Physics of reological explosion

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Abstract. The paper presents the results of experimental research of patterns of relationship and features of reological explosion. Revealed and studied traces at materials, which were in contact with exploded bodies. Presented and analyzed rapid filming of this explosion. Established and described it’s mechanism.

1. Introduction

The situation in the field of researches of reological explosion becomes very strange – there appeared many inconsistent reports about discoveries of a lot of patterns of relationship and features of reological explosion, including the nature of this phenomenon, as it is, along with full ignoring of all, what was done in this field before 1982, although main patterns of relationship and features of reological explosion were revealed namely before this year. The term «reological explosion» is using as if it is spontaneously generated. Such situation demands some preliminary notes.

Reological explosion is one of the phenomena which are arising in solids when its plastically deformed under high pressure. The results of simultaneous action of pressure and plastic deformation are not a sum of its solitary actions, what causes occurrence of a lot of phenomena, which are heavy explainable from generally accepted points of view. Already M. Carey Lea carried out the experiments with shear deformation of solids under pressure and have found this case. He carried out a lot of qualitative investigation [1, 2], but could not to do a quantitative ones, because of absence of technical possibility to construct the apparatus with required characteristics. Such possibilities obtained P.W. Bridgman, who carried out infinite volume of investigations in high pressure in whole [3, 4] and jointly with shear, in particular [5, 6, 7], but did not mentioned, for some reasons, the works of M. Carey Lea, although repeated his observations. P.W. Bridgman does not investigated reological explosion as self-contained phenomenon, because on the one hand, his apparatus with two pairs of anvils gave no possibility for revealing of any patterns of relationship proper to this phenomenon and on the other hand, he does not noticed anything interesting for researching, considering that it was a harmful disturbance in his works. Numerous Bridgman's followers held anyway his main direction of researches [8-20]. The first, who investigated the reological explosion comprehensively as the self-contained phenomenon and gave it the name «reological explosion» were T.Gorasdovskii and V. Shienok [21-25]. They revealed main patterns of relationship and features of reological explosion and carried out the researches to the stage of practical applications, including industrial and scientific [26-32]. M.Yaroslavskii took a part in some theirs works [33, 34] and published later the monograph [35] as result of this activity. This monograph became the first and sometimes the only source of information about reological explosion for all investigators who’s work concerned anyway the field of
high pressure and shear. The author claims, that systematic researches of reological explosion never carried out and just nothing was known about this phenomenon, which was not studied at all before appearing of this monograph, in spite of the works of T.Gorasdovskii and V.Shienok, mentioned above. Moreover, there are not mentioned the works of the author himself [33, 34], which were done at the same apparatus, as was used by T.Gorasdovskii and V.Shienok, and which are the solitary result (except the Ph.D. thesis, replicated this works), of his work not only on the topic of denomination of monograph, but in the field of high pressure on the whole. It don’t contain any mentioning not only of the works on topic of it’s denomination [21-28], but the works in the field of shear under pressure on the whole, where described the best apparatuses and mostly interesting and useful investigations [8-13, 15-20, 36-38]. The monograph do not contain information about technical requirements for high pressure-shear apparatuses, quite perfect one of which exceeds manifold in all parameters all existing ones [38]. The information about the used apparatus, which was worked out by T.Gorasdovskii with consider of his previous experience and worked in practical construction by A.Mishin, (the order of authors in original title of the patent [39]) is not correct. The term «reological explosion» is used by the author as for the first time. This peculiarities of the monograph leads to problems for predecessors, such as faults in experimental technique, due to using of simple apparatuses, reiteration of already done and aberrations in interpretation of obtained results.

Apparatus for investigations of reological explosion must not give incorrectness more, than some angle minutes, because the minimal angle of rotation of the anvil, which is necessary for explosion is about one angle degree. It means, by-turn, that the mismatching of axes of symmetry of working surfaces of anvils and axis of rotation of moving anvil, as well as perpendicularly of said surfaces to said axes and backlashes of any kind under shock loading must not be more, than some angle minutes. The investigations with apparatuses, which are not fulfilling mentioned demands, becomes senseless. The researchers, which reported recently about investigations of relogocal explosion’s features, have not at theirs disposal the apparatuses with characteristics, mentioned above. As a result, appeared descriptions of apparatuses, the «best» of which even have not rotating anvil [40-45]. One who, consider with a glance of existing information, the results of researching of features of reologocal explosion with apparatuses which have no rotating anvil can see, that said results are characterizing the features of apparatuses, but no features of reological explosion. It is known even from practice of high pressure industry, such as diamond synthesis industry, that one-axis loading of solid leads to explosion only in presence of asymmetry of the field of the stresses of any kind in said solid due to misalignment, inhomogeneity, or something else. This work and other works of the authors [46, 47] gives very useful information for those, who intends to continue the study of such interesting phenomenon, as reological explosion and helps them to find the right way.

