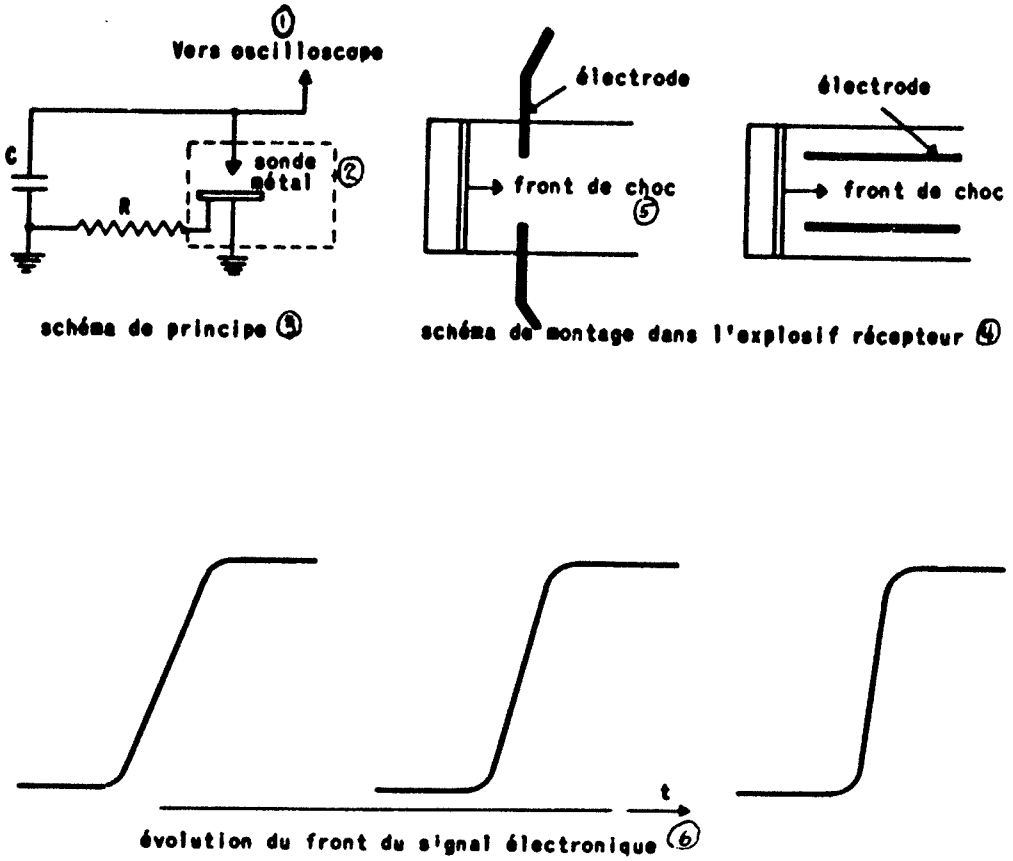


(1) Explosive which has been subjected to shock; (2) Argon flash; (3) Fresnel lens; (4) To slit camera; (5) Shock front; (6) Inert explosive.

The last method presents, in addition to the advantage of furnishing a continuous recording of the phenomenon, that of not requiring that the latter be luminous. This is, no doubt, the most precise procedure at the present time, despite the fact that one-dimensional character of the phenomenon is not strictly assured (see Chapter 3, paragraph 3.2.1, and [9, 20, and 29].

A variant consists in placing a grid or wires between the flash and the wedge. The grid and its image by the tinsel are simultaneously recorded; this image is displaced in the course of time as a function of the advance of the shock front. This method is hardly satisfactory since, in addition to the fact that it records the evolution of the phenomenon at a finite number of points, these points are not fixed on the receptor.

Another method is that of electric probes. It is less accurate than the preceding one since it permits the recording of the passage of the shock only at a finite number of points; moreover, it requires an electronic setup with highly comparable circuits so as to prevent the introduction of dispersion in the recording [8, 9, 17].



(1) To oscilloscope; (2) Metal probe; (3) Schematic drawing of the principle; (4) Schematic drawing of the assembly in the receptor explosive; (5) Shock front; (6) Variation of the front of the electronic signal.

Its operating principle is slightly different from that called upon when it is used with metals. In the latter case the probe serves simply as a circuit breaker, where the displacement of the metal closes a discharge circuit. In the study of the initiation of detonation the operation is based on the variation of electric resistance of the medium subjected to shock. This variation is not yet completely explained. It may be said that it depends roughly on the state of advance of the reaction. Its start is linked to the passage of the shock front, and its variation in the course of time is a function of the conductance of the medium which surrounds the two electrodes after the passage of the shock. Even though

the results obtained in this way cannot at the present time be exploited quantitatively, they are the only ones available after the passage of the shock.

In view of the impossibility of interpreting the whole recorded signal, the use of this method reduces, for the most part, to the determination solely of the moment of passage of the shock front. Its precision is quite low: in effect, since the recorded signal depends on the state of advance of the reaction, its front gradually straightens out in the course of time (case of heterogeneous explosives). Hence the recordings are not directly comparable and for this reason the exact moment of the passage of the shock front cannot be determined with precision. On the other hand, the introduction of electrodes may perturb the phenomenon and lead to erroneous results.

2.2. DIFFERENCES OF BEHAVIOR BETWEEN THE TWO TYPES OF EXPLOSIVES (HOMOGENEOUS AND HETEROGENEOUS) DURING THE INITIATION OF DETONATION BY SHOCK WAVE

The various experiments carried out for the study of the initiation of detonation have revealed differences of behavior according to the explosive under consideration. These differences were found to be considerable, and have led to the classification of the explosives into two categories:

-- Homogeneous explosives (single crystals, liquids);
-- Heterogeneous explosives (granular solids).

Let us see how each of these behaves.

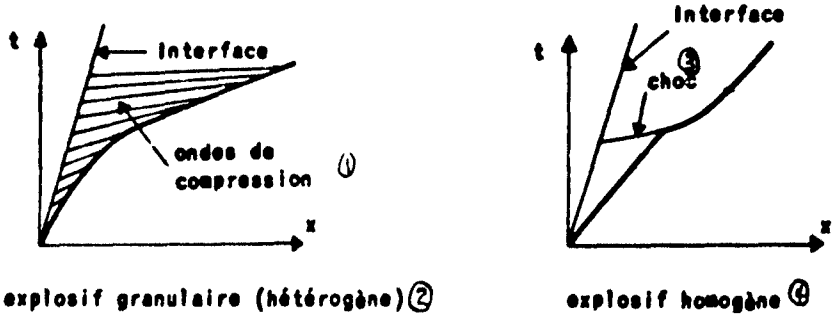
2.2.1. Diagram of the Progress of the Shock Front

The study of the detonation by shock wave of solid or nonsolid heterogeneous explosives by one of the above methods [7, 9, 11, 12, 13, 15, 17, 19, 22, 27, 29, 30] yielded the following result:

First the shock front exhibits a progressive acceleration, then in a short but measurable time it attains a value close to the velocity of stable detonation (see, however, Jacobs and Seay for some exceptions obtained when the density of the charge approaches that of the crystal [21, 28]).

This result is clearly different from that obtained with the homogeneous explosives (single crystals, liquids). In effect, in the case of the latter it is found that the shock

first propagates at an essentially constant velocity up to the moment when the velocity suddenly becomes greater than the velocity of stable detonation, after which it gradually returns to the latter velocity [8, 20].



(1) Compression waves; (2) Granular explosive (heterogeneous); (3) Shock; (4) Homogeneous explosive.

The interpretation which may be given to these two recordings is as follows:

Since in the homogeneous explosive the velocity of shock propagation is constant (or slightly decreasing -- the accuracy of measurement is low) during the first part of the phenomenon, the reaction does not intervene to a notable extent; during this period the explosive behaves as an inert substance. Then, abruptly, the reaction is initiated at the interface -- the region which was the first to undergo the shock. This reaction immediately leads to detonation. The latter is then propagated in the compressed explosive. Its velocity is greater than the normal detonation velocity of the explosive. It overtakes the shock wave and, for some time, imposes a superdetonation on the nonshocked explosive. The final evolution leads to the steady state of detonation [8, 10].

By contrast, in the case of the heterogeneous explosive, the reaction is triggered immediately and it progressively accelerates the shock front. It then follows that at no time can the explosive be considered as inert. At a given moment a rapid velocity jump leads to the steady state which is attained asymptotically [9].

It is nevertheless possible, for each of the two types of explosive, to determine a time which we shall call "induction period" after which the steady state of detonation is established. This parameter will be rather poorly defined in the two cases, since it is found that it is not obtained after an abrupt discontinuity but attained gradually by a deceleration of the shock front in the homogeneous case, and by an acceleration of the shock front in the heterogeneous case.

Even though its absolute measurement is not accurate, it is nevertheless possible to study its relative variation as a function of the initial conditions.

2.2.2. Threshold of Initiation of the Detonation

If the shock is too weak the signal obviously decays without causing detonation. Hence it is only above a certain threshold value that the chemical process which leads to detonation is initiated. This threshold is very different according to the explosive being tested. Whereas a few kilobars suffice to detonate the heterogeneous explosives, a large signal is necessary for bringing about the detonation of homogeneous signals (85 kb for nitromethane, 112 kb for a pentrite crystal) [20, 29].

2.2.3. Initial Point of the Start of Detonation

In the case of granular heterogeneous explosives, the experiments have been carried out on cartridges of rather small dimensions. In this case the "edge effects" intervene and the phenomenon no longer exhibits the one-dimensional characteristic.

These experiments have nevertheless permitted to demonstrate the fact that the detonation does not take place

-- In time: immediately after the shock;

-- In space: at the interface.

It should be mentioned that this result does not contradict that mentioned above for the same explosives. In effect, while the chemical reactions indeed take place at the interface, the shock becomes gradually "more and more reactive" but nevertheless it cannot be said that detonation has occurred.

These results were first published by Hertzberg and Walker [19] -- initiation of detonation by means of a

detonator -- and have since been verified by numerous authors, using different methods:

-- The integral-image camera (10^6 images per second) clearly shows that the initially luminous point in the receptor is situated at a certain distance from the interface;

-- The slit camera, during a chronological study of the luminosity of the edge of the cartridge, registers this lag in time and space in a quantitative manner;

-- The method of probes reveals a progressive conductivity of the medium after the passage of the shock, in direct proportion to the distance from the interface [9, 17, 27].

Beginning at this first point of initiation, a detonation wave is propagated in the inert explosive. Another detonation wave issuing from the same point may rise toward the interface if the already shocked explosive has reacted only to a slight extent. This phenomenon, called "retonation," has been observed experimentally [11, 12, 13, 17, 27]. Its interpretation has generally been that it is a consequence of the expansion effects due to the edges of the cartridge, since the one-dimensional character of the phenomenon was no longer assured.

By contrast, in the case of homogeneous explosives, the photos taken by means of the integral-image camera [8] show that a clearly detached shock precedes the detonation. The slit camera [8, 31] permits the recording of a rather low luminosity -- associated with the detonation wave in the compressed explosive -- prior to the much more intense luminosity of the state of superdetonation in the nonshocked explosive. Finally, measurements by electric probes [8, 31] show that after a certain "incubation" period the reaction is abruptly initiated at the interface.

These various experiments do not furnish a direct measurement of the first point of the initiation of the detonation, but they constitute excellent indirect proofs with which to confirm the idea that the detonation is initiated

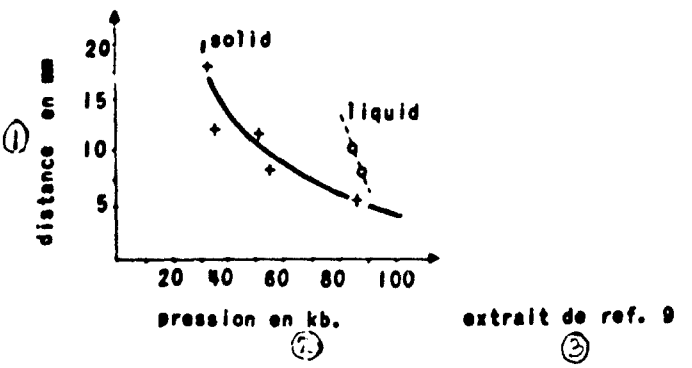
-- In the case of heterogeneous explosives: within the explosive;

-- In the case of homogeneous explosives: at the interface.

2.2.4. Influence of the Intensity of the Pressure Signal

In proportion to the increase of the intensity of the pressure signal, the steady state of detonation sets in sooner in time and closer to the interface in space. However these variations are notably different for the two types of explosive.

While in the case of the heterogeneous explosives there is a progressive variation as a function of the intensity of this signal, this is not the case for the homogeneous explosives where, once the threshold has been reached, the variation is abrupt. In the case of nitromethane, for example [8], when the shock changes from 86 kb to 89 kb (a 3.3% increase), the "induction" time is decreased by 26%.



(1) Distance in mm; (2) Pressure in kb;
(3) Extracted from [9].

This comparison leads one to think that in the case of the homogeneous explosives there exists a "threshold state" below which the process leading to detonation is not initiated. However once this threshold has been exceeded the phenomenon is very abrupt. In the case of the heterogeneous explosives, on the other hand, the duration of the transitory state varies continuously, and assures a more gradual construction of the detonation wave.

2.2.5. Effect of the Initial Temperature

The initial temperature also intervenes in a clear manner in the differentiation of these two types of explosive. In the case of the homogeneous explosive, a temperature increase of 30°K divides by 3 the time necessary for the establishment of the steady state of detonation [8] while in the

case of the heterogeneous explosive, the influence is much less, and undetectable for such a small temperature variation [9].

2.3. MECHANISMS OF THE INITIATION OF DETONATION

Various mechanisms have been proposed to explain the physical-chemical phenomena which take place prior to the establishment of the steady state of detonation. Few of these mechanisms have received any experimental support in view of the microscopic scale on which these mechanisms take place, and also because of the fact that at the present time it is only possible to study experimentally the macroscopic aspect of this problem.

2.3.1. The Hot Spots

A frequently proposed mechanism (cf. Bowden and co-workers) is the creation, within the explosive, of hot spots by adiabatic compression of the occluded gases.

Although this hypothesis has received satisfactory experimental support in the case of shocks of low intensity, this is not so in the case which is of interest to us. It permits the qualitative explanation of certain well-known facts. For example we know that the lower the charge density of a granular explosive, the easier it is to initiate the detonation. Likewise the fine-grain charges are more sensitive to shock, and this difference of behavior as a function of grain size gradually becomes attenuated as one approaches the density of the crystal. Hence the predominant role seems to be played by the occluded gases.

If the phenomenon is a thermal one, then the kind of gas is an important factor. In effect, depending on the value of the ratio of specific heats of this gas, the temperature at the end of the compression may vary considerably for a shock of the same intensity.

Experiments carried out with argon ($\gamma = 1.67$), methane ($\gamma = 1.31$) -- the case of a perfect gas leads to $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$ and $\frac{\gamma - 1}{\gamma} \simeq 0.40$ for $\gamma = 1.67$ while it is 0.246 when $\gamma = 1.31$ -- have shown that while the discounted variation indeed takes place in the anticipated direction, it is very far from the calculated value. Moreover, by replacing the gas bubbles with

balls made of different materials -- particularly tungsten -- the obtained delays are of the same order of magnitude. The situation is the same when a high vacuum is created [9, 29].

Hence these various experiments make us believe that the influence of the hot spots cannot be considered as a fundamental mechanism, since the initiation of the detonation practically does not involve the temperature after the passage of the shock wave.

Nevertheless, both in the case of the homogeneous explosives and that of heterogeneous explosives it is well observed that the detonation starts out from these points.

This cause and effect relationship has been demonstrated in several ways:

In the case of the homogeneous explosives, the introduction of fine gas bubbles at the interface, or the scratching of grooves on the barrier [8, 31], has shown that the reaction starts from these bubbles or grooves, provided that, in the case of the bubbles, their diameter is not less than a certain minimum value (approx. 0.7 mm for nitromethane).

In the case of the heterogeneous explosives, realization of these fine grooves on the surface of the explosive subjected to the shock wave considerably decreases the delay which precedes the establishment of the stable detonation regime [9; 31, p 56].

Mader has proposed that the experimental results obtained with homogeneous explosives be interpreted by taking into account the hydrodynamic character of the phenomenon ("hydrodynamic hot spot") [26].

Basing himself on the theoretical results of Evans, Harlow and Meixner [16] who have calculated that the interaction of a shock with a bubble created within the perturbed medium a hot spot which possesses essentially the same volume as the bubble, he confirmed theoretically the dimensional effect obtained experimentally.

The "hydrodynamic hot spot" has a temperature (case of the "temperature hot spot") and a pressure (case of the "pressure hot spot") which are above those of the environment. The law of chemical kinetics employed is Arrhenius' law. It can be seen then that, depending on the diameter of the sphere constituting the hot spot, the reaction may or may not have

the time to be initiated before the expansion waves propagating toward the center of the hot point had sufficiently decreased the latter's temperature.

The transposition of this study to the heterogeneous medium can only be suggested at the present time. But it is hard to see how we will be able to explain, by means of a model which imposes a minimum dimension of the hot spot, why the fine-grained explosives have the highest sensitivity. The minimum intensity of the shock necessary to initiate the detonation is much lower (a few kilobars instead of 80-100 kb), hence the temperature of the hot spot is much lower, and hence Arrhenius' law calls for more time to bring about the initiation, whereas it is found experimentally that there is no delay due to "incubation" in the case of these explosives, in contrast with the homogeneous explosives.

On the other hand, since Arrhenius' law entails an abrupt release of detonation, the gradual acceleration of the reactive shock front of the granular explosive seems difficult to explain.

2.3.2. Other Mechanisms

By contrast, the above-mentioned experiments support the fact that if a discontinuity exists within the explosive, the detonation is initiated from that point. This discontinuity may be present in various forms: gas bubbles, foreign bodies, grooves, etc. The physical fact which may be associated with it is the perturbation which it entails with respect to the shock front. The latter is no longer plane. Various mechanisms have been proposed on the basis of this remark: the formation of these sinusoid shock waves may lead to the pulverization of the grains of explosive. This is so since, if they are convergent, they produce local overpressures and bring about hollow-charge effects; if they are divergent, they produce in the grains tensions which may lead to mechanical ruptures favored by the crystal defects (scaling) or chemical ruptures due to the changes in the molecular bonds [3, 4, 5, 7, 28]. An increase in temperature may also produce bursting of the grain as a result of expansion.

All this leads -- as suggested by Andreev [2] -- to the formation of a fine suspension whose pressure is abruptly increased by the explosion, and this pressure increase assures the gradual generation of the stable detonation regime. However, the assumption that this mist acts by impact or by friction on the following grains does not represent a supplementary explanation but takes up on the microscopic scale the mechanisms which have been refuted macroscopically.

2.4. SPECIFIC RESULTS OBTAINED BY IMPACT

The only known results are those of Brown and Whitbread [6]. Although they are not one-dimensional, they nevertheless permit the estimation of the influence of the special parameters linked to this mode of generation of the shock wave. The pressure signal obtained by this procedure is, in effect, of a rectangular shape, constant during a certain period of time and then decreases rapidly (see Chapter on the study of shock generators). This particular form of the pressure signal has made it possible to show that, in order to bring about the detonation, its intensity and its time of application must be greater than the minimum values p_m and τ_m (τ_m being the minimum associated with p_m).

If the intensity is less than this minimum (p_m), the signal, regardless of its duration, cannot assure the detonation of the explosive. On the other hand, if the intensity is greater than this minimum, it is possible that the detonation will be established, even if the time of application is less than the minimum time τ_m.

2.5. ANOTHER MODE OF GENERATION OF DETONATION: THE TRANSITION: DEFLAGRATION - DETONATION

The transition: deflagration - detonation, which to be sure is slower than the transition: shock - detonation, is nevertheless capable of furnishing certain data with regard to the mechanism leading to the initiation of detonation in the explosive.

Whereas the steady states of deflagration and detonation are sufficiently well known, the passage from one to the other is much less well known, despite numerous studies [18, 23, 24, 25, 32, 33].

It is nevertheless obvious that the establishment of the steady detonation state by this process is necessarily accompanied by the formation of a shock. Various authors [23, 25, 33] believe that the formation of this shock is the direct cause leading to the detonation. By means of this hypothesis, the transition may be described as follows: The rapid increase of pressure behind the combustion front produces compression waves which are propagated in the non-burned explosive in front of the flame. The combining of these elementary waves produces a shock wave which initiates the detonation.

Experimental measurements made by Macek [24] show well the exponential variation of the pressure at the shock front with time during the transition: deflagration - detonation, and the theoretical study carried out by Zovko and Macek [33] with this hypothesis leads to a rather satisfactory representation of the whole phenomenon.

The various studies which have been carried out tend to prove that the pressure is indeed the predominant factor in the establishment of the detonation. Thus the assumption that it is also the predominant factor in defining the reaction rate of the explosive is not without foundation.

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Chapter 3

STUDY OF THE EXPERIMENTAL APPARATUS EMPLOYED

3.1. THE SHOCK GENERATOR

3.1.1. The Lifting of a Plate

The experimental procedure chosen for bringing about the impact is that of lateral projection, by the so-called "plate lifting."

As we shall recall, it consists in projecting a metal lining of low thickness by means of an explosive initiated in such a manner that its detonation front is perpendicular to the plate Experience shows that after a zone of accleration, the plate becomes essentially plane and assumes a direction which makes a constant angle with that which it had originally [9] (Plate I, Fig. 1).

The shock- and wave-reflection phenomena induced in the lining by the detonation of the explosive are sufficiently fast to be able to neglect the zone of acceleration in first approximation, and assume that the plate has been set into motion instantaneously.

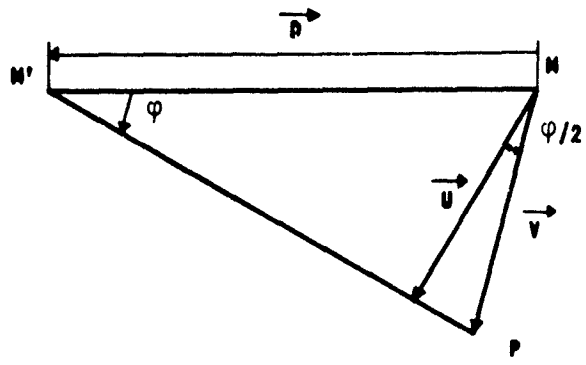
This may be represented schematically as follows: During a unit time interval during which the detonation wave has shifted from point M to point M' (MM' = D, detonation velocity of the explosive), the particles of the material originally situated at M have reached P.

The velocity vector $\vec{V}$ of the particle is defined by

$$(\vec{D}, \vec{V}) = \frac{\pi}{2} - \frac{\varphi}{2} \qquad V = 2 D \sin \frac{\varphi}{2}$$

and the plate has an overall movement defined by the vector $\vec{U}$

$$(\vec{D}, \vec{U}) = \frac{\pi}{2} - \varphi \qquad U = D \sin \varphi$$



Hence the plate has an overall displacement in the direction of vector $\vec{U}$ (component of vector $\vec{V}$ normal to the plane of the raised plate) by gliding along the tangential component of this same vector $\vec{V}$.

To be sure, the friction phenomena studied by Bowden [2, 3] at lesser velocities nevertheless show that the delays necessary for assuring the detonation of the explosive are very much greater than those which we wish to study here. Hence it seems that these delays, while not negligible in absolute value -- the velocity of lateral displacement is equal to $2\ D \sin^2 \varphi/2$ -- do not have the time to perturb the principal phenomenon linked to the overall velocity U of the plate, and we shall assume that it is this value that represents the velocity of impact of the plate projected on the target.

3.1.2. Practical Execution

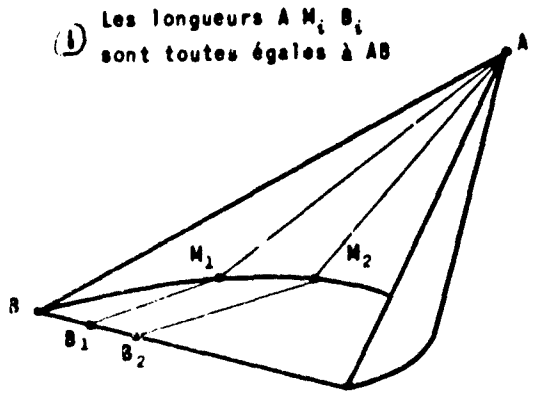
The experimental apparatus comprises three parts:

-- The primer which assures the detonation of the explosive;

-- The explosive in the form of a thin rectangular plate;

-- The metallic plate to be projected, in contact with the explosive.

To obtain a plane two-dimensional phenomenon, it is necessary to assure the simultaneous detonation of one of the ends of the explosive plate. Since the latter is thin compared to its other two dimensions, the problem becomes that of bringing about the simultaneous detonation along a straight-line portion. The primer is then constituted of a "linear generator." The model retained, as described by Erkman [6], is a surface constituted of a portion of a cone of revolution and a plane.



Schematic drawing of a linear generator. (1) - Lengths A, M_1, B_1 are all equal to AB.

Such "surfaces" have been molded from explosives (average thickness 10 mm) and the simultaneousness of the arrival of the detonation wave on the exit surface was checked by means of a slit camera. The maximum error is equal to $\pm$ 0.07 μsec.

The explosive plate is sufficiently wide so that the edges of the lining, which are raised to a lesser extent than the central part since they do not undergo the same thrust as a result of the lateral expansions to which the detonation products are subjected, do not perturb the two-dimensional character of the phenomenon. They are sufficiently long so that the states of stable detonation and constant life are established.

Through these precautions a "useful" zone, measuring several centimeters on a side, could be obtained. Tests for

planeness and for simultaneity on impact -- have been carried out in the two dimensions by means of the slit camera. The useful part is plane to within ± 0.05 μsec, or for an impact velocity of 1,000 m/sec, to within ± 50 μ. This is the mechanical precision with which the thickness of the lining is defined.

3.1.3. Experimental Measurement of the Impact Velocity of the Projected Plate

The determination of $U = D \sin \varphi$ depends on the expermental measurement of the two quantities:

-- D, the velocity of detonation of the explosive;

-- φ, the angle of lift of the projected lining.

The velocity of detonation of the explosive was obtained by the classic method consisting in measuring the time elapsed during the passage of the detonation wave between two points materialized by probes. Their positioning (± 0.5 mm for a base of 100 mm) combined with the use of an electronic chronometer having an accuracy of ± 1/40 μsec leads to a measurement of the velocity of detonation having an accuracy of the order of 1%.

For the measurement of angle φ, its order of magnitude may be obtained in various ways:

-- Photographically by means of the integral-image camera (10^6 images/sec);

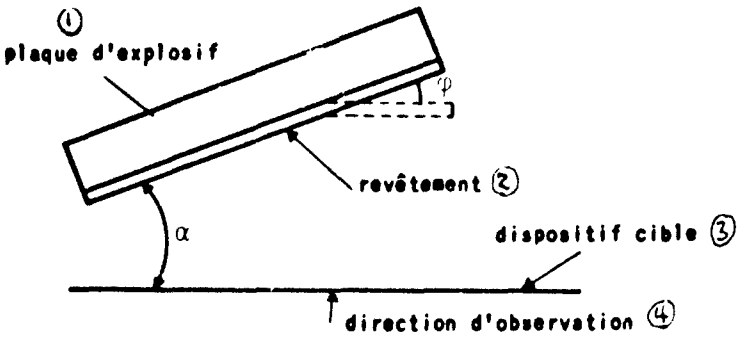
-- By flash radiography (exposure time about 0.1 μsec).

As a result of the inaccuracy regarding the exact position of the lining on these recordings (blur due to the non-negligible exposure time and to the grain of the film), the measurements carried out do not permit an accuracy greater than ± 30' in the measurement of angle φ.

In order to obtain a better result, the slit camera was used. The schematic drawing of the assembly is shown below: [next page]

Angle α, whose magnitude is close to angle φ, is adjusted prior to the experiment by means of an autocollimator device for angle measurement. A series of standard wedges make it possible to obtain a precision of the order of one minute. However, such a precision is an illusory one, since

despite the fact that the shock-generating assembly is rigid, the metal lining to be projected does not have a planeness which is sufficiently stable mechanically to guarantee this precision. However an accuracy to within a few minutes may be considered reasonable.



Schematic drawing of the assembly for the measurement of φ.
(1) - plate of explosive; (2) - lining; (3) - target device; (4) direction of observation.

