INITIATION OF EXPLOSIVES: A MULTI-LAYERED PROBLEM IN DETONATION PHYSICS

Initiierung von Sprengstoffen, ein vielschichtiges Problem der Detonationsphysik

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EXPVA

INITIATION OF EXPLOSIVES: A MULTI-LAYERED PROBLEM IN
DETONATION PHYSICS

DR. M. HELD

10 Years of the Schrobenhausen Works

These days the Schrobenhausen Works of Bölkow-Apparate-
bau GmbH is celebrating its tenth anniversary. These ten years
are so closely tied to the activities of its founder, Dipl.-Ing
Franz Rudolf Thomanek, that we will introduce him here, along
with the Works, to those readers who do not yet know him.

Born in Vienna, Thomanek was 55 years old on July 17, 1968. His interest in rocket technology and space travel started early. At 17 he came to know Oberth, von Pirquet and Zwerina, became a member of the Verein für Raumschifffahrt [Space Ship Travel Association] e.V., Berlin, organized the first exhibition of the Oberth liquid fuel rocket at the Vienna Exposition, and became a founding member of the board of the Austrian Society for Rocket Technology.

In 1931 he began his studies of technical physics at the Technical University in Vienna. When he ran into the description of the shaped-charge effect in 1932, it was to become a decisive influence on his whole life. He decided to apply this effect to tank warfare, and designed his one-man 70 mm anti-tank gun, the first shaped-charge weapon in the world.

This weapon was built after surmounting great difficulties, and he presented it in 1935 to the government of the German Reich and the heads of the Wehrmacht. In spite of this successful demonstration, it took five more years until his ideas were applied practically. In the meantime, Thomanek studied experimental and theoretical ballistics at the Technical University in Berlin, as well as studying explosive chemistry with Cranz, Rothe and Poppenberg. In 1938, at the German Research Facility for Air Travel in Braunschweig, he discovered
the liner effect. After his activities at the Ballistics Institute of the Air War Academy in Gatow, with Prof. Schardin, in 1940 he founded the Sprengstoff-Versuchsgesellschaft m.b.H. (Explosive Experimentation Company) in Berlin and Kaufbeuren for the development and production of shaped charges.

The end of the war interrupted Thomanek's work in the area of shaped-charge research and explosive physics. In 1957, answering Ludwig Bölkov's invitation, he began work again. He looked for a suitable factory, and in 1958 found it in Schrobenhausen. This factory, built in 1939 for the production of pentaerythritol by Montan GmbH, covering roughly 46 ha, served for a time as a refugee camp after being dismantled in 1946.

Its spread-out layout and its self-enclosed position in an extensive forest are combined favorably to allow placement of laboratories, production buildings and test facilities together in the same place. On May 28, 1958, work began under these conditions, in a very limited way.

In the subsequent years, with his initiative, his style of leadership and his experience, Thomanek created today's Schrobenhausen Works with the largest and most significant group of specialists in terminal ballistics and explosive physics in Germany. The facilities and equipment, some of which are unique, have made it possible to provide significant contributions to defense above and beyond shaped-charge technology.
Today Thomanek is a partner and manager of Bölkow Apparatebau GmbH, as well as a deputy manager of Bölkow GmbH. In addition to his work with the Bölkow group, in the last few years he has expended increased effort on his scientific successors in the field of weapons technology. Since 1966, at the Munich Technical University, he has given the only lecture course in West Germany on "Introduction to Ballistics."

Today, ten years after its founding, Thomanek's influence extends far beyond the Schrobenhausen Works. Nevertheless, his colleagues hope and wish that in the coming years, just as before, he will remain the motor behind the factory.

Dr. Manfred Held
Initiation of Explosives: A Multi-Leveled Problem in Detonation Physics

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1. Induction

The following will treat the induction or the excitation of a more or less continuous process, a process about which not much is known. By the process we mean here the detonation of solid (especially military) high-energy explosives such as TNT, hexogen and octogen and their mixtures.

The induction of detonation, or the excitation of explosive charges to undergo detonation-type decomposition is called "initiation."

The first part discusses the general theory of initiation, and the second part reports on results and peculiarities in the initiation of explosive charges, as found at Schrobenhausen during the handling of various kinds of projects.

2. Physical and Chemical Concepts
2.1 Detonation

In order to describe the induction of detonation, it is necessary to review in general terms the current status of detonation theory.

Detonation is a shock wave with a subsequent reaction, where the energy of the reaction continuously maintains the shock wave (Fig. 1).

Fig. 1 Characteristics of a detonation

Key:  
a. shock wave  
b. reaction energy  
c. reaction  
d. the following are characteristics for:  
e. velocity  
f. pressure level  
g. pressure variation  
h. molecular transformation  
i. size  
j. temporal release
Thus for a detonation-type decomposition, three things are necessary. The shock wave, which triggers a reaction. A reaction by itself, however, is not sufficient; rather, positive reaction energy must be available quickly enough to maintain the shock wave.

The individual steps of molecular transformation and reaction energy release are not known. It is only known that the so-called "gross energy conversion" of the reaction is a determining factor for detonation. The shock wave is characterized by its velocity, pressure level and pressure behavior; the reaction is characterized by the transformation of molecules, and the reaction energy is characterized by its size and temporal release of energy.

The time variation of pressure in pressure impulses is not included in the physical representation of the shock wave. But for initiation by means of a shock wave, the variation of pressure plays a significant role (Fig. 2), especially when reaction times are short. This fact is often overlooked.