2. Experimental Procedure
The studies were carried out with the apparatus and instruments, which are described in the works [46, 47].

3. Results and Discussions
First object of study was the anvils. The working surfaces of the anvils was flat an had only straight parallel traces of grinding with dimensions less, than a few microns. The exploding material was chalk. Traces of grinding which are visible at photos, can be used, as reference marks.

The general view of the working surface of steel (HRc55) anvil after explosions (fig. 1, a) and the surface of hard alloy (80 % WC + 20 % Co) anvil (fig. 1, b). Reological explosions are effecting not only on the surface of anvils, but on the inner structure of it’s material. The fracture surface of steel anvil, which was broken after some explosions (fig. 1, c). One can see segment-formed region with dramatically changed structure under working surface of anvil. Such regions were formed step-by-step with increasing of number of explosions. Dimensions of said regions depended on the number and force of survived explosions. The material in this region had a hardness about HRc 5-8 less, then hardness of unchanged material and was weakly bonded to it. The form of this regions shows the distribution of pressure over the surface of the anvil.
Figure 1. Working surface of steel (a), hard-alloy (b), fracture of steel anvil (c).

Figure 2. Kinds of damages: straight and pseudo-straight scratches (a-e), curved scratches (f), fringe-formed scratches (g), slingshot-formed scratches (h), tick-formed pits (j), rounded pits (k), right-angled pits (l), strip of melting (m)

A lot of manifold traces appeared at this surfaces after explosions. The traces divided at two classes: «waves» and damages such as scratches, pits, strips of melting. The dimensions of the traces
depends on the hardness of anvil’s material: higher hardness – smaller dimensions. The «waves» are better visible at the steel anvils due to its comparatively low hardness, but scratches are better visible at the hard alloy anvils because the «waves» are small and don’t obstruct examination of damages. Orientation of damages is very different – from random to radial (fig. 2).

«Waves» picture gives a lot of information about character of processes in exploding material and required detailed study. There were used spacers of comparatively soft and plastic materials with this aim. The spacers were made of Fe-Ni-Mn alloy or Al-Cu-Mg alloy and were placed at the surface of bottom anvil. The spacers decreased the force of explosions – for example: it was necessary to increase the pressure by 20-30 % when used 1 mm spacer of Fe-Ni-Mn alloy to keep the force of explosion without change (fig. 3).

Figure 3. Explosions of different forces and directions at Fe-Ni-Mn and at Al-Cu-Mg spacers

«Waves» pictures of 5 explosions of different forces and trace of pressurizing of chalk to maximum pressure without explosion, which were formed at Fe-Ni-Mn spacer (fig. 3, a). «Wave» picture of directional explosion with Fe-Ni-Mn alloy spacer at the anvils, one of which had a radial groove (fig. 3, b). «Wave» picture formed with explosion of chalk at Al-Cu-Mg spacer (fig. 3, c).

The ridges of «waves» are perpendicular to the directions of its propagation. Dimensions and quantity of «waves» depends on force of explosion: higher force of explosion – smaller «waves» and greater it’s quantity. The square of damaging of spacers depends on force of explosion too: stronger explosion – larger said square.

Second object of study were the exploding materials. The tablet was formed from material under study when it was subjected to the pressure and looked like lentil. The thickness of tablet depends on mechanical characteristics of material and value of pressure. The thickness of tablet than decreased under shear deformation and stabilized at any value in absence of explosion, or decreased unevenly about twice during explosion.