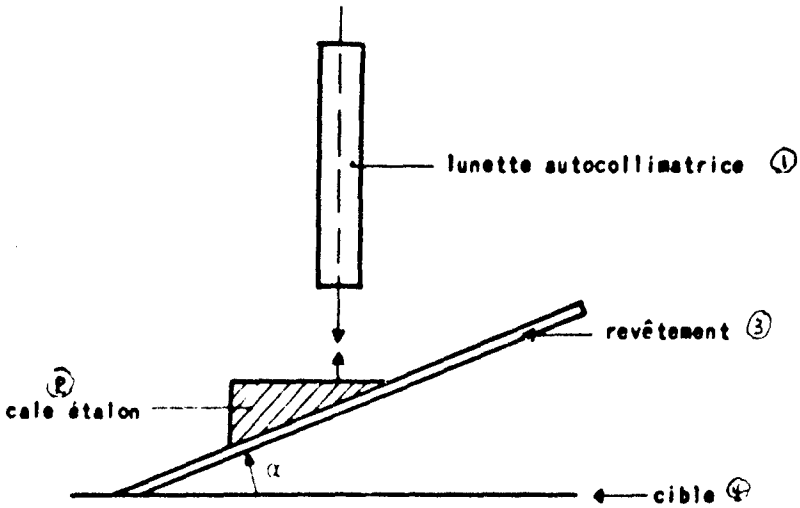
The projected plate strikes a target which lights up under the impact. This luminosity is obtained by an argon chamber. The slit camera registers this phenomenon chronologically.

The treatment of these firings is carried out in the following manner: The preliminary recording on film of two luminous points placed in the exact area where the target will be placed permits the measurement of the magnification of the whole setup ($k = x_1/x$), where x_1 is the distance between the two lines recorded on the film, and x the distance between the two luminous points.

The measurement of the slope (tan Γ) of the signal recorded on the film (Γ is the angle between this trace and the line perpendicular to the time axis) as well as the sweeping velocity (V) of the camera at the moment of firing then permit the determination of φ by the equation

$$\operatorname{tg} \varphi = \frac{\sin \alpha}{\cos \alpha + k \frac{D}{V} \operatorname{tg} \Gamma}$$

Tan Γ is positive if φ is smaller than α, and negative in the opposite case.



Adjustment of angle α.
(1) - autocollimator; (2) - standard wedge; (3) - lining; (4) - target.

The accuracy of the measurement of Γ is not excellent, since the signal recorded is not strictly linear (deviation $\pm$ 0.05 μsec). Nevertheless it seems that the maximum error is about 1/2 degree, which causes an error in the value of φ of less than 5 minutes. Finally, the angle of lift of the plate is determined to within $\pm$ 10'.

3.1.4. Theoretical Aspect of the Lateral Projection

Richter [8], has studied in 1945, by classical mechanics, the movement of the metal lining subjected to the effect of the explosive. He made certain simplifying assumptions regarding the behavior of the products of detonation and of the lining, calling upon fluid mechanics (theory of shock waves and method of characteristics) only for a qualitative explanation of the phenomena. These assumptions enabled him to give this problem simple and completely integrable solution.

Moreover, he made an effort to determine the effect of various factors on the idealized solution. This has enabled him to show that the compressibility of the metal, its resistance

to deformation and the pressure gradients appearing in its interior only change the idealized solution by a few percent.

After a brief recapitulation of Richter's theory adapted to the two-dimensional case, we shall treat the same problem by the method of characteristics.

-- Richter's Method:

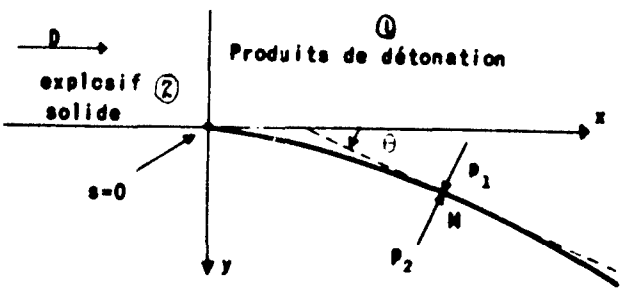
The metal plate is considered as being constituted of a sequence of independent, juxtaposed material points. Since the flow is steady, we look for the path of one of these points with which mass $\rho_0 \varepsilon$ is associated, which is the surface density of the lining where ρ_0 is the density of the metal employed in the form of a plate of thickness ε.

In the reference system linked with the detonation front, the acceleration of such a point M is given by the two equations:

$\gamma_t = 0$ tangential acceleration (constant velocity)

$\gamma_n = \frac{v^2}{R}$ normal acceleration

Hence this point has a movement defined by the sole equation $\rho_0 \varepsilon \gamma_n = p_1 - p_2$ where p_1 represents, at this point, the pressure of the detonation products, and p_2 the pressure of the medium adjacent to the plate.



(1) - detonation products; (2) - solid explosive.

Since the flow is assumed to be steady, v is equal to D (= ds/dt), s is the curvilinear abscissa of point M, measured for example from the detonation front).

If θ is the angle between the tangent to the path of point M and the reference axis (separating the explosive and the metal prior to detonation), $R = ds/d\theta$ and the preceding equation is transformed into

$$\rho_0 \varepsilon D^2 \frac{d\theta}{ds} = p_1 - p_2 \qquad (1)$$

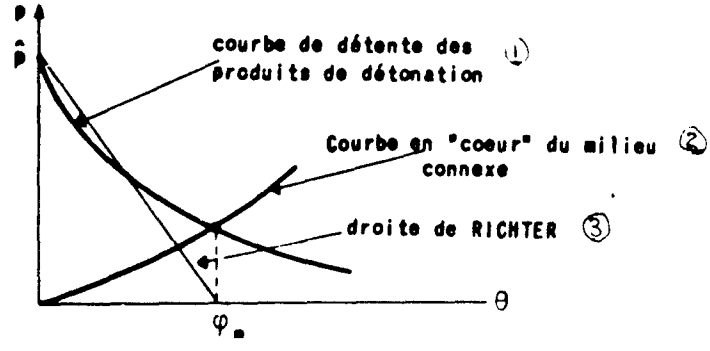
The assumptions made by Richter with regard to p_1 and p_2 are as follows:

To determine $p_1(s)$, he associates two expansions: the first produced by the lifting of the plate, the second due to the finite thickness of the explosive.

If the thickness of the explosive is infinite, only the first expansion exists. The latter may be estimated by means of the $p(\theta)$ curve derived from Busemann's epicycloid by assuming the existence of an isentropic expansion at Γ which is constant and equal to 3. Richter likens this curve to a straight line whose initial conditions are as follows:

$\theta = \varphi_0 \longrightarrow p_1 = 0$

$\vartheta = 0 \longrightarrow p_1 = p$ (detonation pressure)



(1) - expansion curve of the detonation products; (2) - "heart-shaped" curve of adjacent medium; (3) - Richter's straight line.

The angle of the smokes φ_m is the angle of deviation of the detonation products when the explosive detonates without lining ($\varepsilon = 0$). We obtain,

$$p_1 = \rho \left(1 - \frac{\theta}{\varphi_m}\right)$$

whence

$$\frac{dp_1}{ds} = -\frac{\rho}{\varphi_m} \frac{d\theta}{ds}$$

When the thickness of the explosive is finite (= e), there is added to this expansion the wave bundle centered on the edge of the detonation front, on the side opposite to the plate. Richter evaluates it for this two-dimensional case as

$\frac{dp_1}{ds} = -\frac{\lambda}{De} p_1$ where λ is a parameter which depends solely on the explosive.

The combination of these two expansions leads to

$$\frac{dp_1}{ds} = -\frac{\rho}{\varphi_m} \frac{d\theta}{ds} - \frac{\lambda}{De} p_1 \qquad (2)$$

The pressure p_2 is furnished by the determination of the supersonic flow of the medium adjacent to the lining (in general, air). It is of the order of a few hundred kg/cm^2 only, and cannot modify the behavior of the lining. Hence it is legitimate to neglect it.

Combination of equations (1) and (2) leads, after integration, to

$$\theta = \frac{\rho}{c\, \rho_m\, \varepsilon\, D^2} \left[1 - e^{-Cs}\right]$$

where C is given by

$$C = \frac{\rho}{\varphi_m\, \rho_m\, \varepsilon\, D^2} + \frac{\lambda}{De}$$

When s approaches infinity, θ approaches φ, the angle of lift of the metal plate.

$$\frac{1}{\varphi} = \frac{1}{\varphi_m} + \frac{D\lambda}{\rho} \frac{\rho_m\, \varepsilon}{e}$$

The experimental results which we have obtained by the method presented in the preceding paragraph confirm this linear law $\frac{1}{\varphi}(\rho_0 \frac{\varepsilon}{e})$ in the range of values of ε and e employed (Plate I, Fig. 2).

- Method of Characteristics

In order to improve the theoretical determination of the lift of the plate, it is necessary to follow in a more precise manner the behavior of the different media: detonation products, lining.

In effect, Richter's theory leads to satisfactory results if the respective values of ε and e are sufficiently small (a few millimeters for ε, a few centimeters for e). Nevertheless, it furnishes a dimensionless result in ε/e, but it is obvious that there exists a minimum value of e beyond which the explosive no longer intervenes to raise the metal plate. Likewise the value of the lifting angle obtained for a large ε is not confirmed experimentally. This has to do no doubt with the assumptions made with regard to both the laws of expansion of the detonation products and the fact that it is only the density which intervenes in the characterization of the material which constitutes the lining.

The theoretical study by means of the method of characteristics itself requires that certain assumptions be made.

The most important of these assumptions -- since we use the general hydrodynamic equations without a conduction or viscosity term -- is that the metal is a fluid which behaves as such at the pressures under consideration. This is quite justified, as is shown by current studies of its behavior at high pressure [1, 7]. The plastic character is no longer taken into consideration, but an analysis of its influence [P. Béatrix, unpublished results] has revealed that this characteristic modified the behavior of the metal only to a negligible extent.

Experimentally the explosive and the metals are surrounded, except under special conditions, by air at atmospheric pressure. We have already seen that the influence of the latter is negligible. Theoretically we have not taken it into consideration. Hence this amounts to considering that physically the experiment is carried out in vacuo.

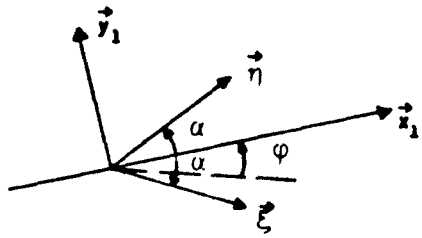
It is not our intention to present at this point the mathematical theory of characteristics (cf. [4] and [5] in this connection), rather, we shall be content with pointing out the various particular aspects of its use in the problem of the lifting of the plate.

The steady supersonic two-dimensional flows admit of three families of characteristic lines, to wit:

-- The flow lines $\vec{x}_1$;

-- The Mach lines which form with $\vec{x}_1$ the angles

$$\pm\ \alpha = \pm\ \arcsin \frac{a}{V} ;$$



where a is the velocity of sound in the flow of velocity V.

In order to preserve a parallel with the perfect gases by introducing a polytropic coefficient of expansion Γ such that

$$a^2 = \left(\frac{dp}{d\rho}\right)_s = \Gamma \frac{p}{\rho}$$

the thermodynamic relationship

$$T\,dS = dH - \frac{dp}{\rho}$$

with $H(p, \rho)$ (enthalpy), leads to

$$\Gamma = \frac{\dfrac{\partial H}{\partial \operatorname{Log} \rho}}{\dfrac{p}{\rho} - \dfrac{\partial H}{\partial \operatorname{Log} p}}$$

If we apply this result to the equation of state of a solid of the form

$$p = p_1 + \varepsilon\,(T - T_0)$$

we get

$$\frac{\partial H}{\partial \operatorname{Log} p} = \left(\frac{v C_s}{g} \frac{dp_s}{dv} - v g T_0 + p_i v - p v\right)$$

$$\frac{\partial H}{\partial \operatorname{Log} p} = p \left(\frac{C_s}{g} + v\right)$$

and

$$\Gamma = \frac{v}{p} \frac{g}{C_v} \left[g T_0 - p_i + p\right] + \frac{1}{pv} \frac{dp_s}{d\varphi}$$

In the contacting media (explosive, detonation products, metal), the flows cannot be treated separately since each of them reacts with that adjacent to it in order to assure the equality of pressures (p) and deflections (φ) at all points situated on the interface. Hence it is preferable to choose these two variables for the solution of the problem.

Then the relationships along the characteristics are expressed by (Ref. P. Carrière, course of the CESM*):

$$(+\alpha) \qquad \frac{\sin\alpha\cos\alpha}{\Gamma p} \frac{\partial p}{\partial \eta} + \frac{\partial \varphi}{\partial \eta} = 0$$

$$(-\alpha) \qquad \frac{\sin\alpha\cos\alpha}{\Gamma p} \frac{\partial p}{\partial \xi} + \frac{\partial \varphi}{\partial \xi} = 0$$

$$\frac{\partial S}{\partial x_i} = 0$$

and the curvature of a flow line is given by

$$k = \frac{\partial \varphi}{\partial x_i} = \frac{\sin\alpha}{2\Gamma p} \left(\frac{\partial p}{\partial \xi} - \frac{\partial p}{\partial \eta}\right)$$

The solution is carried out by successive approximations.

We have assumed that the shock waves intervening in the calculations are plane, hence the flow downstream is isentropic. Moreover we have assumed that the compression waves which may appear in the flow are sufficiently weak so as not to lead to shocks, and consequently, to entropy variations.

The detonation front of the explosive is assumed to be plane and perpendicular to the interfaces (explosive side).

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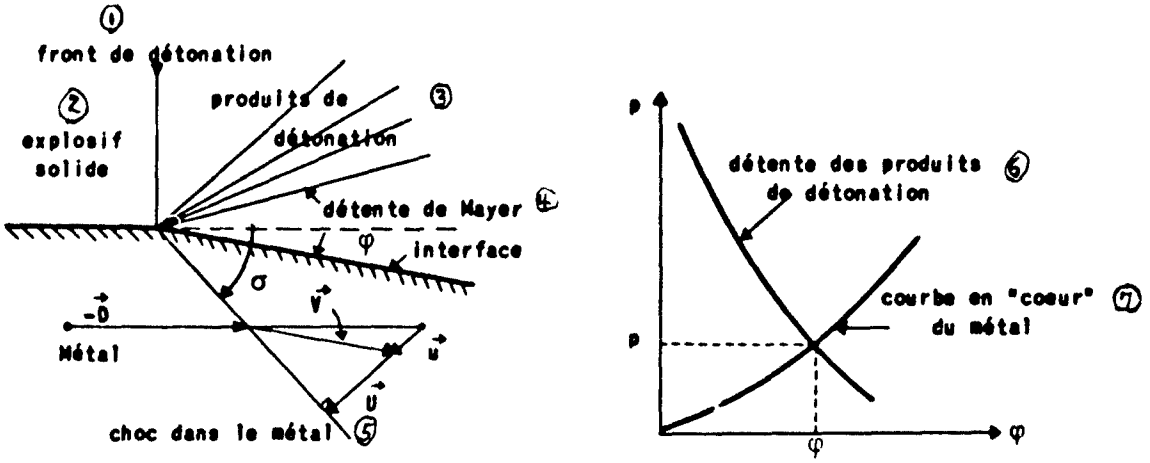
We neglect the reaction zone and assume that the conditions of Chapman-Jouguet (C.J.) are realized immediately behind this front which constitutes the sonic line of the flow of the detonation products. In addition we assume that the latter behave like a perfect gas having a polytropic coefficient of 3.

While the metal is compressed, the detonation products expand until the equality of the pressures and deflections in the two media in the vicinity of the interface is assured.

To this end the metal is subjected to a plane shock wave, making an angle σ with the original direction of the interface, while a Mayer expansion, centered at the point of contact of the detonation front and the interface, governs the flow of the detonation products.



(1) - detonation front; (2) - solid explosive; (3) - detonation products; (4) - Mayer expansion; (5) - shock in the metal; (6) - expansion of the detonation products; (7) - "heart-shaped" curve of the metal.

Let $\vec{U}$ and $\vec{u}$ be, respectively, the velocity of the shock and of the material behind the shock front in the metal in a reference system linked to the laboratory, $\vec{V}$ the velocity of the material in the reference system linked to the detonation front:

$$\vec{V} = -\vec{D} + \vec{u}$$

The various relationships linking the flow parameters are:

-- Geometric relationships derived from the configuration of the shock.

$$U = D \sin\sigma \qquad \frac{u}{\sin\varphi} = \frac{D}{\cos(\sigma - \varphi)} = \frac{V}{\cos\sigma}$$

$$\frac{U - u}{V} = \sin(\sigma - \varphi)$$

-- Equations of the shock:

$$p = \rho_0 Uu \qquad \rho(U - u) = \rho_0 U \qquad E - E_0 = \frac{1}{2} p \left(\frac{1}{\rho_0} - \frac{1}{\rho}\right)$$

(p_0 is neglected compared with p).

-- Equation of state of the metal.

$$f(E, \rho, T) = 0$$

These equations permit, in particular, to determine for each value of p the corresponding value of φ, when the velocity of detonation D of the explosive is given ("heart-shaped" curve of the metal).

The intersection of the shock curves of the metal and the curves of the expansion of the detonation products furnishes in plane (p, φ) the values which determine the initial conditions of flow in the metal after shock.

It is to be noted that tensions (negative pressures) have appeared within the metal in the course of the study. They were treated simply by extending the calculations to values of ρ greater than ρ_0. The calculations, which were carried out up to -50 kb, did not reveal any anomalies.

The numerical values employed during the study of the lifting of copper plate of thickness ε by a plate of explosive of thickness e, such that $\varepsilon/e = 0.148$, are:

-- Explosive: $\hat{p}_{cj} = 3 \times 10^7$ piezes; D = 8,100 m/sec

-- Metal (copper): $\rho_0 = 8.92$ g/cm^3.

Coefficients of the P.E.J. equation of the metal:

α = 381 x 10^5 piezes; β = 10.831 (nondimensional)

g = 6,809 piezes/°K; C_v = 373.3 kJ/t

Initial conditions after shock in the metal:

P_H = 2 x 10^7 piezes; a_H = 4,785 m/sec

T_H = 403.5°K; ρ_H = 9.9457 g/cm^3

σ = 35°15' (angle between the shock and the metal/explosive interface)

φ = 2°55' (angle of initial deflection)

V_H = 7,828.33 m/sec (velocity of the material in the reference system linked to the detonation front).

The critical angle obtained in this way is in very good agreement with the experiments (deviation of the order of the experimental error): Plates 2 and 3.

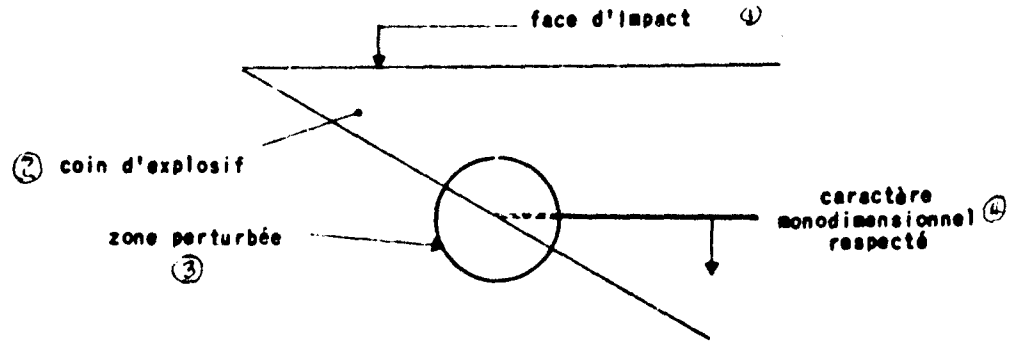
3.2. THE TRANSITION: SHOCK - DETONATION

3.2.1. Validity of the Experimental Method Employed

The experimental study of the generation of detonation by impact in a solid granular explosive has been carried out by the wedge method, described in Chapter 2.

Thus, the one-dimensional character of the phenomenon is realized within the block of explosive while it is probably not realized in the vicinity of the free surface of the wedge where the measurement is carried out. In effect, in this region the shock is not plane and its form changes during the entire transitory period which precedes the establishment of the steady state of detonation, since the conditions downstream of the shock front constantly change during this period. Hence the experimental measurement is fundamentally distorted by errors.

A theoretical study of this influence is impossible at the present time since the phenomenon is three-dimensional (two-dimensional if the medium is homogeneous), unstationary with chemical kinetics.



(1) - impact surface; (2) - explosive wedge; (3) - perturbed zone; (4) - one-dimensional character respected.

Despite this serious defect, this method is the only one, to our knowledge, which permits a continuous recording of the variation of the reactive shock in the explosive.

Although the results are different in absolute value when the angle of the wedge is varied, it is nevertheless feasible that for the same angle they should be directly comparable.

A second difficulty is due to the impact itself. Since the experiments were carried out at atmospheric pressure, some air is captured between the projectile and the target. The influence of this gas is twofold:

-- It acts like a piston to assure that the target is gradually brought into motion; at the time of the impact, the target no longer has zero velocity;

-- This air has a high temperature as a result of the numerous reflections of the shock between the target and the projectile. Consequently, before the pressure signal furnished by the impact, the explosive is subjected to a high-intensity thermal signal.

The influence of the air which acts like a piston contributes only a slight advance into the determination of the initial moment of entry of the signal into the target. This error is eliminated once the shock due to the impact overcomes the compression waves induced by the compressed air.

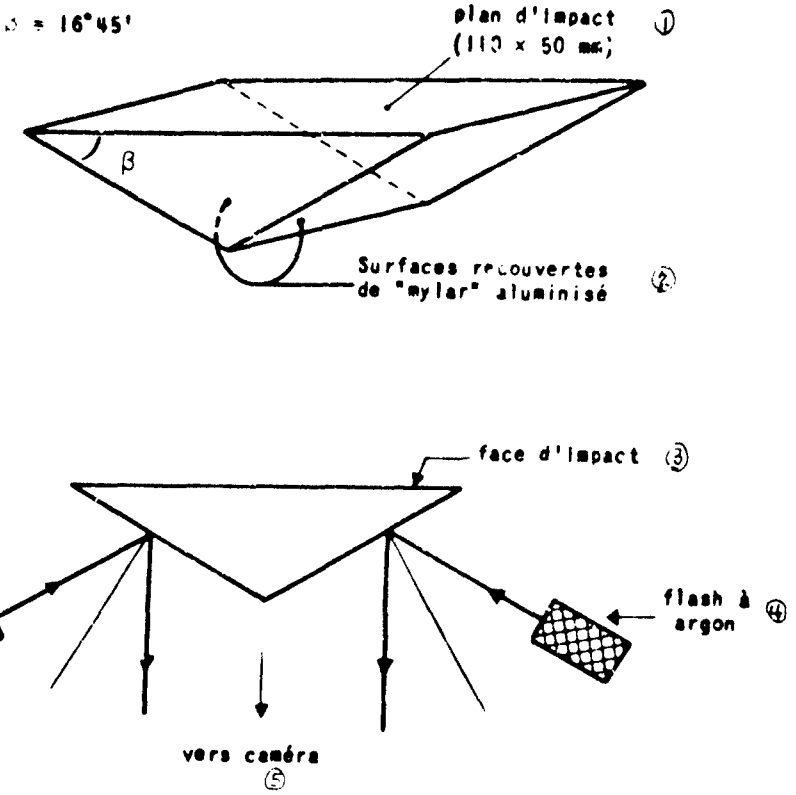
As for the thermal pulse, theoretical studies [10] show that it does not have the time to modify the behavior of the explosive on account of the low thermal conductivity of this substance.

3.2.2. Practical Arrangement

The experimental device comprises two parts:

-- An argon chamber placed in the plane of impact of the projectile;

-- An explosive prism cut out of the mass, whose cross section is an isosceles triangle. Two of its faces are covered with mylar (10 μ thick), which has been aluminized so as to reflect the luminosity produced during the experiment by argon flashes.



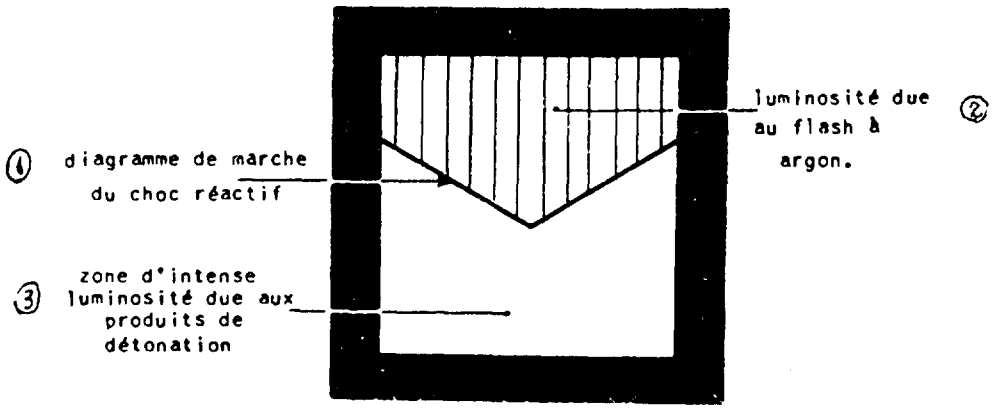
(1) - impact plan; (2) - surfaces covered with aluminized "mylar"; (3) - impact surface; (4) - argon flash; (5) - toward camera.

This device, which permits the simultaneous examination of the shock on two faces of the explosive prism, makes it possible to take into account, during the treatment of the results, the slight obliqueness of the projectile with respect to the impact plane.

The recording is made by means of a slit camera.

The whole assembly of the projection device plus target is shown on Plate 4.

It is found experimentally that when the shock attains a point of the free surface of the explosive, the deflection of the mylar stops abruptly the reflection of the luminosity originating from the argon flash. This is reflected, for the whole of the target explored by the slit of the camera, by a curve which is detached in black on a white background given before the passage of the reactive shock by the argon flash, and after its passage by the detonation products.



(1) - progress diagram of the reactive shock; (2) luminosity due to the argon flash; (3) - zone of intense luminosity due to the detonation products.

Such an assembly makes it necessary to place in the image plane of the input objective of the slit camera not one slit as in the usual case but two, the first for the argon chamber and the second for the explosive prism.

Hence on the photographic plate, one obtains:

-- The visualization of the planeness of the projectile on impact as well as the angle at which it strikes the target;

-- The progress diagram of the gradually reactive shock front, which is propagated on the two sides of the explosive prism;

-- The magnification of the optical assembly, obtained by preliminary recording of two luminous points placed in the impact plane of the projectile.

Finally, various marks placed on the argon chamber make it possible to determine the extremities of the explosive prism with precision.

3.2.3. Control of the Conditions of Impact on an Inert Target

To verify whether the experimental device is satisfactory, we have carried out experiments in which the explosive constituting the target was replaced by an inert substance -- copper or aluminum (AU4G).

When the projectile and the target are of the same substance, the determination of the conditions of shock is immediate. In effect, the measurement of the impact velocity (V_p) furnishes the velocity of the material u, $u = V_p/2$, while the pressure is obtained by means of $p = \rho_o U u$, where U is the shock velocity determined experimentally.

These calculations are valid if the projectile and the target are under the same thermodynamic conditions at the moment of impact. The projection procedure used probably does not ensure this possibility, and the projectile, even if it is at zero pressure at the moment of impact, is probably not at the same temperature as the target.

A theoretical study was undertaken in order to take this difference into account, and the projectile was assumed to be at a temperature of 500°K instead of 300°K:

-- The determination of the shock polar of the copper from the initial conditions ($p_o = 0$; $T_o = 500°K$; $\rho_o = 8.842$ g/cm^3 instead of 8.92 g/cm^3 for 300°K) while preserving the same coefficients for the equation of state shows that the pressure is 1 to 2% lower than that in the case of 300°K for the same value of material velocity;

-- Calculation of this polar from the coefficient of expansion of copper furnishes a much lower deviation, of the order of 0.1--0.2%.

Since the experimental dispersion is greater than these values, it is not possible to judge whether it is necessary to take into account the temperature rise of the projectile during the time that it is set to motion in order to calculate the conditions of the shock (see diagram 6, a detailed example of the treatment of the experimental data with the three shock polars, to calculate the shock conditions).

When the projectile and the target are made of two different materials, the problem is more complicated. It is in effect necessary to know the shock polar of the projectile to determine the conditions of impact in the target.

The small deviation observed above between the different shock polars calculated for copper makes it possible for us to carry out the data treatment with only one of them. We chose that which verifies the conditions: $p_0 = 0$; $T_1 = 300^\circ K$.

Moreover the projectile does not simultaneously strike the entire target surface, since angle α of the experimental setup is not strictly equal to φ, the angle of lifting of the plate. We have taken this slight obliqueness on impact into account and determined V by the equation

$$V_0 = 2D \sin \frac{\varphi}{2} \cos \left(\alpha - \frac{\varphi}{2}\right)$$

instead of $V_p = D \sin \varphi$, which is valid only when $\alpha = \varphi$.