The transformation of a hexogen molecule is shown in a purely schematic manner in Figure 3.

Figure 4 shows the reaction energy or energy gain when a molecule decomposes.

The molecule—shown here as a ball—must be raised to a somewhat higher energy level, so that the energy stored
Fig. 2 Shock wave and its mathematical-physical description

\[ \begin{align*}
U & \text{ = shock wave velocity} \\
u & \text{ = material velocity} \\
p^0 & \text{ = initial density} \\
p & \text{ = density behind the shock front} \\
P & \text{ = initial pressure} \\
P^0 & \text{ = shock wave pressure} \\
e & \text{ = internal energy behind the shock front} \\
e^0 & \text{ = internal energy in front of shock front} \\
Q & \text{ = heat of reaction}
\end{align*} \]

Key: 
- a. conservation of mass
- b. conservation of momentum
- c. energy equation
- d. from (1) and (2) one gets:
Fig. 3 Schematic transformation of a hexogen molecule.

Fig. 4 Diagram of activation.

Key:  

a. activation energy  
b. energy gain (heat of reaction)
in it—the potential energy of the ball—can be released. The energy gain or heat of reaction is equal to the difference between the total energy released and the activation energy applied.

Segment L in Figure 5, the reaction zone in which the basic processes of molecular excitation and molecular transformation occur, is not needed, and is therefore completely neglected. Here

\[
\begin{align*}
    \rho_o &= \text{initial density of the intact explosive} \\
    D &= \text{detonation velocity} \\
    W &= \text{velocity of clouds of gas or smoke produced} \\
    P &= \text{pressure in these clouds} \\
    \rho &= \text{density in these clouds} \\
    Q &= \text{gross energy conversion}
\end{align*}
\]

Fig. 5 Stylized representation of reaction zone L
According to Wecken [1], the pressure variation, temperature variation and percentage transformation of molecules (degree of advancement of reaction) can be shown schematically approximately as in Figure 6.

![Diagram](image)

Fig. 6 Variation of degree of advancement of reaction $\lambda$, of pressure $P/P_{CJ}$ and of temperature $T/T_{CJ}$ along the length of the reaction zone.

Molecular transformation or the reaction occurs after a certain induction period, and then progresses relatively quickly. In the length of the reaction zone, pressure declines from the shock wave pressure of the intact explosive to the Chapman-Jouguet pressure. The shock wave pressure [2] in a gas is twice as high as the Chapman-Jouguet pressure. In the case of solid explosives a factor of 1.7 was found [3]. As yet no measurements are known for the development of the degree of advancement of reaction $\lambda$, pressure $P$ or temperature $T$ in the reaction zone.

Image converter pictures (Fig. 7) with extremely
Fig. 7 Image converter photo of a detonating explosive charge 4 mm wide, 50 mm high and 25 mm thick made of 60:40 hexogen-TNT, with a density of 1.70 g/cm$^3$.

Photos were taken with a Beckmann-Whitley image converter camera with a beam splitter (type 515 B), at the same time, with exposure times of 10 ns and 100 ns.

short exposure times yield no insight, even with 1:1 imaging.

The image quality is 0.1 mm, and the temporal blurring at 10 ns is ca. 0.08 mm. If one observes the edge zone, which appears more brightly luminescent in thicker layers, in Figure 7 one could draw in a shock front a few millimeters ahead of the first flecks of light. However, only the clouds of gas and smoke issuing from the surface of the explosive luminesce. It is assumed that the pressure on the surface is released so quickly that the crystals at the surface no longer react completely, and instead are flung off burning. The
grains are then fully burnt down in the gas/smoke clouds.

One also gets this impression from pictures of an explosive foil (Fig. 8) in which one can also see the luminescent shock wave clearly.

Fig. 8 Image converter photo of an explosive foil 3 mm thick, from Dynamit-AG (photography technique: see Fig. 7).

The "reaction" luminescence of the gas/smoke clouds starts later here at the edge than it does at the middle of the foil.

If one desired to treat the processes in the initiation of explosives, one would have to know the processes in
the reaction zone precisely. But since these processes are not yet known, one can posit them only from theory and from the results of indirect experiments.

2.2 Activation

Activation, therefore, must raise the molecule to such an energy level that it is ready on its own to release the latent energy lying within it (the reaction energy). Here we may again refer to Figure 4. The ball must first be raised up the hill (molecule has to be activated) and then it will fall on its own into the deep valley and release its potential energy (reaction energy) in the process. Some molecules need only a low activation energy, but others have to be raised very high. Explosives which require only a slight activation are called primary explosives, while those for which higher activation energies have to be developed to get a detonation-type decomposition are called secondary explosives (Fig. 9).

Explosives with low activation energy usually present a lower energy gain than do secondary explosives.

In general, the energy is not released in a single step; rather, the total energy developing in the decomposition of a hexogen molecule is probably released in several stages by way of various molecular transformations and intermediate states, such as states with several successive electron promotions, vibrational and rotational quanta, and recombination processes involving the emission of radiation (Fig. 10).
Fig. 9 Schematic representation of primary and secondary explosives.

Key: a. energy
b. activation energy
c. energy gain
d. excited state
e. initial state
f. basic state
g. primary explosives
h. secondary explosives

Certainly only some of the energy steps will occur so quickly that their energy can serve to maintain the shock wave.

