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Opredeleniye otnositel'noy rabotosposobnosti vzryvchatykh veshchestv metodom ekvivalentnykh zaryadov po velichine rasshireniya v bombe Trauzlya

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DETERMINATION OF THE RELATIVE EFFECT OF HIGH EXPLOSIVES BY THE METHOD OF EQUIVALENT CHARGES BASED ON THE MAGNITUDE OF EXPANSION IN A TRAUZL BOMB

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Tests performed in a Trauzl bomb are the oldest method of evaluating the relative effect (fugacity) of explosives (VV).

The Trauzl bomb is a massive cylinder 200 mm high, with a 200 mm diameter, cast of pure lead. The bomb has a 25 mm diameter cylindrical shaft extending along the axis of the bomb to a depth of 125 mm. An explosive charge (normally 10 g.) with an electric detonator is placed at the bottom of the shaft. The upper part of the cavity not occupied by the explosive is filled with sand. Explosion of the charge expands the bomb. The amount of expansion beyond the calculated volume of the cylindrical aperture (61 - 62 cm^3) is a measure of the productive capacity of an explosive. Sometimes a 30 cm^3 deduction is made from the calculated expansion, as an allowance for the effect of the electric detonator.

Detonation of 10 g of an explosive of low specific power produces an expansion of 150 - 250 cm^3. Medium-power explosives produce an expansion of 250 - 400 cm^3; High-powered explosives expand to 450 - 600 cm^3.

Article [1] describes experiments and some conclusions relating to the mechanics of behavior of a charge within a Trauzl bomb. It was determined that the process of expansion of the lead casing extends over the period of 0.4 - 0.5 msec following the detonation of the charge; discharge of gases occurs 0.4 - 0.5 msec after the instant of explosion, that is, after the completion of expansion of the chamber. The absolute magnitude of work of plastic deformation of the lead bomb was determined by means of simple calorimetric measurements. This provided a means of establishing a direct relation between the magnitude of expansion in the bomb and of the corresponding work performed.

This paper analyzes the relation of expansion to the true relative productive capacities of explosives. (Let us remind you that productive capacity is the work which can be performed by a unit weight of an explosive). It is often assumed that these two values have a simple linear relationship. For example, let us assume that a 10 g. charge of some explosive produces a 200 cm^3 expansion in the bomb, while a 10 g. charge of another explosive - a 400 cm^3 expansion. The ratio of expansions is 2. It is frequently assumed that, in conformity with the ratio of expansions, the ratio of productive capacities of these two explosives is also 2 and that, under all conditions, including practical applications in the field, the explosion producing a two-fold expansion in the Trauzl bomb is capable of accomplishing a double amount of work. However, a more detailed analysis shows that this simplest assumption calls for a considerably more precise definition.

The method of equivalent charges described below shows that, for the specific case under consideration, productive capacity increases ~1.7 times.

The essence of the equivalent charges method consists of determination of an equivalent charge of Ammonite 6, producing the same expansion as the selected explosive. The latter may be a 10 g. charge (as required in the standard test), or it may depart somewhat from that weight. A constant volume of the charge is an absolutely rigid requirement of the method of equivalent charges. As a matter of fact, when the shape of the charge is changed, no attempt is made to retain any similarity. A taller charge would produce a greater deformation of the lead, thus a larger cavity would result from an equal amount of energy expended [1]. If the requirement for constant height and volume of charges is met, equal amounts of work produce identical expansions, $A = aC$, where a - - work capacity of the explosive (work performed by a unit weight) and C - weight of the charge. Let us call the weight of a charge of a given explosive C_x and let $C_э$ (equivalent) denote the weight of an Ammonite 6 charge which produces an equal expansion. Let a_x denote the work capacity of the selected substance and a_6 - work capacity of Ammonite 6.

Since the weights of the charges (in adhering to constant volumes) are selected so as to produce equal expansions, it follows that the amounts of work performed are also equal, $A_x = A_6$ or

$$a_x C_x = a_6 C_э, \quad \text{or} \quad \frac{a_x}{a_6} = \frac{C_э}{C_x}$$

Ammonite 6 is used as a standard because it has the highest detonating capacity of all the widely used industrial Ammonites. Of course it is practically inconvenient, having tested a charge of a given explosive weighing C_y, to select for each case the corresponding weight of Ammonite 6 which would produce the same expansion. For this reason we have plotted a curve, representing the relation of expansion in a Trauzl bomb to the weight of charge of Ammonite 6, which was used thereafter. As mentioned previously, in observing a requirement of similarity, it is necessary to use charges of constant volume and height; with this requirement we could only change the weight of the charge by changing its density. In this connection Ammonite 6 is also particularly convenient as a standard because its specific heat is practically independent of its density (as an example, the specific heat of Trotyl increases materially with an increase in its density). It is true that any explosive of greater density has a higher initial pressure of explosion gases, which produces a slight increase in the expansion of the bomb; However, this additional effect does not exceed 2 - 3 % of the total expansion and can be neglected.