The velocity of the shock (U) in the target was determined in two ways:

-- By means of the time which separates the impact of the projectile on the two ends of the target (which may be used when α is sufficiently different from φ);

$$r = \frac{X}{X'} \qquad \operatorname{tg} \gamma = \frac{r}{1 - r} \operatorname{tg} \beta$$

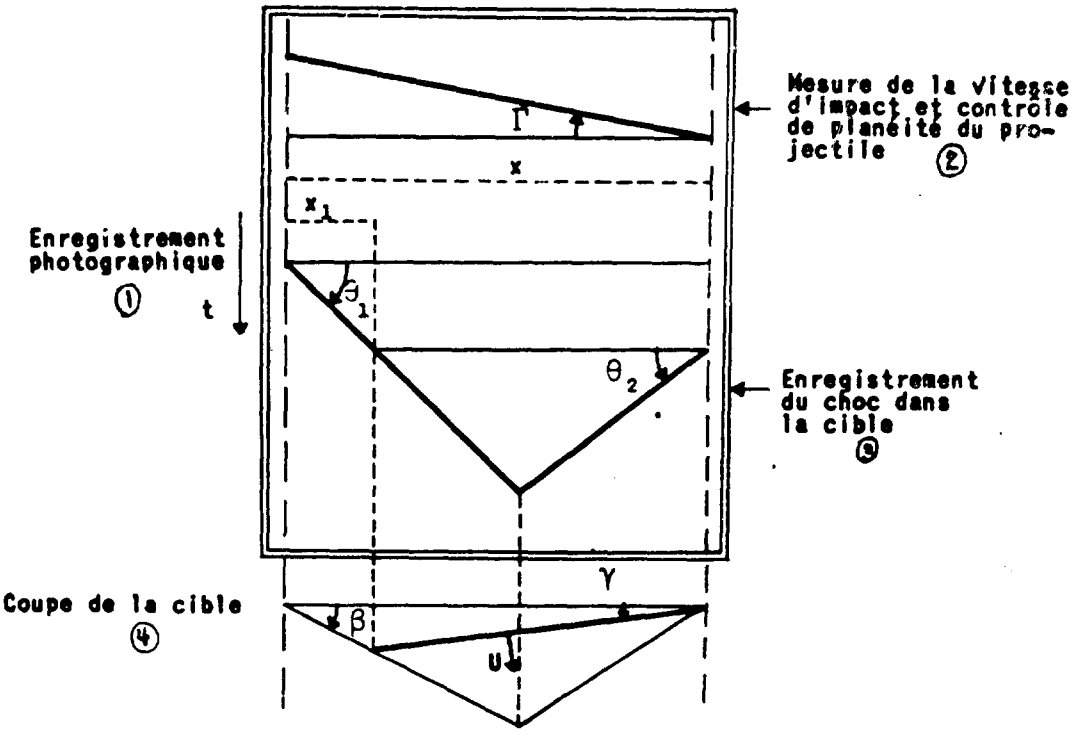
$$U = \frac{r D \sin \frac{\varphi}{2} \operatorname{tg} \gamma}{\sin (\varphi - \alpha) \sqrt{(1 - r)^2 + r^2 \operatorname{tg}^2 \gamma}}$$

(for notations, see diagram below).

-- By means of the registering of the diagram of progress of the shock in the target:

$$U = \frac{V \sin(\beta \pm \gamma)}{k \operatorname{tg} \vartheta \cos \beta}$$

where V is the sweeping velocity of the camera, and k the magnification of the installation.



(1) - photographic recording; (2) - measurement of the velocity of impact, and control of the planeness of the projectile; (3) - recording of the shock in the target; (4) - section of target.

Such a type of recording is shown in Plate 5, Fig. 1.

The results furnished by the two methods are in good agreement, and the values of p, u obtained are shown in diagram 7 and Table 8.

It is noted that the conditions of impact determined in this way are situated in a rather satisfactory manner on the shock polars derived by other experimental methods (cf. [7], for example).

3.2.4. Experimental Results Obtained with Explosive D

We have seen that, in order to initiate the detonation, the intensity and duration of application of the pressure signal induced in the target explosive should be greater than the minimum values p_m and τ_m.

In the experimental study which follows, only the first point was examined, even though the device selected permits varying the two parameters. However, our current knowledge of the behavior of metals at relatively low pressures (below 100 kb) do not permit relating the duration of the signal induced in the target to the thickness of the projectile. In effect, the assumption which we have made -- of a behavior governed by the laws of hydrodynamics (perfect fluid) -- is no longer acceptable on account of the non-negligible influence of the elastoplastic character of the metal constituting the projectile. The present deviation between hydrodynamic theory and experiment is very large. In certain cases, the duration of application of the pressure signal is but one half of the theoretical time (cf. Chapter 5, [6]).

In order to vary the impact velocity (V_p), we changed the thickness ($\mathcal{E}$) of the projectile while maintaining the characteristics of the projecting explosive (material and thickness) constant.

This procedure has permitted us to obtain the following impact velocities with a copper projectile, while the theoretical determination of the shock polar of the inert explosive from the experimental results (cf. Chapters 1 and 5) has furnished us the intensity of the shock induced in the target (diagram 9).

The values obtained are listed in the table below:

Epaisseur du projectile ε (mm) (1)	2	3	4	5
Vitesse d'impact V_p (m/s) (à ± 30 m/s) (2)	1870	1500	1200	1000
Pression induite (kb) (3)	131	96	70,5	55,5

(1) - Thickness of projectile; (2) - Impact velocity (to within ± 30 m/sec); (3) - Induced pressure.

The precision with respect to the pressure is certainly quite low due to the experimental difficulties encountered during the determination of the dynamic adiabatic of the inert explosive.

Experiments carried out at 800 m/sec have not permitted us to observe the detonation of explosive D on impact, since no luminosity has been recorded by the photographic plate.

The results obtained for impact velocities greater than this value show that the latter is a fundamental parameter of the phenomenon under investigation.

While for V_p = 1,000 m/sec the steady detonation state is attained in approximately 3 µsec, this time is reduced to 1 µsec when V_p = 1,200 m/sec. This value then varies very little when the velocity of impact increases, as can be seen on the photographic plates, since the zone in question is then very small and the smallest deviations of the planeness of the projectile notably perturb the recording.

It should be remarked that in this type of experiment the moment of impact of the projectile on the target is not defined with precision. It cannot be given by the argon chamber which has a certain "response time," and the start of the diagram of the progress of the shock in the target is difficult to read off, as we shall see below.

With regard to all these recordings we can make the following observations which are more obvious as the impact velocity is lower:

-- Before impact the extreme edges of the target no longer reflect the light furnished by the argon flash. This may be due to the presence of the air cushion which precedes the projectile. This air cushion may either perturb the target explosive by the generation of compression waves in the latter's interior, or project beyond the side of the target and deviate the light beam originating from the argon flash. Nevertheless, the thickness of the explosive subject to this effect is small, of the order of a millimeter, and the length of time during which this perturbation makes itself felt is of the order of 2 µsec. Under these conditions it is impossible to define precisely the moment of impact of the projectile on the target;

-- Immediately upon impact the luminosity due to the argon flash is abruptly stopped, and the phenomenon is analogous

to the case of an inert target, despite the fact that the progress diagram recorded shows a slight acceleration of the shock;

-- Finally, the explosive becomes luminous as soon as the shock wave arrives; a distinct slope discontinuity appears on the recording and the velocity of displacement of the recorded phenomenon gradually approaches the value of the steady detonation state.

For reasons mentioned above the moment of impact is not known accurately. We have determined it by extrapolation of the curve representative of the shock on the photographic plate, in order to compare the various recordings of the same series of experiments. Then it may be thought that for two identical assemblies, this moment is defined to within a constant, while the time deviations shown on the diagrams are determined with the following precision: the deviation between two points of the recording is measured to within $\pm$ 5/100 mm, which corresponds to a determination, in time, to within $\pm$ 10 nanoseconds (sweeping velocity 6.4 mm/μsec) and in space to within $\pm$ 2/10 mm (magnification of the setup 1/4).

Some experiments have been carried out with larger explosive wedges in order to follow the reactive shock in the explosive for a longer period of time (see Plate 5, Fig. 3).

The results obtained in this way are shown in diagrams 10, 11, 12 and 13.

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In [8] and [9] Rapport = Report.]

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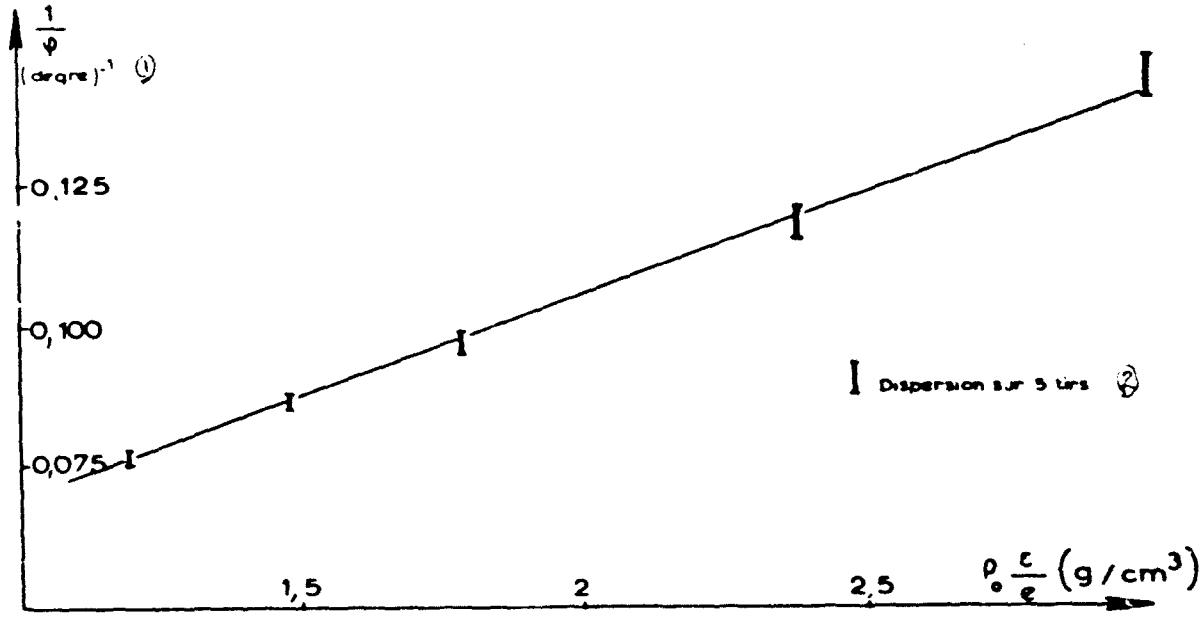
Fig.1. Flash radiography of the lifting of a copper plate (ε = 2 mm) by explosive D (e = 15 mm)

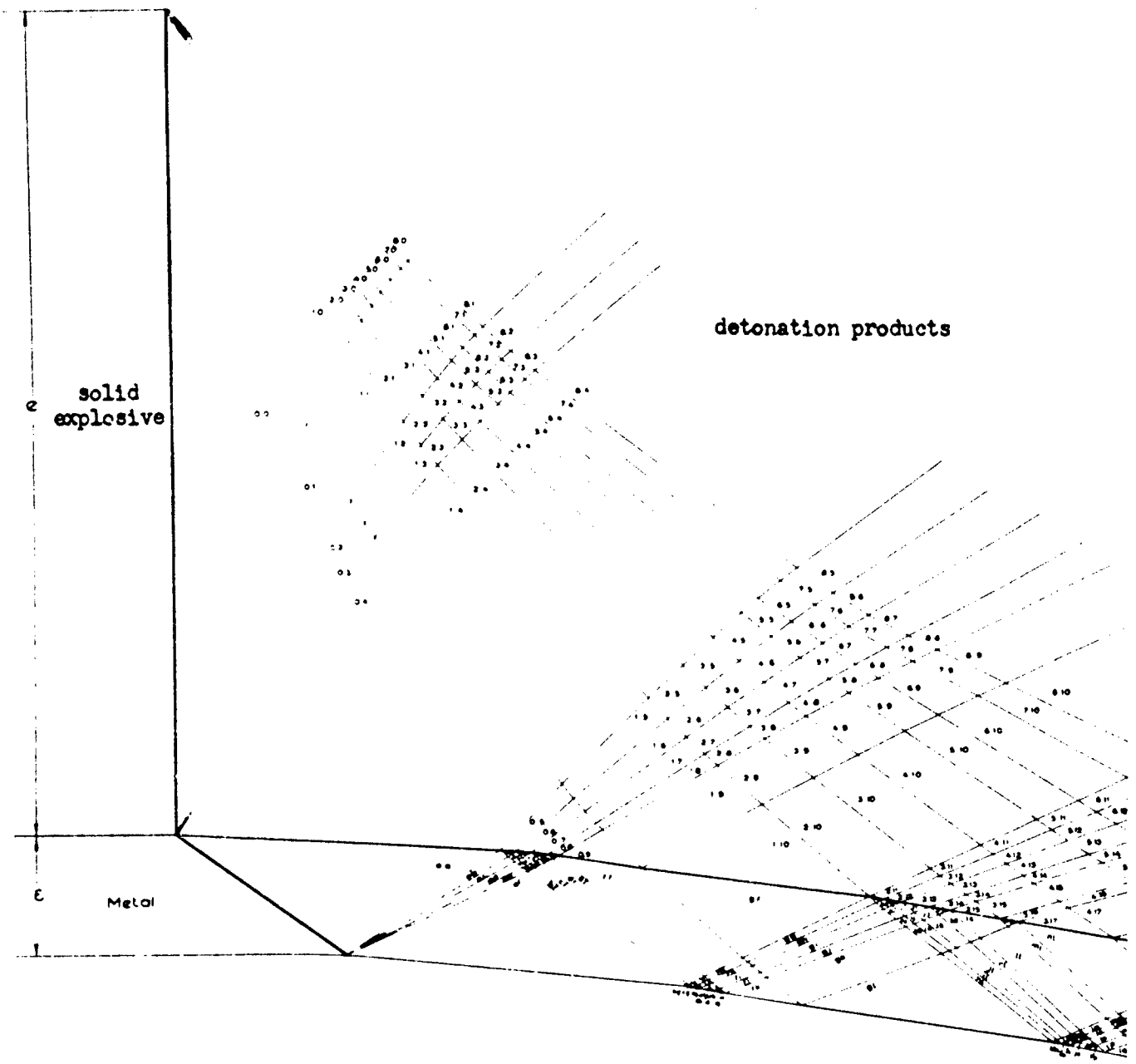


Lifting of plate

Experimental results obtained with explosive D

Fig. 2

(1) degree: (2) dispersion in 5 firings

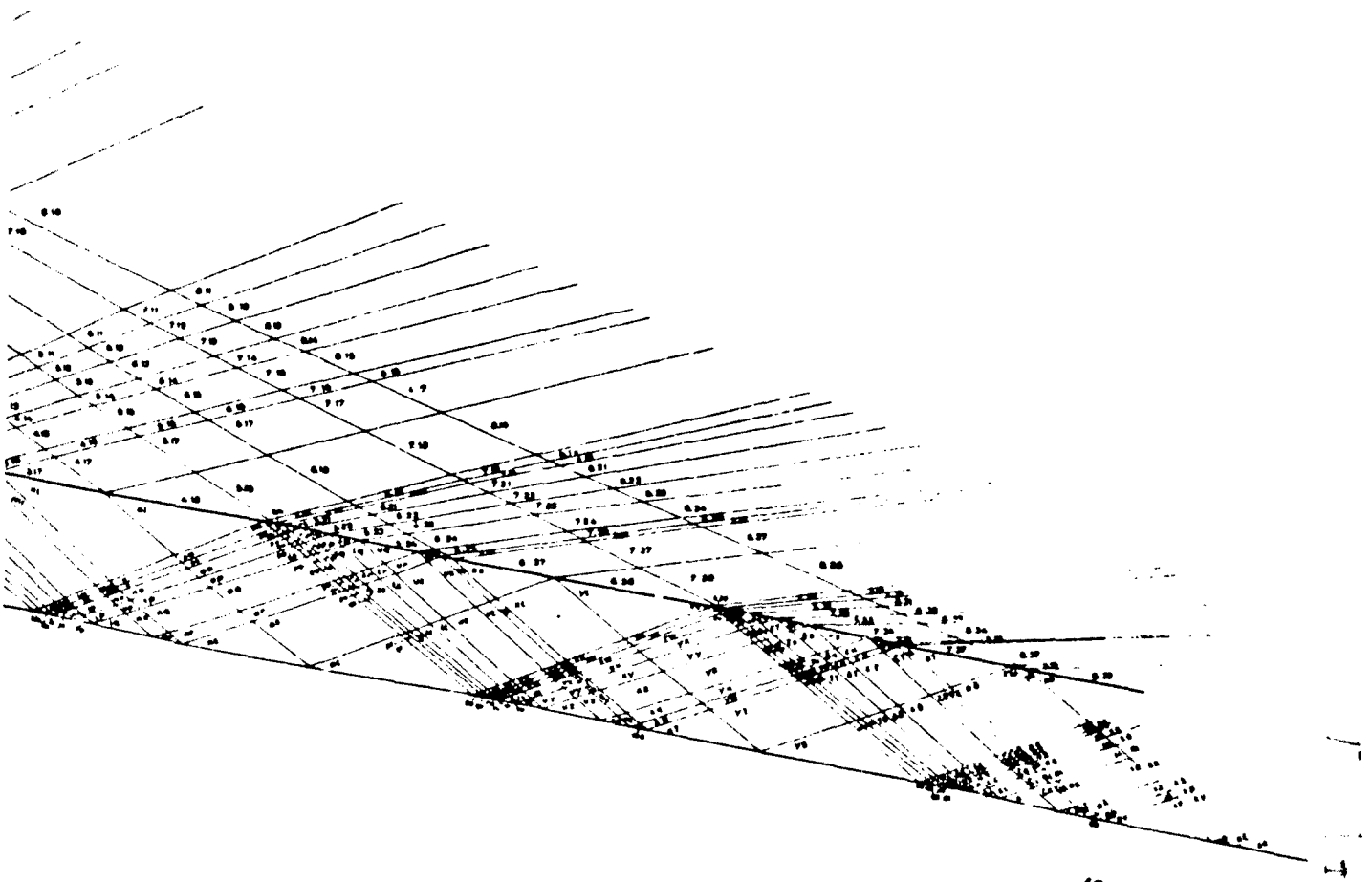


A

Plate 2.

Lifting of Plate

Explosive: $\Gamma = 3$
Metal: Copper
$\frac{\delta}{a} = 0,148$



61a

B

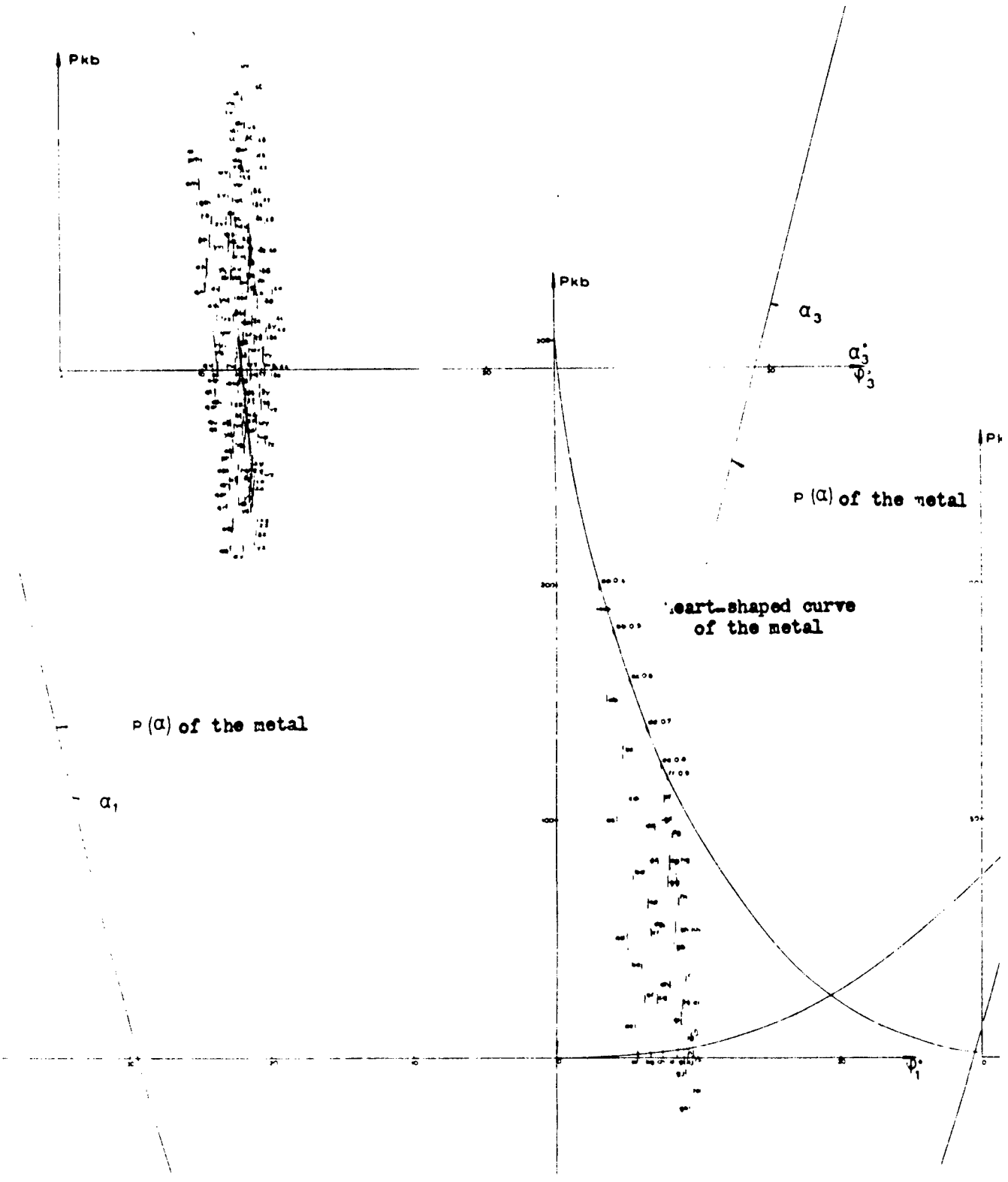

Pkb
Pkb
α_3
α_3°
φ_3°
P (α) of the metal
eart-shaped curve
of the metal
P (α) of the metal
α_1
φ_1°

Plate 3.

Lifting of Plate

State Diagram of the Metal

Explosive: $\Gamma = 3$
Metal: Copper
$\frac{\rho}{\rho_0} = 0{,}148$

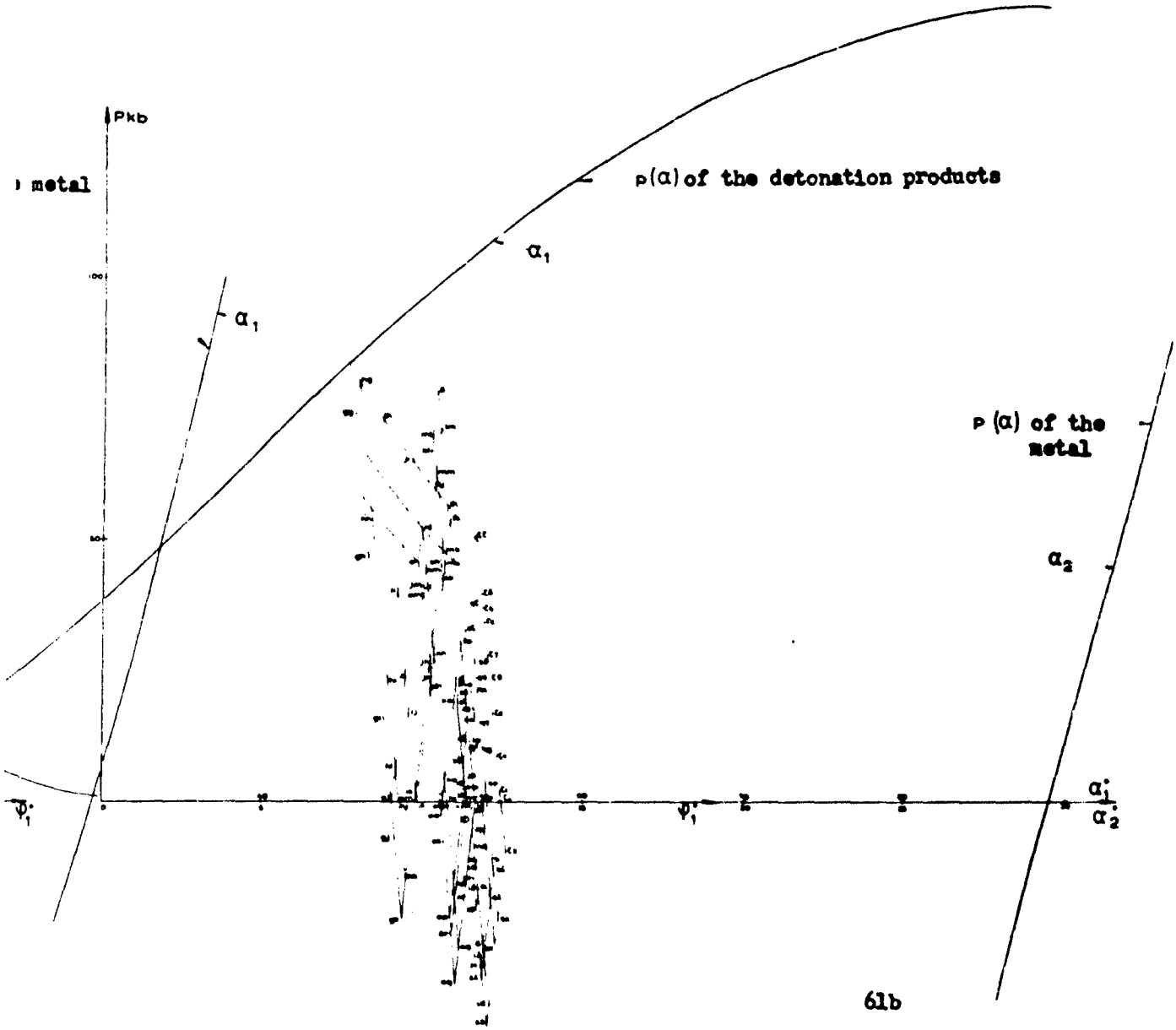
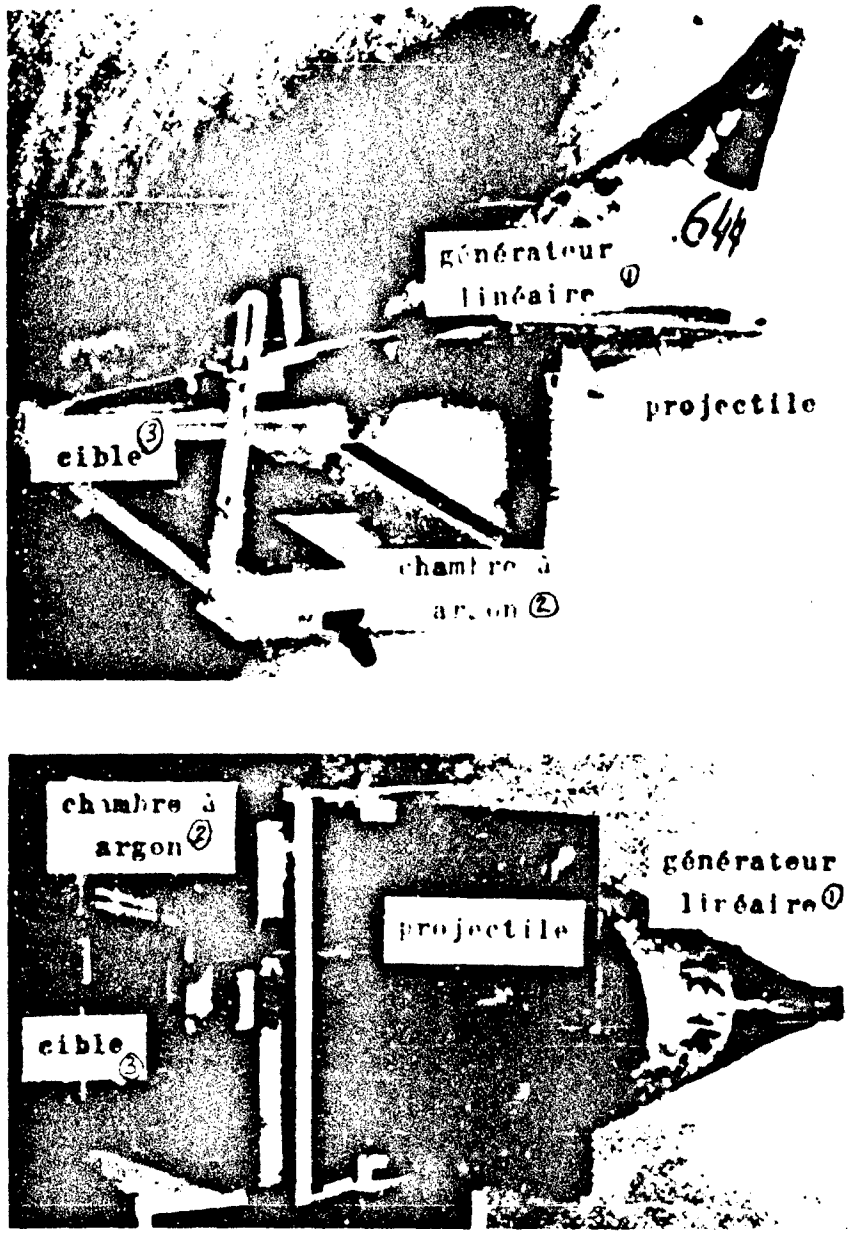
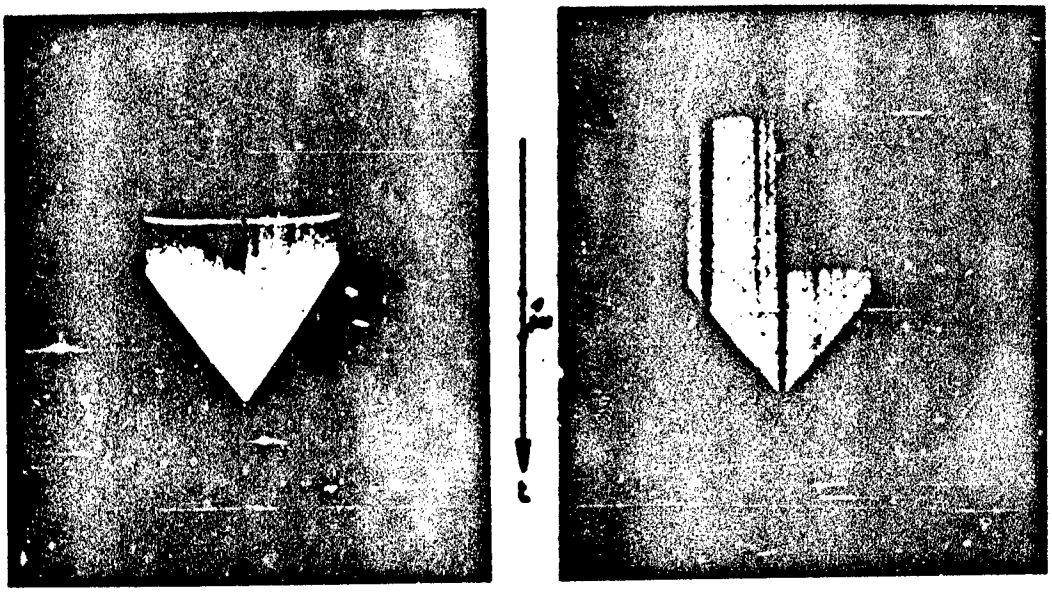


Plate 4



Assembly of the shock-generating device and target.
(1) - linear generator; (2) - argon chamber; (3) - target.

