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Towards Detonation Theory

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ABSTRACT: Experimental findings inconsistent with both the CJ and the ZND detonation theories are discussed. These are the unstable detonation and the weak dependence on charge diameter of liquid explosives detonation velocity at sizable value of their failure diameter. The investigations have resulted in the discovery and introduction into detonation theory of two new theoretical notions: chemical reaction breakdown (BD) and shock discontinuity zone (SDZ). It is shown that the BD governs the limits of the following phenomena: the shock-to-detonation transition, the detonation stability, and the detonation failure diameter, whereas the SDZ governs the regularities of EMs change at detonation.

1. INTRODUCTION

Detonation phenomenon is known since the previous century. The phenomenon thermodynamic analysis performed by Michelson [1], Chapman [2] and Jouguet [3] has resulted in the shock wave theory generalization. Detonation wave has been represented as a shock wave with energy evolution inside the wave front. It was the most prominent step in detonation theory progress. However, it is a well-known fact that the CJ hydrodynamic theory of detonation has not been fully developed. It has formulated some principle for detonation velocity choice. But the principle has not been substantiated enough, namely the impossibility of self - sustaining weak detonation has not been proved in general.

In essence the CJ theory deals only with energetic characteristic of detonation waves. The theory has not taken into account chemical reaction kinetics. Moreover the theory followers believed that explosives at detonation transform into detonation products practically instantaneously. The idea seemed to be justified once it had been revealed that for all gaseous mixtures investigated shock wave pressure initiating chemical reaction with a vanishing small time delay characteristic of detonation practically coincide with the CJ pressure, the shock wave velocity being considerably smaller than the mixtures detonation velocities (see for example [4] and references in). It was because of this experimental finding that the CJ theory followers thought that explosive at detonation transform into detonation products during the process of their compression within detonation wave shock front. Therefore the CJ detonation wave model was sometimes called the "Zero-reaction zone" model. The definition of the detonation model employed was in apparent contradiction with the usual concept of chemical reaction process. The matter is that shock wave front width totals only some free paths of molecules (see [5] and references in) and according to the concept reagents need many thousands collisions to reach the process final product.

Apart from the above-mentioned contradiction the CJ detonation theory has other shortcomings. Since the theory had not taken into account the finite zone of chemical reaction and any perturbations

originating behind the zone can not reach the front of self-sustained detonation wave it failed to give any interpretation of the detonation failure diameter d_f [6] (the smallest diameter of explosive charge which can detonate without any outside support). It failed to interpret the so-called spinning detonation [7] as well.

In 1940 Zeldovich substantiated theoretically detonation wave physical model with finite reaction zone [8]. Since von Neuman [9] and Döring [10] obtained independently related results the new theory was named the ZND theory.

According to the ZND theory the detonation wave front has become complicated. Really, at the CJ detonation, explosive transforms into detonation products completely during its compression inside the wave shock front and at the ZND detonation, quite the reverse, explosive does not change chemically at all within the shock front, it is only compressed inside the front and its decomposition sets in behind the front in the shock-compressed state under the effect of the high temperature due to the shock compression. In essence detonation has changed into deflagration moving behind the shock front with the front velocity. The zone consisting of the shock-compressed explosive and its transformation into detonation products is characterized by high pressure and has been called the chemical spike. The spike time t_{cs} is the time of the explosive transformation at detonation.

Correct way to the d_f phenomenon understanding was directed by Rosing and Chariton [6]. According to Rosing and Chariton explosive detonation capability is governed by some equilibrium between, heat evolution due to explosive chemical transformation into detonation products, on the one hand, and, on the other hand, explosive energy loss due to its scattering from the zone. The equilibrium is disturbed at the d_f , so that at smaller diameters detonation can not travel at all. Thus, it results from the above-said that according to Rosing and Chariton any substance can detonate if its decomposition reaction is exothermal and charge diameter is larger than the d_f .

Taking into account that explosive scattering is in fact some rarefaction which proceeds with sound velocity c , Chariton advanced [11] some formula to estimate failure diameter value: $d_f \approx 2ct_{cs}$. Experimental data gained in a number of year [12-15] lend support to the validity of the d_f qualitative concept [6,11] and the ZND detonation theory [8,10]. However, it should be noted that they failed to interpret some contradiction between rather weak dependence of liquid explosives detonation velocity on charge diameter, on the one hand, and finite value of the explosives d_f , on the other. Indeed, according to the d_f theories developed on the basis of the concept (see, for example, [6,11,16-20]) the d_f value is proportional to explosive detonation chemical transformation time t_{cs} , the larger being the time, at the larger charge diameter detonation velocity depending on the diameter value. And on the contrary, the smaller is the time, at the smaller charge diameter detonation velocity depends on the diameter value. So that at the time approaching zero detonation velocity dependence on charge diameter has to vanish. Naturally as this takes place the d_f value has also to approach zero. However, in the case of liquid explosives the detonation velocities of which as a rule do not practically depend on charge diameter, the d_f by contrast are not equal to zero and amount to considerable values. For example, nitromethane detonation velocity at room temperature is equal to 6.3 km/s and changes insignificantly near by its d_f . Nevertheless nitromethane d_f is rather sizable ≈ 15 mm at room temperature [21]).

The spinning detonation phenomenon was discovered by Campbell and Woodhead in 1926 [7]. The appearance of some spot of bright luminosity on detonation wave front at inner side of tube containing gaseous explosive mixture and the spot spin around the tube axis were found to be basic features of the phenomenon [22-24]. It was later revealed that the spinning detonation always originated nearby any limits of detonation propagation [25-30].

For a long time the spinning detonation was considered as an original phenomenon. Shchelkin was the first who had realized and declared that the spinning detonation was in fact some limit of unstable so-called pulsating detonation [31,32]. By now the pulsating detonation as well as the spinning detonation have been investigated in considerable detail [32,33]. Shchelkin starting from the ZND detonation wave model [8-10] was of the opinion that close to the detonation propagation limits chemical reaction proceeds slowly at the shock-compressed state in the detonation wave plane

smooth front and therefore spin originates. According to Shchelkin spin is conducted by some oblique detonation wave appearing on the basic detonation wave shock front and being sustained by the ZND chemical spike high pressure [32,34]. The idea was substantiated theoretically by Zeldovich who called attention to the fact that the oblique detonation wave was a strong detonation [35]. The oblique detonation wave origin was explained by Shchelkin in the framework of his notion of detonation waves kinetic instability [31]. According to the notion some casual perturbations of the detonation wave ignition plane can overcome the detonation wave shock front and bend it bringing the oblique detonation wave into being.

