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Characteristics of High Explosives Obtained from Cylinder Test Data

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Abstract: New methods to calculate the acceleration ability of detonation products and the detonation energy of explosives with the cylinder expansion test data were applied to determine the performance characteristics for some high explosives of military interest. The obtained results were also compared to the calculation results with CHEETAH code. Moreover, the detonation pressure for chosen explosives was evaluated on the basis of a variation of the cylinder test in which a cylindrical water layer was loaded by detonation wave propagating along an explosive charge confined by the water envelope. Results of the tests and thermochemical calculations were used to deduce constants of the JWL equation of state. Finally, the JWL isentropes obtained were applied to calculate the theoretical expansion work of detonation products.

Key words: explosion mechanics; high explosive; detonation characteristics; equation of state; cylinder test; detonation energy

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1 Introduction

The so-called cylinder expansion test includes in recording the initial stage in the acceleration process of a cylindrical metal envelope driven by expanding detonation products grazing along the internal surface of the envelope (usually, it is a copper tube). Its expansion is monitored with precise measurements of quickly changing processes such as streak photography, laser interferometry or X-ray impulse photography. Results of the acceleration process recording are commonly employed as an experimental basis for deducing semi-empirical equation of state of detonation products[1-7]. Moreover, cylinder test data can be used to determine some other important detonation and performance characteristics of explosives. For example, with dependence of radial displacement of the external tube wall on the axis co-ordinate, it is possible to determine the velocity of the expanding envelope and, then, the Gurney energy (E_G) and the detonation energy of an explosive tested[8]. Both parameters characterise a degree that the chemical energy of the explosive converts into the expansion work of its detonation products. The detonation energy is equal to the maximal theoretical isentropic expansion work of detonation products. E_G is defined as the final energy of the driven metal and the expanding detonation products per mass unit of an explosive. This parameter describes the acceleration ability of detonation products and its value, determined for chosen expansion degree of detonation products, is a characteristic feature of the explosive. In this paper, the metal acceleration ability of test explosives was described with the dependence of energy given by the Gurney formula on the expansion degree of the metal tube driven by detonation products. In this way an investigation of energy transfer into the kinetic energy was studied in the course of the tube expansion.

A variation of the cylinder expansion test is described in Ref. [9]. In the test an explosive charge is detonated inside a cylindrical layer of water, and X-ray photograph of an oblique shock wave propagating in the water layer is obtained. The experimental wave configuration at a chosen moment of the charge detonation process is used to evaluate the isentropic exponent of detonation product that finally enables us to calculate the detonation pressure. The latter value is one of the additional parameters that are needed, alongside with the cylinder test data, for parametrization of the semi-empirical equation of state of detonation products.

In this work, both tests were done for chosen high explosives of military interest. The acceleration processes of

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copper tube and detonation of an explosive inside the water layer were recorded using X-ray impulse photography. The Gurney energy, the detonation energy and the detonation pressure for test explosive were determined, and the JWL isentrope coefficients of detonation products were found. With the isentropes obtained, the theoretical expansion work of detonation products were calculated. In this way we tried to show a new approach to determine some detonation performance of explosives using the cylinder test data.

2 Experimental

2.1 Test explosives

The test explosive compositions are listed in Table 1. The phlegmatized explosives (HMX_{ph}, RDX_{ph} and $PETN_{ph}$) and TNT were commercial grade. To prepare aluminized samples, flaked aluminium powder (Al) was used. Its particle sizes were below 75 μm, and it contained 92% of active metal at least.

Mixtures of TNT with RDX and aluminium powder were prepared by mixing the ingredients in a presence of acetone. RDX or RDX and Al were added to an acetone solution of TNT. After vaporising the solvent, mixtures were ground and pressed into cylindrical charges at a pressure of 250 MPa. Each charge was 25 mm in height.

Table 1 Explosives tested

explosives	composition/wt. %
HMX_{ph}	HMX/wax 96/4
RDX_{ph}	RDX/wax 95/5
$PETN_{ph}$	PETN/Viton 95/5
TNT	TNT 100
tritonal	TNT/Al 85/15
hexatol	TNT/RDX 50/50
hexatonal	TNT/RDX/Al 42.5/42.5/15

2.2 Experimental arrangements

The cylinder expansion and water test were recorded with a SCANDIFLASH X-ray impulse set. Fig. 1 showed the charges used in the tests.