The inner structure of the tablet have a lot of layers, which are laying under ± 45° to the axis of symmetry of the tablets. The fracture surfaces of tablet are similar to the cleavage surfaces in crystals. The microlevel structure of tablets is same, as the structure of pressed micropowder as opposed to continuous structure of starting material and therefore the tablets are decomposing to suspension in water. This structure is a result of explosion, because not exploded tablets have homogenous structure. It was revealed, that explosiveness of materials is very different. Metals are not exploding under any conditions, whereas dielectrics are exploding more or less strongly under conditions, which are depends on it’s mechanical characteristics, type of chemical bonds in molecules and it’s structure. Good explosiveness, for example, demonstrates CaCO3 in all forms, bad – NaCl, whereas ordinary glass don’t explode under available conditions. The tablet, which is forming from glass under high pressure and shear deformation, looks like a pillow with semi-transparent thin slimy pillowcase filled with micron-sized powder. Said «pillowcase» acting as lubricant, which protects the inner part of tablet from plastic deformation and thus preventing the explosion. Explosiveness of dielectric decreased when metal powder was introduced in it and disappeared if quantity of metal was more,
than some ten of weight percents. Chalk, for example, no exploded under any conditions, if more than 20 % weight of Mo powder was added to it. Metal added to dielectric formed plain flakes, which dimensions and quantity was depended on concentration of metal. Flakes merged to layers perpendicular to the axis of rotation of anvil, when quantity of metal was enough for disappearing of explosiveness of dielectric. The chemical activity of added metal, which survived reological explosion, increased. For example: molybdenum which was extracted from exploded chalk colored water to dark blue after some hours, while control Mo powder no colored water at all.

Figure 4. High-speed films of explosions

The material, which is flying out at the explosion have a form of dust, what one can see at the high-speed films of explosions (figs. 4), speed of filming 10,000 frames/sec. This dust have very special spectrum of particles dimensions and forms. Most of the particles (about 90 %) have dimensions of 1-2 microns and are just isotropic.

Figure 5. The damaged sheet of brass (a) and damaged sheet of organic glass (b)

Flying dust damaged materials, which were placed at it’s path. The damaged sheet of brass with thickness of 0.5 mm (fig. 5, a) and damaged sheet of organic glass with thickness of 4.0 mm (fig. 5, b), where the holes with traces of melting are well seen. The sheets were at 10 cm from center of the anvils.

Analysis of experimental data generates some questions, which can not be answered from the point of view of contemporary common knowledge in physics and chemistry.

1. How can explode chemically stable solids under room temperature and how can energy of such explosion be twice greater, than energy of explosion of TNT?
2. Why some solids explodes, and others do not?
3. Why reological explosion can occur only if the pressure is higher [22, 46], then some initial value?
4. What is the nature of «charged» state of solid, which generates «related» reological explosion [22, 46], which is observing only under the pressures higher than some critical value?
5. What is a source of enormous speed of products of explosion, if one have in mind, that speed of piston of hydraulic press can not excide some tens of m/sec in the case of instant releasing?
6. What is a cause of hard electromagnetic radiation and any radiation at all with energy, exceeding the maximal energy of chemical bond, in absence of any strong fields?

7. How can be formed scratches at the anvils of any form, except right radial and annular even in assumption of presence of superhard inclusions in exploding material, which are absent in reality?

8. Why products of explosion have a form of dust with narrow range of dimensions?

9. And finally: what is the nature and mechanism of reological explosion?

All this questions can be answered without any stretches and guess-works in assumption, that atoms can form some analogs of molecules with bonds at electron shells, following after external shell. Let’s name such analogs as «super-molecules» for simplicity of exposition. It is known, that chemical bonds between atoms are forming when colligation of electrons of it’s external shells becomes energetically profitable. It is necessary to expend some energy for convergence of atoms to the distance, at which forming of the bond becomes possible and than some energy liberates in process of forming of the bond. The bond will be stable if expended energy is less, than liberated. The bond will exist until the atoms will get, as a result of any impact, some energy, which value exceeds the value of liberated energy.