Thus according to Shchelkin the oblique strong detonation wave is the principal element of spinning detonation structure. In contrast to Shchelkin siberian scientists Voicekhovsky, Mitrofanov, and Toptshijan, have proposed and elaborated in detail the spinning detonation with some transverse detonation wave as the principal element of the spinning structure [33,36,37]. They also start from the ZND detonation theory. In accordance with the theory they believe that at gaseous detonation the shock-compressed and heated substance without chemical reaction appears between the detonation wave shock front and its combustion plane, the appearance being conditioned by a large value of the substance ignition delay time. Furthermore, they consider that owing to some casual reason a perturbation can arise inside the heated zone and it will lead to the transverse detonation wave origin. As far as the oblique wave is concerned it appears in their view on the basic detonation wave shock front under the effect of the transverse detonation wave high pressure. It should be mentioned that siberian scientists have also shown that even far from the detonation propagation limits the transverse waves exist and the waves are not distinct in nature from that of the spinning detonation [34].

It should be mentioned that Manson [38,39], Fay [40] have succeeded to explain some features of the instable detonation wave by the effect of burned gas acoustic vibrations. They have clearly demonstrated that the unstable detonation front perturbations and the burned gas acoustic vibrations are interrelated. However, the problem needs some further investigations. It is unlikely that the unstable pulsating detonations appear owing to the burned gas acoustic vibration. Conversely, more likely the burned gas acoustic vibration are governed by the unstable detonation front perturbations [33].

So, there results from the foregoing that there are some experimental findings which are consistent neither with the CJ nor with the ZND detonation theories. The findings are the following:

- The spinning and the pulsating detonations; the question - how does the unstable detonation originate? - is still open.
- The fact that the dependence of liquid explosives detonation velocity on their charge diameter is very weak at a sizable value of the explosives d_f .

In the paper the interpretation of the findings founded on the notion of the chemical reaction breakdown phenomenon (BD) [21] are presented. Some considerations based on the notion of the shock discontinuity zone (SDZ) effect [41] on the mechanism of ideal explosives (these explosives contain fuel and oxidizer in their molecules) transformation at detonation are discussed as well.

2. BREAKDOWN PHENOMENON

The BD phenomenon has come to light in the course of the investigation of liquid explosive detonation processes [21]. Exactly speaking it was discovered in the course of the elucidation of the second above-mentioned experimental finding inconsistent with the available detonation theories.

The greater part of the investigations have been performed with nitromethane and its mixture with acetone. The explosives detonation front is unstable. Clearly the most feasible approach was to use the unstable detonation decomposition mechanism concept in order to look for the finding cause. By this was meant that the unstable detonation failure diameter theory had to be developed. The theory had been elaborated on the basis of decomposition mechanism concept worked out by Shchelkin and Troshin [32] in the early sixties for gas unstable detonation.

Shchelkin's and Troshin's explosive detonation transformation mechanism dissimilarity from that of the ZND detonation theory consists in the following. The ZND detonation front is stable; explosive transformation reaction originates behind the detonation wave shock front in the explosive shock-compressed state simultaneously over the wave front. In Shchelkin's and Troshin's case detonation front is unstable; explosive transformation reaction originates non-simultaneously over the detonation wave shock front but at discrete spots of double collisions of the contrary-moving triple-shock configurations (TSCs) [32]. According to Shchelkin and Troshin the explosive transformation reaction spots will not appear over the detonation wave shock front if the double collisions do not take place. In their view the TSCs originated exist then in the detonation wave shock front owing exclusively to the configurations repeated collisions with each other or with gas containing tube walls; each separate configurations passing away inevitably. However, the collisions give rise to new explosive spots which lead to new TSCs origin. The TSCs originated collide again and so on. Taking into account the mechanism one could imply that the sequence of the events never ceases at the stationary detonation wave front except at the front edge of the charge lateral free surface. In the case the last TSCs moving to the charge free surface at the detonation front edge have no contrary partners to collide with. Due to the reason the explosion spots can not appear close by the surface. It follows from this that new TSCs can not origin too and in one's turn it has to result in the impossibility for neighbor explosive spots located more distant to the surface to appear. So the charge free surface presence has to lead to explosive spots nonoriginating successively in the direction from the surface, that is to the appearance of some reaction-quenching wave moving from the charge free surface towards its axis.

The reaction-quenching waves have been really found by specially arranged experiments. In the experiments the explosives detonation wave moving inside some metal tube transits through a sudden enlargement of the tube diameter. The detonation wave front occupies the first tube cross section entirely. In accordance with the foregoing in means that the TSCs collisions with the tube wall result in the explosive spots appearance in the same manner as at their collisions between themselves. Owing to the fact the reaction-quenching waves do not originate during the detonation wave motion inside metal tubes. (It stands to reason that the contention is valid only in the case when the tube's inner surface is smooth). Also in accordance with the foregoing considerations on the reaction-quenching wave origin cause it has been implied that the last TSCs round the unstable detonation wave front edge will have nothing to collide with at the first tube end and it will bring the reaction-quenching wave appearance and the detonation death.

It has been verified in the experiments that the reaction-quenching waves really appear at the first tube end. However, it turns out that they spread over the detonation wave front towards the charge axis only to some depth. Moreover, it has been found that the detonation wave moves along the charge axis without change its velocity if the first tube radius is larger than the depth and the detonation wave generally ceases if the reaction-quenching waves shut down the tube cross-section entirely. It has been shown that for liquid explosives unstable detonation the depth coincides with the explosives detonation failure radii [42]. The failure diameter theory developed [42,43] was founded on the experimental finding.

The fact that the reaction-quenching wave can penetrate from the charge lateral free surface towards its axis only to some depth is a convincing explanation of the liquid explosives detonation wave velocity independence on the charge diameter. It goes from the finding that the explosive detonation wave moves along the charge axis and it "knows" nothing about the events which take place in neighbor parts located some distant apart the charge axis at the charge diameter larger than the failure one.