The copper tube (Fig. 1a) filled with a test explosive was placed at a distance of 2.7 m from the X-ray source and 0.5 m from the film. The charge was fixed vertically and perpendicularly to the line linking X-ray source with the film. The copper tube was 250 mm in length, and its internal diameter and wall thickness were 25 mm and 2.5 mm respectively. The sensor to trigger X-ray pulse was placed at a distance of 50 mm from the end of the charge. This enabled us to observe continuously the expansion process of the copper tube in a range of delay of 25 μs from the moment when detonation wave reached the charge section including sensor 5.

In the case of water test (Fig. 1b), a cylindrical charge of 25 mm in diameter and 250 mm in length was placed inside a PVC tube with an inner diameter of 71 mm and wall thickness of 2 mm. The tube was filled with water. Short-circuit sensors were located in the charge to measure the detonation velocity (VOD) and to trigger the X-ray apparatus.

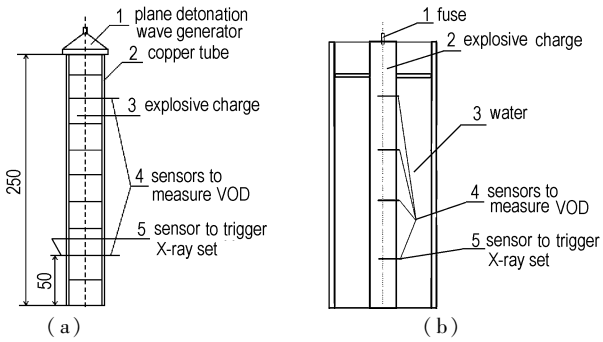


Fig. 1 Schemes of the charges used in the cylinder (a) and water (b) tests

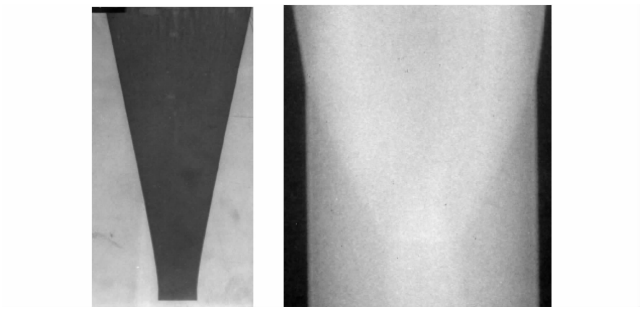
3 Results

Exemplary radiographs of the copper tube and water envelope driven by detonation products are shown in Fig. 2. From Fig. 2(a), dependence of external surface radius of the tube on the axial co-ordinate was constructed using graphical computer programs. From Fig. 2(b), the shape of an oblique shock wave in water was determined.

The average values of detonation velocity measured during cylinder and water tests are given in Table 2.

3.1 Gurney energy

To determine the radial velocity of the copper tube, that was necessary to calculate the Gurney energy, the data obtained from the cylinder test were recalculated using the method proposed in Refs. [4, 8]. A brief description of the theoretical model of the cylindrical liner driving process is given below. A diagram of a copper tube accelerated by the detonation products is shown in Fig. 3.



(a)　　(b)

Fig. 2　Inverse radiograph of the copper tube (a) and radiograph of water envelope (b) driven by detonation products of HMX_{ph}

Table 2　Average densities and detonation velocities

explosives	density/kg · m^{-3}	detonation velocity/m · s^{-1}
HMX_{ph}	1780	8730
RDX_{ph}	1650	8390
$PETN_{ph}$	1710	8080
TNT	1590	6910
tritonal	1690	6800
hexatol	1640	7610
hexatonal	1710	7210