Likewise, a molecule as complicated as hexogen cannot be raised to the excitation state with a single quantum of energy (Fig. 11).

For instance, the hexogen molecule might need many excitation quanta to bring it at various points to the energy levels from which it can quickly release its latent stored energy. Probably the individual excitation stages from which
the molecule decomposes are also not reached in a single step, but rather require the absorption of several quanta of energy in quick succession.

2.3 Initiation

What possibilities exist to activate the molecule? In the case of explosives, activation is specifically called initiation. An initiation (Fig. 12) can occur by way of percussion, sound waves, shock waves (which are simply "harder"
sound waves), heat, light, electricity or even radioactive radiation.

All these forms of energy can cause ignition-primers to detonate [6]. However, one must take care that the individual forms of energy are partially transformed into other forms of energy. For instance, an electrical spark produces heat or shock waves, and the latter two energy forms can produce activation.

A simple molecule like lead azide probably needs only one quantum of energy for excitation, and reacts from its excited products quickly and immediately within $10^{-7}$ seconds.
Fig. 12 Possibilities for Initiation.

Key:  
- a. percussion  
- b. sound  
- c. shock wave  
- d. heat  
- e. light  
- f. electricity  
- g. radioactive radiation  
- h. activation = initiation

[4] to form the new molecules which lie at lower energy levels:
\[ \text{Pb}(\text{N}_3)_2 \rightarrow \text{Pb} + 3 \text{N}_2 + Q \]

As has already been mentioned, high-energy organic explosives need a large number of simultaneously-acting quanta of excitation energy. These, however, are only present in sufficient numbers when heating or shock wave stress is applied. The atoms or atom groups in the molecule in both cases are excited to vigorous vibration, so that if enough energy is
applied they will even fly apart from one another and be present and highly available for reaction as radicals. Heating must occur quickly, so that none of the combustion or deflagration which occurs at lower temperatures develops, and instead one achieves detonation, which is triggered at higher temperatures.

Now it is still unclear whether the explosives are caused to detonate by a "heat shock" or by a "mechanical shock" (shock wave).

Let us first of all consider two experimental arrangements:

One is the so-called "gap test" (Fig. 13 left), in

![Diagram](image)

**Fig. 13 Gap test and heat test.**

Key:

a. electrical detonator
b. primer charge
c. donor charge
d. heat barrier
e. receptor charge
f. primer capsule
g. black powder
h. type of explosive
i. crystal size
j. crystal surface (crystal shape)
k. surface treatment (desensitization)
l. gas inclusions
m. density (density gradient)
n. geometry (diameter \( \phi \), length \( L \))
o. confinement
which a donor charge sends a shock wave through a barrier to a receptor charge. The barrier is called a "shock pass-heat filter" by Cook [5].

Since the receptor charge detonates if the dimensions are right, it will be concluded from the experiment that only shock waves initiate explosives. But this experiment is contrasted with another. A steel tube is filled from one end with explosive, and from the other end a black powder charge with a primer is put in (Fig. 13 right).

Since the explosive likewise detonates with this arrangement, although only after a certain start-up distance, heating is the inducing mechanism for the initiation of the explosive.

The question whether or not a detonation will occur is dependent on several factors in both arrangements—such as kind of explosive, crystal size and surface, surface treatment, additives, gas inclusion, confinement, dimensions of the explosive charge, density of explosive charge, etc. We thus have two different excitation mechanisms for the activation of explosives—shock waves and heating. The gap test provides the proof that it is the shock wave, and the black powder experiment shows that heating is the cause of detonation.

As is well known, a shock wave heats a solid explosive only very slightly. According to Bowden [6], the so-called "hot spots" in the explosive (Fig. 14)—these need not
be only gas inclusions in pores 1.0 to 0.001 mm in diameter: other kinds of inhomogeneities are also included—provide the heating points from which the molecules are excited and detonation is induced. Thus in spite of shock waves, activation is indeed caused by heating.

On the other hand, one can conceive of the transition from combustion to detonation in such a way that the initial combustion engenders pressure, which in turn increases the velocity of combustion (Fig. 15). Thus combustion is constantly accelerated and the pressure is built up steeply, until finally a shock wave of sufficient intensity develops and it induces and continues detonation. This would be one explanation for the contention that in spite of the combustion of black powder, initiation still occurs by way of a shock wave.
Figure 15 Schematic representation of the combustion-detonation transition in the heat test.
Key: a. combustion front b. shock wave

Figure 14 shows the meeting of "hot spots" and a shock wave. The shock wave does indeed compress the gas bubble. But the bubble itself collapses after the flaw has been passed by. As is well known, when two shock waves collide an increased pressure develops. At such hot spots, then, a shock wave which in itself is too weak to initiate the explosive can still achieve the pressure level needed to activate the molecules and initiate the explosive charge.

Figure 16 once again summarizes the dualism between shock wave and heat shock, with the fundamental experiments and their possible interpretations.

Various papers [7] have shown that small gas bubbles in fluids, or even in explosives, cannot be heated up very
Fig. 16 Comparison of initiation theories

Key: a. initiation  
b. shock  
c. steep increase in shock wave  
d. shock-wave collision  
e. heating  
f. combustion-detonation

much at all by heat exchange with their environment.

Figure 17, however, shows that very high temperatures can develop in small gas gaps with very slight layer thicknesses, due to multiple reflections of the shock wave.