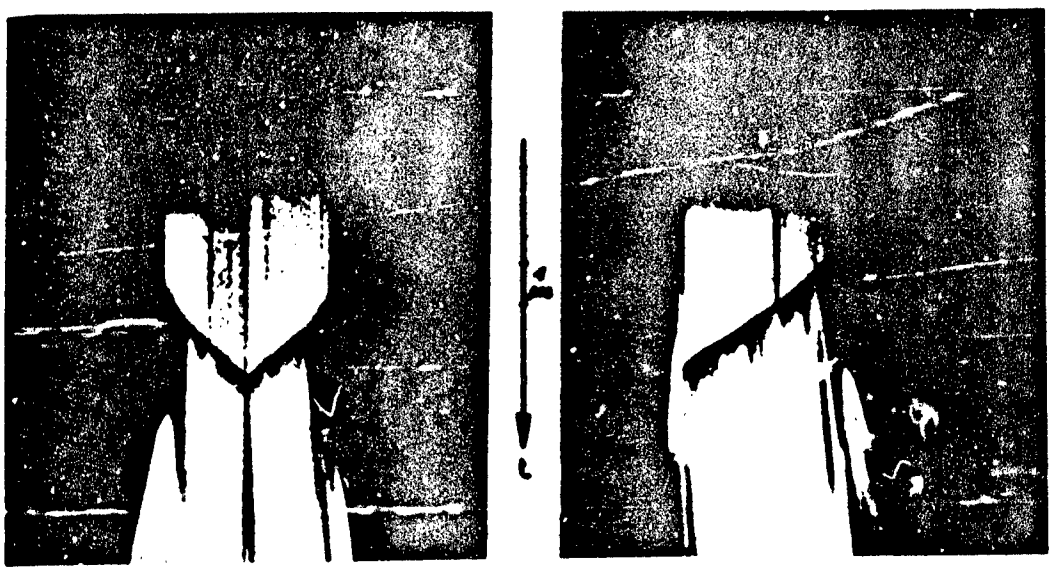
Plate 5



a : V_p 1.873 m/s

b : V_p = 1.208 m/s

Fig. 1. Impact on an inert target.
a) made of copper; b) made of aluminum (AU 4G).

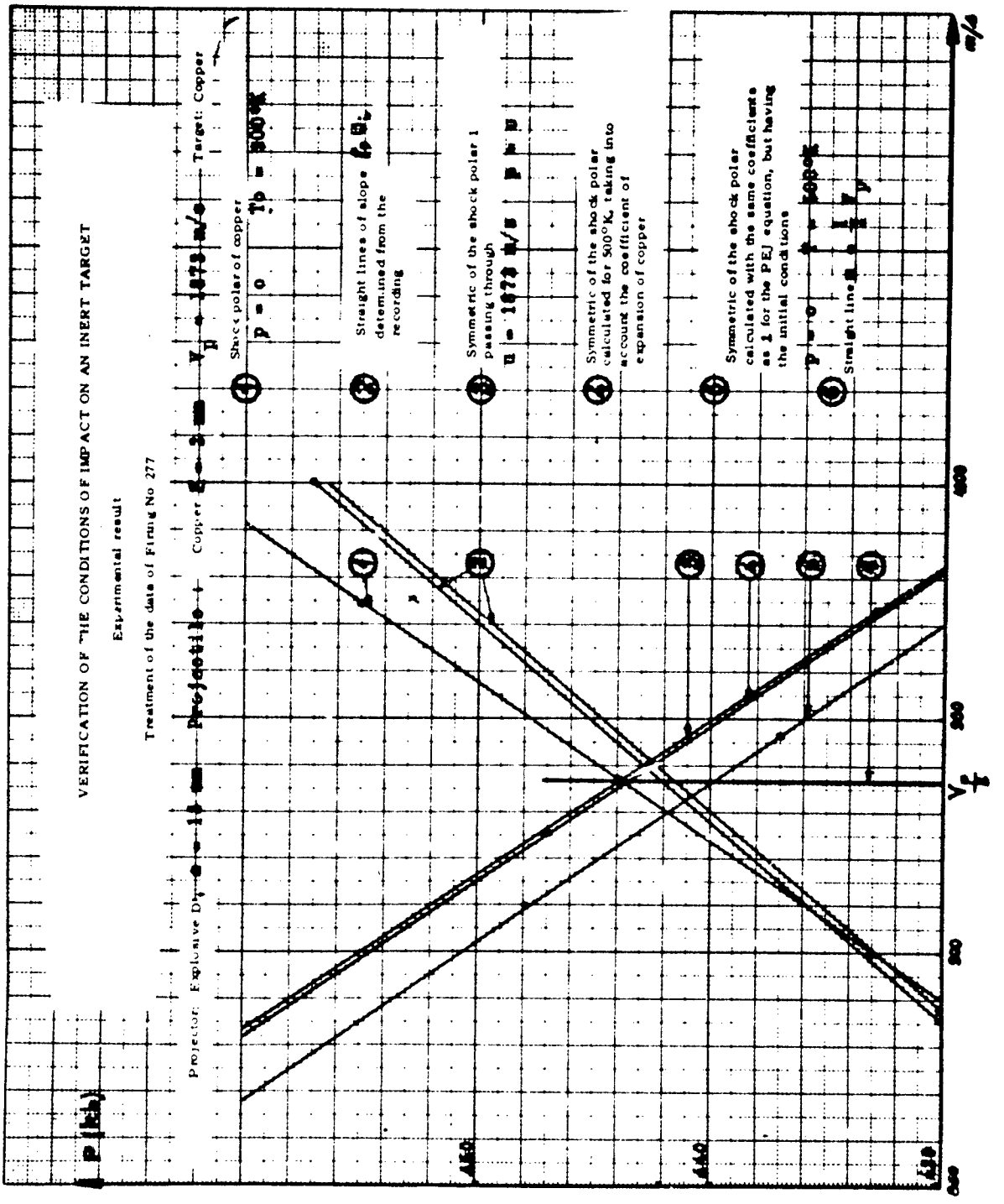


double wedge
V_p = 1.020 m/s

single wedge
V_p = 1.000 m/s

Fig. 2. Impact on a target made of explosive D.
Note: On each photo the distance between the two vertical lines is 200 mm.

Diagram 6


VERIFICATION OF THE CONDITIONS OF IMPACT ON AN INERT TARGET
Experimental result
Treatment of the data of Firing No 277
Projector: Explosive Dy
Projectile
Copper
Target: Copper
Shock polar of copper
Straight lines of slope
determined from the recording
Symmetric of the shock polar 1 passing through
Symmetric of the shock polar calculated for 500°K, taking into account the coefficient of expansion of copper
Symmetric of the shock polar calculated with the same coefficients as 1 for the PEJ equation, but having the initial conditions
Straight lines
m/s

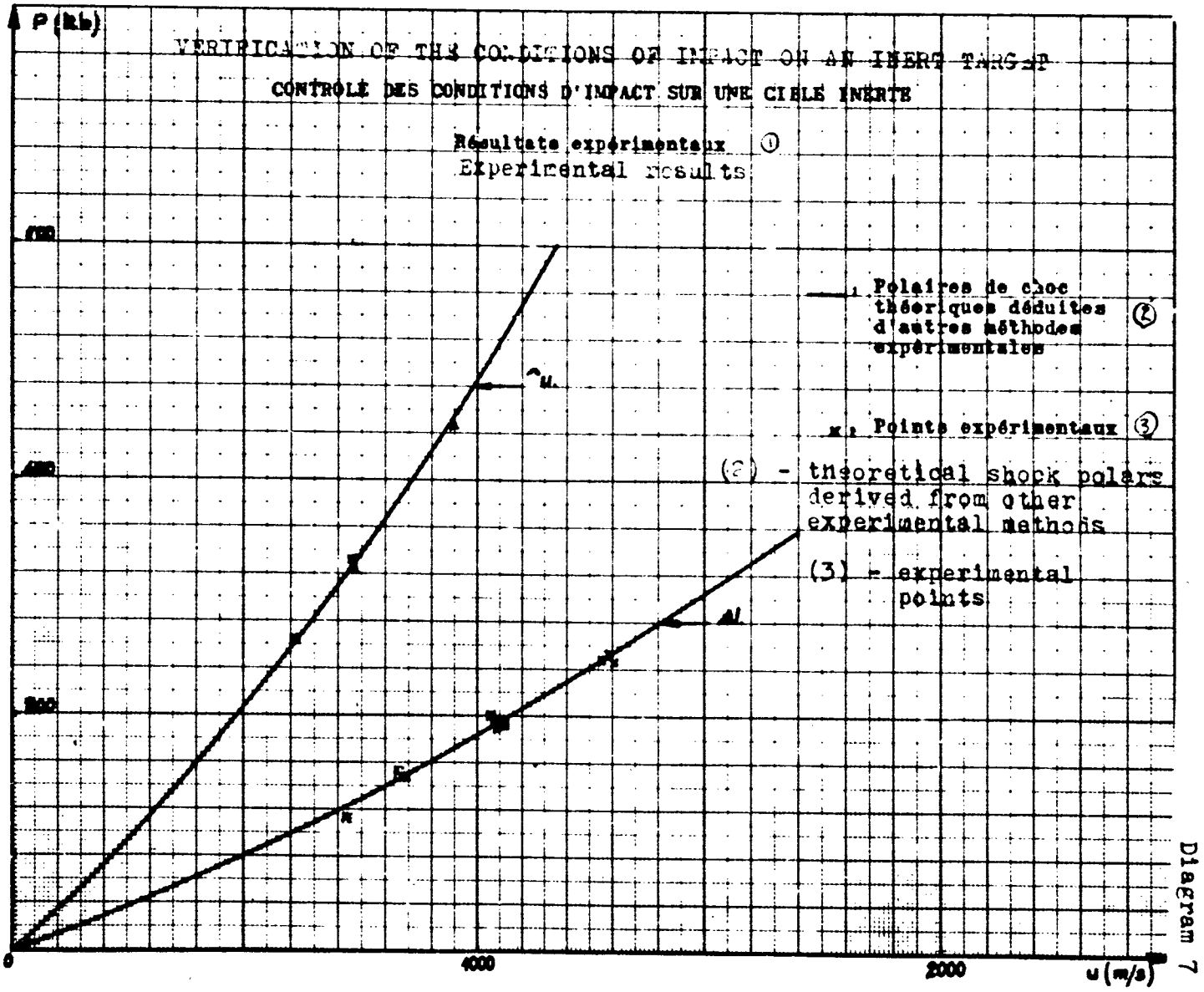

P (kb)
VERIFICATION OF THE CONDITIONS OF IMPACT ON AN INERT TARGET
CONTROLE DES CONDITIONS D'IMPACT SUR UNE CIBLE INERTE
Résultats expérimentaux ①
Experimental results
Polaires de choc théoriques déduites d'autres méthodes expérimentales ②
Points expérimentaux ③
(2) - theoretical shock polars derived from other experimental methods
(3) - experimental points
4000
2000
u (m/s)

Diagram 7

Table 8

N° de (1) l'expérience	Projectile (2) épaisseur	Cible (3) Matériau	Conditions d'impact dans la cible (4) V_p m/s	U(r) m/s	$U(\theta_1)$ m/s	$U(\theta_2)$ m/s	P kb	u m/s	Observations
248	2 mm	Alu (AU 4G)	1867	--	6854	--	248	1305	
264	2 mm	Alu (AU 4G)	1849	--	7034	--	247	1271	
278	2 mm	Alu (AU 4G)	1883	7174	7129	7189	255	1285	
277	2 mm	Cuivre (5)	1873	α très voisin de φ (6)	5310	5298	448	936	
263	3 mm	(8) Alu (AU 4G)	1497	--	6844	--	191	1034	(7)
262	3 mm	Alu (AU 4G)	1515	6643	6828	6833	192	1042	(*) : U(r) est très différent de U(θ)
281	3 mm	Cuivre	1457	4516(*)	5044	5182	328 336	728	
246	4 mm	Alu (AU 4G)	1220	--	6395	--	150	842	
247	4 mm	Alu (AU 4G)	1208	--	6727	--	153	820	
280	4 mm	Alu (AU 4G)	1208	6917	6614	6588	151	825	
279	4 mm	Cuivre	1215	4950	4872	4854	264	607	
250	5 mm	Alu (AU 4G)	1000	--	6809	--	125	681	

(1) - number of experiment; (2) - thickness of projectile; (3) - target material; (4) - conditions of impact in target; (5) - copper; (6) - α very close to φ; (7) - U(r) is very different from U(θ); (8) - Al.

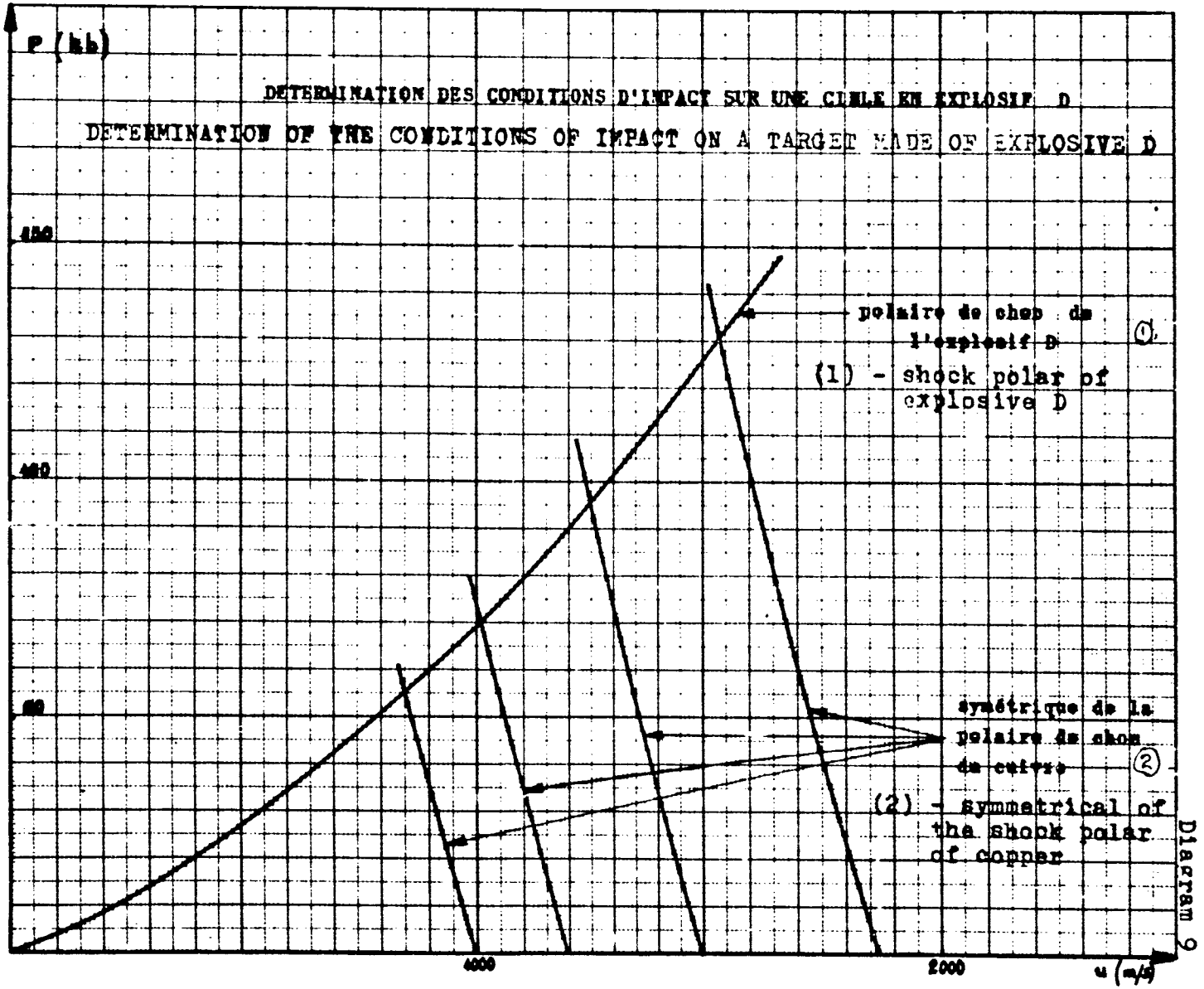
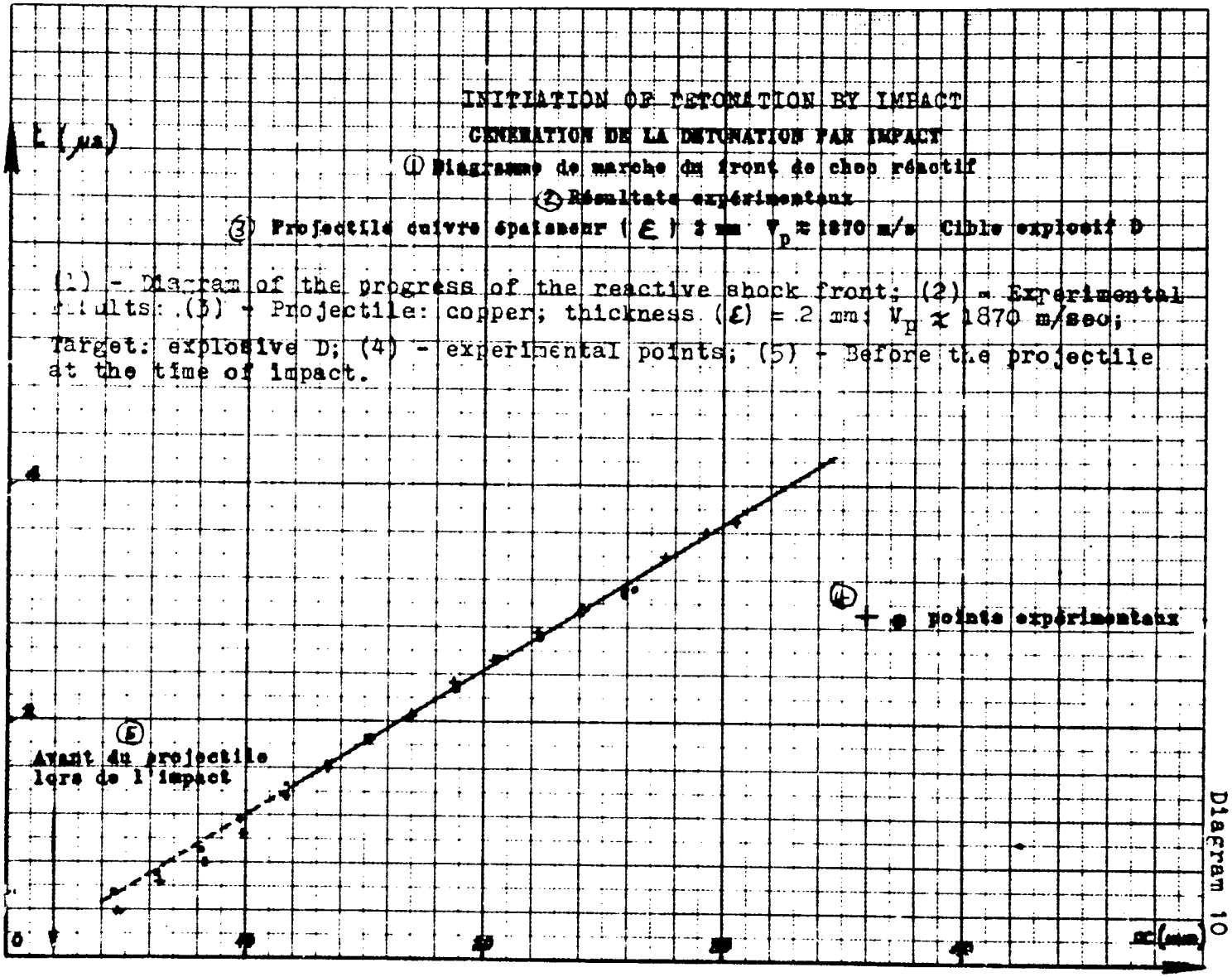
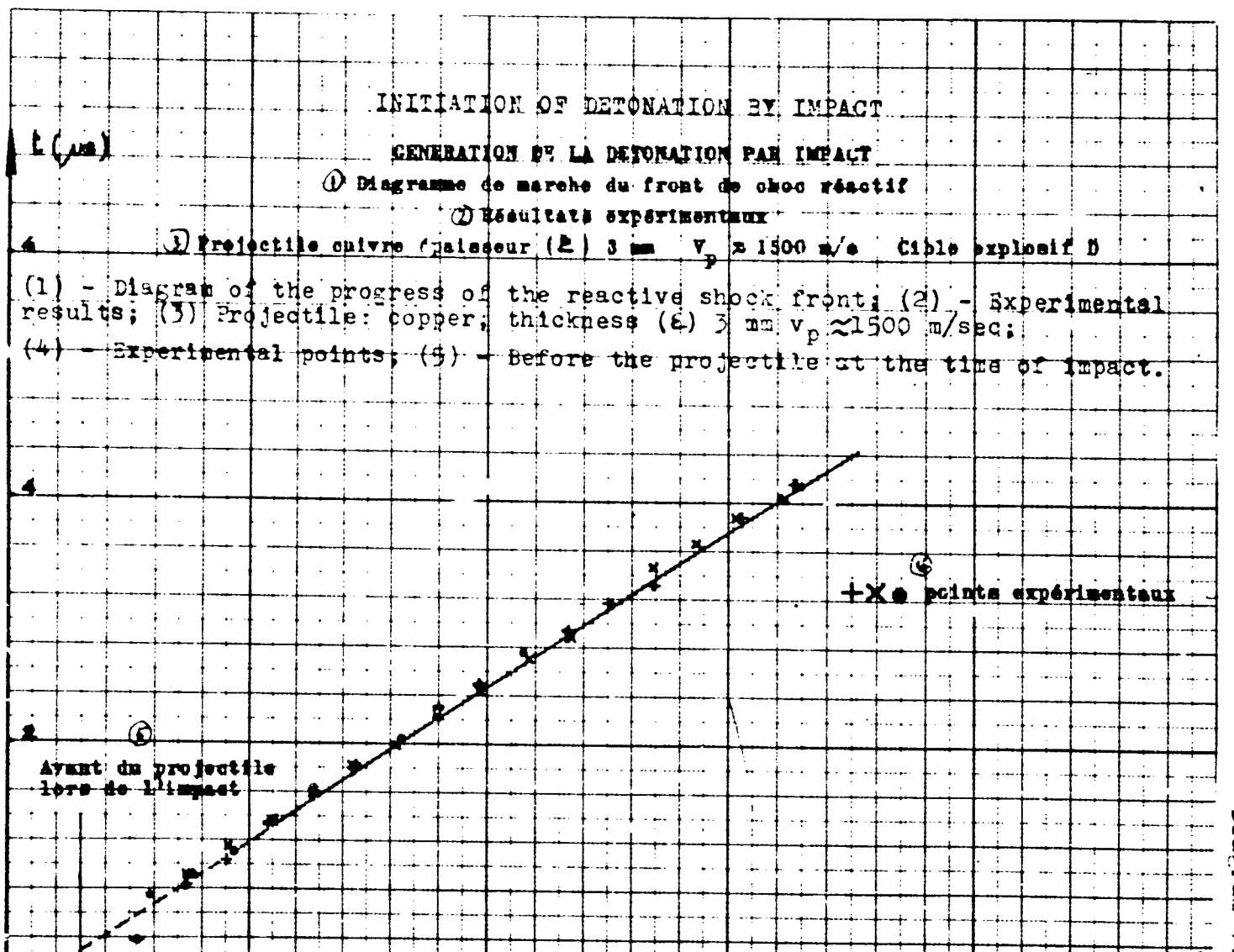

P (kb)
DETERMINATION DES CONDITIONS D'IMPACT SUR UNE CIBLE EN EXPLOSIF D
DETERMINATION OF THE CONDITIONS OF IMPACT ON A TARGET MADE OF EXPLOSIVE D
polaire de choc de l'explosif D
(1) - shock polar of explosive D
symétrique de la polaire de choc de cuivre
(2) - symmetrical of the shock polar of copper
4000
2000
u (m/s)

Diagram 9



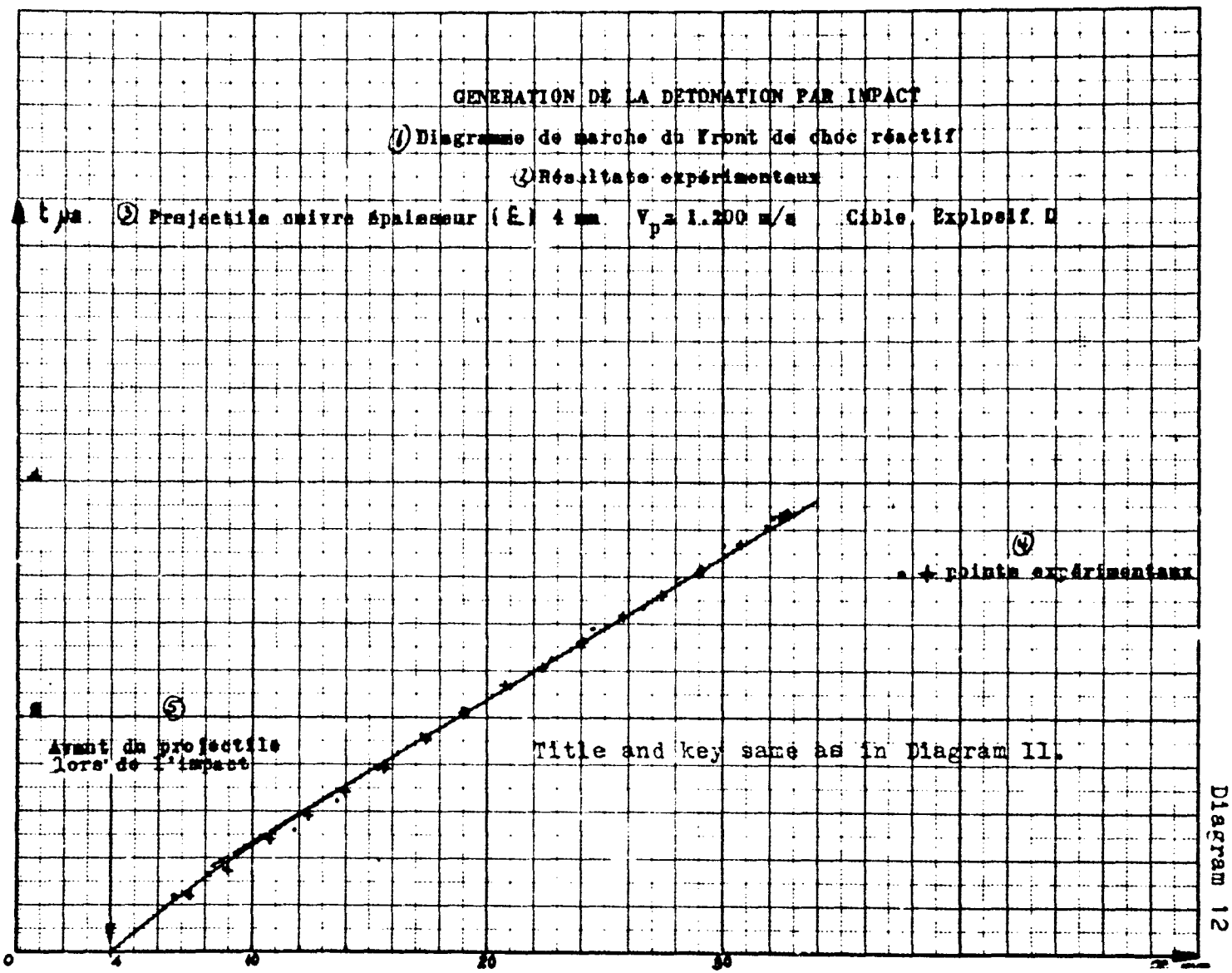
(1) - Diagram of the progress of the reactive shock front; (2) - Experimental results; (3) - Projectile: copper; thickness (ε) = 2 mm; V_p ≈ 1870 m/sec; Target: explosive D; (4) - experimental points; (5) - Before the projectile at the time of impact.