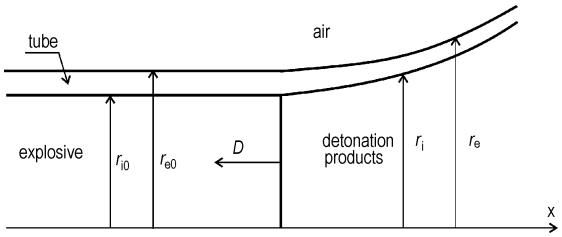


Fig. 3　Diagram of the copper tube accelerated by detonation products

A plane detonation wave propagates at a velocity of D in a cylindrical explosive charge. The gaseous detonation products expand, thus driving the tube. It is assumed that the time of detonation wave propagation is long enough to neglect the influence of the initiation of detonation. Then the motion of the detonation products and the tube material can be treated as a stationary one. Therefore, the axis co-ordinate and time are associated by the following relation:

$$x = D \cdot t \tag{1}$$

First, the position of the central cylinder surface is determined. Assuming a complete incompressibility of the tube material, this position is established from the relation:

$$r_m = \sqrt{r_e^2 - \frac{1}{2}(r_{e0}^2 - r_{i0}^2)} \tag{2}$$

where r_{e0} and r_{i0} denote the initial radii of external and internal surfaces of the tube respectively, r_e and r_m represent the radii of external and central surfaces of the tube for given value of co-ordinate x, respectively.

By using relation (1), we replace the dependence of the tube radius on axis co-ordinate by the time function of this radius. The time dependence of central position of the tube is approximated by the following function:

$$r_m = r_{m0} - \sum_i a_i \{ b_i (t - t_0) - [1 - \exp(-b_i (t - t_0))] \} \tag{3}$$

where a_i, b_i, t_0 are parameters. In Ref. [8], it was proved that sufficient accuracy of approximation of the experimental results was achieved by assuming $i = 2$ in the funciton (3).

The radial velocity of the central part of the tube, u_m, is calculated by differentiating function (3):

$$u_m \equiv \frac{dr_m}{dt} = \sum_i a_i b_i [1 - \exp(-b_i (t - t_0))] \tag{4}$$

To determine the kinetic energy of the tube, the magnitude of velocity of the tube element must be calculated. From geometrical relations it follows that the deflection angle (the angle between the line being tangential to the trajectory of the central surface of the tube and the x-axis) are specified by the relation (5):

$$\Theta = \operatorname{arctg}\left(\frac{u_m}{D}\right) \tag{5}$$

On the other hand, the magnitude of velocity of the central part of the tube (a cylindrical liner) is expressed by the equation (6):

$$u_L = 2D \sin\left(\frac{\Theta}{2}\right) \tag{6}$$

The acceleration ability of an explosive can be described by the so-called Gurney energy, which is defined as a sum of kinetic energies of driven tube and detonation products related to unit mass of explosive. For cylindrical envelopes, the Gurney energy is expressed by the following relation[8]:

$$E_G = \left(\mu + \frac{1}{2}\right)\frac{u_L^2}{2} \tag{7}$$

where μ denotes the ratio of tube mass to explosive mass.

In literature, the final values of the Gurney energy or Gurney velocity $u_G = (2E_G)^{1/2}$ are usually given. The parameters correspond to the tube velocity at the radius for which continuity of tube material is still preserved.

However, applying this methodology to analyse X-ray records of expanding copper tubes, it is possible to research changes of the Gurney energy by equation (7) during the tube expansion. Dependence of the parameter on relative volume of detonation products is given in Fig. 4.

Values of the Gurney energy and velocity at a relative volume of detonation products are listed in Table 3.

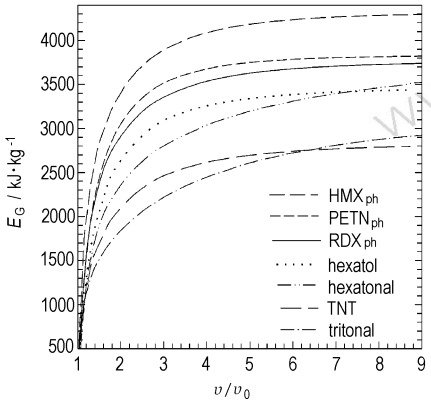


Fig. 4 Dependence of the Gurney energy on the relative volume of detonation products

Table 3 Gurney energy and velocity at $v/v_0 = 9$

explosive	E_G/kJ · kg^{-1}	u_G/m · s^{-1}
HMX$_{ph}$	4300	2930
RDX$_{ph}$	3740	2730
PETN$_{ph}$	3820	2760
TNT	2795	2360
tritonal	2920	2420
hexatol	3440	2620
hexatonal	3520	2650

From the analysis of curves in Fig. 4, it shows that for explosives without aluminium, the Gurney energy does not increase for $v/v_0 > 7$. For aluminized explosives, a continuous increase is observed within the whole tested range of the relative volume variability.