Table 1.

Bomb expansions ΔV produced by explosions of Ammonite 6 charges of various weights C_6 and with different densities ρ.

C_6, g	ρ, g/cm³	ΔV, cm³	$\overline{\Delta V}$, cm³
6	0.6	214	217
6	0.6	220	
8	0.8	291	296
8	0.8	301	
10	1.0	406	393
10	1.0	380	
11	1.1	425	435
11	1.1	445	
12	1.2	476	482
12	1.2	476	
12	1.2	494	
13	1.3	488	510
13	1.3	533	

We carried out the practical tests in accordance with the following specifications: a weight of 10 g. was used during the standard test. With the density $\rho = 1.0$, the volume of the charge was 10 cm^3. Allowing for the volume of the electric detonator, dimensions of the charges were as follows: diameter d = 25 mm and height h = 21.4 mm. The weight of Ammonite charges varied between 6 and 13 g. in the course of our experiments; densities of charges also varied, as explained previously; the diameter and height remain constant ($d = 25$ mm and $h = 21.4$ mm). To maintain more accurate control over density and initial volume we used a slight modification of the standard procedure: in our tests the explosive was poured directly into the bomb cavity and was then compacted to the required density with the aid of a special device; a well to accomodate the electric detonator, penetrating to the center of the charge, was molded in the course of compaction.

The data obtained appears in Table 1.

It should be noted that the tabulated expansions are beyond the volume of the original cavity (~ 61 cm^3), but no correction for the electric detonator has been applied.

Data from Table 1 is plotted in a graph (abscissal axis - expansions, ordinate axis - weights of charges). The lower curve shows the relation of expansions to the weights of charges, neglecting the electric detonator. Normally, a correction for the detonator is made by deducting 30 cm^3 from the total volume of expansion (thus assuming that for any charge the electric detonator produces a uniform 30 cm^3 expansion). It should be noted that, if 30 cm^3 is deducted from the expansion produced by a standard 10 g. charge, we get virtually the same value $393 - 30 = 363$ cm^3 which is recommended as the standard one for Ammonite 6.

The correction was made as follows: seven capsules of No. 8 detonators were exploded simultaneously in the bomb. The resulting expansion was found to be 235 cm^3. The same expansion is produced by a 6.5 g charge of Ammonite 6 exploded by an electric detonator. It is evident that 6 detonator capsules are equivalent to 6.5 g of Ammonite 6, or 1

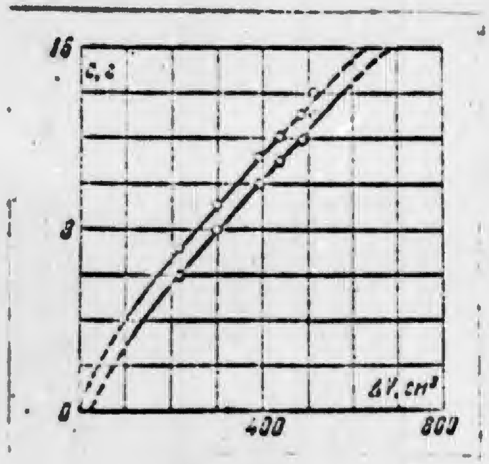

Fig. 1.

detonator capsule (electric) No. 8 is equivalent to 1.08 ≈ 1.1 g. This means that an expansion of 393 cm^3 is produced not by 10 but by 11.1 g. of Ammonite 6 (10 g. of the basic charge and 1.1 g. - the equivalent charge of the electric detonator).

The upper curve of Fig. 1 represents the relation of expansions to the weights of charges, taking into consideration the effect of the electric detonator. The method of plotting this curve was explained previously. For any value of the abscissa the ordinate increases by 1.1 g. (the equivalent value of the electric detonator). Obviously, the upper curve must pass through the origin of coordinates.

Comparing the two curves, (horizontal transition from one curve to the other must represent the expansion produced by the detonator capsule), we see that the amount of correction depends upon the degree of expansion: with an expansion of ~ 150 cm^3 it is approximately 30 cm^3, for ~ 200 cm^3 it is on the order of 40 cm^3; at 300 - 45 cm^3 , etc.