Diagram 10



(1) - Diagram of the progress of the reactive shock front; (2) - Experimental results; (3) Projectile: copper, thickness (ε) 3 mm $v_p \approx 1500$ m/sec; (4) - Experimental points; (5) - Before the projectile at the time of impact.

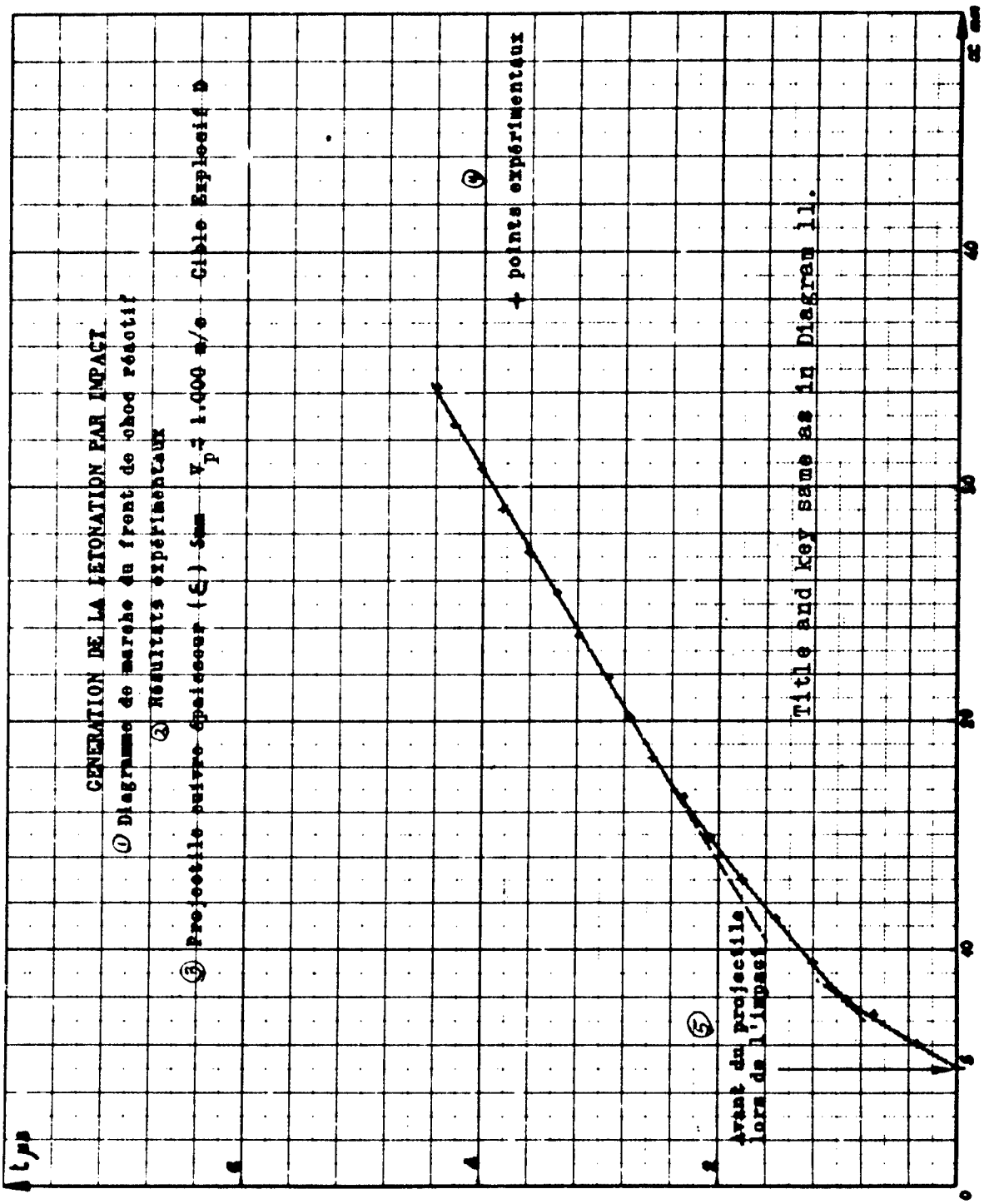
Diagram 11



Title and key same as in Diagram II.

Diagram 12

Diagram 13


GENERATION DE LA DETONATION PAR IMPACT
① Diagramme de marche du front de choc réactif
② Résultats expérimentaux
③ Projectile métro épaisseur (e) 5mm V_p = 1.000 m/s Cible Explosif D
④ points expérimentaux
⑤ Avant du projectile lors de l'impact
Title and key same as in Diagram 11.
t µs
0
10
20
30
40
50

Chapter 4

CRITICAL EXAMINATION OF THE VARIOUS THEORETICAL STUDIES OF THE INITIATION OF DETONATION BY SHOCK WAVE

The theoretical study of the initiation of detonation by impact or by frontal shock transmitted by means of a barrier is essentially the same. We have seen that the experimental setup differs only in regard to the shape of the pressure signal induced in the explosive. The signal, furnished by the impact of the projectile in the first case, is of rectangular shape at a given instant in plane x, p, while the signal transmitted by the inert barrier in the second case is of triangular shape.

The present theoretical schemes do not permit giving an account of the behavior of the heterogeneous solid explosive, whereas in the case of homogeneous explosives they furnish results which are in rather good agreement with experiments.

In a system using the Lagrange variables (X, t), the number of functions which we must determine is seven in the most simple case: u, x, ρ, E, p, T and m (for notations, see table at the end of the chapter).

The four hydrodynamic equations must be completed by three other equations in order to be able to solve completely the system of seven functions with two variables.

Two of these three equations involve the behavior of the medium; of the two, one is an equation of state $f(p, v, T) = 0$, while the other permits the determination of its internal energy for all values of (p, v, T), or $E(p, v, T) = 0$.

The last relationship is the law of liberation of chemical energy, which furnishes the reaction rate of the explosive.

4.1. HYDRODYNAMIC EQUATIONS

In a system of Lagrange coordinates, the three flow equations are written as follows, if the viscosity and thermal conduction are neglected:

$$\frac{\partial X}{\partial x} = \frac{\rho}{\rho_0} \qquad \text{(conservation of mass)}$$

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial p}{\partial X} = 0 \qquad \text{(conservation of momentum)}$$

$$\frac{\partial E}{\partial t} - \frac{\partial (Qr)}{\partial t} + p \frac{\partial v}{\partial t} = 0 \qquad \text{(conservation of energy)}$$

To these three equations we have to add the kinetic equation:

$$u = \frac{\partial x}{\partial t}$$

which links the particle velocity to Euler's variable [x(X, t)].

The phenomenon which we want to study has a duration of the order of a few microseconds, hence neglecting the viscosity and the heat conduction is a justified assumption, since the effects for which they are responsible are much slower than those produced by the dynamic parameters (a few milliseconds instead of a few microseconds).

Nevertheless, Enig takes these two factors into account in his theoretical study, while expressing some doubt as to their physical meaning. Their interest lies rather in the interpretation which they give to Richtmeyer's concept of pseudoviscosity, introduced in the system of hydrodynamic equations for the treatment of shocks [4].

4.2. EQUATION OF STATE

The simplest system, containing seven equations, requires the use of a single equation of state to represent the solid explosive, the detonation products and the gradual passage from one to the other.

Let us see what knowledge we have of these various states.

The dynamic methods now make it possible to know, with good precision, the dynamic adiabatic of an inert solid, and to derive from it the solid's equation of state, at least in a limited area of Clapeyron's plane. However we are reduced to guesses when this substance is capable of "reacting." In effect, as we have seen above, the measures carried out in this case are then distorted by the start of the chemical reaction. Only those results which have been obtained at low pressure may be considered valid.

For the detonation products, the equation of state is known sufficiently well only at the Chapman-Jouguet (C.J.) point. It should be noted, moreover, that the study of the isentropic expansion, which takes into account, for each pressure, the new conditions of thermodynamic equilibrium of the constituent gases, is in rather good agreement with the experiments.

Finally, there are no data which would make it possible to form an idea of the behavior of the solid-gas mixture during the reaction. Nevertheless we assume that this reaction zone may be divided into small regions in which thermodynamic equilibrium is established, making the unequivocal definition of the parameters of state possible in each medium (pressure, specific volume, temperature).

Hubbard and Johnson [7] -- the first researchers to have proposed a mathematical model on this subject -- employ a single equation of state valid for the solid and for the detonation products:

$$p(v - b) = n R T$$

This equation is that of a gas whose internal energy is a function only of the temperature: $E = C_v T$. This system obviously does not take into account the state of advance of the reaction and can only furnish a highly approximate agreement with experiments.

In particular, although this equation of state represents the detonation products rather well, it furnishes for the initial conditions of the solid explosive a particularly low temperature, not related to reality. In effect, the equation $p(v - b) = nRT$ must be satisfied both by the solid explosive before the reaction p_0, v_0, T_0, and by the detonation products (C.J. conditions: $\hat{p}$, $\hat{v}$, $\hat{T}$).

Hence we must have, with b and nR being constant,

$$R(v_o - b) = nRT_o \quad \& \quad \hat{p}(\hat{v} - b) = nR\hat{T}$$

or

$$T_o = \hat{T}\,\frac{R(v_o - b)}{\hat{p}(\hat{v} - b)}$$

Now, the denominator of the right hand side of this expression is very much greater than the numerator, since the numerical value of $\frac{v_o - b}{v - b}$ is only a few units while $\hat{p}$ is of the order of 200,000 p_o [12].

A numerical application, using the values associated with the explosive employed in the calculations below, gives the following results:

$$T_o = 0.057^\circ K$$

with $\quad b = 0.430 \quad v_o = 0.588 \quad \phi = 0.480 \quad (cm^3/g).$

$$\hat{p} = 216 \text{ kb} \quad \& \quad \hat{T} = 4.124^\circ K$$

The use of such an equation entails serious difficulties for the initiation of the reaction if we assume that this initiation is a function of the temperature through the intermediary of Arrhenius' exponential law.

Hence it is desirable to look for a way of improving the representation of the transition: solid $\longrightarrow$ gas. The use of a single equation -- even if it takes into account the degree of advance of the reaction -- cannot lead to satisfactory results. Hence it is preferable to look for a model which employs one equation of state for each of the two media, the solid and the gas. This method, however, considerably complicates the mathematical model.

Assuming that there is a single reaction having the form

Solid explosive $\longrightarrow$ Detonation products

with an equation of state for each medium, we introduce the variables p_s, v_s, T_s, E_s and p_g, v_g, T_g, E_g, with subscript s denoting the solid medium and g the gaseous medium.

To simplify the mathematical model, various authors have assumed in their study of homogeneous explosives that during the entire reaction $p_s = p_g = p$ and $T_s = T_g = T$ [4, 10, 11]. Let us see what these simplifications represent, and examine whether it is possible to accept them for the study of heterogeneous granular explosives.

At equal pressures (of the order of the C.J. pressure), the temperature of a gas is much higher than that of a solid (for example 4,000°K instead of 1,800°K) -- see the numerical application to the explosive used in the calculations below). The equality of temperatures can only be conceived if the thermal conduction permits the establishment of equilibrium between the two media within a short time (meaning short with respect to a microsecond). Now, we know that this is not so at all [5], since the explosive has hardly the time to heat up during the few microseconds during which the initiation of detonation takes place. Hence the assumption $T_s = T_g$ cannot be accepted for the study of the behavior of granular explosives, while it is fully justified in the case of homogeneous explosives.

The second simplification, equality of pressures, while still debatable, is nevertheless closer to reality. In effect, this equality is linked to the wave velocities in the two media: solid and gaseous. For neither of these media is the velocity of sound measurable, and it is necessary to make some highly debatable assumptions to determine it theoretically.

For the gas, whose pressure constantly changes during the reaction, a value of a few millimeters per microsecond seems to be of a good order of magnitude, if we refer to the sole known value, that obtained theoretically in the Chapman-Jouget plane ($D - u = a$). In the numerical application of the next chapter we obtain approximately 6.7 mm/μsec.

In the case of the solid, let us remember that the grains are of different chemical composition. Hence the determination of a mean value is a delicate undertaking. By analogy with homogeneous solids it may be estimated that it, too, is of the order of a few millimeters per microsecond.

The velocity of sound in each of the media may therefore be estimated to be of the same order of magnitude. Under these conditions, if we assume that a pressure equilibrium may be established for each of them in a negligible time in each of the regions which constitute the space where the reaction

takes place, we are justified in likewise assuming that the two media -- solid and gas -- are in pressure equilibrium. Hence the equality $p_s = p_g$ is acceptable in the case of granular explosives.

The introduction of the new functions p, v, T, E, of the solid (s) and of the detonation products (g) requires, during the moments when these two media are in contact, the determination of the mean values of v and E which enter into the hydrodynamic equations.

These values are defined by

$$v = (1 - m)\, v_s + m\, v_g$$
$$E = (1 - m)\, E_s + m\, E_g$$

Enig [4] has selected, as equations of state, Tait's equation generalized for the solid $(p + B)\, v - (p_0 + B)\, v_0 = (\gamma - 1)(E - E_0)$ and an equation of polytropic gas (γ = constant for the detonation products. Mader has improved the preceding scheme by using equations of state that are better adapted: Gruneisen's equation for the solid, the equation of Fickett and Wood for the detonation products. These equations have allowed him to obtain, in the case of homogeneous explosives, an excellent agreement between theory and experiment [10].

4.3. CHEMICAL KINETICS

The last equation determines the rate of liberation of the chemical energy of the explosive. This is in a way its rate of reaction. The solid explosive and the detonation products are treated as homogeneous bodies, and it is assumed that the reaction goes to completion.

Solid explosive $\longrightarrow$ detonation products

The law of chemical kinetics most frequently used is that of Arrhenius of the type:

$$\frac{\partial m}{\partial t} = \nu (1 - m)\, e^{-\frac{\dot{E}}{RT}}$$

The use of this law is based essentially on the fact that we are in the presence of a chemical reaction. The activation energy used is obtained by extrapolation to the

detonation temperatures from measurements of the rate of decomposition of explosives, carried out at ambient temperature (at the most a few hundred degrees centigrade). The measurements carried out by various laboratories on a large number of explosives lead to an activation energy which is not too variable -- 30 to 50 kcal/mole -- but they lead to frequency factor (ν) situated between 10^{10} and 10^{20} sec^{-1} [5].

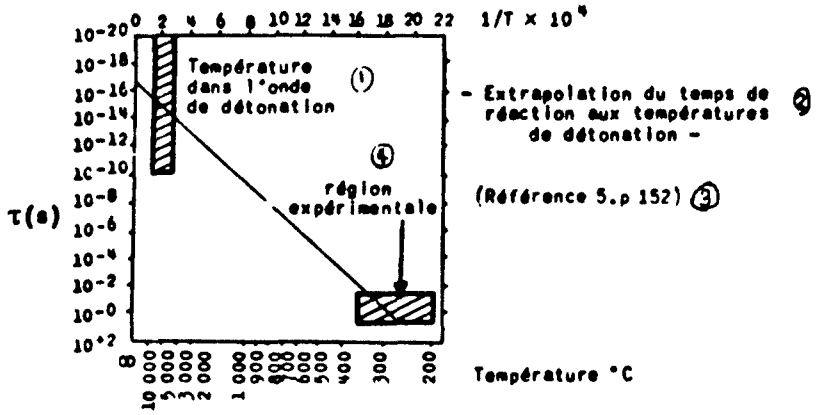
This extrapolation to the detonation temperatures of the results obtained at a few hundred degrees is highly debatable, since the chemical phenomenon is not governed strictly by a single equilibrium equation but by a number of equations such as

$$CO_2 + C \rightleftharpoons 2\,CO$$
$$CO_2 + H_2 \rightleftharpoons CO + H_2O$$
$$2\,H_2O \rightleftharpoons 2\,H_2 + O_2$$
$$\cdots\cdots\cdots\cdots\cdots$$

Of all these reactions the slowest one is that which, at a given instant, imposes its velocity as a function of the thermodynamic conditions of the medium. However these conditions constantly change as a result of the evolution of the "reaction," and there is no assurance that the slowest of them remains the slowest for a given pressure and temperature regardless of the magnitude of these two parameters.

On the other hand, the frequency factor which may be obtained from these experiments varies to a considerable extent ($\pm 10^5$). This then makes it possible to adjust the theoretical and experimental results in a relatively easy manner. Then the conclusion drawn from this that the order of magnitude of the "incubation time" of homogeneous explosives found by calculation is compatible with that obtained experimentally is not a surprising one.

Because of its exponential term, this law is particularly sensitive to the temperature and if we do not want to have an abrupt increase of the reaction rate for a small temperature increase, we must use in the numerical calculations very small Δx and Δt steps. Choosing a Δx of the order of a micron for a homogeneous substance is acceptable, but this value seems to be low for a heterogeneous explosive whose average grain size is a hundred times greater.



(1) - Temperature in the detonation wave; (2) - extrapolation of the reaction time to the detonation temperatures; (3) - [5, p 152]; (4) - experimental region.

The exponential character of this law is reflected also by the fact that a temperature difference of a few tens of degrees is sufficient to bring about or prevent the initiation of the reaction. This temperature variation may be obtained in two ways, by modifying

-- The intensity of the initiating shock-wave,

-- The initial temperature of the explosive.

While this law explains the behavior of homogeneous explosives in a satisfactory manner -- in this case it is found that above a certain pressure- (or temperature-) threshold the reaction is violent -- it does not make it possible to account for the much more gradual variation of the initiation of detonation in a granular explosive when the temperature generated by the shock wave is modified.

Finally, the exponential term of Arrhenius' equation intervenes for the determination of the initial point of the complete reaction. In effect, after the passage of the shock, the amount of chemical energy liberated is very small. Only, through the cumulative effect which it gives rise to, time ensures the continual increase of the liberated energy. It

can be seen then that it is the interface, the region which is subjected to this heating for the longest period of time, that attains the temperature above which the abrupt character of Arrhenius' law makes itself felt. This particularity is so sudden that it does not give the hydrodynamic phenomena time to attenuate, in the explosive, this abrupt pressure increase which would be slowed down by a beam of expansion waves while compression- or shock waves would be propagated in the shock generator.

Nevertheless it is found experimentally in the case of the device with barrier that, since the pressure signal is not constant as a function of the time, the liberation of chemical energy ought to slow down at the interface. The measurements which have been carried out [3] show, however, that in the case of the homogeneous explosives the detonation indeed begins in this area. Consequently the decrease of pressure, and hence that of temperature, is not sufficient to compensate for the effect of time on the liberation of the chemical energy of the explosive.

All these remarks lead us to prefer a more gradual law of energy liberation, not of an exponential character, in our attempt to explain the behavior of granular explosives.

For the sake of convenience we may, as suggested by Kistiakowsky [9] choose a law of energy liberation which is a function of the pressure, a parameter which intervenes explicitly in the hydrodynamic equations, instead of linking it to the temperature.

This choice is quite arbitrary, since these two variables are not independent. Their direction of variation is the same, and during the reaction, the knowledge of one of them determines the other.

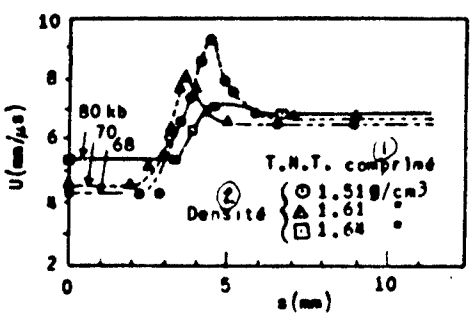
This idea has been recently taken up by Adams [1], and numerical calculations have been carried out by Warner [12] by adding a pressure term to Arrhenius' law. Then the law of liberation of chemical energy has the following form:

$$\frac{\partial m}{\partial t} = k\, p\, e^{-\frac{b}{T}}$$

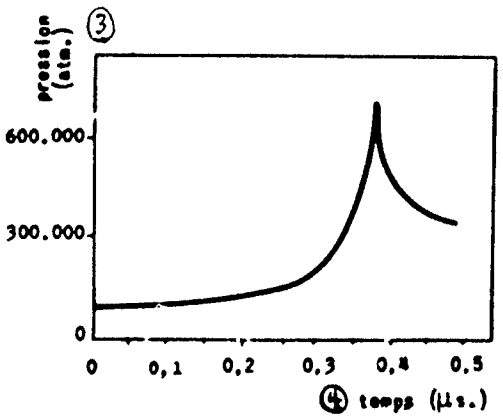
It makes it possible to obtain a pressure rise as soon as the shock passes, in contrast with the results obtained with Arrhenius' law alone, but it does not assure the progressive variation of the "induction" time as a function of the intensity

of the pressure signal. The reason for this is, probably, that the exponential term becomes predominant during the few moments which precede the detonation, whereas it is the pressure term which imposes the rate of reaction during the first part of the phenomenon. The boundary of these two influences should be quite sharp and independent of the initial conditions. These calculations have been slightly improved [Warner, Discussion at the 9th Symposium on Combustion, p 527] by the use of a law of energy liberation which is a function of the state of advance of the reaction. This makes it possible to find the "overshoot" obtained experimentally by Jacobs [8] with a particular explosive, compressed TNT, without, however, granting to the pressure peak obtained in this way the certainty of being able to vary as a function of the intensity of the shock.

Finally, the influence of the charge density, insofar as it decreases the "induction" delay when the porosity of the explosive is increased, does not lead to the appearance of a true variation of these delays as suggested by Arrhenius' law.



Velocity of the shock as a function of the distance, for various densities. (1) - compressed TNT [s = sec]; (2) - density.



Pressure peak. Holeburning. (3) - pressure (atmospheres); (4) - time.

To conclude we shall mention that the agreement between theory and experiment which is attained in certain specific cases is no longer present when the initial conditions of the shock are modified, hence a more gradual law of energy liberation, i.e., one without an exponential term containing $e^{-\frac{K}{T}}$

or $e^{-\frac{K}{p}}$ (which is essentially the same thing) [2, 6, 12] seems preferable. In the mathematical model which we are proposing the energy is liberated linearly as a function of the pressure.

NOTATION

x	Euler's variable (abscissa of grid X at time t)
X	Lagrange's variable (initial abscissa of a grid)
t	time
p	pressure
v_o	initial specific volume
v	specific volume at time t
T	temperature
u	material velocity
E	internal energy
E^*	activation energy
Q_r	heat of reaction
m	mass of gas formed by 1 g of initial solid explosive
C_v	specific heat at constant value.

Subscripts:

s = solid; g = gas; S = isentropic; H = dynamic adiabatic (Hugoniot); i = isothermal; o - initial value.

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Chapter 5

MATHEMATICAL MODEL PROPOSED

5.1. PRESENTATION OF THE MODEL

In order to assure ourselves of a better representation of the experimental phenomena, we studied a mathematical model which takes into account the remarks made above. In addition we have tried to re-obtain, by calculation, some experimental results which are not obtained by the current models.

5.1.1. System of Equations

The solid explosive and the detonation products are treated as homogeneous bodies, and it is assumed that the reaction goes to completion:

Solid explosive $\longrightarrow$ detonation products

We have chosen two separate equations of state for representing the solid and the gas, but we assumed that at every moment, in a given mesh, they are at the same pressure even though their temperatures are different. These hypotheses have been discussed in the preceding chapter. (For notations, see table at the end of the preceding chapter.)

For the solid, we have taken an equation of state having the form:

$$p = p_i + g(T - T_o) \qquad p_i = a\left(\frac{v}{v_o}\right)^{-\frac{1}{3}} \left\{ \exp\left[\beta\left(1 - \frac{v}{v_o}\right)^{\frac{1}{3}}\right] - 1 \right\} \qquad (1)$$

where p_i is the isothermal pressure (a function of v alone) which we have chosen as given by the equation of Pack, Evans

and James, and g is the coefficient $\left(\frac{\partial p}{\partial T}\right)_v$, which is assumed to be constant. The change of internal energy from conditions p_0, v_0, T_0 to conditions p, v, T is then furnished by

$$E_1 - E_{01} = C_{v_1}(T_1 - T_{01}) + g\,T_{01}(v_1 - v_{01}) - \int_{v_{01}}^{v_1} p_1\,dv_1 \qquad (2)$$

For the gas, Cook's equation [4, 5] was employed, even though a priori it had been determined for a quite different application. In effect, this law tries to express the state of the detonation products under the conditions of Chapman-Jouguet (C.J.) with the reaction terminated, independently of their composition, while here we are looking for a law which makes it possible, for a given explosive, to follow the behavior of the detonation products during the reaction. Nevertheless, since the products formed are essentially the same regardless of the explosive being investigated, we are justified in believing that the error made by choosing Cook's law is quite small.

$$p\,[v - \alpha(v)] = n\,R\,T \qquad (3)$$

The use of an equation of state of the form $p = RT\,f(v)$ leads, for the determination of the variation of the internal energy, to the simple equation $\left(T\frac{\partial p}{\partial T} - p = 0\right)$

$$E_1 - E_{01} = \int_{T_0}^{T} C_{v_1}\,dT \qquad (4)$$

The specific heat of the gas varies considerably with the temperature. It may be estimated that it goes from 0.15 cal/g/°K at 300°K to 0.8 cal/g/°K at 4,000°K. Hence an average value of 0.4 cal/g/°K may be accepted, all the more so since it leads to quite satisfactory values for the C.J. characteristics of the explosive.