An explosive charge of Th 23 (TNT-hexogen in a 2:3 ratio) was poured onto two glass plates 20 mm wide and 10 mm thick, lying next to each other. The right glass plate was removed after the explosive charge had set. The detonation of this arrangement was recorded with an image converter camera at an exposure time of 100 ns. From the clouds of smoke and gas flowing off to the side, one can approximately indicate the shock front. One finds a very bright band of light on the side of the explosive charge covered by the glass, but this
band lies in front of the shock wave. The explanation is as follows: although the explosive was poured onto the glass plate, due to their different coefficients of heat expansion the glass separated from the explosive and a narrow gap developed. In this gap, the gas/smoke clouds run ahead at a velocity higher than the detonation velocity, and produce the luminescence. This gas is considerably brighter than the luminescence of the reaction products in the cloud. The sharply-defined back edge of the luminescence is explained by the fact that the glass is destroyed by the detonations and shock wave, so that no more light penetrates. The glass plate in this experiment was 10 mm thick. Until the shock wave penetrates to the outside, a running time of approximately $1.5 \mu s = 10$ mm must be present relative to the shock wave front and the back edge of the band of light. Either the glass immediately
becomes opaque when pressure stress is applied, or else the extremely hot gases transmit their heat (estimated at 50,000°C) to the gas/smoke clouds (which are good heat conductors) immediately behind the reaction zone.

If one pours the explosive onto plexiglas instead of glass, one does not get the very brightly luminescent band. The coefficient of expansion of plexiglas is considerably closer to the explosive than is that of glass, so that the plexiglas stays attached and no air gap can form. Figure 18, however, is interesting because one can still recognize a shading of brightness in the band of light on the side covered with glass; it runs parallel with the back edge. No explanation can be given for this phenomenon.

For heat activation and shock wave activation one can produce a large number of various experiments, already performed, which alternately prove one theory or the other. But given the present state of knowledge this dualism cannot yet be resolved.

So much for the general theory of initiation in solid, high-energy explosives.

3. Initiation Phenomena

3.1 Gap Test

In order to get a measure of the sensitivity to
Fig. 18 Image converter photos of detonating explosive charges in which part of the foremost front was covered with glass or plexiglas.

Key: a. glass    b. glass or plexiglas    c. plexiglas

initiation of explosive charges produced by various processes they were studied with the gap test. For this purpose the experimental arrangement of Jaffe, Beaugard and Amster [8] was used with slight modifications. (Fig. 19).

Fig. 19 Gap test arrangement and depth $T$ of the broken test stack plates as a function of length of the plexiglas rod.

Key: a. detonator    d. explosive charge
b. wood    e. plate stack
c. plexiglas
Two tetryl briquettes with a density of 1.51 g/cm³, a diameter of 57.5 mm and a height of 25 mm each were initiated with a No. 8 blasting cap. A plexiglas rod with the same diameter was placed between the tetryl charge and the test explosive charge. A new feature is that the effects of the test charge were determined with stacks of plates. The graph (Fig. 19) shows the number of burst-through plates as a function of plexiglas height. It can be seen that as the height of the plexiglas increases the depth of penetration into the plate stack decreases. Obviously as the plexiglas height increases less and less of the test explosive charge is detonated. This means that the startup distance in the test explosive charge gets larger and larger.

In this simple manner, just a few experiments yield the plexiglas height at which no plates are broken. Jaffe et al. [8] determined the pressure at the end of the plexiglas rod as a function of length $x$, using this gap test arrangement, and give the following equation for it:

$$P = 105 e^{-0.658 x} \quad x > 20 \text{ mm}$$

In this way the pressure of the shock wave prevailing after a distance $x$ in the plexiglas of this arrangement can be calculated (Fig. 20).

For cast "composition B" Trimborn [9] found 17 kbar as the limit pressure at which no further detonation occurs.
Für Plexiglas gilt: \( p = 105 e^{-0.0358 x} \) für \( x > 20 \)mm.

<table>
<thead>
<tr>
<th>Sprengstoff</th>
<th>Dichte (g/cm³)</th>
<th>Hexogen gehalten (mm)</th>
<th>( p_{\text{in Plexiglas}} ) (kbar)</th>
<th>( p_{\text{in Sprengstoff}} ) (kbar)</th>
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<tr>
<td>TH 11 NG</td>
<td>1.71</td>
<td>55%</td>
<td>46.3</td>
<td>20.0</td>
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<tr>
<td>TH 23 NG</td>
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<td>64%</td>
<td>50.0</td>
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<td>1.74</td>
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<td>51.3</td>
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<td>TH 23 VG</td>
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<td>55.0</td>
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<tr>
<td>Tetryl</td>
<td>1.51</td>
<td>—</td>
<td>72.0</td>
<td>8.0</td>
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</table>

Fig. 20 Table of test results with the gap test.

Key: a. For plexiglas the following apply:
   b. type of explosive
   c. density
   d. hexogen content
   e. in plexiglas
   f. in explosive

His cast explosive probably corresponded to the TH 23 used here, for which we found 17.55 kbar. In the literature one finds values between 17 and 30 kbar, but it is often unclear whether this indicates pressure at the end of the transport medium or pressure within the explosive charge.