No obstructions are for same processes with participation of electrons of inner shells. The difference in this case will be only in the values of energies and possibility of existence of stable kinds of bonds. Some limitations are arising only due to the features of filling of electron shells. There are some means for convergence of atoms, one of which is pressure. Pressure permits to converge atoms up to deformation of electron shells, but it can generate any effects, such as phase transitions, only at the level of external shells at technically achievable values. This effects are mostly reversible and are disappearing after decreasing of pressure, because it is necessary to brake existing bonds before forming new ones for saving of new structure. The pressure as such, at technically achievable values, can not result in breaking of bonds between atoms and some other factors are necessary. Plastic deformation is one of such factors. Plastic deformation under normal conditions leads to breaking of interatomic bonds and to fracture of solid as a final result. The process of plastic deformation is changing if the deforming solid is under pressure. Pressure is impeding the distance between atoms of deforming solid to increase and new bonds can form after breaking of the existed ones. The process of breaking and forming of bonds becomes continual and the solid can be deformed without fracture if the pressure is high enough. Additional features are arising due to non-uniformity of distribution of stresses in the solids under pressure, especially in the case of it’s deformation. The cause of said non-uniformity is internal friction, which is immanent attribute of any solids. This non-uniformity can cause the local stresses, which value creates the possibility of convergence of some atoms to the distance short enough for interaction of electrons of inner shells, which can result in forming of bond between atoms with liberation of some energy. Such bond can exist until it will stay energetically profitable. This profitability is maintaining with the pressure, which is holding the atoms at the required distance and creating eo ipso the potential barrier. Some energy is releasing during formation of the bond, and so the difference between values of said barrier, which are necessary for forming and for saving the bond is arising. Thus, this bond is metastable and can exist in material under pressure which is exceeding some minimal value. The bonded atoms just are the components of «super-molecule». This «super-molecules» can associate in clusters with dimensions depending generally on the value of pressure and on sorts of atoms. The consequence of origin of clusters is local decreasing of a stress. Appearance, existence and behavior of such clusters with aggregate of features of changing of state of the material under pressure determines all observed effects of reological explosion. The matter is obtaining some energy when pressure is applying and is returning it when pressure is releasing. If the matter is gaseous, said energy can transform into kinetic form. Matter have some form of order, which depends on state of aggregate. Crystalline solids have long-distance order, liquids have short-distance order and gas have no order. The order exists due to structure bonds between atoms or molecules, which are a result of it’s interaction. The atoms or molecules of gas have in first approximation, only impact interaction and are moving free until any impact will occur. The kind of order under pressure survives, or becomes higher and is returning, as a rule, to initial state after
decompression. The behavior of matter under pressure, combined with plastic deformation depends on the values of pressure and the bond energy of molecules of the matter, namely: the structure bonds only are breaking, if energy of compression is lower, than bond energy and inter-atomic bonds are breaking if energy of compression is higher. The order disappears, atoms becomes quasi-free and state of the matter becomes quasi-gaseous in the second case. The bonds are recovering, when the pressure is decreasing, but not to initial state and not instantly. Some time is necessary for forming of this bonds. This time depends on kind of atoms, type of bonds, the values of pressure and deformation. The matter is acting as a gas if the time of decreasing of pressure is short enough and is less, than the time of forming the bonds. So, it will fly away by the way of dust, as a gas after short-time releasing. The dimensions and speed of the particles of this dust will depend on the same factors, as in the case of the time of recovering of the bonds. The dimensions of the particles can be as small, as dimensions of atoms if the pressure is high enough and the speed is the same, as the speed of free outflow of a gas from any storage.

Now it is possible to explain the observed experimental results and the nature of reological explosion. The material, placed between the anvils, begins to crush and/or to deform and to move in radial direction, when the load is rising. The intension of movement of the material is minimal in the center and maximal at the periphery. Friction is obstructing to this movement and stress in the center becomes higher, than at periphery. Balance between the stress and friction is setting in each moment under certain value of load, but the material is moving, when the load is rising (until the surfaces of anvils are remaining flat). So, the material at periphery with lower stresses becomes the barrier, which is holding the material with higher stresses in the central region. The difference between this stresses can be manifold and named as coefficient of multiplication of pressure at Bridgman’s anvils. This difference is limited if the surfaces of anvils are not plane for any causes (deformation of anvil’s material, for example).

The situation, in which the stresses in the central region can exceed the energy of bonds between the structure elements of the matter without it’s fracture, becomes possible. Meanwhile, the positions of the atoms in the central region are shifting not strongly, the order is just not disturbing, the interatomic bonds are recovering in very short time and the material is returning just to initial state (with moderate grinding), when the pressure is decreasing. The material at peripheral region is grinding, i.e. the ranged regions becomes smaller in process of loading, but positional relationships of atoms in ranged regions are not shifting notably. So, material survives compression-decompression without any effects, except grinding.