Let us examine some conclusions which can be drawn on the basis of the data developed. First of all, let us note that there is no direct linear relationship between the magnitude of expansion and the total weight of the charge (including the electric detonator), which points to the absence of a direct linear relationship between the magnitude of expansion and the total work performed by the explosion (proportional to the weight of the charge). In the transition from a charge with a total weight of 6 g. to one with a total weight of 12 g., possessing a double amount of energy, the expansion has increased not two-fold, but two and a half times.

To increase the expansion from 200 to 400 cm^3, the charge has to be increased only 1.7 times.

Consequently, when the charge increases, expansion increases more rapidly than the weight of the charge and that is what determines the total work performed.

Reference [1] already states that, at low expansions, the work of plastic deformation of lead in the bomb amounts to approximately one-half of the total energy of the explosion; but in the case of large expansions, the work of deformation is approximately two-thirds of the total energy. Let us pause to analyze the factors which produce this effect. One of them has been mentioned repeatedly: as the bomb expands its walls become thinner and their resistance decreases. At the same time it should be noted that this effect becomes important during very large expansions, those exceeding 500 - 600 cm^3.

During practical tests of explosives, expansions are usually within the limits of 200 - 500 cm^3. Within these limits the reductions in the wall thicknesses of the bombs are of less importance, therefore we should consider another factor. The fact is that expansion of the interior cavity - deformation of lead - is not the only work performed in the Trauzl Bomb. A certain amount of work is expended on the ejection of sand, expulsion of gases and creation of a shock wave in the air; this part of the work performed within the bomb cannot be ignored. With an increase in the weight of the charge, all forms of work increase as well, but the work performed in the ejection of sand increases at a relatively slow rate; the percent of energy expended in the ejection of sand decreases and of that used to deform the lead casing increases correspondingly. The above effect, as well as the small decrease of the resistance of the walls as they expand, are the combined factors that cause the expansion to increase slightly more rapidly than the weights of the charges.

At the same time, in practice (naturally, with strict adherence to similarity, both in the arrangement of charges and the procedure under which the explosion is set off) a double charge produces a double ejection (in order to achieve similarity of conditions, the double charge must be placed 2 1/3 times deeper), twice the volume of fragmented ore and a double-size "crater," caused by soil expansion. In this case the work expended on the ejection of the stemming may be neglected, reduction of thickness of the "walls" is virtually non-existant and, in contrast to the Trauzl Bomb, expansion of the soil will actually have a linear relation to the weight of the charge. All of the above considerations lead us to the conclusion that rating of explosives in accordance with their equivalent weight furnishes a better basis of comparison of their quantitative properties than that which can be obtained from a direct comparison of expansions within a Trauzl Bomb. Existance of Fig. 1 permits us to convert from expansions to equivalent charges and, in this manner, to determine the relative productive capacities of explosives. In determining the equivalent charges, it is possible to use either the lower or the upper curve of Fig. 1. The lower curve furnishes directly the value of an equivalent charge of Ammonite 6. If the upper curve is used, it becomes necessary to deduct 1.1 g., in each case (the equivalent of the electric detonator).

From the graph it is seen that a 10 g. charge of Hexogen (expansion $\sim$ 495 cm^3) is equivalent to 12.2 g. of Ammonite 6. It follows that the relative productive capacity of Hexogen (compared to Ammonite 6) is 1.22; similarly, the relative productive capacity of low-density Trotyl (expansion produced by 10 g. - 310 cm^3) - 0.82 and of high-density Trotyl - 1.0.

We must note that the ratio of specific heats of Hexogen and Ammonite $\sim$ 1.23; of Trotyl and Ammonite - $\sim$ 0.825. These ratios virtually match the ratios of productive capacities given previously.

However, it should not be assumed that such a coincidence will always prevail. Properties of the products of explosion of Ammonite 6, Hexogen and Trotyl are similar; in particular, their C_p/C_v values are virtually identical. As a result, the proportion of energy which can be converted into work (the mechanical efficiency of the explosion), is identical for this group. It is for this very reason that the ratios of productive capacities (obtained from data on expansion of bombs by the equivalent charge method) are practically the same as the ratios of specific heats for these explosives.

If the properties of the products are different, the ratios of productive capacities and of specific heats will also differ. For example, let us examine the data relating to the commonest Ammonal 80/20 (a mixture of 20% aluminum powder and 80% ammonium nitrate). A very substantial amount of heat is liberated in an explosion of this agent, but at the same time a large amount of Al_2O_3 in suspension is formed in the products of explosion, which tends to decrease the portion of energy that can be converted into work.