The important feature of the above-presented considerations on the nature of liquid explosives unstable detonation failure diameter is the reaction-quenching wave. It was predicted on the basis of Shchelkin's and Troshin's spot mechanism developed for explosives transformation in the unstable detonation. However, it turns out that the reaction-quenching waves originate as well in the case of liquid explosives stable detonation [21]. The finding has lead to the perception that the reaction-

quenching waves appear in fact not owing to the explosion spots successive death concept given above but due to some general phenomenon which is an inherent characteristic of all energetic materials (gaseous, liquid, solid) explosion processes. In essence it was the discovery of the chemical reaction break-down (BD) phenomenon which governs the limiting conditions of shock-to-detonation transition (SDT) process, the detonation stability, and detonation failure diameter as well [44].

What is the BD phenomenon main point? When does it take place? To begin with the questions one needs to discuss the process of shock wave motion through some energetic material, that is to discuss the SDT process. It is well known that the shock wave intensity decreases during its motion through any inert material if it has no outside support. Behind the front of the shock wave without support there is rarefaction wave which leads to the material adiabatic cooling. However, the effect of the shock wave of any intensity results in EM energy evolution just behind the shock wave front, the evolution favoring the wave support. It should be mentioned that the initial rate of the evolution depends on some factors: on EM type (different materials can release their energy with different rate), on EM charge structural features (on EM particle size and structure - single crystals or fragments of broken cast, on the nature of the filler in the charge pores, on EM state - liquid or solid, density, and so on), and on the shock wave intensity as well (the larger the intensity, the larger the initial rate).

So, the change of the shock wave intensity in any EM is governed by two processes: explosion energy evolution, on the one hand, and the EM adiabatic cooling due to the rarefaction wave effect, on the other. It is obvious that the wave intensity will increase and it results in the initiation of detonation if the initial rate of the EM energy evolution is larger than that of the adiabatic cooling, and vice versa, the wave intensity will decrease if the initial rate of the adiabatic cooling is larger than that of the energy evolution.

The decrease of the shock wave intensity is necessary condition for the BD phenomenon manifestation. However, the condition is not sufficient to provoke the BD. The matter is that the BD can occur only when the dependence of EM transformation time on shock wave intensity is strong. It is really strong at low shock pressures but the dependence falls down with the pressure increase. It follows that the BD does not need to be if the intensities of the shock during its attenuation are sufficiently high. Naturally the question arises - what level of shock intensity is "sufficiently high" to prevent the BD? It seems likely that a shock is sufficiently strong if the shock - induced EM energy evolution rate is maximum just behind the shock wave front, that is if the initial rate of the EM energy evolution is fast. To the contrary it is believed that the shock is weak as soon as the maximum is displaced from the front, which is to say that some induction time of the EM fast transformation appears behind the shock front. In other words, the shock is weak if the initial rate of the shock-induced EM energy evolution rate is slow. The BD is very probable in the EM under the weak shock effect since the induction time is usually strong function of the material state, that is of the shock wave intensity.

3. SDT AND DETONATION INSTABILITY PHENOMENA

It is well known that the response of heterogeneous and homogeneous EMs to the shock effect is very different (see Proceedings of some last Symposium (Int.) on Detonation which contain many papers of the "Shock-to-Detonation" sessions). The differences are the following. First, shock wave critical intensities to initiate detonation at the same experimental conditions differ significantly; in the case of heterogeneous EMs it is considerably smaller than in homogeneous ones. It turns out that rather weak shock of some kbar intensity can initiate detonation in heterogeneous EMs, whereas one needs shock of 5-10 GPa to initiate detonation in homogeneous explosives.

The difference of heterogeneous and homogeneous EMs shock sensitivities is conditioned by marked difference in initial rates of their energy evolution just behind initiating shock waves fronts. In the case of heterogeneous EMs it is usually fast and it leads to the shock gradual transition to detonation if the shock intensity is larger than that of the critical one. In contrast the initial rate of homogeneous EMs energy evolution is usually very slow under the effect of the shock approximating critical intensity, so that the bulk of their energy is evolved at some distance behind the shock wave

front.

The slow rate of EMs energy evolution is the cause why the CJ detonation of homogeneous EMs always originates from strong detonation (SD). It is obvious if the initiating shock pressure is higher than the CJ pressure. However, it turns out that the SD also originates in homogeneous EMs at any initiating shock pressure larger than the critical one, that is at pressures lower than the CJ pressure as well. The matter is that some layer of shock-compressed explosive (SCE) appears (exactly speaking, a layer of partially decomposed SCE, the decomposition scale depending on its decomposition initial rate) and the SCE detonation arises first at the piston-SCE interface in the SCE explosion induction time [21,45,46]. The SCE detonation arises at the interface due to extremely fast energy evolution in the induction time. The SCE detonation pressure exceeds considerably the pressure of initial homogeneous EM CJ detonation. Therefore, the SD appears in the initial EM just as the SCE detonation overtakes the initiating shock wave front. So the CJ detonation appears from the SD at any way of its initiation.

As mentioned above, the mechanism of unstable detonation origin and its structure are governed by the BD phenomenon. It is well known that initiating shock wave transforms into detonation gradually in all heterogeneous EMs. Usually their CJ detonation is reached asymptotically, that is without the SD appearance during the SDT process. Maximum rate of their energy evolution just behind the shock wave front is the very cause of the feature. Homogeneous EMs are another matter; their CJ detonation always originates from the SD. However, it turns out that the energy evolution proceeds with maximum rate in power homogeneous EMs just behind the SD wave front. Due to this reason the BD does not take place during the SDT process and the CJ detonation is stable in the power homogeneous EMs.

As an example of power homogeneous EM one can give liquid nitroglycerine (NG). Its CJ detonation pressure is equal to ≈ 27 GPa, critical intensity of the shock to initiate detonation at laboratory experiments - 12 GPa, and detonation pressure of NG compressed by ≈ 12 GPa intensity shock ≈ 50 GPa [21]. It was shown experimentally that NG SD generated by the SCE detonation attenuates to the CJ detonation without the BD appearance, so that its CJ detonation is stable.

So it was shown experimentally that power homogeneous EM detonation is stable since the BD does not occur during the SDT process [21]. Weak homogeneous EM detonation quite the reverse has usually unstable front since the BD occurs easily during the process of their SD transition to the CJ detonation. It happens for their SD wave front becomes weak and consequently the initial rate of their energy evolution becomes slow under the rarefaction wave effect. In the case adiabatic cooling due to the rarefaction wave effect compensates completely the explosive heating due to its chemical transformation and it leads to the BD appearance. The BD behind the SD results in the wave chemical spike disappearance. After that the following process resembles the SDT process [21,46]. As in the case a layer of SCE appears. It appears under the effect of high pressure just detonated explosive. The SCE state parameters (pressure and pressure gradients) change in such a way that in some time characteristic of the state the SCE detonation originates in the immediate vicinity of the detonation products-SCE interface. (It should be mentioned that for a strong but short duration initiating shock wave the detonation may not originate again after the first BD, however, this case is of no interest for the present discussion). Since the SCE detonation pressure exceeds considerably the CJ detonation pressure the SD will originate again in the initial undisturbed explosive as soon as the SCE detonation overcomes the shock wave front, that is as soon as it consumes the SCE layer. After that the BD and the SCE detonation origin will repeat.