The knowledge of the internal energy of the solid and the gas then makes it possible to determine that of the mixture. By calling m the mass of gas formed at a given instant per gram of initial solid explosive, this energy is given by

$$E - E_0 = m(E_1 - E_{01}) + (1 - m)(E_s - E_{0s}) \qquad (5)$$

Likewise, the specific volume of the mixture is defined by

$$v = m v_g + (1 - m) v_s \tag{6}$$

The equation of chemical kinetics giving the rate of liberation of chemical energy was chosen in various ways so as to show the difference between Arrhenius' law and the linear law as a function of pressure. The latter has even been somewhat complicated so as to account for certain experimental results: its formulation will be specified during the discussion of the theoretical results obtained by this mathematical model; in a general fashion we shall write it as:

$$\frac{dm}{dt} = f(p, T, \ldots) \tag{7}$$

Finally, if the viscosity and heat conduction are neglected, the fundamental hydrodynamic equations furnish the following equations expressed in Lagrange variables (X, t):

$$\frac{\partial x}{\partial X} = \frac{v_0}{v} \qquad \text{(conservation of mass)} \tag{8}$$

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial p}{\partial X} = 0 \qquad \text{(momentum)} \tag{9}$$

$$\frac{\partial E}{\partial t} - Q_1 \frac{\partial m}{\partial t} + p \frac{\partial v}{\partial t} = 0 \qquad \text{(energy equation)} \tag{10}$$

$$\frac{\partial x}{\partial t} = u \qquad \text{(material velocity)} \tag{11}$$

In this way we have a system of eleven equations for the twelve functions of the two variables X and t:

$$u,\ x,\ v,\ m,\ E,\ p,\ v_s,\ T_s,\ E_s,\ v_g,\ T_g,\ E_g$$

Hence we have the choice of an additional equation. We shall assume, since the solid cannot heat up by thermal conduction, that its behavior is linked solely to the pressure variations of the mixture. Hence it can only be subjected to isentropic transformations. Since we have already assumed that the solid and gas are at the same pressure at all times -- in a grid -- ($p_s = p_g = p$), the equation sought is therefore

$$dE_s + p\,dv_s = 0 \tag{12}$$

For the sake of facility of use in the subsequent calculations, we have replaced it by

$$T_i = T_0 \exp\left[\frac{q}{C_{vs}}(v_{si} - v_0)\right] \qquad (12)$$

This system of twelve equations is obviously used only during the reaction, when solid and gas are both present. It reduces to a system of six equations in the following two cases:

The reaction is not initiated, $m = 0$, the functions are then: u, x, $v = v_s$, $E = E_s$, p, T_s and the system is made up of equations 1, 2, 8, 9, 10, 11.

The reaction is terminated, $m = 1$, the functions are then: u, x, $v = v_g$, $E = E_g$, p, T_g. The system is then made up of equations 3, 4, 8, 9, 10, 11.

The impact is furnished by a metal plate of thickness e, moving with a velocity V_p. The pressure at all points of the plate is assumed to be zero.

5.1.2. Conduct of the Numerical Calculation

The choice of the system of equations of finite differences is directly inspired by that of Richtmyer [12] with pseudoviscosity (q).

The three hydrodynamic equations 8, 9, 11, are then written as:

$$v_j^{n+1} = \frac{x_{j+\frac{1}{2}}^{n+1} - x_{j-\frac{1}{2}}^{n+1}}{\rho_0 \Delta X} \qquad (8')$$

$$\frac{u_{j+\frac{1}{2}}^{n+1} - u_{j+\frac{1}{2}}^{n}}{\Delta t} = \frac{-(p+q)_j^n + (p+q)_{j-1}^n}{\rho_0 \Delta X} \qquad (9')$$

$$u_{j-\frac{1}{2}}^{n+\frac{1}{2}} = \frac{x_{j-\frac{1}{2}}^{n+1} - x_{j-\frac{1}{2}}^{n}}{\Delta t} \qquad (11')$$

The pseudoviscosity is given by the equations

$$q = \frac{l^2}{v}\left(\frac{\partial u}{\partial x}\right)^2 \quad \text{if} \quad \frac{\partial u}{\partial x} < 0$$

$$q = 0 \qquad \text{if} \quad \frac{\partial u}{\partial x} > 0$$

where l is a length.

The knowledge at time n of the functions p, v, q in the grids $j - 1$, j, $j + 1$ and of functions u, x at the interfaces $j - \frac{1}{2}$, $j + \frac{1}{2}$ makes it possible to calculate at time $n + 1$ by means of equation 9': $u_{j+\frac{1}{2}}^{n+1}$ by means of equation 11': $x_{j+\frac{1}{2}}^{n+1}$ and by means of equation 8': v_j^{n+1}.

Starting from m_j^n, equation 7 furnishes m_j^{n+1}, regardless of the law of chemical kinetics employed.

$$m_j^{n+1} = m_j^n + |\Delta m_j|_n^{n+1}$$

with

$$\frac{|\Delta m_j|_n^{n+1}}{\Delta t} = f(p, T, \ldots) \qquad (7')$$

Thus we have eight equations left for the determination of the eight functions E, p, v_s, T_s, E_s, v_g, T_g, E_g. The solution of the system of eight equations with eight unknowns is carried out in the following manner: equations 5 and 10 are calculated as a function only of the variables v_s and v_g, themselves related by equation 6. Hence it is possible to determine by iteration the values of these variables which simultaneously satisfy the three equations 5, 6 and 10. Hence this calculation makes it possible to determine, in a stepwise manner, the behavior during the reaction of the mixture of explosive solid and detonation products in space and time. It should nevertheless be noted that equation 10 involves the pseudoviscosity, but this does not essentially complicate the solution of the system of equations.

$$p^{n+1} = p_i^{n+1} + g\,(T_s^{n+1} - T_o) \tag{1'}$$

$$E_s^{n+1} - E_{so} = C_{v_s}\,(T_s^{n+1} - T_o) + g\,T_o(v_s^{n+1} - v_{so}) - \int_{v_{so}}^{v_s} p_i^{n+1}\,dv_s \tag{2'}$$

$$p^{n+1}\,[v_g^{n+1} - a^{n+1}(v_g)] = n\,R\,T_g^{n+1} \tag{3'}$$

$$E_g^{n+1} - E_g^o = C_{v_g}\,(T_g^{n+1} - T_g^o) \tag{4'}$$

$$E^{n+1} - E_o = m^{n+1}\,(E_g^{n+1} - E_g^o) + (1 - m^{n+1})\,(E_s^{n+1} - E_{so}) \tag{5'}$$

$$v^{n+1} = m^{n+1}\,v_g^{n+1} + (1 - m^{n+1})\,v_s^{n+1} \tag{6'}$$

$$(E^{n+1} - E_o) - (E^n - E_o) = -\,(p + q)^{n+1}\,(v^{n+1} - v^n) + Q_r\,|\Delta m|^{n+1} \tag{10'}$$

$$T_s^{n+1} = T_o \exp\left[\frac{g}{C_{v_s}}\,(v_{s_o} - v_s^{n+1})\right] \tag{12'}$$

In all these equations subscript j has been omitted.

During the moments when only the solid exists (m = 0) in a grid, or the solid is completely converted into gas (m = 1), the mathematical model is reduced to six equations. Three of them, which are fundamental hydrodynamic equations, immediately furnish u, x, and v (v_s or v_g) at moment n + 1. Then the system is reduced to three equations comprising the three unknowns p, E_s (or E_g), T_s (or T_g).

The initiation of the reaction was carried out as follows: During the rise of the shock front -- a gradual rise due to the use of pseudoviscosity -- the explosive is treated as an inert substance, and the reaction is released only when the pressure maximum due to the impact has been attained. This state, situated on the Hugoniot of the inert solid, denoted by subscript H, constitutes the initial conditions for the determination of the subsequent behavior of the solid during the reaction (isentropic transformation). Moreover, the temperature T_H is taken as an initial value in the two equations of the determination of the internal energy of the gas, $T_g^o = T_H$ (equation 4), and of the chemical kinetics in the case where the latter is Arrhenius' equation.

5.1.3. Choice of Numerical Values

The object of this study is more that of determining the influence of the various parameters on the generation of the detonation in an explosive than to explain the particular quantitative behavior of one of them. Nevertheless, we have

made an attempt to choose the various constants in such a way as to represent explosive D in a satisfactory manner [2].

For the equation of state of the solid explosive, the experimental measurements of the dynamic adiabatic, carried out on this explosive [8] gave the following linear law U(u):

$$U = 2\,400 + 1.66\,u \quad \text{(MTS)} \quad \text{(meter-ton-second)}$$

The value of the specific heat of this explosive [11] has led us to choose C_v, which we assume constant regardless of the temperature, as equal to 880 kj/ton.

On the basis of these results the constants of the PEJ equation were adjusted, and the values retained are as follows:

$$\alpha = 1.349.10^{6} \qquad \beta = 16.5 \qquad \gamma = 3.491 \quad \text{(meter-ton-second)}$$

for an initial density and temperature of

$$\rho_0 = 1.70\ t/m^3 \qquad T_0 = 300°K$$

respectively.

By means of the equations given in Chapter 1, it is now possible to determine the various functions necessary for the calculation of the behavior of the inert explosive during the shock-detonation transition, in particular the dynamic adiabatic of pole $p = 0$, $v = v_0$, and the isentropic lines each originating from a point of this adiabatic.

The determination of the detonation characteristics of this explosive then consists of solving the system of six equations recapitulated below:

$$p(v - \alpha) = n R T \qquad \text{(equation of state)}$$

$$u = D\left(1 - \frac{v}{v_0}\right) \qquad \text{(continuity equation)}$$

$$D^2 = p \frac{v_0^2}{v_0 - v} \qquad \text{(momentum equation)}$$

$$\Delta E - Q_v = \frac{1}{2} p (v_0 - v) \qquad \text{(energy equation)}$$

$\Delta E = C_v (T - T_0)$ (equation of internal energy)

$D - u = a$ (Chapman-Jouguet condition)

The solution of this system of equations may be carried out in the following manner [2]:

The determination of the velocity of sound $a^2 = \left(\frac{dp}{d\rho}\right)_s$ along an isentropic $dE + p\,dv = 0$ with $dE = C_v dT$, taking into account the equation of state selected:

$$(v - \alpha)\,dp + p\left(1 - \frac{d\alpha}{dv}\right)dv = n R\,dT$$

is furnished by

$$\left(\frac{dp}{dv}\right)_s = -\left(1 - \frac{d\alpha}{dv} + \frac{n R}{C_v}\right)\frac{p}{v - \alpha}$$

or

$$\left(\frac{dp}{d\rho}\right)_s = a^2 = \left(\frac{dp}{dv}\right)_s \cdot \frac{dv}{d\rho} = \left(1 - \frac{d\alpha}{dv} + \frac{n R}{C_v}\right)\frac{p\,v^2}{v - \alpha}$$

Substituting this value into the C.J. condition, after replacing the lefthand side of the latter by the values of D and u taken from the continuity- and momentum equation, we get

$$1 - \frac{d\alpha}{dv} + \frac{n R}{C_v} = \frac{v - \alpha}{v_0 - v}$$

The use of the law $\alpha(v)$, given by $v = a_1 \alpha^2 + b_1 \alpha + c_1$, yields

$$\frac{d\alpha}{dv} = \frac{1}{2 a_1 \alpha + b_1}$$

The equation to be solved then reduces to

$$1 + \frac{n R}{C_v} = \frac{v - \alpha}{v_0 - v} + \frac{1}{2 a_1 \alpha + b_1}$$

The lefthand side of this equation is constant, hence v and α are obtained directly. The combination of the energy equation leads, after elimination of the temperature, to the determination of p by means of

$$p\left[(v-\alpha)-\frac{nR}{2C_v}(v_0-v)\right]=\frac{1}{2}R\left[T_0+\frac{Q_v}{C_v}\right]$$

The other equations then permit solving the problem completely.

We have chosen the function $\alpha(v)$, directly inspired by Cook's curve [4, 5], given by

$$v = 2{,}625\,\alpha^2 - 0{,}8\,\alpha + 0{,}34$$

Using the following numerical values (MTS)

$$n = 32.108 \qquad R = 8{,}3056.10^{-3} \qquad C_v = 1.672 \qquad Q_v = 5{,}225.10^3$$

$$T_0 = 300^\circ K$$

calculation yields

$$p = 216.10^3 \text{ pièzes} \qquad D = 8.305 \text{ m/sec} \qquad u = 1.529 \text{ m/sec}$$

$$T = 4.124^\circ K$$

Only the velocity of detonation is slightly too high with regard to the values of pressure and material velocity. A more elaborate equation of state would permit a better adjustment of these values with respect to each other, but apart from the fact that it would considerably complicate the calculation, it would probably contribute only a very slight improvement to the proposed scheme.

5.2. RESULTS

This system of equations was adapted for numerical calculation on an electronic digital computer. Its stability was verified numerically.*

5.2.1. Arrhenius' Law

A first series of calculation was carried out using Arrhenius' Law as the law of chemical kinetics:

$$\frac{dm}{dt} = \nu(1-m)\,e^{-\frac{E}{RT}}$$

*The program was prepared by Mr. Vidart and Mme Prouteau, and used on the Bull Gamma 60 electronic computer.

The temperature T was chosen as that of the gas (T_g). However, the use of two different temperatures (T_s and T_g) for the same pressure (the gas is at 4,000°K when the solid is at 1,800°K) entails the rapid initiation of the reaction. Then the latter is complete in a short time, since Arrhenius' law is very sensitive to the temperature.

Under these conditions the detonation starts at the interface as in the case of homogeneous explosives but takes place so rapidly that there is hardly any "incubation" period, since the inert shock does not have the time to be propagated in the explosive.

Nevertheless, there is obtained a gradual rise of the velocity of the shock front which is reactive from the beginning (the pseudoviscosity is only an artifice for the calculation), but the reaction is such that the steady detonation state is attained very fast and without the possibility of a slowdown.

5.2.2. The Law of Pressure

The following numerical study was not oriented toward the explanation of the quantitative behavior of a particular explosive but rather toward determining the influence of various parameters on the process of initiation of the detonation, in order to compare their variation with the experimental values.

In effect, the use of a numerical method with finite differences for the solution of the system of equations is not without introducing some inconvenience. In order to reduce the fluctuations as much as possible, we have been led to choosing a dense grid in space and time. The grid chosen (Δx = 0.1 mm, Δt = 5 nsec) requires a large number of calculations. So as to make sure that a complete calculation does not require a prohibitive number of machine hours, we were forced -- while preserving an order of magnitude compatible with the experimental values -- to obtain the stable detonation state in approx. 2 μsec for the "average" case (impact velocity of a copper projectile: 1,600 m/sec), even though this is slightly low in absolute value.

Since we wish to study the behavior of granular explosives, we were first motivated by Eyring's law grain-burning [7], then by the law of holeburning.

In the first law it is assumed that the explosive is present in the form of spheres having an average radius R. The chemical decomposition takes place only on the surface, and the influence of the pressure on the rest of the grain is neglected. Strictly speaking, with the characteristics which we have chosen for the solid explosive, when the pressure changes from 100 kb to 200 kb the radius of the grain decrease by about 3.5%.

This hypothesis leads us to the assumption that the mass of the sphere of radius R is directly proportional to its volume during the entire reaction.

By calling m the mass of gas formed per gram of initial explosive, and r the radius of the sphere at moment t,

$$\frac{r^3}{R^3} = 1 - m$$

whence we get: $r = R(1 - m)^{\frac{1}{3}}$

and by differentiation:

$$\frac{3r^2}{R^3}\frac{dr}{dt} = -\frac{dm}{dt}$$

Hence the equation of the rate of reaction has the following form:

$$\frac{dm}{dt} = -\frac{3}{R}(1 - m)^{\frac{2}{3}}\frac{dr}{dt}$$

In this case, dr/dt is negative, and the radius of the grain decreases during the reaction.

The term $(1 - m)^{\frac{2}{3}}$ is the equivalent of the "geometric form function" of the combustion equations of powders, while dr/dt corresponds to the linear combustion rate and dm/dt to the rate of consumption.

Next, our reasoning was influenced -- under the same assumptions -- by holeburning. Then the reaction is assumed to propagate in a divergent spherical manner from the center of the explosive grain. We then get

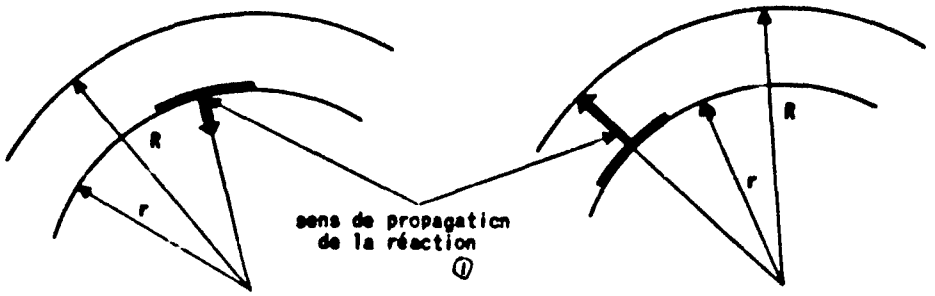
$$\frac{r^3}{R^3} = m$$

whence $r = R\, m^{\frac{1}{3}}$

and $\frac{3 r^2}{R^3} \frac{dr}{dt} = \frac{dm}{dt}$

whence $\frac{dm}{dt} = \frac{3}{R} \cdot m^{\frac{2}{3}} \cdot \frac{dr}{dt}$

this time dr/dt being positive.



Combustion par grain (2) (grain-burning)

Combustion par trou (3) (holeburning)

(1) - direction of propagation of the reaction; (2) - grain-burning; (3) - holeburning.

The essential difference between these two equations of chemical kinetics, all things being equal, is that the first leads to a slowing down of the rate of reaction dm/dt in direct proportion to the increase in the mass (m) of gas formed, while the second, on the contrary, causes its acceleration.

The last point which we have to make explicit for carrying out the complete calculation is the manner in which the radius of the grain varies in time, in other words, specify the combustion rate dr/dt.

This variation depends on the thermodynamic conditions of the grain and of the medium surrounding it. It is not possible at the present time to determine it experimentally, as a function of the various parameters (pressure, temperature, etc.). We can only be guided in our choice by analogies with

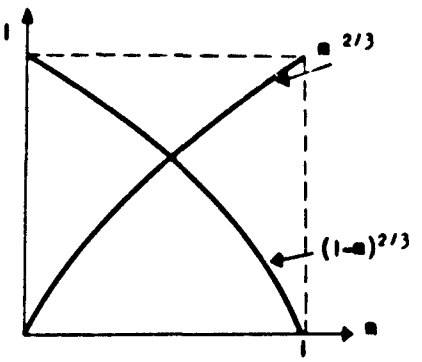
similar phenomena (chemical reactions, combustion) and the comparison between the theoretical and experimental results:

-- The predominant influence of pressure in the transition: deflagration-detonation (see Chapter 2);

-- The progress diagram of the reactive shock front during the initiation of the detonation in a granular explosive where the compression waves accelerate the shock as they overtake it;

-- The combustion of powders both at low pressure (solid propergols) and at several thousand atmospheres (internal ballistics of cannons);

-- The measurements made by certain researchers up to 10 kb on solid explosives [9].



The whole body of these partial data has led us to prefer, as independent variable, the pressure to the temperature, all the more so since it is directly involved in the hydrodynamic equations.

Hence we are led to choose a law of the form: $|\frac{dr}{dt}| = ap^{\alpha} + b$ with α close to 1.

In first approximation, we chose

$$\alpha = 1 \qquad \text{or} \qquad |\frac{dr}{dt}| = ap + b$$

The use of a linear law is a priori quite satisfactory, since we have seen that the choice of an exponential law entails a much too abrupt release of the reaction, and does not allow the representation of the experimental results of solid granular explosives.

The majority of theoretical results presented below were obtained by means of this linear law of pressure.

Under the assumption of a reaction governed by the law inspired by grain-burning, the equation of chemical kinetics defined above is written as

$$\frac{dm}{dt} = \frac{3}{R}(1 - m)^{\frac{2}{3}}(ap + b)$$

In order to make evident the pressure threshold p_1 below which it seems that the reaction cannot be initiated experimentally, we gave b the value of $(- ap_1)$.

Then the final equation employed is

$$\frac{dm}{dt} = \frac{3a}{R}(1 - m)^{\frac{2}{3}}(p - p_1)$$

and under the assumption of the law inspired by holeburning, we get

$$\frac{dm}{dt} = \frac{3a}{R} m^{\frac{2}{3}}(p - p_1)$$

- Diagram of the progress of the reactive shock front:

The use of a law of chemical kinetics depending on the pressure, combined with a function having a form analogous to that of grain-burning, furnishes a progress diagram of the reactive shock which shows a rather good agreement with experimental results. In effect we obtain, immediately upon the passage of the shock, a very high rate of reaction. Hence the pressure increases abruptly, and then gradually decreases to the conditions of Chapman-Jouguet. The reactive shock front accelerates from the moment of impact, to attain gradually the steady detonation state (diagrams 1 and 3). By contrast, in the case of holeburning, the reaction is quite weak after the passage of the shock. The latter is therefore propagated in the explosive at an almost constant rate, as in an inert medium. It is at the target-projectile interface, the region which is compressed for the longest period of time, that the

reaction first becomes considerable; then compression waves are propagated toward the shock front, the pressure signal gradually straightens out and finally assumes a form analogous to that obtained under the assumption of grain-burning. Hence during the first moments the reactive shock front propagates at a constant velocity, then it becomes accelerated quite abruptly when the compression waves originating from the interface catch up with it, and finally gradually attains the velocity of the steady detonation state. Hence a slight slope discontinuity is observed in this case in the progress diagram (x, t) of the shock in the explosive (diagrams 2 and 3).

The use of a form function involving the average diameter of the grains makes it possible to represent, at least qualitatively, the following experimentally observed finding: the smaller the average grain diameter, the easier it is to bring about the detonation, and the faster the steady state is attained. It should nevertheless be pointed out that the threshold of the initiation of the reaction does not intervene in this model simultaneously with the radius of the grain, as may be assumed on the basis of experiments.

Three calculations were carried out for grain sizes of 50, 100 and 140 μ, for the case of grain-burning. The results are shown on diagrams 1 ($R = 140\ \mu$), 4, 5 and 6.

If we consider the experimental results in greater detail, the progress diagram of the shock front exhibits two important characteristics:

-- The acceleration takes place from the moment of impact;

-- There is an abrupt change in this acceleration.

The above calculations do not lead to these results. The law of reaction inspired by grain-burning expresses only the first of these characteristics, while the law inspired by holeburning expresses only the second.

To obtain the acceleration of the shock front from the moment of impact, it is necessary that the reaction be initiated from this moment to a non-negligible extent. This is realized by the use of a gradual law of energy liberation, for example, a linear law as a function of the pressure, which is more gradual than any exponential law.

The abrupt change of acceleration can be conceived only if an abrupt excess pressure appears behind the shock front. This excess pressure can be produced only by the arrival of a train of compression waves (or a second shock) which, arising in the already perturbed explosive zone between the impact surface and the front of the first shock, overtakes the latter.

This is the explanation given for interpreting the experimental results obtained with the homogeneous explosives where it is assumed that the second shock arises at the barrier-explosive interface (see preceding chapter).

However, in the case of the granular explosives, the second shock ought to be propagated in a medium which has already strongly reacted -- the progress diagram (x, t) of the initial shock shows an acceleration from the moment of impact. Moreover, the reaction, after the passage of this wave train, does not have to be complete, since the velocity of the steady detonation state is attained only gradually, and by a lower value after the slope discontinuity of the progress diagram.

In order not to obtain excess velocity -- as in the case of the homogeneous explosives -- before the establishment of the steady detonation state, we have been led to believe that it is in the vicinity of the initial shock front that the excess pressure is brought about abruptly. Accordingly this would be provoked by an abrupt liberation of chemical energy, and hence would correspond to a jump in the evolution of the "reaction." This abrupt liberation of energy may be accepted if we remember that several reactions are involved, and that the chemical kinetics of the whole phenomenon is not known.

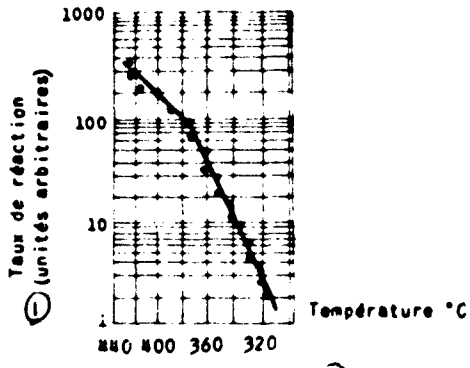
This assumption is strengthened by the following observations:

-- The examination of the decomposition of metal nitrides has revealed an abrupt variation of the reaction rate as a function of temperature [1].

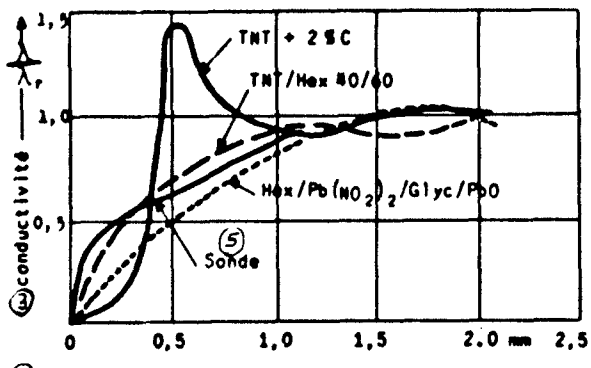
-- The study of electric conductivity in the reaction zone of various granular explosives (detonation in steady state) reveals notable differences in the form of the electric signal recorded. The observations make one assume that the appearance of ionization is intimately linked with the chemical reaction. The deviations seem to be due to the differences with respect to the mechanism of reaction, with the transitory appearance of intermediary products, related to the physical-chemical properties of the explosive in question, while the

determination of the detonation characteristics with the aid of the hydrodynamic theory, where it is assumed that a thermodynamic equilibrium has been achieved, only considers the final products [13].

-- The behavior of certain explosives where a state of "low order detonation" is established, gives rise to the belief that the liberation of chemical energy is capable of not being total under certain conditions, while still assuring a steady state [14].



d'après AUDUBERT - Réf 1 (2)



(4) d'après R. SCHALL et K. VOLLRATH. Réf 13

(1) - rate of reaction (arbitrary units); (2) - according to Audubert [1]; (3) - conductivity; (4) - according to R. Schall and K. Vollrath [13]; (5) - probe.

It follows from these remarks that the mechanism of the "reaction" depends on the explosive in question and varies during the evolution of all the chemical reactions which lead to detonation.

This explains why it is sometimes possible to observe, experimentally, an "overshoot" during the establishment of the steady state of detonation of certain explosives [10]. The ease with which the train of compression waves is transformed into a shock is greater when the intensity of the initial shock is lower -- a longer time for the establishment of this shock by the combination of the various compression waves which arise in a medium which has not reacted to a great extent. Hence the overshoot is greater when the initial shock is weaker (see Jacobs diagram, Chapter 4).

Hence the general case -- without overshoot -- requires the introduction of a discontinuity into the liberation of chemical energy in the vicinity of the shock front.

The use of an exponential law gives a good overall representation of a threshold state, but we have already seen that the "discontinuity" introduced in this fashion is much too abrupt to represent the real situation.

The use in the calculation, presented above, of a form function analogous to holeburning does entail a progressive acceleration of the reaction in proportion to its state of advance, but the slope discontinuity obtained in this way is small, while the shock propagates during the first moments as an inert shock.

While a combination of the two laws of reaction, having the form

$$\frac{dm}{dt} = \frac{3a}{R}\left[k_1 m^{\frac{2}{3}} + k_2 (1 - m)^{\frac{2}{3}}\right] (p - p_1)$$

indeed furnishes both the acceleration from the moment of impact and the velocity jump obtained experimentally, these two characteristics are much too attenuated to permit us to consider this law of chemical kinetics satisfactory. In effect, each mode of reaction weakens the peculiarity contributed by the other. In this equation coefficients k_1 and k_2 would represent the percentages of each of the two geometric forms, values linked to the charge density of the explosive.

Calculation leads to the following result: The pressure gradually rises, in the course of time, in the zone perturbed by the shock, while at a given instant the pressure maximum is situated either at the target/projectile interface or immediately behind the shock front, depending on the relative values of k_1 and k_2. In all cases the deviation is small, and the progress diagram of the shock front is intermediate between those obtained above for each of the two modes of reaction (by grain or by hole).

In view of the lack of success with these different methods, we have chosen the model of grain-burning -- which furnishes the acceleration of the shock front from the moment of impact -- and the slope discontinuity in the progress diagram of the shock was obtained by the artificial introduction of a jump in the liberation of the chemical energy. This

jump was related to a threshold value of the pressure since at a given moment, the pressure is maximum in the vicinity of the shock front in this model (Diagram 7).

- Threshold of Initiation of Detonation:

Since the pressure threshold is made directly explicit in the equation of chemical kinetics, it is a known quantity. Hence the scheme presented here does not permit its theoretical determination.

- Initial Point of Release of the Detonation:

The experimental results show that the detonation is initially established, in the case of granular explosives, in the interior of the explosive and not on the impact surface as is the case for the homogeneous explosives.