If the Hugoniot curves of the materials, i.e., the curves of the shock wave transport medium and the explosive, are known, then one can give the pressure as it builds up within the explosive charge. The Hugoniot curves of plexiglas [10] and of composition B-3 [11] are graphed in Fig. 21. From the formula given previously, the pressures \( P \) in the plexiglas, at which initiation barely ceases to occur, were calculated. The points were included in the Hugoniot curve for plexiglas, and the plexiglas Hugoniot curve was reversed around them.
Fig. 21 Determination of the pressure values building up in the explosive by means of the Hugoniot curves of plexiglas and composition B-3.

Key: a. plexiglas     b. inversion

The points of intersection between this mirror-image curve and the Hugoniot curve of composition B-3 yield the pressure values at the plexiglas-explosive interface and the level of the shock waves as these run into the variously produced explosive charges at the boundary layer.

Surprisingly, vibration castings (the casting type with the highest density) are most easily initiated. It was originally assumed that the high density would mean there were so few flaws that this explosive could only be initiated at higher pressures. The greater sensitivity is obviously caused by the high hexogen content. The gap test is a good auxiliary means to test the sensitivity of types of explosives or of explosive charges produced by different methods. Heterogeneous explosives are more sensitive. The more homogeneous the structure of the explosive, the less sensitive it is. The values
found in the literature [12] can be arranged in a scale of sensitivity (Fig. 22).

Fig. 22 Scale of sensitivity for explosive charges of one kind of explosive produced in different ways.

Key:  
a. heterogeneous explosives / very sensitive  
b. pressed explosives  
c. explosives with inert material  
d. desensitized explosives  
e. synthetic-bound explosives  
f. cast explosives  
g. flawed crystals  
h. single crystals  
i. bubble-free liquid explosives  
j. homogeneous explosives / very insensitive

Pure pressed explosives have the highest sensitivity. They also present the most imperfections. Explosives with inert materials (such as NaCl) which absorb only a limited amount of shock energy are also very sensitive. If one
desensitizes an explosive (i.e., if one covers the individual crystal grains of the explosive with a wax coating) the number of gaps and cracks is decreased, and one achieves a lower sensitivity to initiation. Moreover, the reacting surface is diminished. This effect is more significant for plastic-bound explosives.

Cast charges present a significantly lower number of cracks and irregularities, so that their sensitivity is still lower. Large crystals with flaws are very insensitive, and therefore single crystals or fluid explosives without bubbles are very difficult to initiate.

3.2 Initiation with a Shaped-Charge Jet

The gap test can only determine the sensitivity of an explosive to shock waves spreading out along a surface. In order to get the most point-shaped initiation possible, it is necessary to know what energy one must apply to the explosive charge in point form, or at least within a small radius, in order to cause it to detonate.

For this we chose the following experimental arrangement (Fig. 23). Unconfined shaped charges with Cu-funnels 1.5 mm thick, having an angle of aperture of 60°, were exploded against test stacks. The thickness of the test stack was varied in such a way that residual particles of the jet developed with different velocities at their tips. These flying particles were recorded by x-ray-flash photography before they
Fig. 23 Experimental arrangement and results with the initiation of a cast explosive charge made of TNT-hexogen in a 40:60 ratio, with density 1.70, by means of copper particles from shaped-charge jets, from shaped charges of different sizes.

**Key:**
- a. experimental arrangement
- b. initiation
- c. particle

collided with the test explosive. In addition to the test arrangement, Figure 24 also shows a typical x-ray-flash photograph of a residual jet. The thickness of the test stack was varied.

### Table

<table>
<thead>
<tr>
<th>KH-0 (mm)</th>
<th>27</th>
<th>32</th>
<th>44</th>
<th>96</th>
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<tbody>
<tr>
<td>Initiation (mm)</td>
<td>25</td>
<td>10</td>
<td>160</td>
<td>240</td>
</tr>
<tr>
<td>Weight (mg)</td>
<td>2.10</td>
<td>1.72</td>
<td>1.30</td>
<td>1.00</td>
</tr>
<tr>
<td>Particle (mm)</td>
<td>1.73</td>
<td>5.8</td>
<td>12.5</td>
<td>29</td>
</tr>
<tr>
<td>Particle (mm)</td>
<td>125</td>
<td>15</td>
<td>3.75</td>
<td>5.5</td>
</tr>
<tr>
<td>Particle (mg)</td>
<td>22.4</td>
<td>12.60</td>
<td>12.80</td>
<td>19.00</td>
</tr>
<tr>
<td>P (liber)</td>
<td>233</td>
<td>8</td>
<td>9</td>
<td>22</td>
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Fig. 24 Experimental arrangement and x-ray-flash picture of the jet from a 64 mm $\Phi$ shaped-charge jet, passing through the interposed elements; the jet still was able to initiate the explosive charge at right.
until the point was found at which the tip particles of the residual jet were still barely capable of initiating the test explosive charge. Differing particle velocities were obtained for different shaped-charge diameters.

Figure 23 lists the particle limit velocities, particle diameters and particle lengths at which the test explosive charge was just barely initiated. If one graphs the obtained limit velocities over particle diameter on logarithmic paper (Fig. 25), one gets a straight line with the equation:

\[ v = \frac{2.41}{\sqrt{a_{\text{Particle}}}} \]

A certain degree of error arises from the fact that with small shaped charges, the particles are spread wide apart, while with larger shaped charges they follow each other more quickly. In the test series carried out, emphasis was not placed on getting a constant sequence of particles, but rather on getting a constant distance between the shaped charge and the test explosive.