So it follows from the afore-said that the pulsating detonation is a property of those explosives which energy evolution rate at detonation conditions is slow [47]. For the Arrhenius kinetics it corresponds to a high value of the EMs transformation activation energy, on the one hand, and relatively low explosive temperature, on the other [48,49]. The list of the EMs consists of practically all gas explosive mixtures [32,33] as well as some weak liquid explosives [21]. As an example of weak liquid explosive one can give nitromethane (NM). At room temperature NM CJ detonation pressure is equal to ≈ 13 GPa, critical intensity of the shock to initiate detonation at laboratory experiments

≈ 8 GPa, and detonation pressure of NM compressed by 8 GPa intensity shock - 25 GPa [21].

It also follows from the afore-said that one would have to observe so-called one-dimensional instability at weak homogeneous EM detonation since the sequence: the BD during the SD transition to the CJ detonation - the SCE layer appearance after the BD - the SCE detonation origin in some induction time - and finally the SD appearance again will repeat continuously. However, the one-dimensional instability is not observed in spite of the fact that the sequence does repeat continuously. The point is that for some casual reasons the BD and subsequent SCE detonation in reality do not take place simultaneously over the whole detonation front, but do occur at randomly distributed individual spots [21,50].

The SCE detonation from each spot spreads hemispherically in the SCE. Each individual detonation overcomes the shock front and causes the SD diverging in the initial undisturbed explosive. The rarefaction rate behind these detonation fronts is larger in comparison with that behind the plane front and therefore the reaction breaks down easily again. After the BD in some strong divergent detonation the SCE detonation spreads over the SCE layer like a ring, some islet of a new SCE appearing in the ring center. The ring cross-section represents the TSC. The TSC consists of the straight shock wave, the principal element of the configuration - the transverse wave representing the SCE detonation, and the oblique wave which is undisturbed explosive SD. The straight shock wave pressure is on average equal to the CJ pressure, the transverse detonation wave spreading over the SCE of the CJ pressure. The oblique SD wave pressure decreases rapidly away from the TSC triple point and finally reaches the straight wave pressure. Due to the reason the unstable detonation front surface irregularity is not considerable; the relation of average inhomogeneity size over the front surface to the average size of the front departure from the plane is as large as ten [21].

The ring detonation progress over the detonation wave front is accompanied by the increase of the ring islet, new SCE local explosions originating in the center of some islets (at the detonation products - SCE interface) before the islets merging if the SCE life time exceeds its explosion induction time. In the other case the islets merge all together with the SCE continuous layer origin as the TSC exits only until the meeting with each other in the course of non-steady process of the SD transition to the CJ detonation. However, since the SCE local explosions originate at the beginning chaotically at randomly distributed spots, the SCE continuous layer is not a constant thickness. Therefore new SCE explosions arise again nonsimultaneously. It should be noted that the average induction time of the local explosions in each next subsequently appearing SCE layer increases in comparison with that of the previous one as the SD attenuates during its transition to the CJ detonation. Due to the reason the SCE ring detonations corresponding to each new explosion spread over the detonation wave front surface and consume adjacent parts of the SCE layer with the result that the explosions have no time to occur in the parts. Just for this reason the explosions number in the detonation front decreases during the process of the strong detonation transition to the CJ detonation or to some final stationary detonation characteristic of explosive composition and charge diameter. The number decrease looks superficially as the increase of the detonation front non-homogeneity scale. The reason seems likely to be also responsible for the regularity of the unstable detonation front non-homogeneity.

It should be noted that the same mechanism of the local explosions number change governs steady scale of the spherical unstable detonation non-homogeneity. Indeed, since the spherical detonation front surface increases the free path of each ring detonation as well as their SCE islet size increases too. The process leads inevitably to the appearance of the new SCE local explosions in the center of those islets which SCE life time exceeds its explosion induction time.

So it follows from the foregoing that the mechanism of the SCE local explosion origin governs any change of the explosions number: the number decrease at the process of the SD transition to the CJ detonation and the explosion number increase in the spherical unstable detonation front. The mechanism can be also employed to interpret the second experimental finding inconsistent with the CJ and the ZND detonation theories. The finding consists in the fact that in gaseous as well as in liquid explosive unstable detonation [21] the decomposition time at the CJ detonation velocity

corresponds to the shock of the CJ pressure. In accordance with the above-presented considerations the fact means that the SCE pressure in the center of the islets on average is equal to the CJ pressure. For gaseous detonation it is easy to show that the velocity of the shock of the CJ pressure is of $\sqrt{2}$ times smaller than the CJ detonation velocity.

It follows from the foregoing that the unstable detonation front with its SCE local explosions is rather complicated. However, the front in fact can be even more complex. The matter is that there are SCE local explosions of different orders. Those which have been discussed above are the first order local explosions. The explosions are basic and they originate at the SCE-detonation products interface at the pressure level which is equal on average to the CJ pressure. The maximum amplitude of the unstable detonation front pulsations is governed by the explosions. Moreover, the existence (macrostability) of the unstable detonation wave is governed by the first order local explosions as well; if the explosions do not appear the detonation will cease.

The next order local explosions in essence govern fine (superfine and so forth) structure of the unstable detonation front [47,50]. Their origin is some manifestation of oblique wave instability: the second order local explosions - the instability of the oblique waves of the TSCs originating under the effect of the first order (basic) local explosions, the third order local explosions - the instability of the oblique wave of the TSCs originating under the effect of the second order local explosions and so forth.

Maximum order of the local explosions along with all other peculiarities of the unstable detonation wave is governed by the BD phenomena. It follows from the fact that the local explosions follow the BD since the SCE in which they originate appears only after the BD. So, as soon as the BD does not take place the local explosions will not appear.