3.2 Detonation energy

In order to estimate the detonation energy of test explosives, dependence of square of tube velocity on reciprocal volume of detonation products was constructed (Fig. 5), according to the method proposed in Ref. [8]. Next, for $v/v_0 = 0.1$ values of u_L^2 were found and used to calculate the detonation energy from the relation:

$$\frac{e_0}{e_0^{st}} = \frac{\left(\mu + \frac{1}{2}\right)}{\left(\mu^{st} + \frac{1}{2}\right)}\left(\frac{u_L}{u_L^{st}}\right)^2 \quad (8)$$

where e_0 and e_0^{st} are detonation energies of an explosive tested and a standard explosive, respectively.

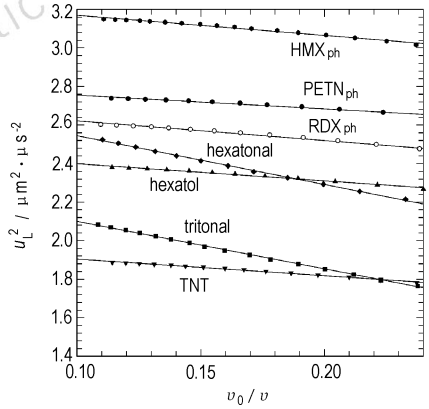


Fig. 5 Velocity square of the copper tube versus reciprocal volume of detonation products

As a standard explosive, phlegmatised RDX was chosen. Its heat of detonation (q = 5450 kJ · kg^{-1}) was determined in a calorimetric bomb filled with compressed argon [10]. We assumed that the heat of detonation is close to the detonation energy, and thanks to this, we were able to calculate values of detonation energy for the explosives from equation (8). The calculation results (e_0) are given in Table 4. In Table 4, there are also values of detonation energy calculated with CHEETAH[11] code (e_0^t) and values of detonation heat (q) measured with water calorimetric set in Ref. [10].

Table 4 Detonation energy of the explosives tested

explosive	e_0/ kJ · kg^{-1}	e_0^t/ kJ · kg^{-1}	$\frac{e_0 - e_0^t}{e_0^t}$ / %	q / kJ · kg^{-1}	$\frac{e_0 - q}{q}$ / %
HMX$_{ph}$	5920	5804	+2.0	5850	+1.2
RDX$_{ph}$	5450	5442	+0.1	5450	–
PETN$_{ph}$	5550	5509	+0.7	–	–
TNT	4150	4516	-8.0	4050	+2.5
tritonal	4440	6162	-28.0	5050	-12.1
hexatol	5010	5055	-0.9	4780	+4.9
hexatonal	5330	6608	-19.3	5790	-7.9

The calculated values of detonation energy of aluminised explosives are considerably higher than the values obtained from cylinder test. However, it should be pointed out that the calculations were done with an assumption of full thermochemical equilibrium in detonation products, both in the zone of chemical reactions and during their expansion. In reality, the temperature of aluminium particles in the initial stage of expansion process can be different from the temperature of gaseous detonation products. Moreover, contact of aluminium with oxygen is hampered because most aluminium is in condensed phase. This means that detonation energy values calculated with CHEETAH may be too high. Fact that for these explosives the values of calorimetric detonation heat are also lower than calculated values of detonation energy is in favour of the above conclusion. The detonation energy obtained from the cylinder test is comparable to detonation heat-differences which do not exceeds 5% for non-aluminised explosives and are slightly higher for aluminised ones (Table 4).

3.3 Detonation pressure

To determine the detonation pressure of some test explosives, a variant of the cylinder test was applied [9]. In this method, profiles of an oblique shock wave propagating in a cylindrical layer of water during detonation of the test cylindrical explosive charge are recorded by an X-ray set (Fig. 2). The experimental profiles are then compared with results of numerical modelling of the expansion process which have relation between the position of the front of oblique shock wave in water and the exponent of isentrope (γ) of detonation products. The value of γ corresponding to the solution that overlaps the experimental profile is accepted as the exponent sought. Having determined γ, the detonation pressure is calculated according to the following equation:

$$p_{CJ} = \frac{\rho_0 D^2}{\gamma + 1} \tag{9}$$

where D, p_{CJ} denote the detonation velocity and pressure, respectively, and ρ_0 is the density of the test explosive.