From the impact velocity of the copper particles one can determine the necessary impact pressure or shock wave pressure occurring in the explosive for shaped charge particles flying at different velocities. For this one needs the Hugoniot curve of copper [10] and of the explosive [11]. The Hugoniot curve of copper, inverted with \( p = 0 \), is graphed at the obtained particle velocities \( u_p \) (Fig. 26), and from the points of inter-
Fig. 25 Limit velocity of jet particles initiating explosive charges, as a function of particle diameter of the jet.

Key: a. limit  b. particle

Fig. 26 Determination of impact pressure developing upon impact of copper jet particles with various velocities into explosive (TH 230) using Hugoniot curves.

section with the Hugoniot curve for TH 23 one gets the impact or shock wave pressure that develops upon impact of these
particles with the explosive charge. Too few experiments have been performed as yet with this test arrangement, so that the results obtained represent only guideline values.

If one graphs the obtained pressure over particle diameter, on logarithmic paper, one gets a straight line (Fig. 27). The initiation pressure as a function of particle diameter can thus be represented sufficiently by the equation:

\[ P = 28 \phi^{{-3/4}} \]

From Figs. 23 and 27 one can see that for instance a shaped charge 96 mm in diameter, with particles 5.8 mm thick and a pressure of 7.5 kbar, is enough to initiate the explosive.

---

**Fig. 27** Pressure necessary to initiate a TH 23 explosive charge, as a function of the diameter of the impacting particle.

Key: a. particle diameter
With the gap test a necessary shock wave pressure of 17.5 kbar was found.

The explanation is quite simple, if one considers the pressure profile of the two shocks. The gap test involves, as a first approximation, a triangular shock, while with particle impact one gets a rectangular shock. The particle is practically unbraked and hence not consumed, as the Hugoniot curves show (Fig. 27).

3.3 Initiation without Ignition Primers

One patent [13] describes an electrical bridge detonator with ignition-primer-free initiation. A steel tube with 8 mm i.d. and walls 3 mm thick is filled with explosive—e.g., pentaerythritol tetranitrate (P.E.T.N.) with a grain size of 150-300—and compressed at 300 kp/cm². On the side opposite the compression piston, a small amount of black powder is ignited with a primer capsule.

As the x-ray pictures show (Fig. 28), as desensitization increases there is a longer startup distance before the explosive detonates. At 5% desensitization, there is only a rather strong deflagration, as the time measurements show. The steel casing then only falls apart into a few large pieces with low fragment velocity.

If the P.E.T.N. is compacted in an argon atmosphere instead of air, with argon one would necessarily obtain shorter startup distances, if one considers heating in the hot spots to be the initiation mechanism. In adiabatic processes argon,
X-ray-flash photos of so-called ignition-primer-free initiations with undesensitized P.E.T.N. (NP 0) and P.E.T.N. desensitized 2% and 5% with lignite wax (NP 2 and NP 5, respectively).

Key:  
- a. structure  
- b. primer capsule  
- c. black powder  
- d. trigger probe

because of its higher adibatic exponent of 1.67, compared to air at 1.40, is heated to higher temperatures by the same increase in pressure.

However, the experiments (Fig. 29) showed that while
this is indeed the case with P.E.T.N. 0 (0% desensitized), it is not the case with P.E.T.N. 2 and P.E.T.N. 5.

3.4 Diabolo and Pointed Detonators

If one wants to get shaped-charge jets directed straight ahead, among other things the initiation must occur as much as possible along the axis of the charge (Figs. 30 and 31).

Fig. 30  Jet formation in a shaped charge initiating at an angle. The individual jet elements fly in straight lines from the point of their development, and thus produce a "cut-like" effect.

Key:  a. No. 8 instantaneous detonator  d. jet
      b. explosive charge  e. target
      c. pin

Fig. 31  X-ray flash photograph of the jet from a shaped charge construction as shown in Fig. 30. The time difference between the detonation of the charge and the x-ray flash was 130 μs. The cutting effect in the target is reproduced at the right of the picture, rotated 90°.
For precise induction of initiation, therefore, so-called "diabolo and pointed detonators" were developed [14] (Fig. 32).

![Diagram of diabolo and pointed detonators](image)

**Fig. 32** Basic diagram of diabolo and pointed detonators. \( D_1 = D_2 \) are explosives with high detonation velocities, and \( D_3 \) is an explosive with a low detonation velocity.

Key: a. pointed detonator

Here a point (Fig. 32 right) or a double cone (Fig. 32 left) in which the two tips of the cones are contiguous are made of a fast-detonating explosive and surrounded with a slowly-detonating explosive. Thus no rarefaction wave from the surrounding medium can enter into this pointed detonator (Fig. 33).

As is well known, with high-energy explosives one has a thickness effect, i.e., as the radius of the charge decreases the detonation velocity becomes lower. With the diabolo or pointed detonator arrangement of the explosive charge, quick detonation is produced with certainty at the most favorable cross-section at which any fast detonation is possible. Hence the smallest radius is achieved for fast detonation, while pre-
Fig. 33 Development of wave fronts (detonation waves) in 2 media with different velocities, and the energy flow.

Key: a. detonation waves c. shock wave energy
b. reaction energy d. energy flow

venting detonation from getting stuck in any part which might be too thin.

With a calculation model one can calculate the maximum permissible velocity $D_3$ in the slowly-detonating explosive charge as a function of diameter $2R$, of the height $H$ of the structural group, of the angle $\alpha$, of the detonation velocity $D_1$ or $D_2$, of the quickly-detonating cone and of the chosen non-axial initiation $J$, in order to get a detonation wave progressing from the constriction point $t_2$ (Figs. 34, 35 and 36).