The use of a very gradual reaction velocity makes it possible to bring about a sufficiently slow rise in the reaction rate so that the hydrodynamic equations may intervene in the course of the reaction. The gradual pressure rise on the impact surface of the explosive is slowed down by the perturbations produced by the equality of pressures which is established in this plane at all moments. These perturbations are constituted of a train of compression waves which propagate in the projectile, while the expansion waves propagate in the explosive.

The use of a law of chemical kinetics linked to the pressure then makes it possible to observe that the initial point of the complete reaction ($m = 1$) is not situated at the projectile/target interface but in the interior of the explosive.

This result is still sharply different from that yielded by Arrhenius' law where the first point of complete reaction is always situated on the impact surface of the explosive.

The explanation offered by various researchers of this phenomenon obtained by means of a frontal shock (barrier-receiver assembly) as being the consequence of expansion effects due to the edges of the cartridge of explosive is in agreement with the preceding results. Moreover this expansion is not the only one which intervenes, but we have to add to it that which rises from the barrier. Hence these two results bring about a decrease of pressure on the surface of entry of

the explosive, hence a decrease of the reaction rate, since we have linked the latter to the pressure. Hence the mathematical model proposed here makes it possible to explain this phenomenon.

A difficulty nevertheless persists, since, despite the use of a very gradual law of chemical kinetics, the distance separating the initial point of detonation (m = 1) from the surface of entry of the shock into the explosive is quite small, while experimentally the distance found is much greater.

To subject this problem to a strict treatment it would be necessary to take into account the two expansions indicated above. Then the phenomenon becomes two-dimensional non-stationary. We did not undertake this complex study with three variables.

However, the study of the progress diagram of the reactive shock front has shown us that to obtain a good agreement between theory and experiment it is necessary to introduce a discontinuity in the chemical kinetics. This considerably facilitates then the obtainment of the initial point of detonation in the interior of the explosive, at a considerable distance from the impact surface (diagrams 7 and 8).

From the initial point of complete reaction the end reaction front propagates toward the shock front and then reduces the thickness of the zone in the process of reaction until the establishment of the steady state.

If the explosive between the face of entry of the shock and the initial detonation front has reacted only slightly, which favors the use of a discontinuity in the liberation of chemical energy, the phenomenon of "retonation" is re-encountered on the theoretical level: an end reaction front propagates toward the face of entry. The wave associated with this phenomenon is called "retrograde" wave.

- Influence of the Intensity of the Pressure Signal:

The intensity of the pressure signal generated in the receptor explosive depends on the material of the projectile and the velocity of impact. Hence the modification of one of these two parameters makes it possible to vary the intensity of the pressure signal induced in the explosive target. We have chosen to modify the impact velocity by using a copper projectile.

Three calculations, giving respectively 65, 100 and 135 kb, have been carried out. They made it possible to verify (diagram 9) that the distance covered by the reactive shock without the establishment of the steady detonation state is greater when the pressure is lower. This steady state, attained in an asymptotic manner, does not permit a precise determination of the "induction period," but by contrast, the velocity jump in the progress diagram of the reactive shock is easier to demonstrate.

These results are in rather good agreement with the experimental results [3] since they furnish a gradual variation of this "induction period," in contrast to Arrhenius' law which leads to a pressure threshold below which detonation does not take place, and above which the time of establishment of the detonation is almost independent of the initial conditions.

A calculation was attempted for an induced pressure of 180 kb: numerical instabilities prevented us from carrying out this study successfully. A grid more compact in space and time for the solution of the equations with finite differences should permit solving this difficulty, but this kind of modification was not undertaken since it would lead to very lengthy periods of machine calculation.

- Influence of the Duration of the Pressure Signal

The experimental studies on the duration of the pressure signal as a function of the thickness of the projectile have revealed in the case of aluminum that the decay of the shock takes place much sooner in space and time than could be predicted by the hydrodynamic theory [6]. To explain this phenomenon it is suggested that the elasto-plastic behavior of the material constituting the projectile cannot be neglected. To our knowledge, analogous experiments have not yet been carried out on copper, and it is possible that the hydrodynamic theory, too, is deficient.

In the theoretical study which we have undertaken we did not take into account this characteristic, and we have assumed that the projectile behaves like a fluid. On the other hand, the use of a law of chemical kinetics which is a gradual function of the pressure does not permit stopping the reaction even when a beam of expansion waves rises in the perturbed products. The reaction is slower, but it leads inexorably to the detonation except if the pressure becomes less than 20 kb, the threshold which we have chosen for its initiation.

On Diagram 10 are plotted the results obtained for the two projectiles launched at the same velocity (800 m/sec) but having different thicknesses: 1 and 3 mm, respectively. At the start of the phenomenon, the two curves coincide (0.5 μsec on the diagram), since the beam of expansion waves which rises in the projectile has not yet attained the interface. They separate at around 0.6 μsec, and those obtained for the projectile of 1 mm thickness show that the expansion is much greater at the interface than in the interior of the explosive. At 2 μsec the detonation develops, leading to the steady state in the case of the 3 mm projectile, while at no point did the reaction rate (m) attain the value of 1 in the case of the 1 mm projectile.

- Influence of the Initial Temperature

To determine whether the proposed model is sensitive to the initial temperature conditions of the explosive, two calculations were carried out. We assumed that before impact, the explosive had an initial temperature of 300°K in one case, 350°K in the other. The constants of the equation of state of the inert explosive were not modified for such a small temperature variation since at the present time it is impossible to distinguish experimentally between the two dynamic adiabatics corresponding to the initial conditions of 300°K and 350°K.

The results of the calculation are very similar, and exhibit no experimental dispersion. As a result, in this scheme, the temperature is only of slight importance which is quite different from the result obtained by Arrhenius' law. Thus the agreement with the experimental results is quite satisfactory [3].

- Study of the Steady State of Detonation

The preceding model is still valid when the stable state of detonation has been established. Hence it furnishes a schematic representation of the reaction zone.

In the first place it should be noted that the values of the detonation characteristics in the Chapman-Jouguet (C.J.) plane are not re-encountered exactly by machine calculation. In particular, the detonation velocity is considerably greater (by about 20%) that that calculated directly by means of the hydrodynamic equations. The C.J. point itself is slightly displaced in the (p, v) plane with respect to the theoretical values. It is possible that this is due to the introduction of the pseudoviscosity as well as to the choice of numerical method itself (equations with finite differences).

The examination, in plane (p, v), of the behavior of the mixture of the explosive solid and detonation products during the reaction shows (diagram 11) that it starts from point H of the Hugoniot of the solid defined above, first increases in pressure, then decreases to attain finally the values which we have denoted as computed C.J. values, rather close to the theoretical C.J. conditions; this curve is intermediate between the adiabatic of the inert solid and the isentropic of the detonation products which passes through the C.J. point. It is to be regretted that few points are situated in the ascendant part of this curve as a result of the overly large Δx, Δt grid employed in the equations with finite differences.

It may be observed that the pressure maximum remains below the value of Von Neumann's peak. This is normal, since the shock is immediately reactive. A more dense grid would perhaps permit to reduce even further the pressure maximum obtained by this model.

The thickness of the reaction zone depends on the constants introduced into the law of chemical kinetics. With the values which we have chosen, it is of the order to one millimeter, the result of the order of magnitude of the currently assumed values. The choice of 0.1 mm which we have made for the Δx grid would hardly permit us to decrease notably the thickness of the reaction zone, but a more compact grid would assure this possibility.

5.3. CONCLUSION

The experimental study of the generation of detonation in a solid granular explosive has permitted us to derive a few simplifying assumptions for expressing this problem in the form of equations. The mathematical model prepared in this way furnishes results which are in rather good agreement with the experiments. Nevertheless, numerous experiments -- more accurate than those described here -- and more complex calculations will be necessary to illuminate fully this delicate problem of the hydrodynamics and chemical kinetics of explosive substances.

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Diagrams 1--11 are interrelated and the keys are numbered consecutively as follows:

Key: (1) - Generation of Detonation by Impact; (2) - Profile of the pressure signal in the explosive as a function of time; (3) - theoretical results; (4) - copper projectile; (5) - chemical kinetics; (6) - position of the impact surface at the initial moment; (7) - progress diagram of the reactive shock front; (8) - law of reaction inspired by holeburning; (9) - free surface; (10) - solid explosive; (11) - law of reaction inspired by grain-burning; (12) - detonation products; (13) - reactive shock front; (14) - end of reaction; (15) - retrograde detonation, or "retonation"; (16) - regardless of the value of p; (17) - variation of the reaction rate; (18) - identical to that mentioned on diagram 7, reference [2]; (19) - effect

of the intensity of the pressure signal; (20) point where the velocity discontinuity is situated; (21) - initial point of the establishment of the steady state of detonation; (22) - study of the steady state of detonation; (23) - Von Neumann's Peak (theoretical); (24) - mixture; (25) - gas; (26) - machine calculation; (27) - theoretical; (28) - dynamic adiabatic of the solid explosive without chemical reaction (machine calculation); (29) - isentropic originating from H of the solid explosive without chemical reaction (machine calculation).

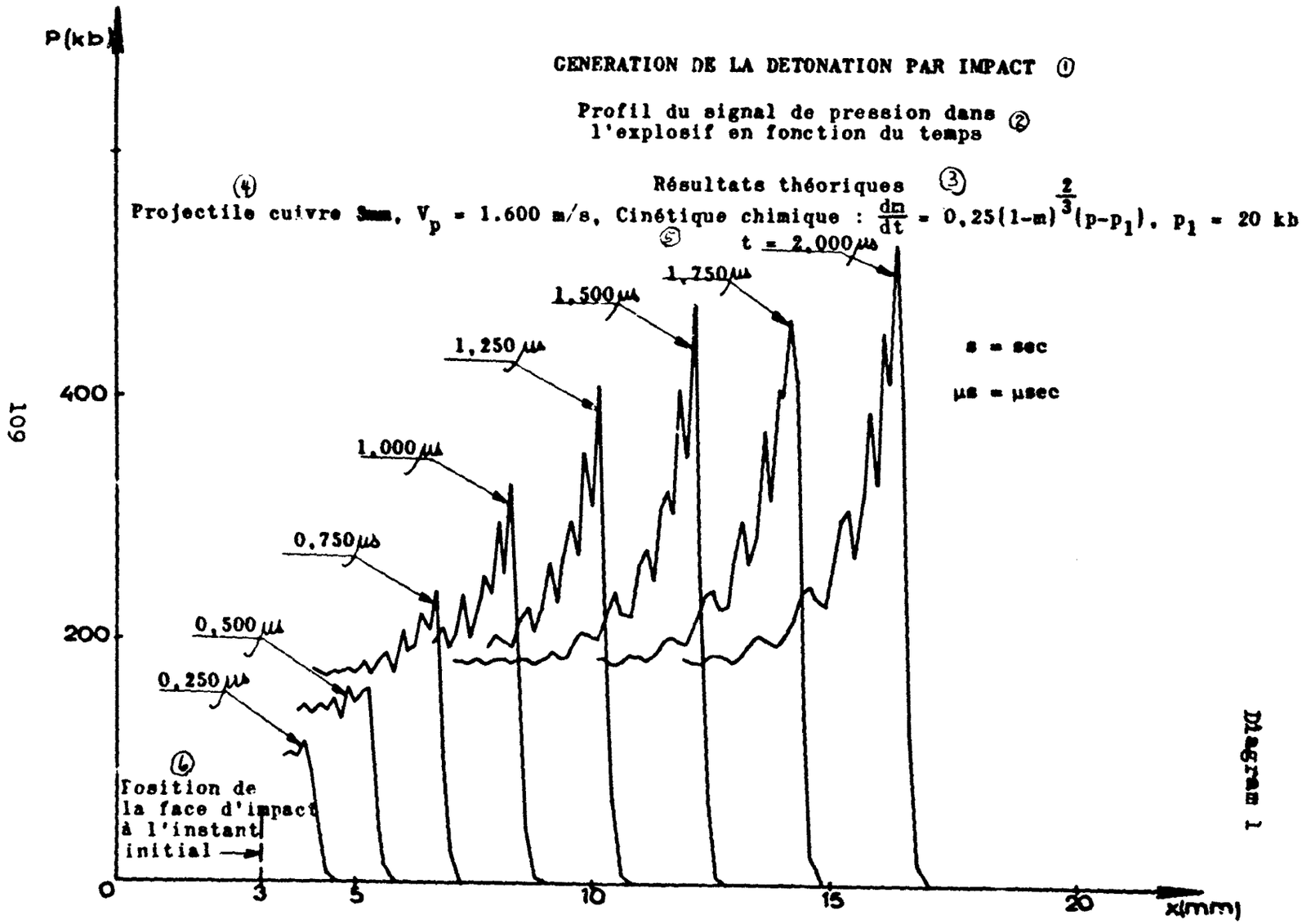

P(kb)
GENERATION DE LA DETONATION PAR IMPACT ①
Profil du signal de pression dans ② l'explosif en fonction du temps
Résultats théoriques ③
④ Projectile cuivre 3mm, V_p = 1.600 m/s, Cinétique chimique : $\frac{dm}{dt} = 0,25(1-m)^{\frac{2}{3}}(p-p_1)$, p_1 = 20 kb
⑤
t = 2,000 µs
1,750 µs
1,500 µs
1,250 µs
1,000 µs
0,750 µs
0,500 µs
0,250 µs
s = sec
µs = µsec
400
200
0
109
⑥ Position de la face d'impact à l'instant initial
3
5
10
15
20
x(mm)

Diagram 1

GENERATION DE LA DETONATION PAR IMPACT (1)

Profil du signal de pression dans l'explosif en fonction du temps (2)

Résultats théoriques (3)

Projectile (4) cuivre 3 mm, V_p = 1.600 m/s, Cinétique chimique (5) : $\frac{dm}{dt} = 0{,}25\ m^{\frac{2}{3}}(p-p_1)$, p_1 = 20 kb

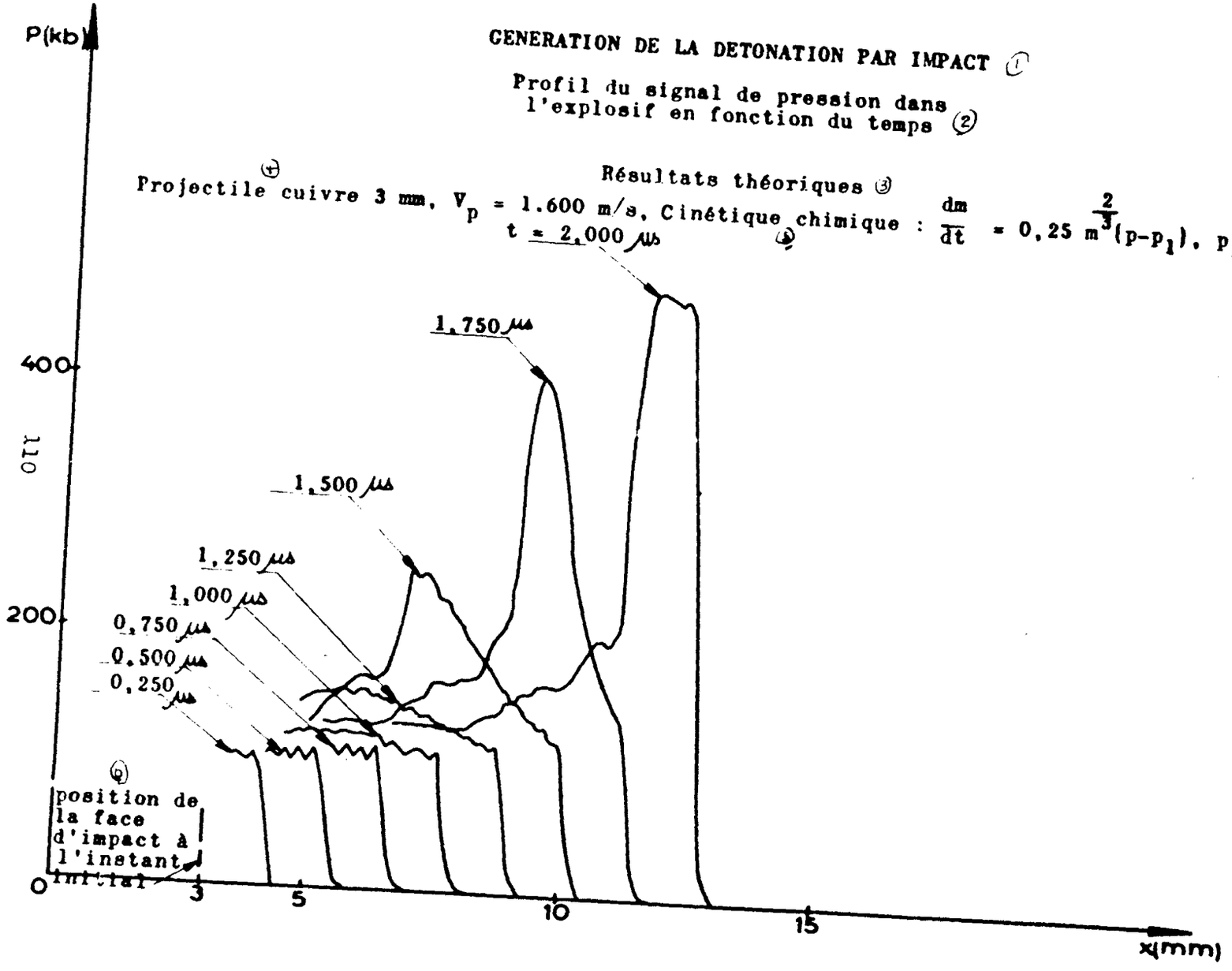
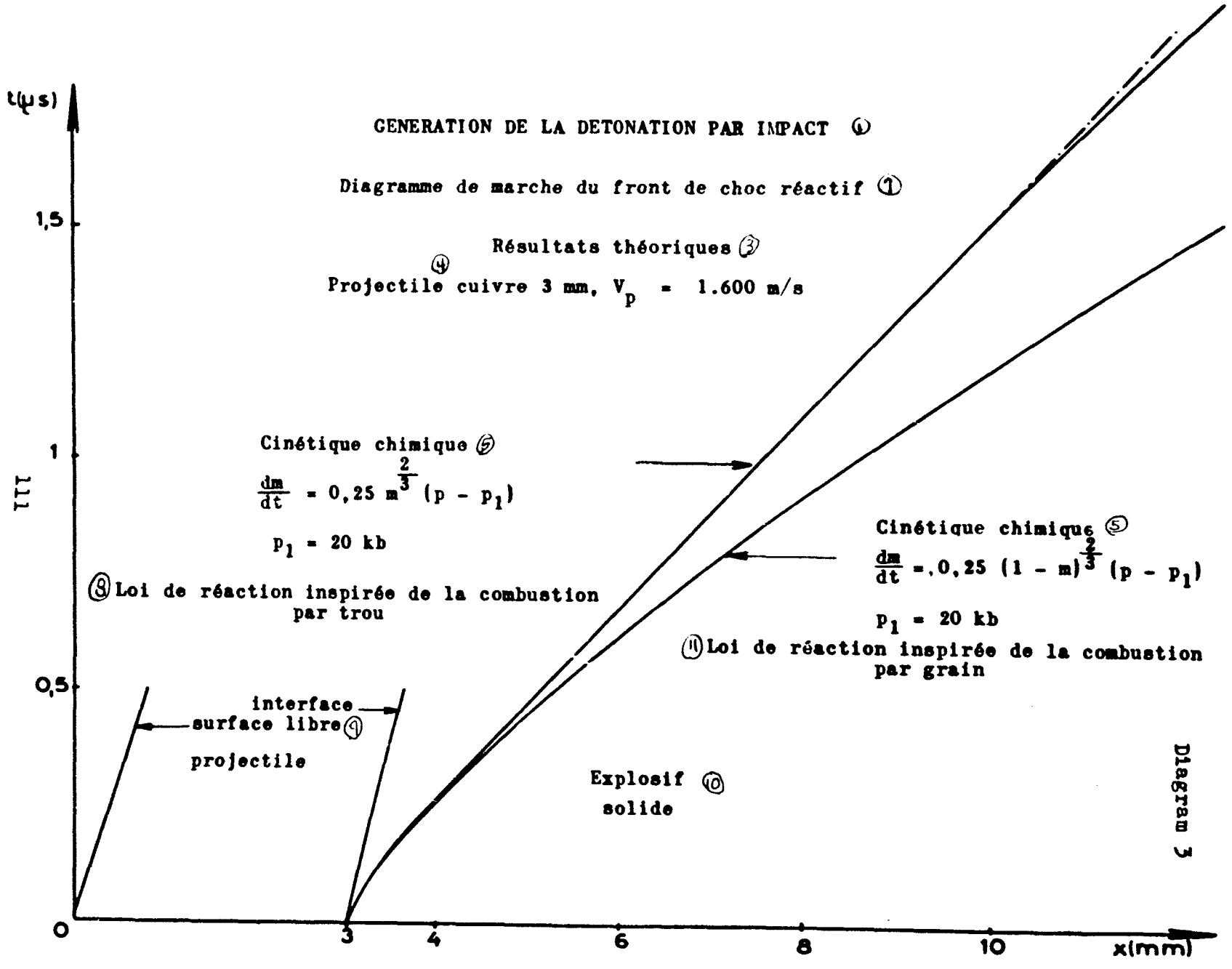


Diagram 2


GENERATION DE LA DETONATION PAR IMPACT ⑥
Diagramme de marche du front de choc réactif ①
Résultats théoriques ③
④ Projectile cuivre 3 mm, V_p = 1.600 m/s
t(μs)
1,5
1
0,5
0
111
Cinétique chimique ⑤
$\frac{dm}{dt} = 0,25\ m^{\frac{2}{3}} (p - p_1)$
p_1 = 20 kb
⑧ Loi de réaction inspirée de la combustion par trou
Cinétique chimique ⑤
$\frac{dm}{dt} = 0,25\ (1 - m)^{\frac{2}{3}} (p - p_1)$
p_1 = 20 kb
⑪ Loi de réaction inspirée de la combustion par grain
interface
surface libre ⑨
projectile
Explosif ⑩
solide
3
4
6
8
10
x(mm)
Diagram 3

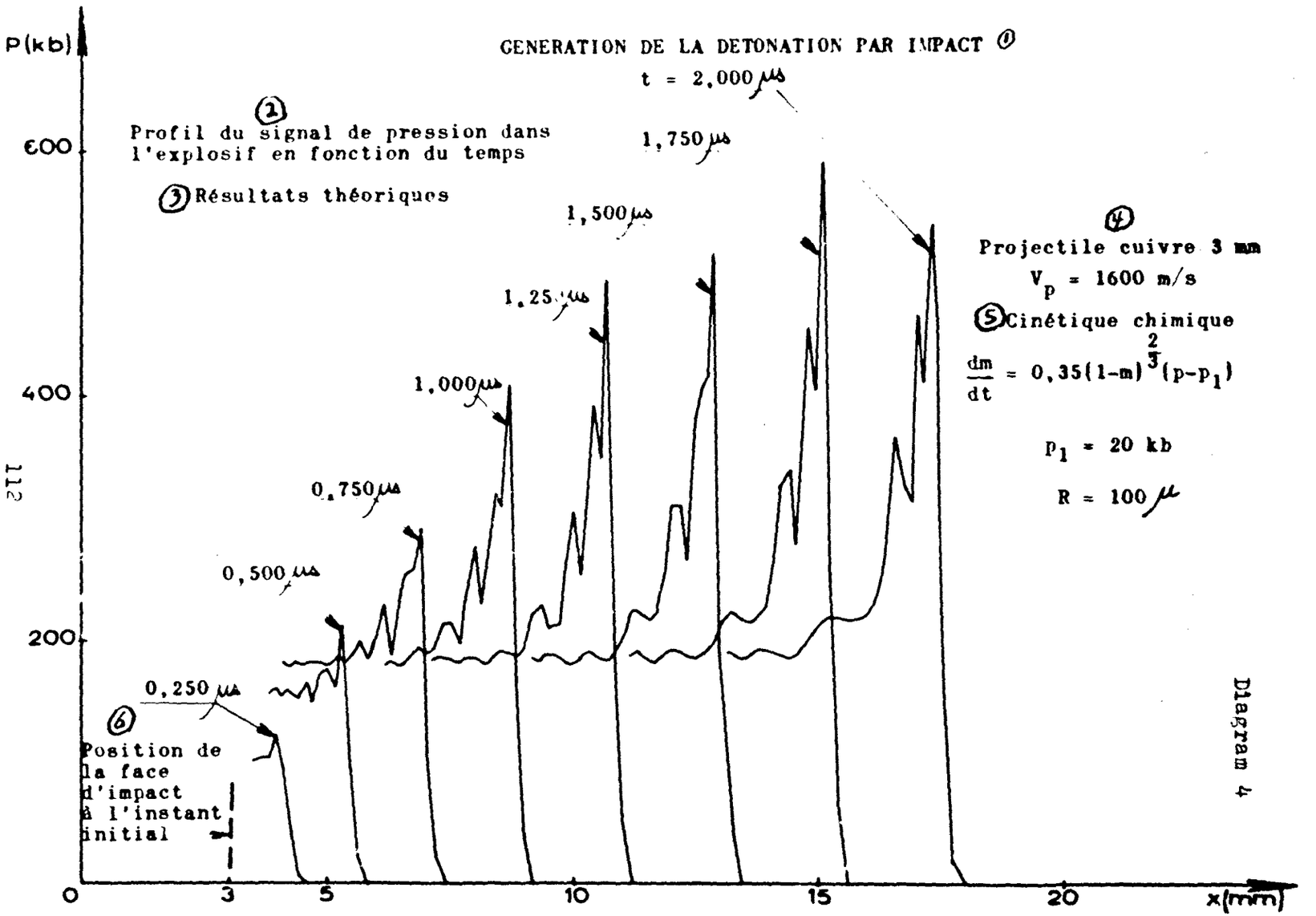

P(kb)
GENERATION DE LA DETONATION PAR IMPACT ①
t = 2,000 µs
1,750 µs
1,500 µs
1,25 µs
1,000 µs
0,750 µs
0,500 µs
0,250 µs
② Profil du signal de pression dans l'explosif en fonction du temps
③ Résultats théoriques
④ Projectile cuivre 3 mm
V_p = 1600 m/s
⑤ Cinétique chimique
$\frac{dm}{dt} = 0,35(1-m)^{\frac{2}{3}}(p-p_1)$
p_1 = 20 kb
R = 100 µ
⑥ Position de la face d'impact à l'instant initial
600
400
200
0
3
5
10
15
20
x(mm)
112