The oblique shock waves of the TSCs in the unstable detonation front are the SDs and their pressure is larger than that in front of the transverse waves of the same TSCs, the pressure of each next order oblique SDs and consequently the initial rate of explosive energy evolution just behind of its front being larger than these of the previous order. Due to the reason the BD probability in the front of each next order oblique SD becomes smaller in comparison with that of the previous one, so that eventually the oblique SD of some higher order will be stable.

It should be mentioned that the local explosion induction times in each unstable oblique SD waves increase away from the TSC triple point since the wave pressure decreases in the direction. Usually the dependence is very strong, so that the BD and the reinitiation cease at some distance from the triple point, the new local explosion appearing in the center of the islet if the islet size is sufficiently large. In that case one can consider a sequence of the BDs and reinitiations with the beginning nearby the triple point and the end in the islet center as the single sequence.

At gaseous detonation in a strong tube the stationary detonation regime is governed by the tube diameter. The point is that the wave loses its energy at the expense of its interaction with the tube walls (friction and thermoconductivity), the wave energy loss increasing with the tube diameter decrease. It was shown experimentally that the wave inhomogeneity scale increases with the tube diameter decrease [33]. In accordance with the above-presented concept of the unstable detonation origin it means that the induction time of the SCE explosion in the wave front increases and the number of the local explosions decreases, so that at some tube diameter proper for each gaseous mixture the spinning detonation originates. It originates during the SD transition to the final stationary regime. Since the SD attenuates faster at the tube walls its front bends and chemical reaction breaks down first in the front at the wall. After the BD the unstable detonation wave front changes into the ordinary shock wave, the SCE layer originating behind its front. Some double-shocked substance has to appear owing to the inclined shock wave reflection from the wall. It is not improbable that the local explosions occur at the walls just within the double-shocked substance.

It seems likely that random local explosions appear at the walls just before the spinning detonation origin. Each explosion gives rise to a strong local divergent detonation in the initial substance. However, as noted above chemical reaction ceases in the strong divergent detonation front. From this point onwards the SCE detonation (that is the transverse detonation) spreads over the SCE-

detonation products interface in approximately a half-ring from. It is well-known that the spin head occupies only part of a tube radius [32,33]. In accordance with the foregoing concept of the detonation instability nature it means that the transverse detonation is discontinued at this distance from the wall. Specific reasons of the detonation cessation are not known. However, it stands to reason that it is also due to the chemical reaction breakdown in its front.

So the SCE transverse detonations originated at the wall are discontinued at some distance from it. However, the detonations run along the SCE layer edge around the tube diameter to meet each other. Let's assume that an explosion from the number of random local explosions appearing at the walls just before the spinning detonation origin takes place some time prior to the others and the transverse detonation waves originated by reason of the explosion break into run in both directions. Let's also assume that some local explosions appear in front one of these detonations. As it has been above-mentioned transverse detonation waves exists only until the meeting with each other during the basic SD transition to its final stationary regime. It means that all contrary transverse detonation waves of these local explosions will disappear, in this instance, except the most distant one which will continue its motion till the meeting with the other transverse detonation wave generated by the first local explosion.

Obviously the strength of the TSCs originated at different times is different. Therefore, their collisions will look as though the stronger TSC sweeps off the weaker one, that is the stronger TSC as if absorbs (eats up) the weaker one. By and large the collision process appears as the stronger TSC continuous motion and the weaker TSC death. At this very instant the spinning detonation will come into being if the explosion induction time of the SCE just in front of the SCE transverse detonation wave of the remaining TSC is larger than the time of the transverse detonation wave motion around the tube diameter.

Thus, it follows from the foregoing that the transverse wave is the principal element of the triple-shock spin configuration. It should be noted that Voitsekhovskiy, Mitrofanov and Topchiyan have shown experimentally that the wave front is unstable, spinning detonation fine structure experimentally observed being the wave kinetic instability manifestation. However, it is evident that this wave instability has in all appearance a little to do with the stability of spinning detonation as a whole. It is likely that the existence of actually spinning (that is one-headed) detonation is governed by two circumstances. In the first place, SCE explosion induction time in front of the transverse wave has apparently to be larger than the time of the wave motion about the tube axis. Secondly, it is the oblique wave instability. The matter is that, local explosions can originate behind the oblique detonation wave front and it leads to the appearance of the second order TSCs which try to travel in all directions (like ring detonations of shock-compressed explosive). However, spinning detonation can come into being only under such conditions (initial pressure of gaseous mixture, tube diameter) when the second order TSCs suffer loss of their capability of traveling in the direction from the triple point of the first order TSC (as it is often observed in the case of liquid explosives). The fact means that chemical reactions cease (that is BD takes place) behind their transverse waves. The reverse statement regarding the second order TSCs motion is also valid: as soon as the TSCs regain their capability of traveling in all directions, spinning detonation will immediately transform into pulsating one.

It should be mentioned that the spinning detonation is not the limit of gaseous detonations as it was believed earlier [25-30]. Later so-called galloping detonation was discovered [51-53]. Along with the pulsating and the spinning detonations it originates from the SD, however, at smaller tube diameters than the spinning detonation. During the SD attenuation process the BD and reinitiation take place, the number of the local explosions decreasing to zero in the course of the process at the tube diameter proper for the galloping detonation. After that a cylinder of the SCE appears inside the tube under the effect of the detonation products high pressure, the cylinder length being considerably larger than its diameter. In some induction time characteristic of the SCE state the SCE detonation originates at the SCE-detonation products interface all over the tube cross-section. It means that the detonation appeared in one or some local explosions at the interface spends far

less time to spread all over the interface than it needs to overcome the shock wave of the SCE cylinder. So the SCE detonation front occupies all cross-section of the tube and when it consumes the SCE cylinder the SD in undisturbed explosive will appear again. After that the sequence of the above-mentioned events will repeat. From that point of view the sequence looks as though it were the detonation wave one-dimensional kinetic instability.

The spinning as well as the pulsating detonations differ fundamentally from the ZND detonation. The mechanism of initial substances transformation into their detonation products at the unstable detonation is of a radically different kind from the mechanism characteristic of the stable detonation waves which is implied to be described by the ZND theory. It is absolutely wrong to treat the instability as the manifestation of some fine structure of the ZND detonation wave model [32, 33]; it is absolutely wrong to consider that the TSCs of the unstable detonation front exits on the ZND detonation chemical spike level, that is to consider that the pressure of the straight waves of the unstable detonation front TSCs is equal to the ZND detonation chemical spike pressure. In reality chemical spike, in the ZND detonation theory sense, does not exist at all in the unstable detonation; it disappears as soon as the BD takes place during the SD transition to some final steady-state detonation regime. At the unstable detonation initial substance transformation into detonation products is largely brought about by the transverse detonation waves inside the SCE, the pressure of the straight shock waves of the TSCs in the unstable detonation front being approximately equal to the CJ pressure. The BD and reinitiation of chemical reaction were shown above to be the chief causes of the SCE and the transverse detonation waves origin in the unstable detonation wave front.