From Fig. 37, one can get the penetration depth $T$ as a function of the eccentricity $J$ of the H5 briquette rela-
Fig. 34 Calculation model for diabolo: the L limit may not be exceeded, if the detonation wave in the lower part of the cone ($D_2$) is to proceed only from point $t_2$.

Key: a. detonation front   b. L limit

Fig. 35 Maximum permissible detonation velocity $D_3$ as a function of $a$ for detonation velocity $D_1 = D_2 = 7000 \text{ m/sec}^3$, diabolo radius 6 mm, eccentric detonation induction $J$ of 3 mm, and diabolo heights $H$ of 10, 15 and 20 mm.

Key: a. $D_3$ as a function of $a$ with $H$ as a parameter
b. (degrees)
Fig. 36 Maximum permissible detonation velocity $D_3$ as a function of radius $R$ or eccentric initiation $J$, set equal to $R$, for detonation velocities $D_1 = D_2 = 700 \text{ m/sec}$, angle $\alpha = 45^\circ$, and diabolo heights $H$ of 10, 15 and 20 mm.

Key: a. $D_3$ as function of $J$ with $J$ as parameter

Fig. 37 Depth of penetration into test stack as function of distance of initiation axis from charge axis.

Key: a. penetration depth c. pointed detonator
b. HS briquette d. eccentricity
tive to the charge axis with the use of a pointed detonator.

The gain in penetration depth and decrease in scatter by the use of a pointed detonator is best shown in Figure 38.

![Figure 38](image_url)

**Fig. 38** Coefficient of variation of explosion series versus mean penetration depth for various initiation arrangements.

**Key:**
- a. coefficient of variation
- b. probability of complete penetration

In the graph the coefficient of variation is graphed versus penetration depth. The coefficient of variation is the quotient of the standard deviation divided by average penetration depth. The penetration depths and their scatters were
determined for various initiation systems, and the clear superiority of the pointed detonator was demonstrated.

3.5 Initiation with Bickford Detonation Fuse Cords

Several interesting effects were found with the initiation of cast explosive charges with lead-clad detonation fuse cords.

As is well known, detonation fuse cords are not capable of initiating cast explosive charges either head-on in an axial direction or radially through the lead coating (Fig. 39).

Fig. 39 X-ray-flash photos of lead-clad detonation fuse cords (Bickford A5) ending in cast explosive made of 40:60 TNT-hexogen (axial action), or else cast into this explosive (radial action). The photos were taken 50 µs after complete detonation of the detonation fuse cord. With axial stress the explosive broke up, while with radial stress the lead gas/smoke clouds can be seen penetrating into the quickly-forming gaps. The explosive charge then deflagrated.
Rather, a primer of pure P.E.T.N. is needed, as shown in Fig. 40. If this arrangement is enclosed experimentally in an axial bore hole in an explosive charge, no initiation occurs. But if explosive is cast around it, the charge does detonate (Fig. 40).

![Diagram](attachment:image.png)

Fig. 40. X-ray-flash photo of a detonating explosive charge made of cast 40:60 TNT-hexogen, initiated by means of a detonation fuse cord (Bickford A5) and a P.E.T.N. primer. To make the cloud fronts visible, a lead foil 0.5 mm thick and 5 mm wide was wrapped around the explosive charge.

Key: a. steel tube

The explosive charge was surrounded with lead foil 0.5 mm thick, so that the expanding clouds of gas and smoke could be better recognized. Curiously, the figure shows that up to the time of the photograph the explosive charge had only detonated in the part of the charge affected by the shock wave from the detonation fuse cord. There was no time measurement performed, so that it is impossible to say how much later the
explosive charge itself detonated, after the Bickford detona-
tion fuse cord had completely detonated.

In order to decrease confinement due to the base
board, in the next figure (Fig. 41), the explosive charge was
separated from the support board.

![Fig. 41 X-ray-flash photo of the arrangement in Fig. 40, except that the support board, which might have a shock wave or confinement effect, was put at a distance.]

Key: a. separation

Here, too, however, initiation was somewhat one-
sided.

It must be noted that with the chosen primer we were obviously at the limits of the initiation capacity of cast explosive charges.

To weaken the effects of the shock wave from the detonation fuse cord, the conductor tube was surrounded with a second steel tube with a wall thickness of 2 mm. Here almost-even initiation occurred (Fig. 42).
Fig. 42 X-ray-flash photo similar to the arrangement in Fig. 40, except that a second steel tube, 18 x 2 mm, is slipped over the inner steel tube, 10 x 2 mm, to attenuate the shock wave.

For a special piece of equipment, we desired a detonation wave developing from a precisely defined plane—and hence from a very narrow ring zone. Therefore silopren* cylinders were put around the P.E.T.N. charge. Here already a larger amount of the P.E.T.N. had to be used with a strong encasement** [?] in order to get any initiation at all. The two x-ray photos show an extremely irregular expansion of the detonation waves in different directions (Fig. 43).

The figures prove that when initiation is weak, detonation occurs irregularly in different directions. If one increases the P.E.T.N. level from 5 to 7.5 mm, and uses a ring made of a desensitized P.E.T.N. charge instead of a cast TH 23

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* [or possibly "siloprene"--Tr.]