The character of processes in material is changing strongly when shear is adding to high pressure. The anvils are acting like simple mill, if the pressure is not high and shear enhances the degree of grinding only. The shear deformation becomes plastic and grinding of material is changing to flowing if the pressure is high enough. The bonds are breaking, new bonds are forming and positions of atoms are shifting strongly in this process, as mentioned above. Some time is passing between breaking and forming of bonds and so, some quantity of non-bonded, i.e. quasi-free, atoms are existing in each moment. This atoms creates a local instability, which leads to local rupture when pressure is decreasing. The quantity of non-bonded atoms is increasing while the order is losing with pressure due to decreasing the difference between energies of bonded and non-bonded atoms and so, instability of all material is arising and increasing. Majority of atoms becomes non-bonded if the energy of compression becomes comparable with the bond energy of material. Moreover, the material becomes quasi-gaseous due to loss of order and can fly away like a gas if the pressure drops so fast, that the bonds will not be in time to recover. So, the material at the anvils in this situation is like a gas under pressure in a vessel, where the role of wall plays the periphery material and the role of gas plays the material in the central region. It becomes possible to explain the observed features of reological explosion, if one have in mind the possibility of forming of «super-molecules» and it’s clusters, mentioned above, and to get the answers to the question, put above.
4. Conclusion

- The explosion is rapid (with velocity, equal or exceeding velocity of sound) changing of structure and state of material, having excess energy in comparison with average heat energy, which is attended by transformation of this energy into kinetic energy of products of said changing.

- Pressure gives such energy to material and plastic deformation changes it’s structure. The changed structure can turn out stable only under pressure in some conditions and will break if the pressure will decrease. Breaking of the structure will be as rapid, as rapid will be decreasing of the pressure. The excess energy of material will release in heat and kinetic forms. The explosion will take place, if the pressure will decrease with a rate, comparable to the velocity of sound. The triggers of such rapid decrease are clusters of «super-molecules», which are creating local breakings and drop of ruggedness of material due to its’ disintegration in process of plastic deformation. No chemical reactions or heating are need for such kind of explosion. The energy of explosion have no limitations, which is specific for chemical explosives, because the source of this energy is infinite external pressure, while the source of the energy of explosives is internal and limited, because the energy of chemical bonds have maximum, which can not be excided.

- The ability of materials to reological explosion depends on nature and parameters of inter-atomic and inter-molecular bonds, which determines the value of energy, which there is possible to give to material, the value of inhomogeneity of distribution of stresses and minimal time, which is necessary for recovering of crushed bonds after disappearing of crushing factors. The more energy of bonds, the more energy is possible to give to material without full breaking of it’s structure. The more the quantity of energetic levels, which atoms have to overcome and the larger displacement of atoms, which is necessary for revivification of original structure, the more time is necessary such process. So, the matters with simple one-level structure, which consists of one sort of atoms have minimal ability to explosion, while the matters with complex many-levels structure, which consists of atoms of many different sorts, have maximal ability to explosion.

- Specific properties from the point of view of ability to explosion, have metals. Metallic type of bond covers all volume of metallic solid and have very short recovery time and therefore the pressure, which gives to solid an energy manifold greater, than bond energy and which drops very rapid, is necessary. There is no technical possibility to reach such conditions statically, but it is possible dynamically with high-speed impact, for example. Metal solid will convert in this case into very fine powder with particle dimensions of atomic scale, which have high kinetic energy.

- Reological explosion can occur, if energy of compression of the matter is higher, than energy of any bonds, which exists in it. Only breakage of material can occur in process of deformation, if said energy is lower, than bond energy.

- The «charged» state is the result of arising of clusters of «super-molecules» in the solid, which are metastable until the pressure is high enough and which are breaking down and are creating local ruptures, when the pressure falls down. So, clusters of «super-molecules» are playing the role of detonators, which are dispersed in the volume of the solid, which is able to explode and are actuating simultaneously in all volume, when pressure drops. The explosion, as result spreads randomly in all volume of solid.