Diagram 4

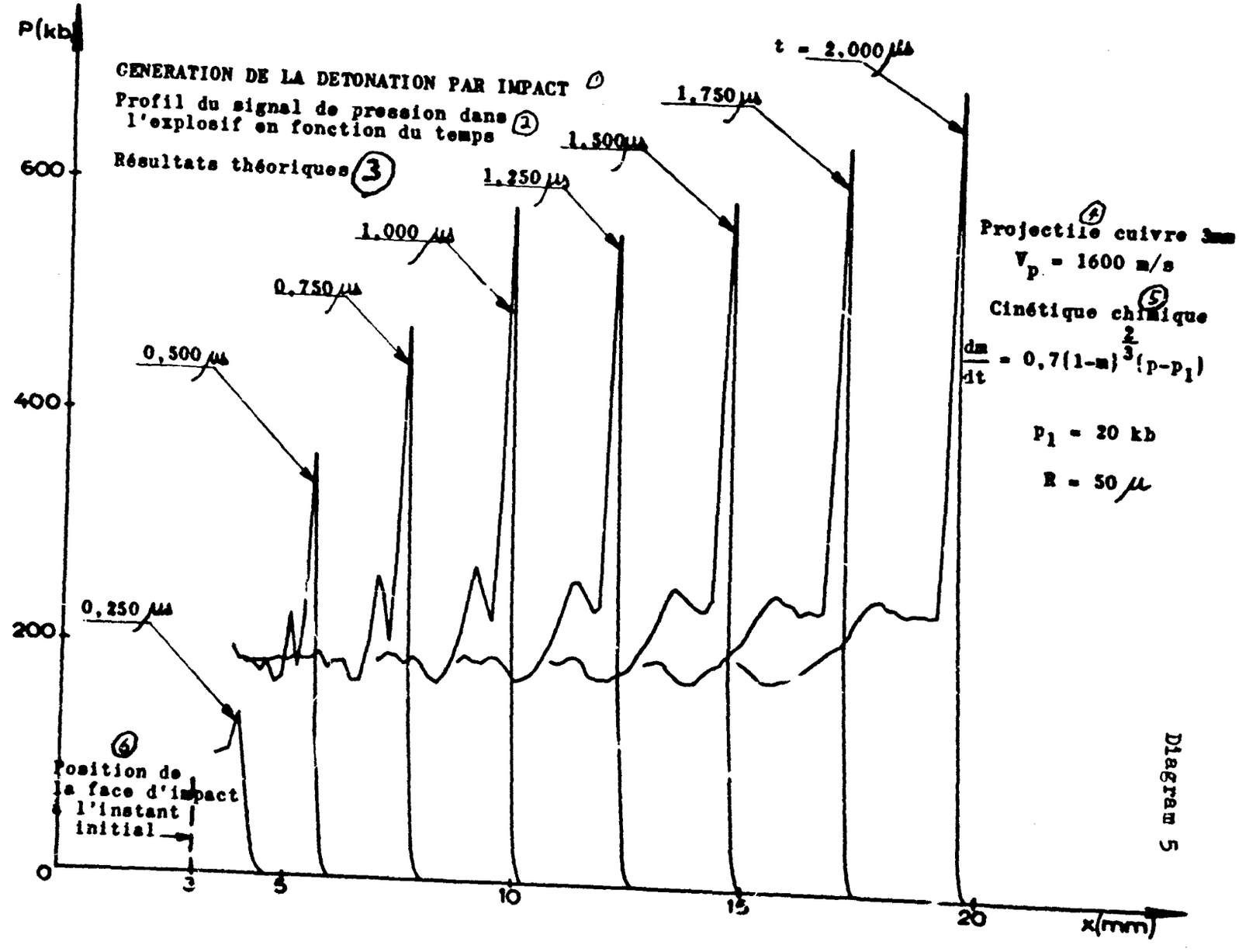

P(kb)
600
400
200
0
GENERATION DE LA DETONATION PAR IMPACT (1)
Profil du signal de pression dans l'explosif en fonction du temps (2)
Résultats théoriques (3)
0,250 µs
0,500 µs
0,750 µs
1,000 µs
1,250 µs
1,500 µs
1,750 µs
t = 2,000 µs
Projectile cuivre 3mm (4)
V_p = 1600 m/s
Cinétique chimique (5)
$\frac{dm}{dt} = 0,7(1-m)^{\frac{2}{3}}(p-p_1)$
p_1 = 20 kb
R = 50 µ
(6) Position de la face d'impact à l'instant initial
3
5
10
15
20
x(mm)

Diagram 5

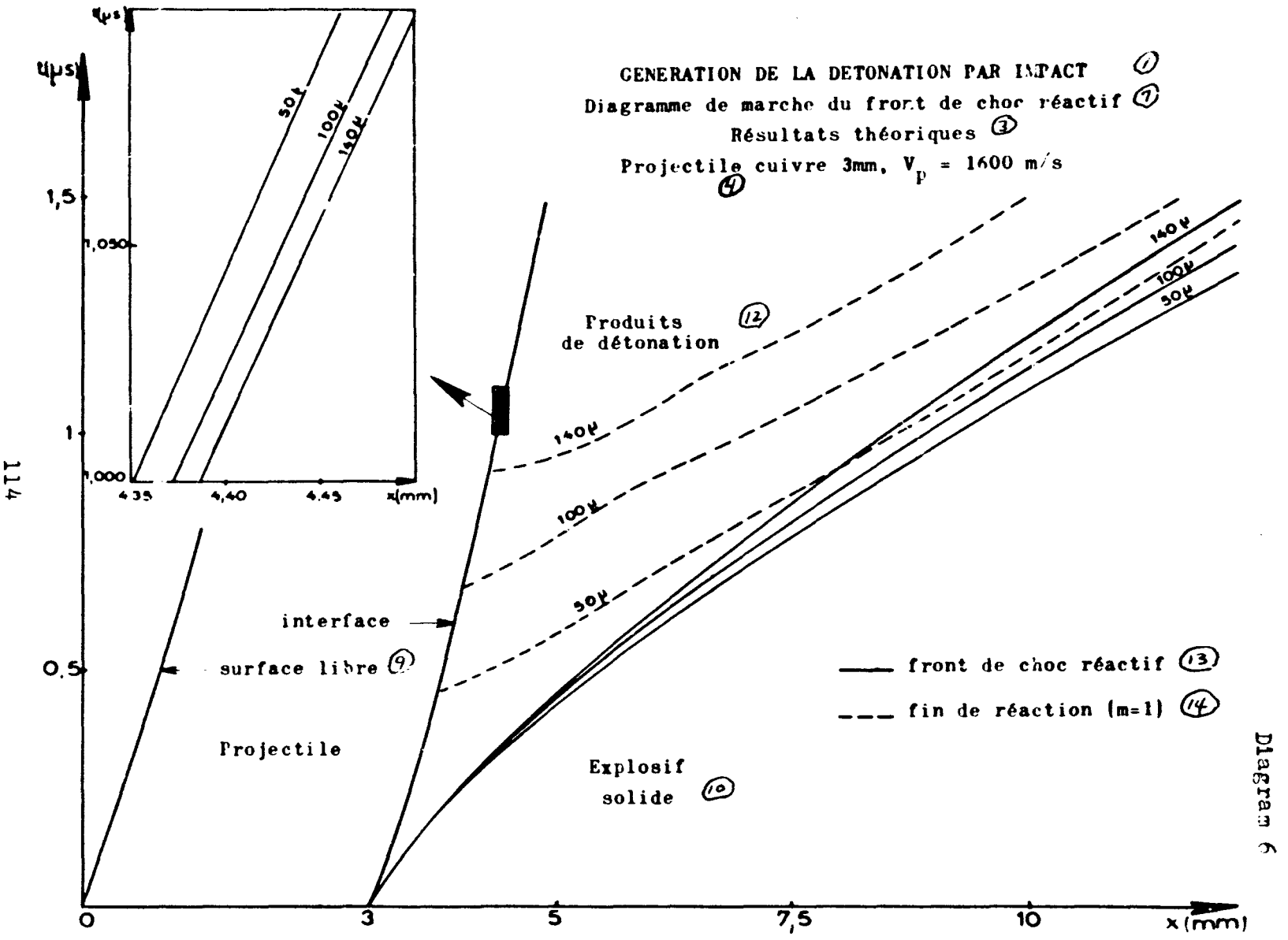

GENERATION DE LA DETONATION PAR IMPACT (1)
Diagramme de marche du front de choc réactif (7)
Résultats théoriques (3)
Projectile cuivre 3mm, V_p = 1600 m/s (4)
Produits de détonation (12)
140 µ
100 µ
50 µ
interface
surface libre (9)
Projectile
Explosif solide (10)
front de choc réactif (13)
fin de réaction (m=1) (14)
µs
1,5
1,050
1
1,000
0,5
0
3
5
7,5
10
x (mm)
4,35
4,40
4,45
x(mm)

Diagram 6

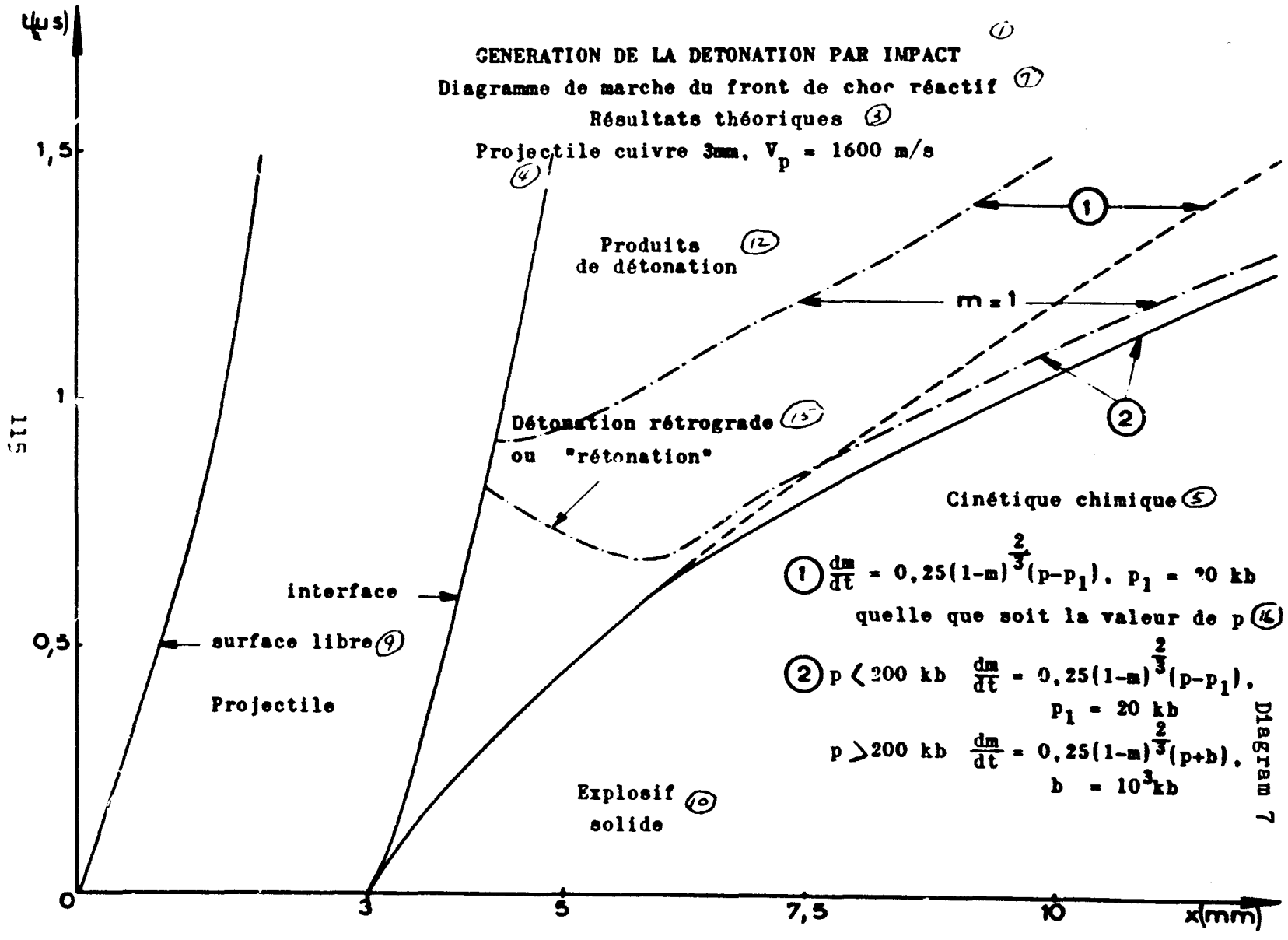

GENERATION DE LA DETONATION PAR IMPACT
Diagramme de marche du front de choc réactif
Résultats théoriques
Projectile cuivre 3mm, V_p = 1600 m/s
t(µs)
1,5
1
0,5
0
3
5
7,5
10
x(mm)
Produits de détonation
m = 1
1
2
Détonation rétrograde ou "rétonation"
Cinétique chimique
(1) $\frac{dm}{dt} = 0,25(1-m)^{\frac{2}{3}}(p-p_1)$, p_1 = 20 kb quelle que soit la valeur de p
(2) p < 200 kb $\frac{dm}{dt} = 0,25(1-m)^{\frac{2}{3}}(p-p_1)$, p_1 = 20 kb
p > 200 kb $\frac{dm}{dt} = 0,25(1-m)^{\frac{2}{3}}(p+b)$, $b = 10^3$ kb
interface
surface libre
Projectile
Explosif solide

Diagram 7

GENERATION DE LA DETONATION PAR IMPACT (0)

Evolution du taux de réaction. (17)

Résultats théoriques (3)

Projectile cuivre (4) 3mm, V_p = 1600 m/s, Cinétique chimique (5) : identique à celle mentionnée (15) sur le graphique 7 sous la rubrique (2)

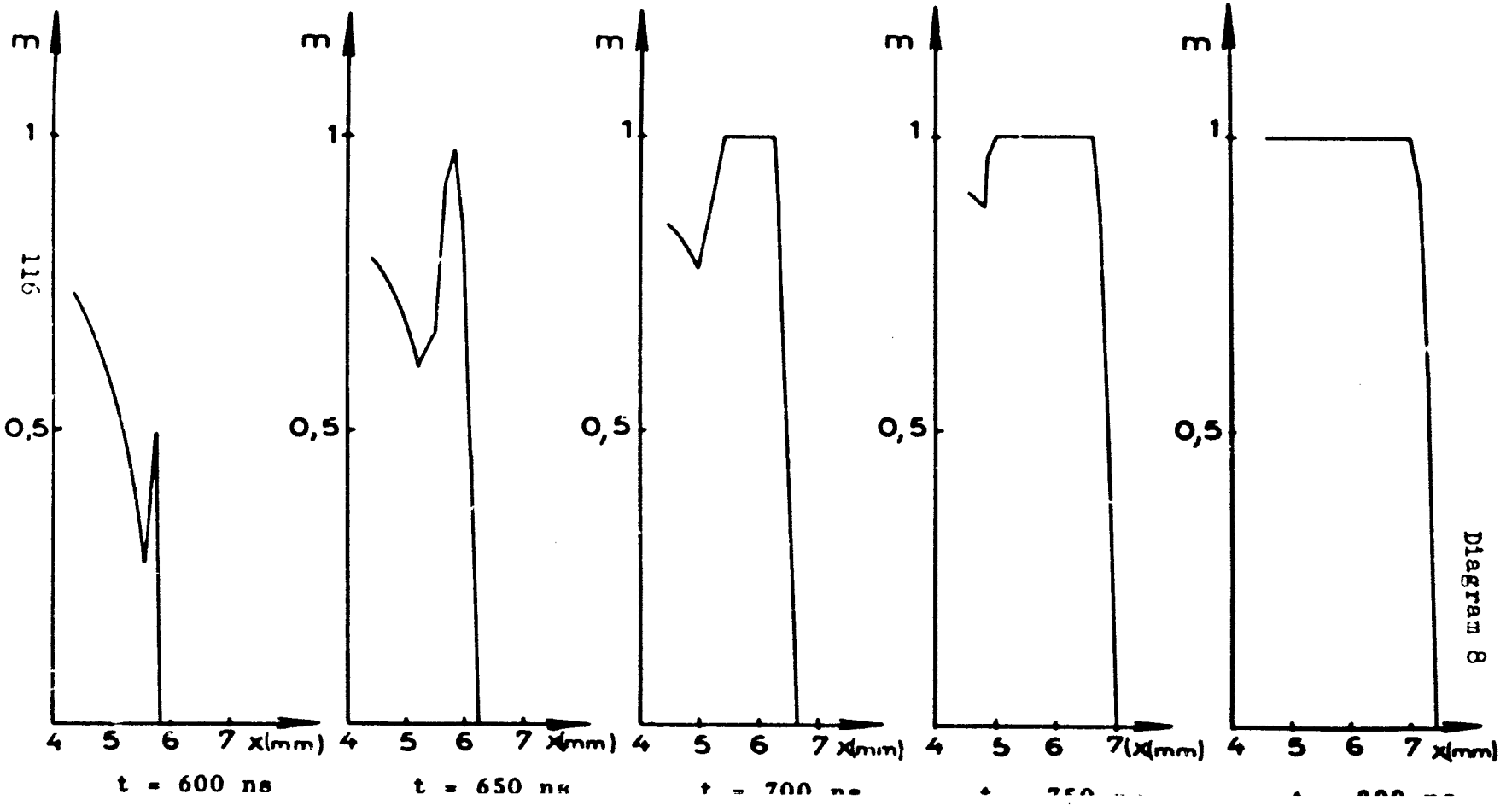
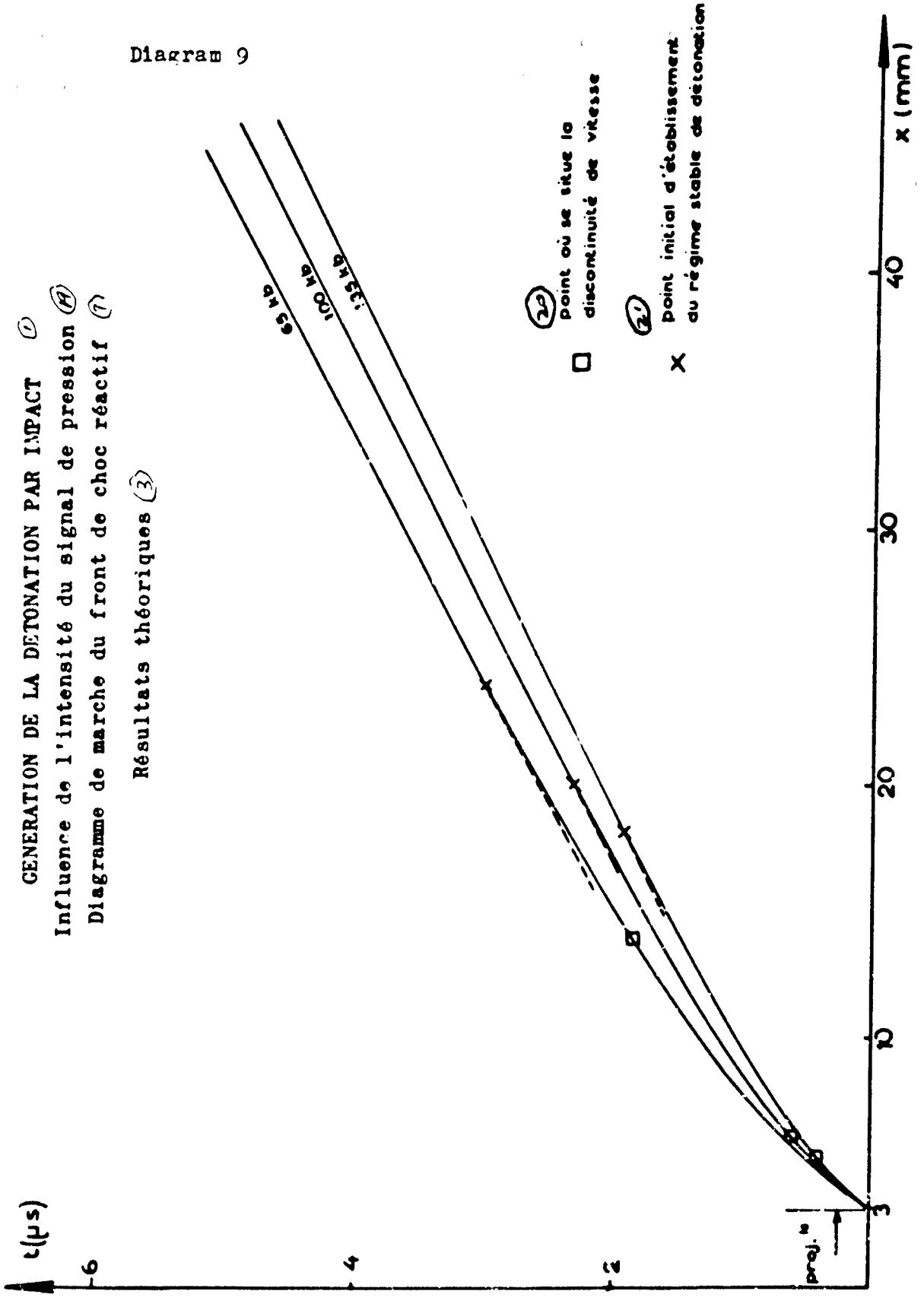


Diagram 9


GENERATION DE LA DETONATION PAR IMPACT (1)
Influence de l'intensité du signal de pression (4)
Diagramme de marche du front de choc réactif (7)
Résultats théoriques (3)
65 kb
100 kb
135 kb
(2) Point où se situe la discontinuité de vitesse
(2') Point initial d'établissement du régime stable de détonation
t(μs)
x (mm)
6
4
2
3
10
20
30
40
proj.

GENERATION DE LA DETONATION PAR IMPACT (1)
Evolution du taux de réaction (17)
Résultats théoriques (3)

Projectile cuivre V_p = 800 m/s (4) Cinétique (5) chimique identique à celle du graphique 7 référence (2) (18)

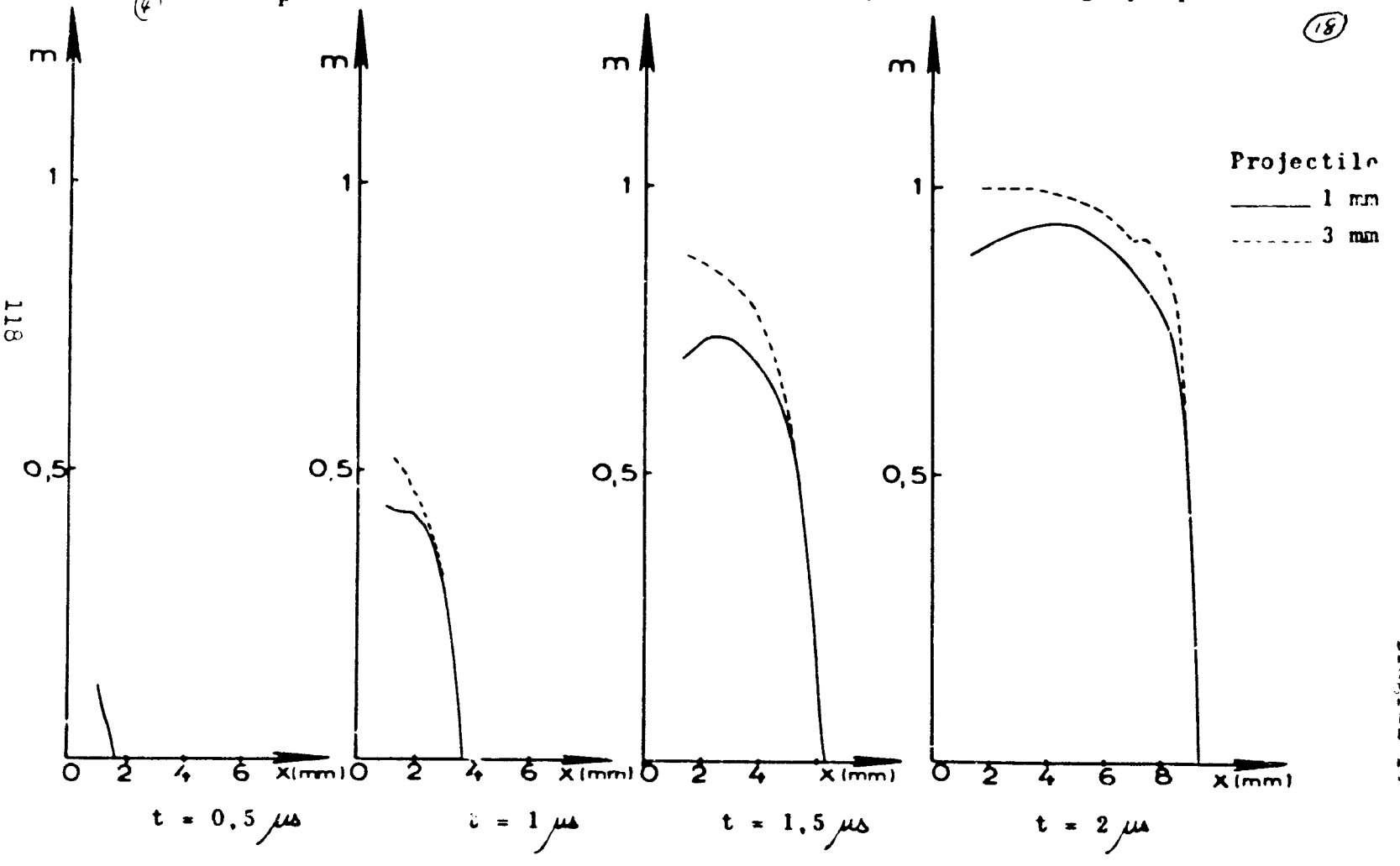


Diagram 10

GENERATION DE LA DETONATION PAR IMPACT (1)
Etude du régime stable de détonation (2)
Résultats théoriques (3)

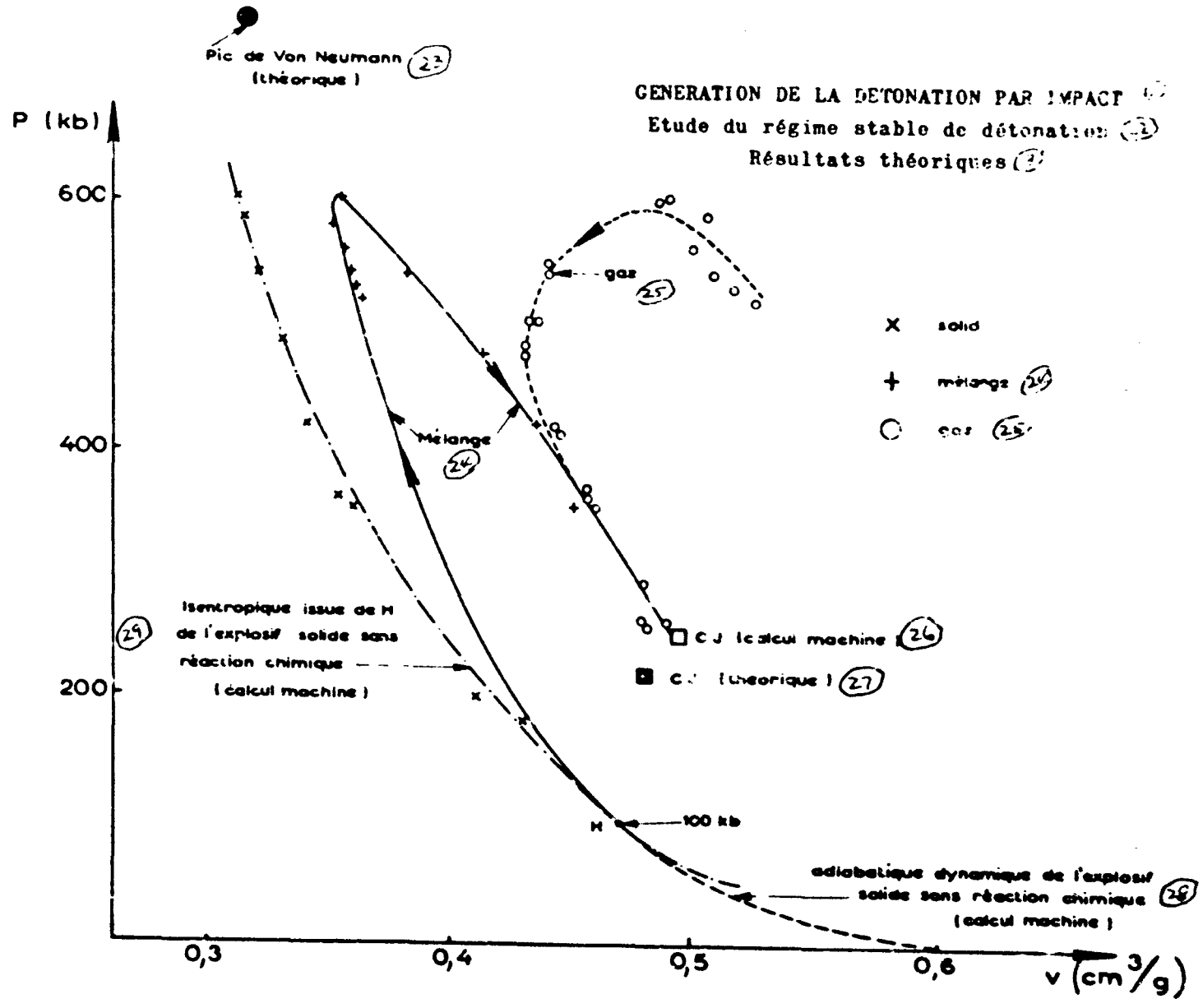


Diagram 11

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1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Picatinny Arsenal, Dover, N. J.	Unclassified
	2b. GROUP

3. REPORT TITLE

CONTRIBUTION TO THE STUDY OF THE INITIATION OF DETONATION PRODUCED BY IMPACT ON AN EXPLOSIVE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Translation of a French doctoral dissertation published as Report CEA R2497 by the Commissariat a l'Energie Atomique.

5. AUTHOR(S) (Last name, first name, initial)

Bernier, Henri

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1966	121	

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	Technical Translation 9
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
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The initiation of detonation by impact on an explosive is described and discussed in detail. The differences in behavior of homogeneous and heterogeneous explosives are delineated and discussed. A mathematical model is proposed which provides results agreeing rather well with the results of an experimental study of the generation of detonation in a solid granular explosive. A critical examination of various theoretical studies of the initiation of detonation by shock wave is included.

DD FORM 1 JAN 64 1473

UNCLASSIFIED
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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Explosives						
Detonation						
Homogeneous explosives						
Heterogeneous explosives						
Solid granular explosive						
Shock wave detonation						
Impact detonation						
Hydrodynamic equations						
Deflagration						
Shock generator						
Equation of state						
Chemical kinetics						

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