** [German "Einschuss": probably a typographical error for "Einschluss"--Tr.]
Fig. 43 X-ray-flash photos of detonating explosive charges, similar to structure in Fig. 40, except that silopren covers were put over the induced-detonation charge to produce a gap of 5 mm, so that narrow detonation starting fronts were produced. In the lower picture, in addition to the 0.5 mm lead foil, lead foil sheets 0.2 and 0.1 mm thick were applied one on top of the other to the outside of the explosive charge. The interesting thing in these photos is that in spite of rotationally symmetrical structure, explosive charges still obviously detonate irregularly because of small, unintentional asymmetries, if weak initiation is present.

3.6 Reversal of Detonation Direction

In inducing detonation in rod-shaped explosive
Fig. 44 X-ray-flash photo similar to Fig. 43. The gap between the silopren covers was expanded from 5 to 7.5 mm, and filled up with a ring of pressed P.E.T.N. (and not with TNT-hexogen explosive as in Fig. 43).

Figures of charges initiated from a bore hole along the longitudinal axis of the rod, an interesting effect was also found. Some of the rods had the cross-section of a quarter of a circle, and were thus called quadrant rods, while others had a round cross-section and were initiated from a concentric tube.

X-ray-flash photographs (Fig. 45) showed that with the cylindrical rods only the part of the rod lying in the direction of initiation detonates, while in the quadrant rods there was completely thorough initiation and hence reversal of the original direction of detonation.
Fig. 45 X-ray-flash photos of explosive rods in quadrant or round shape initiated axially with No. 8 detonator.

Here the explosive charge was initiated through two steel tubes, 1 mm thick, by way of the central bore hole approximately in the center of the explosive charge, using a No. 8 detonator and a P.E.T.N. briquette. In order to weaken the confinement, in the inner tube 6 mm bore holes were drilled in the same plane as the briquette; some of these holes were left empty and others were filled with P.E.T.N. The quadrant rods prepared in this matter detonated completely, while again the round rods detonated only partially, in the direction of initiation (Fig. 46).
Fig. 46 Various initiation arrangements.

Key:  a. arrangement  c. partial detonation  
b. rod  d. bore holes

This effect was originally attributed to the fact that the shock wave from the electrical No. 8 detonator compacts the explosive charge through the synthetic covering of the detonator and the central tube, so that no detonation can pass through at the time of compaction.

For this reason, the experiments were repeated with the electrical ZP 71 detonator, which has only a very small structural length of 8.3 mm. The influence of the shock wave is eliminated, since the ZP 71 can initiate the P.E.T.N. briquette used within a short startup distance, as the x-ray photos show (Fig. 47). Here, however, detonation also occurs only in the part of the round rod lying in the direction of initiation, even when the primer is placed at the base of the charge. Because of the reflection waves occurring, a possible "retonation" had been expected.
Fig. 47 X-ray-flash photos of explosive rods with a round cross-section initiated axially (at the end and in the middle of the bore hole) with electrical ZP 71 detonators. The upper picture was taken 49 μs after the ignition impulse, and the lower one 4 μs after the explosive detonated at its right edge.

If the central tube with the initiation is installed eccentrically in the cylindrical rod, from a certain axial displacement onwards one gets complete detonation (Fig. 48).

As yet no study has been given to whether the lesser or greater distance of the edge of the casing from the point of initiation is the decisive factor for the complete detonation which occurred.

However, these experiments show clearly that it is very difficult to reverse the direction of detonation. Perhaps
Fig. 48 Eccentrically arranged central tubes; the round rods were initiated with electrical ZP 1 detonators.

Key:  
- a. arrangement  
- b. partial detonation  
- c. complete detonation

One must adjust one's general notions of detonation. One cannot, as in optics, consider each detonation point as a starting point for a new detonation wave.

Behind the detonation shock wave, the flow of gas/smoke clouds occurs in the direction of propagation of the detonation. This flow of the cloud cannot of course easily produce the pressure buildup needed for continuing detonation if it must go around corners or even backwards to do so.

This train of thought can be further firmed up with image converter photos of a detonating explosive charge. Here the detonation wave had to run around an inert body which was built half rounded and half square.

Here the radii \( R_z \) and \( R_r \) were chosen so that the path lengths from the initiation point around the inert body to the charge axis were the same. In the first detail of the
figure the detonation on the basis of the larger radius $R_2$ on the rounded side is not as far advanced as with the square side. In the second picture, however, we have already achieved the rotational symmetry of the foremost shock wave front. On the cornered side the luminescence of the detonation wave is distinctly less, however, than on the rounded side. Obviously here the shock wave pressure, caused by the newly-developing cloud flow around the edge, is lower than on the rounded side of the body.
4. Conclusion

A clear, unambiguous conclusion about the initiation of high-energy solid explosive charges cannot be made.

On the contrary, the reader is confronted with a number of unexplained effects.

In spite of this, the author hopes to have excited, activated and initiated the reader to work to clarify the interesting and often important effects of initiation, and likewise to publish the "nonsensical" effects he may find in his own work. Perhaps then one day a clear mosaic picture of initiation can be built up from these fragments.

Bibliography


(14) German Patent "Auslegeschrift" [see preceding entry] 1 241 734 of 8/12/1965, Detonation system for the point-shaped initiation of explosive charges and for the production of detonation waves spreading out from it subsequently in a rotationally symmetrical manner in the explosive charge.