Consequently, the relative productive capacity of Ammonal (the expansion for 10 g. is 530 cm^3), obtained by the method of equivalent charges (~ 1.3), is considerably lower than the heat ratio (1.5 - 1.55). The ratio of productive capacities obtained (~ 1.3) is consistent with a large expansion of the products of explosion, which is typical for the Trauzl Bomb and, in most cases, in the practical applications of explosives.

If the conditions are such that the expansion of products is low, the ratio of productive capacities will be lower. For example, with an expansion of 8.25 in a ballistic mortar, in which the products of explosion propelling the cylindrical shell are quickly liberated into the atmosphere, the productive capacity of Ammonal is only 1.1 times that of Ammonal 6, as mentioned by the authors of paper [2].

Table 2 presents the data obtained for standard-size charges weighing 10 g. (consequently, the density of all charges was approximately 1.0). This Table covers a very limited number of explosives, however it does include the most important ones.

As stated previously, evaluation of an equivalent charge and that of relative productive capacity can also be accomplished with the use of charges of different weights; the dimensions of the charges must remain constant; the expansion values ΔV of Table 2 do not include a deduction for the effect of the electric detonator; the symbol C_3 is representing the weight of an equivalent charge of Ammonite 6, (a_x/a_6) is the relative productive capacity.

For explosives listed in Table 2, magnitudes of expansion ΔV should be considered sufficiently reliable. For other explosives comparable available data requires additional verification. For example, the published expansion for ammonium nitrate is listed in the range of 165 to 230 cm^3. We must bear in mind that the commonly used Tetryl detonator capsules produce a considerable amount of incompletely burned matter, while ammonium nitrate is rich in excess oxygen. During the reaction of products of incomplete combustion of Tetryl (CO, C, H_2, CH_4, etc.) with oxygen of the nitrate a relatively large amount of heat must be liberated (up to 50% of the total heat liberated during an explosion of 10 g. of ammonium nitrate). Due to the generation of additional heat, expansion of the bomb is much greater than that which would result from an explosion of 10 g.

Table 2.

Expansions ΔV, equivalent charges C and relative productive capacities of standard charges (10 g.) of some explosives.

Explosive:	ΔV, cm^3	C_u, g	a_x/a_6
Trotyl	310	8,2	0,82
Picric acid	335	8,7	0,87
Ammonite 9	350	9,1	0,91
Ammonite 6	390	10	1,00
Tetryl	390	10	1,00
Hexogen	495	12,2	1,22
Pentrite	500	12,3	1,23
Plain Ammonal	530	13,0	0,30

When we calculate the relative productive capacity of ammonium nitrate, disregarding the interaction between ammonium nitrate and the detonator-capsule, we obtain a relatively high value of the ratio $a_x/a_6 \approx$ $\approx 0.60 - 0.65$; if an allowance is made for this interaction, we find that $a_x/a_6 \approx 0.40 - 0.50$. Therefore, determination of expansion in the Trauzl Bomb, as well as the relative productive capacity of ammonium nitrate calls for greater precision; this also holds true for the case of available data relating to some protective explosives.

We have previously listed the data covering the relative productive capacities of low-density explosives ($\rho \approx 1.0$). The method of evaluating such explosives is, in principle, also applicable in the case of high-density explosives, and particularly for liquid ones. However, this calls for additional experiments to determine the relation of expansion to the weight of a charge of any substance chosen as a standard (for example, Pentrite). The weights of charges must be reduced by cutting down their height, or possibly their diameter ($\sim$20 mm). With the use of standard dimensions, charges of powerful explosives would produce inadmissibly large expansions, or would simply destroy the bomb.

CONCLUSIONS. 1. Data on the extent of expansion in a Trauzl Bomb, obtained by the method of equivalent charges, can be used for the evaluation of the true relative productive capacities of explosives. To do this, it is necessary to determine the equivalent weight of an Ammonite 6 charge (or of one of some other explosive, chosen as a standard) with the help of a specially constructed graph. The charge of the standard explosive must produce the same expansion as the charge of the explosive being investigated. Volumes (heights) of the charges must be identical.

2. For explosives having similar properties of their products of explosion the ratio of true productive capacities, determined from the expansions, is virtually equal to the ratio of specific heats.

3. If the products of an explosion contain polyatomic molecules, or a suspension of the condensed phase, the ratio of productive capacities will be less than the ratio of specific heats.

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