- The force of 100 kN (or one-sided pressure of 10 kbar, acting at isometric body), is necessary for acceleration of 2 g (mass of calc tablet) up to 1000 m/sec at the distance of 1cm (the time of passing of this distance is 20 μs). This force must be perpendicular to the force of press in the case of explosion at the anvils. Said pressure and pressure between anvils are equal-ordered. The pressure between anvils is not uniaxial, is acting in all directions, including the perpendicular to the force of press (quasi-hydrostatic with correction on inner friction) and so, can cause acceleration of the matter between anvils up to speed with a value from hundreds to thousands m/sec. It is good explanation for observed average speeds of particles, but is not explanation at all for maximal observed speeds of hundreds km/sec, because pressure of some Mbar is necessary in such a case. The assumption of existence of clusters of super-molecules gives simple explanation: the kinetic energy of the accelerated matter is a part of energy of said clusters, which is liberating in process of it’s disintegration. The pressure drops,
when the matter is flying out, because the speed of piston of a press is very low versus a speed of process of explosion. For example: the speed of piston of used hydraulic press with mass of piston of about 500 kg is not exceed 0.5 m/sec in the case of instant releasing and can be ignored in consideration of the process of explosion. Process of flying out of material is lasting until pressure will drop to the value, which is insufficient for existence of quasi-gaseous state of matter. So, a part of the matter, which was not in time for fly out, returns to ordinary state and forms the residuary tablet between anvils.

• Electromagnetic radiation is a consequence of accelerated motion of an electrical charge. The electron, as charged particle can move with acceleration in three cases: 1 - quantum transition between energetic levels, 2 - movement in electric field, 3 - interaction with obstacle, i.e. – with a matter, which have a velocity different from velocity of this electron. The efforts of explanation of occurrence of electromagnetic radiation with energy more, than some electronvolts during reological explosion from generally accepted positions leads to conclusion about it’s impossibility, because: 1 – quantum transitions of electrons of first shell have energy about some electronvolts, 2 – electric field can not exist in space between electrically connected metallic bodies, 3 – energy of particles with average speed of some km/sec corresponds to energy of some electronvolts per atom and can not transform to energy of hard radiation.

• The origin of hard radiation have a simple explanation from the point of view of existence of clusters of «super-molecules». The bond energy of such formation can have a value from hundreds to tens of thousands of electron-volts. This energy is releasing in process of disintegration of said formations in electromagnetic and kinetic forms. So, there are two sources of radiation, which differs with parameters: 1 – direct radiation with discrete spectrum and diffused upper edge due to quantum transition of electrons in mentioned formations, 2 – secondary (impact) radiation with continuous spectrum and sharp upper edge which is a result of impact interaction of flying particles with any obstacles, such as other particles or molecules of air gases. Parameters of secondary radiation are determining with velocities of particles and have total correlation with the spectrum of this velocities.

• The scratches with smooth edges can be formed at the surface of material only with a material, which have a hardness, at least by an order of magnitude greater, than hardness of scratched material. The material of anvils is hard alloy, which Knoop hardness is about 15 GPa and so, scratching material must have a hardness about hundreds GPa, i.e. it must be diamond, or something like it. No such inclusions was revealed in exploding materials. Thus, even presence of right scratches, say nothing of traces of every other kind, can not be explained from generally accepted positions, however it have very simple explanation in assumption of existence of clusters of super-molecules: there are a traces of it’s disintegration. Energy, which releases in process of said disintegration is more, than enough for accelerating ambient material up to speed, at which this material can crush any other materials. Concrete form of damages of the surface of anvils depends on the value and direction of velocity of the matter, which is a sum of radial velocity of all mass of exploding material and local velocity of the mass of disintegrated cluster.

• Two processes takes place in the solid during reological explosion: free movement of elements of the matter and recovering of crushed bonds between this elements. The process of recovering of bonds is possible until the distances between elements are small enough. This processes leads to forming of moving particles and have no preferred directions. The time of forming of this particles is just equal for every ones, because it is the time of explosion, which occurs in all volume of solid contemporaneously. So, the particles are small, just isotropic and similar.

• Everything above-said leads to next conclusion. Reologial explosion is rapid transformation of the energy of compression of the matter, on conditions that this energy is higher, than bond energy of this matter, to kinetic energy of components of this matter. The triggers of explosion are clusters of super-molecules, which are arising in the matter in the case of it’s plastic deformation under the pressure.

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