Values of exponent γ and p_{CJ} for HMX_{ph}, RDX_{ph} and TNT obtained in this way are listed in Table 5, and other values of γ and p_{CJ} in this Table were calculated with CHEETAH. Inert aluminium was assumed for calculations of the detonation parameters of Tritonal and Hexatonal.

Table 5　Exponent and detonation pressure

explosive	γ	p_{CJ}/GPa
HMX_{ph}	3.05	33.5
RDX_{ph}	3.09	28.4
$PETN_{ph}$	3.10[1)]	27.5
TNT	3.12	18.4
tritonal	3.50[1)]	16.6
hexatol	3.00[1)]	23.7
hexatonal	3.49[1)]	19.8

Note: 1) is value calculated with CHEETAH.

3.4 JWL EOS and expansion work

Jones, Wilkins and Lee proposed the equation of the isentrope for the detonation products of explosives in the following form[1, 2]:

$$p = Ae^{-R_1 V} + Be^{-R_2 V} + CV^{(-1-\omega)} \tag{10}$$

where $V = v/v_0$. The following equation of state (JWL EOS) corresponds to this isentrope:

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{11}$$

where A, B, C, R_1, R_2 and ω are constants for given explosive. Some connections between coefficients following the conservation laws written for the CJ point are used in this method[7]. As a result, parameters A, B, and C are expressed as functions of R_1, R_2, ω and ρ_0, D, E_0 and p_{CJ}. Density of explosive ρ_0 as well values of detonation velocity D, detonation energy E_0 and pressure p_{CJ} at the CJ point is established experimentally. Thus, only the constants R_1, R_2 and ω remain to be determined.

They are calculated by the method in which the experimental dependence of radial displacement of the outer tube wall on the axial co-ordinate is compared with that obtained from a numerical simulation[6]. The set of JWL constants is chosen for which the experimental and simulated displacements are sufficiently close to each other. Parameters R_1, R_2 and ω are obtained from comparison of the experimental and calculated radial position of the tube wall at chosen m values of the axial co-ordinate x_j. So, the values of these parameters are determined by minimising the following function:

$$f(R_1, R_2, \omega) = \sum_{j=1}^{m} [r_{ej} - r_{ej}(R_1, R_2, \omega)]^2 \tag{12}$$

where r_{ej}, $r_{ej}(R_1, R_2, \omega)$ are the experimental and calculated positions of external surface of the tube, respectively.

Using the model proposed in Refs. [6, 7], as well as the values of detonation velocity, detonation pressure and detonation energy obtained with methods described in Sections 2.2, 3.2 and 3.3, the constants of the JWL equation for the explosives were calculated. Results of the calculations are given in Table 6.

After determining the JWL isentropes, the expansion work of detonation products was calculated from equation:

$$W(v) = -e_c + \int_{v_{CJ}}^{v} p_i \mathrm{d}v \qquad (13)$$

where $e_c = (p_{CJ} - p_0)(v_0 - v_{CJ})/2$ denotes the energy of explosive compressed at the front of detonation wave, p_i is the pressure on the isentrope.

Table 6 JWL isentropes of the explosives examined

explosives	A/GPa	B/GPa	C/GPa	R_1	R_2	ω
HMX_{ph}	1093.813	23.36811	1.248955	5.08	1.46	0.30
RDX_{ph}	1104.218	25.20760	1.014462	5.39	1.50	0.31
$PETN_{ph}$	1023.793	22.22933	1.247964	5.34	1.46	0.31
TNT	695.7615	10.66460	0.6606919	5.23	1.22	0.26
tritonal	948.0147	6.254951	0.7129381	5.47	0.97	0.19
hexatol	708.6056	13.16457	1.058238	4.94	1.35	0.28
hexatonal	1273.284	9.119345	0.8682816	5.77	0.98	0.22

Dependence of the expansion work on the relative volume of detonation products is presented in Fig. 6. From an analysis of the curves shown in Fig. 6, it follows that aluminized explosives (Tritonal, Hexatonal) are better than pure TNT and TNT/RDX mixture with regard to the final value of expansion work. It is a result of an additional energy release behind detonation wave due to aluminium oxidation in expanding detonation products.