The followers of the CJ theory believed that explosive at the detonation changes into detonation products during its compression inside the detonation wave shock discontinuity zone (see [4] and references in). It should be noted that the followers know nothing at that time about the detonation instability. The matter is that there is no in fact any reaction at all in the shock discontinuity zone; initial substance is only compressed inside the zone. It changes into detonation products behind the zone at shock compressed state, the state pressure being equal approximately to the CJ pressure in spite of the fact that the detonation wave travels with the CJ velocity [33,21]. The finding seems to be absolutely impossible from the standpoint of the ZND detonation theory [8-10] since the theory implies that initial substance is at first compressed without any chemical change inside the front of the shock wave of detonation velocity, the detonation wave being beyond question stable. But gas detonations to which the CJ theory was applied at first are always unstable. The unstable detonation front pulsates, that is its CJ velocity is in fact average. The characteristic time of the pulsation is equal to the average space size of the front inhomogeneity over its surface divided by the SCE transverse detonation wave velocity. During this time different part of the front pulsate non-simultaneously. Nevertheless each part of the front changes its velocity from the velocity of the strong attenuating detonation till down (after the BD) the velocity of the shock of pressure somewhat smaller than the CJ pressure in the initial undisturbed explosive.

It is well-known that at liquid explosives detonation the SCE layer appears at lateral free parts of the detonation front of any uncovered cylinder charge [21,54]. The layer originates due to the BD in the detonation front under the lateral rarefaction waves effect. It is also known that the SCE detonation can originate in the layer and reestablish the detonation wave front over the whole charge diameter. However, the question whether the SCE detonation can rotate around the charge axis or not is still open. There was some informations that the spinning detonation in some liquid explosives had been observed [54]. However, in the light of the above-stated it seems unlikely. Most likely had been observed some pattern of the process of the detonation front restoration rather than the SCE detonation rotation around the charge axis.

There are some observations which are interpreted as manifestations of the spinning detonation in solid explosives (see, for example, [55] and references in). But the data are very restricted and the problem needs to be investigated further.

4. EM SHOCK WAVE CHEMISTRY

It follows from the foregoing that the limits of the SDT, the detonation kinetic stability as well as the d_f phenomena are governed by the BD, and the BD, in turn, is governed by the regularities of EMs explosion energy evolution. A long-standing investigations of the SDT process lead to the conclusion that condensed EMs change proceeds in the course of the process through so-called "hot spots" mechanism [21,56,57]. The conclusion was shared by many investigators (see the Proceedings of every Symposiums (Int) on Detonation) and the hot spots mechanism was intensively employed for numerical modeling of detonation processes (see, for example [58-62]) over a wide range of shock pressures from a few kbar to several tens of GPa.

Two experimental lines of attack were employed in the Department search of data on the regularities of EMs explosion energy evolution: first - the investigations of the SDT process and, second - the investigations of the detonation chemical reaction zone (chemical spike time t_{cs}) both versus EMs charge properties (initial density, particle size and their structure - single crystals or fragments of broken cast, nature of fillers in pores, EMs' structure - solid or liquid, ...). It has been found out that there exists some shock wave pressure P^* characteristic of each EM charge such that EMs charge properties influence their explosion energy evolution rate under the shock effect of lesser intensity than the P^* , and vice versa EMs charge properties don't influence the regularities of their energy evolution at all under the shock effect of larger intensity than the P^* [63]. It means that surroundings influences on the regularities of EMs explosion energy evolution are dominant under the shock of lesser intensity than the P^* , that is EMs transformation proceeds through the hot spots mechanism at low shock pressures. It follows from the well-known fact that the mechanism is strongly governed by EMs charge structure. On the other hand, it means that the regularities are some properties of explosive molecules in themselves under the shock effect of larger intensity than the P^* , that is EMs molecules structure rather than their charge properties governs their energy evolution regularities.

It should be mentioned that the P^* value of each EM charge turns out to be smaller than the charge CJ pressure, that is the regularities of EMs explosion energy evolution at detonation are the properties of their molecules as well. In accordance with the inference it has been found out that the detonation chemical spike time t_{cs} does not practically depend on EMs charge properties; it depends only on the detonation wave pressure, the dependence being rather weak [64]. For example, t_{cs} for the detonation of TNT changes from ≈ 1.5 mks to ≈ 0.2 mks while the detonation wave pressure changes from 5 GPa to ≈ 20 GPa. It is obvious that the temperature of the explosive changes considerably in this same pressure interval. If the shock decomposition mechanism were the same as the mechanism under ambient conditions, the change in t_{cs} would be much greater.

In searching for an explanation for the $t_{cs}(P)$ weak dependence, a surmise on the possible break-up of explosive molecules in the course of explosive compression within the detonation wave shock front has come to mind; that is a suspicion has appeared that the ZND detonation theory concept regarding explosive molecules invariability during the compression process is invalid, the sequence of considerations being the following. It has been assumed after the ZND detonation theory founders that detonation reactions proceed in a similar way to thermal explosions. (The considerations proposed below are also valid for chain explosion regularities). It is known that during the explosion induction period (activation-stage time), which is the main part of the entire reaction time, only a small portion of the explosive decomposes but, the reaction later becomes of an explosive nature. It follows also from the theory that the activation-stage time of the explosive is a strong function of the explosive state and, on the contrary, the time for the final stages depends only weakly on the initial chemical state [48]. Logically the surmise - whether the reaction tail is only registered at detonation

is based on understanding various features of the explosion, which are that only a small part of the explosive decomposes during the explosion activation stage, and that the final stage of the explosion only depends weakly on the initial state. If this is so, it means that the process activation stage does take place during the explosive's compression within the shock front. In essence it means the following. Events which occur during the induction period of a thermal explosion take up most of the time of explosion. However, in a detonation the events proceed some orders of magnitude faster within the extremely narrow shock front zone. The final stages of both processes proceed rapidly

with times which depend only weakly on the initial state of the explosive.

It should be mentioned that it has since become clear that some experimental results testify in favour of the surmise. The point is that an induction period for detonation has not yet been observed in any of the explosives investigated. One has always registered a very sharp decrease of pressure (or particle velocity) within the chemical spike [21,65,66]. It corresponds to the maximum rate of the EMs energy evolution just behind the detonation wave shock front. Therefore, one could infer that the progress of the reaction had been conditioned by some preparatory process inside the shock front which is still beyond the reach of observation by present techniques. However, the possibility of the destruction of complex polyatomic molecules inside the shock front has been substantiated by special experiments in which samples of aromatic compounds (benzene, naphthalene, anthracene) have been recovered and investigated after shock of 1.1 – 1.5 GPa (100 – 200°C) intensity. It was found that the compounds partly decomposed ($\approx 1\%$), the destruction corresponding to the rupture of bonds of the benzene ring (see [67] and references therein). It should be noted that at the same static pressure and temperature the compounds investigated never decompose entirely [68]. At normal pressure and high temperature they decompose without breaking the benzene ring. Chemical ring condensation and hydrogen elimination happen during the process. Complete graphitization occurs when the temperature reaches $\approx 2000^\circ\text{C}$ [69]. Taking the above facts into account, one can assume that the data testify in favour of the specific action of the shock wave front, that is, the shock front effect is responsible for the unusual destruction products of the aromatic compounds observed in the experiments.

Many explosives are complex organic compounds. Therefore, the decomposition of the explosives molecules inside the shock wave front seems to be a highly probable process. The portion decomposed is not known at present. Obviously it is some function of the wave intensity and can be significant at the detonation of powerful explosives in which the chemical spike pressure amounts to ten or more GPa.

Naturally the question arises: What is the mechanism of the intrafront destruction of complex explosive molecules? There are some papers devoted to the problem [63,70-74]. The accumulation mechanism has been introduced for polyatomic molecules [71]. The gist of the accumulation mechanism is as follows. Because of a tremendous rate of material loading inside the SDZ ($\approx 10^{-13}$ s [75,76]), an excessively high translational temperature (overheat) appears at the beginning, and it is followed by the other-excitation of certain bonds. The overheat effect means a higher temperature level than the equilibrium one behind the front. The over-equilibrium translational temperature arises due to the fact that the kinetic part of the shock compression energy, which behind the shock front, is equally distributed among all the translational, vibrational and rotational degrees of freedom of the polyatomic molecules, is absorbed only by the translational degrees of freedom within the shock discontinuity zone. The maximum translational temperature overheat value is $T_{oh} = 2(n-1)(T - T_o)$ [73], where n is the number of atoms in a molecule, and T_o and T are equilibrium temperatures in front of and behind the shock wave front. It is obvious that due to the translational-vibrational relaxation process the energy of the transitional degrees of freedom is redistributed to the vibrational degrees of freedom. At first, the energy flow will be directed towards those vibrational degrees of freedom which are most easily excited. If the energy flow towards these degrees of freedom exceeds the loss owing to the vibrational-vibrational relaxation process, they will over-excite and decompose faster in the shock front than behind it, where the state is one of equilibrium.

The considerations presented above regarding the T_{oh} origin are phenomenological, however, they have been verified by direct simulation of the process of excitation of polyatomic molecules inside the shock front [73].

The origin of the translational temperature overheat is of great significance for understanding the mechanisms of the shock compression of complex molecules. The translational temperature overheat for molecules consisting of tens of atoms can be tens of thousands of degrees for shock wave intensities characteristic of the detonation of powerful explosives. At such temperatures the process of electronic excitation (activation energy 2–5 eV [77]) and even the thermal ionization process (activation energy

6 – 10 eV [78]) become possible inside the overheat zone.

Thus the non-equilibrium dissociation of polyatomic molecules inside the detonation wave shock front can proceed in three ways: through the accumulation mechanism, through electronic excitation as well as by thermal ionization. The accumulation mechanism has been developed before [71,72,79]. The decomposition mechanism through thermal ionization has not been investigated so far. As far as decomposition by electronic excitation is concerned, there are some experimental data supporting the mechanism. For example, hexogen (RDX, cyclotrimethylene trinitramine) sample recovered in special ampoules after the effect of shocks of 2.0-4.0 GPa have been investigated by X-ray photoelectron spectroscopy and paramagnetic resonance methods [80]. It has been found that shock decomposition products of hexogen differ from those of its thermal decomposition, and are identical to those of the photochemical decomposition. The data testify in favour of decomposition by electronic excitation under the shock, because it is well known that the photochemical decomposition proceeds through the electronic excitation.

Besides the aforesaid, the significant assumption of some preliminary electronic excitation of the molecules, introduced to explain the experimentally observed correlation between the electronic structure of the molecules and their detonation ability should also be noted [81]. However, the assumption has been introduced without any reliable and convincing interpretation of the excitation. But from the results obtained by us it follows that it is just the high-energy molecular collisions inside the translational temperature overheat zone that are responsible for the excitation.

It is obvious that owing to the three aforementioned ways in which polyatomic molecules can be destroyed inside the detonation wave shock front, some active particle (radicals, ions and so on) will originate. The particles behave as if they had been injected into the compressed and heated explosive. Naturally, they influence the subsequent decomposition of the explosive behind the shock front (that is, during the second afterfront stage) in a state of chemical second afterfront stage) in a state of chemical and thermodynamic equilibrium when the translational temperature overheat and overexcitation of certain bonds disappear. The interaction of the explosive molecules with the active particles originating inside the front (that is, during the first intrafront stage) is the main process behind the front. As a rule, the activation energy for this interaction is low (5-15 kcal·mole⁻¹) [78]. Because of the low value of the activation energy the decomposition proceeds extremely fast and is almost independent of the temperature change.

Thus, in accordance with the above-presented conception of the detonation decomposition mechanism of condensed explosives reaction is homogeneous rather than by the hot spot mechanism. The mechanism regularities are the explosives characteristics. The decomposition process does not depend on the initial physical state of the explosive charge (powder, pressed, cast or liquid). The process consists of two stages. The principal stage is the first intrafront stage. Its duration is equal to the time necessary for the most slowly excited bonds of complex polyatomic explosive molecules to be excited ($\approx 10^{-10}$ s). The stage begins with the SDZ of $\approx 10^{-13}$ s time duration [71,75]. The activation and non-equilibrium destruction of some explosive molecules takes place during the first stage and it leads to the fast transformation of the explosive into the final detonation products during the second stage. Since the activation and destruction are endothermic processes the pressure has to increase inside the shock front of the steady-stationary detonation wave, and conversely the pressure decreases during the second afterfront stage for the total exothermic character of the stage chemical reactions.