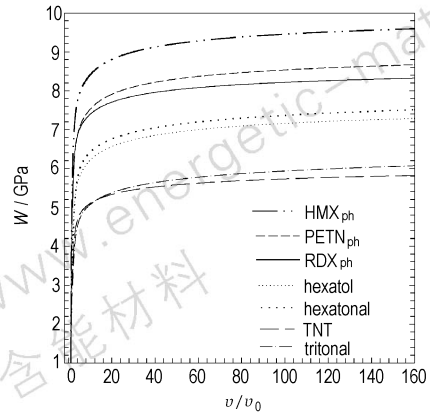


Fig. 6 Dependence of the expansion work on relative volume of the detonation products

Similar dependence obtained from the CHEETAH results are presented on Fig. 7. Two curves were calculated for each aluminised explosive: one for inert aluminium in the detonation products and the another for active aluminium. From the comparison of curves from Figs. 6 and 7 it follows that the amount of aluminium taking part in the reaction with detonation products is relatively small.

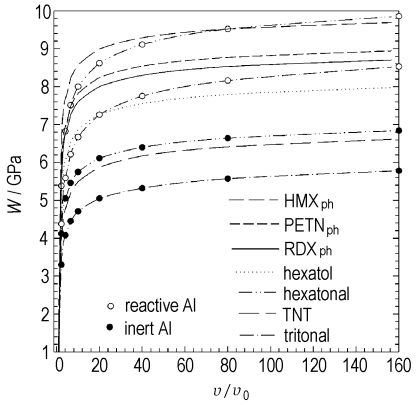


Fig. 7 Dependence of the expansion work on relative volume of the detonation products calculated by CHEETAH code

4 Summary

Cylinder and water tests were made for chosen high explosives of military interests. The processes of copper tube driving and water layer loading were recorded with the SCANDIFLASH impulse X-ray apparatus.

For test explosives, dependence of the Gurney energy on relative volume of detonation products was determined. It is stated that in the case of aluminised explosives the Gurney energy increases with the volume of the tube within the whole tested range of relative volume variability. The Gurney energy of the explosives without aluminium does not practically change with volume when $v/v_0 > 7$.

The cylinder test results were used to evaluate the detonation energy of the explosives, as well. The results obtained in this way were compared with those of calculations by CHEETAH code, and with results of calorimetric measurements. The calculated detonation energy for the explosives containing aluminium is significantly higher than those obtained from the cylinder test or in calorimetric way. In the case of the other explosives, a good consistence of the parameters was observed. Calorimetric values of detonation heat are comparable to those from the cylinder test even in the case of aluminised explosives.

Water and cylinder test results were applied as the basis for deducing the constants of JWL equation of state that finally allowed calculation of the theoretical expansion work of detonation products. In this way it is possible to observe an additional energy release behind detonation wave of aluminised explosives.

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圆筒实验数据研究高能炸药的爆轰特性

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摘要: 根据圆筒实验数据,采用新方法计算了 HMX、RDX、PETN、TNT 等炸药的爆轰能,研究了爆轰产物的加速能力,并与 CHEETAH 的计算结果进行了对比。通过爆轰波在柱壳水介质中传播的圆筒实验方法,预估了炸药的爆压。利用实验和热化学计算的结果推导了 JWL 状态方程的待定常数,并依据 JWL 等熵线计算了做功能力。

关键词: 爆炸力学; 高能炸药; 爆轰特性; 状态方程; 圆筒实验; 爆轰能量

中图分类号: TJ55; O35　　**文献标识码:** A

读者·作者·编者

向作者致谢

2004 年《含能材料》由季刊改为双月刊以来,得到了广大作者的支持,为表达我们深深的谢意,特向两年来发表两篇以上论文的作者(第一作者)赠送 2006 年全年《含能材料》。期望作者们在 2006 年能给予本刊更多的关心与支持! 欢迎赐稿!

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