So, the first stage largely governs the detonation decomposition regularities of condensed explosives. Unfortunately this stage has not been investigated yet. Some Raman spectroscopy techniques have been developed by French (see [82] and references therein) and American scientists (see [83,84] and references therein) for the investigation of shock processes. However, the spectral and time resolution of the techniques is for the present still insufficient. Indeed the spectral resolution of 10 – 20% and the time resolution of about 1 ns have been achieved. It is evidently too low a resolution for the study of the problem discussed since the entire time of the intrafront stage is even smaller. Therefore, one now needs elaboration of theoretical and experimental methods of at least picosecond resolving

power. In that case one will have the possibility of studying the stage in detail. Obviously, until the problem is solved the chemical pathway controlling explosive energy release will be unknown. In this connection the femtosecond spectroscopy [85] is noteworthy; the matter is that the first mention was already made of its use for the problem study [86].

In spite of the fact that the detonation decomposition mechanism of condensed explosives presented above is still mostly qualitative, it is possible even now to advance a certain hypothesis: the highest detonation ability corresponds to the explosive, the electronic structure of which changes at compression in such a way that it favours the explosive molecules electron excitation, as well as explosives in which molecule bonds excitation times differ considerably from each other. However, the problem needs some further investigation. Probably it will be solved when the chemical pathways of molecules inside the detonation wave shock front are studied from the very beginning of explosive loading.

5. CONCLUSIONS

1. Thus, four novelties have been introduced into the detonation phenomenon investigations during last 50 years since the ZND theory advent. Two of them are experimental; first - the unstable detonation discovery; second - the elucidation of the cause of liquid explosives unstable detonation velocity weak dependence on charge diameter at considerable value of their failure diameter. These experimental findings have resulted in the discovery and introduction into detonation theory two new theoretical notions. One of them was named the breakdown (BD) of chemical reaction; the other - the shock discontinuity zone (SDZ). The SDZ denotes the whole process of complex polyatomic molecules excitation and destruction within shock wave front (10^{-10} s). In spite of the SDZ width (10^{-13} s) is considerable smaller than that of the shock front, the whole process was named the SDZ since the process main cause is explosive molecules translational temperature overheat originated just inside the SDZ owing to tremendous rate of substance loading within the zone.

The BD and the SDZ are interrelated in all detonation phenomena; the BD as if follows the SDZ. The SDZ is characterized by the endothermic processes of complex polyatomic molecules excitation and destruction inside the detonation wave shock front and the BD manifests itself behind the front where the exothermic processes of interaction of excited explosive molecules and active particles originated within the front proceed. As this takes place, the larger is the wave intensity, the larger number of the active particles originate inside the detonation wave shock front and at the same time the higher explosive shock compression equilibrium temperature is. It means that the larger is the wave intensity, the higher the explosive energy evolution initial rate is behind the detonation wave shock front and therefore the less probable the BD is. In the contrary, the weaker is the wave intensity, the lower the explosive shock compression temperature is and the smaller number of active particles originate inside the detonation wave shock front. It means that the weaker is the wave intensity, the slower the explosive energy evolution initial rate is behind the shock front and therefore the more probable the BD is. Thus, the more the SDZ manifests itself, the less probable the BD is. And in contrast, the less the SDZ works, the more probable the BD is.

The foregoing means that the BD can occur the most easily in the explosive which energy evolution rate behind the shock wave front is slow (these are usually weak homogeneous explosives - practically all gaseous mixtures as well as some liquid explosives) and the most difficult in the explosive which energy evolution rate behind the shock wave front is fast (these are usually power explosives).

Detonation waves in homogeneous weak explosives are usually unstable, chemical reaction ceasing and appearing continuously and nonsimultaneously over their detonation wave fronts [21,47,50]. The explosives detonation failure diameter theory has been elaborated [42,43]. According to the theory the failure diameter is governed by the depth till which the BD wave originating at the charge lateral free surface can spread over the detonation front to the charge axis.

Detonation wave front in power homogeneous explosives is stable; the BD does not take place in their detonation waves fronts during their strong detonation transition to the CJ detonation at the SDT process. However it happens at the charge lateral free surface. It has been shown experimentally

that the BD governs the failure diameter nature of both power and weak homogeneous explosives with stable detonation fronts [21]. However, these explosives detonation failure diameter theories have not been developed yet.

Detonation front in solid heterogeneous explosives (cast, pressed, ...) has to be stable (in the kinetic instability concept sense) since the BD does not usually take place over the detonation wave front. However, it should be mentioned that chemical reaction ceasing and reinvitation in the detonation wave front at the charge lateral surface have been observed in the case of some cast explosive charges [54,55,87].

2. The problem of a detailed mechanism of detonation is still a central point in the explosion science. To describe sufficiently enough various detonation processes some models of condensed explosives detonation are used. The models are based on different explosive shock decomposition mechanisms. Common short-comings of the model are the fact that each of them uses the same mechanism to describe explosive response to the shock effect within a wide region of pressure from units up to tens of GPa. It is in this way that the hot spots decomposition mechanism in its various versions is used most widely at present [58-62]. However, from the foregoing follows that shock decomposition processes at low and high pressures proceed qualitatively differently. For instance, detonation decomposition of any explosive proceeds equally in both liquid and solid states at pressures larger than the P^* characteristic of each explosive [63]. (P^* is smaller than Chapman-Jouguet detonation pressure.) This means that the hot spots mechanism governed by the solid explosive's initial state does not work at high pressures. It works at low pressures ($P < P^*$, region I). In high pressure regions ($P > P^*$, region II) explosive decomposition is not influenced by the initial state; in the region the regularities of EMs explosion energy evolution are some properties of explosive molecules in themselves.

Thus, it is not correct to describe any explosive shock decomposition in wide pressure regions by only one mechanism. On the other hand, it is also incorrect to develop individual models for different pressures because the transition from the first pressure region to the second one often takes place at some detonation process progress. For instance, it occurs at the most frequently modeling process of detonation initiation by shocks of various intensity and time. Hence, one needs some joint model comprising explosive decomposition features characteristic of each pressure region.

In order to develop a detonation computation model with great predictive power, it is required that the physical model include all physical and chemical processes in explosive under the shock effect. A model of this kind has been elaborated [74,88].

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