THE STUDY ON ATTENUATION RULE OF X-RAY AND γ-RAY IN EXPLOSIVE

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Abstract: In order to test the explosive components by X-ray or ^{60}Co γ-ray non-destructive testing, the attenuation rules that X-ray and ^{60}Co γ-ray attenuate in pure and impure explosive must be known.

10 explosive columns are made for study. The data of X-ray and 60Co γ-ray attenuatedt in explosive is studied on the basis of both theory and experiment. The X-ray and γ-ray attenuation in a certain explosive in different conditions are fitting through the regression analysis. The X-ray attenuation rule in this explosive is educed through analyzing the fitting results and the two kinds of results are compared. For γ-ray, the attenuation, which is calculated theoretically by the method of Monte Carlo (M-C), is compared with the result of experiment.

The results indicate that the attenuation rule of X-ray in a certain explosive accords with cubic equation. The attenuation rule of γ-ray attenuation in pure explosive and impure explosive, which contains copper, iron and lead, is exponent equation. That the X-ray attenuation in impure explosive is obvious shows that it is feasible to test the explosive using X-ray or γ-ray.

Introduction: Explosive is an indispensable component of weapon system, so the reliability of explosive must keep well in order to make sure that weapon system can complete the preset mission. Any defect, such as metal impurity, mustn't occur in explosive component. Although the manufacturer has taken some techniques and detecting measures corresponding to technical requirement to avoid the defects, the performance of dynamite component can still change easily after long period storage, such as cracks and debunking. In order to guarantee its quality and capability we must inspect the internal substance of the component

With regard to the problem mentioned above, there are some foundational researches done and presented in this text. It is mainly the discussion about attenuation rule of X-ray and γ-ray in pure explosive and impure explosive. The main purpose of the experimental mensuration is simulate the defects inside of explosive component and find out its effects on attenuation characteristics of X-ray and γ-ray penetrating in impure explosive. The internal defects include non-uniformity, blow holes, and cracks. The method used to simulate non-uniform density situation is that insert some attenuating metal board (in this experiment we used aluminium , iron, copper, lead .etc) with different density into different place of the explosive column , then observe the change of dose rate and counting rate.

The quantity of the explosive column used in this experiment is 12.95g, the diameter is 2.124cm, and the Density is 1.739 g/cm^3. The composition is:
C□14.5%□H□27.3%□N□26.0%□O□26.5%□Cl□0.08%□F□5.62%.the density of the four kinds attenuation board is : aluminium 2.7g/cm^3
Iron: 7.86g/cm^3; copper: 8.93g/cm3□lead: 11.34g/cm^3.

Results: The experiment result of attenuation rule for X-ray penetrating in pure explosive is shown in table 1, and in impure explosive is shown in table 2.

Table1 the penetrating dose rate when current=5mA

Charge Amount	Permeation dose ratio in different voltage /×104μGy·h-1							
	100KV	120KV	140KV	170KV	200KV	220KV	240KV	260KV
0	1.0	2.2	3.3	8.8				
1	0.5	1.0	1.5	5.9	8.9			
2	0.24	0.56	0.9	4.4	6.6	7.9	9.2	—

3	0.14	0.33	0.55	3.5	5.5	6.4	7.5	8.6
4	0.098	0.22	0.39	3.0	4.5	5.5	6.5	7.5
5	0.075	0.17	0.33	2.8	4.2	5.1	6.0	6.9
6	0.067	0.14	0.28	2.6	3.9	4.9	5.7	6.5
7	0.063	0.14	0.26	2.6	3.8	4.7	5.5	6.3
8	0.058	0.13	0.25	2.5	3.7	4.6	5.5	6.3
9	0.055	0.15	0.23	2.5	3.7	4.6	5.5	6.3
10	0.053	0.12	0.22	2.5	3.7	4.6	5.5	6.3

Annotation: physical dimension and density of the dynamite column are similar

Table 2 current=5mA, height of column is constant; Penetration dose rate for X-ray with different energy

voltage (kV)	dose ratio/×103μGy·h-1						
	Before enetrating	3columns (pure)	3columns (2alminumn Board)	3columns (iron Board)	3columns (4alminumn Board)	3columns (2iron Board)	3columns (1copper Board)
70	1.5	0.22	0.145	0.077	0.14	0.07	0.08
80	3.8	0.52	0.43	0.25	0.4	0.23	0.26
90	6.5	0.87	0.775	0.55	0.75	0.43	0.61
100	10.5	1.5	1.25	1.0	1.15	0.82	1.05
110	16	2.6	2.2	1.7	2.05	1.3	1.8
120	23.5	3.7	3.2	2.6	3.0	2.1	2.7
130	29.5	5.1	4.1	3.6	4.0	2.8	3.7
140	37.5	6.9	5.8	5.0	5.5	4.1	5.2
150	47	8.7	7.5	6.8	7.3	5.9	7.0
160	57	11	9.8	8.5	9.5	7.6	9.0

Annotation: the thickness of each aluminium plate is 0.2mm, iron plate is 0.4mm, and each copper plate is 0.3mm.

Conclusion according to linear regression method: explosive columns which contain metal plate or not all tally with cubic fitting. The result is shown as follow

Using data for dose rate is shown in table 1 and table 2 as the call by value of X-ray attenuation formula attenuation coefficient can be figured out. The following table shows the comparison.

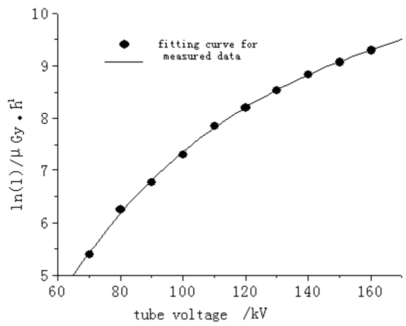

Figure 1

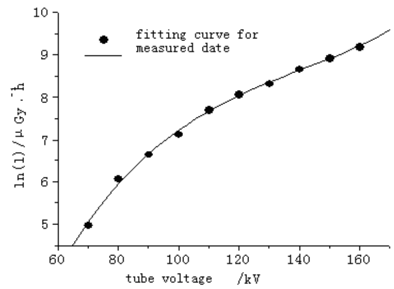

Figure 2

Table 3 comparison of theoretical value with linear measured attenuation coefficient □cm-1□

voltage	pure dynamite		With aluminium plate		With copper plate		With iron plate	
	Theoretical value	measured value	theoretical value	measured value	theoretical value	measured value	theoretical value	measured value
80kV	0.3142	0.3142	0.3153	0.3557	0.3616	0.4501	0.3346	0.4299
100kV	0.2928	0.3074	0.2931	0.3494	0.3166	0.3899	0.3030	0.3715
120kV	0.2794	0.2920	0.2751	0.3252	0.2822	0.3742	0.2781	0.3478
140kV	0.2671	0.2674	0.2639	0.3033	0.2699	0.3421	0.2664	0.3183
160kV	0.2537	0.2599	0.2552	0.2831	0.2649	0.3183	0.2593	0.3006

The experiment result for attenuation rule of γ-ray penetrating in pure explosive is shown in table 4, and in impure explosive, shown in table 5~9.

Table 4 measured data for γ-ray penetrating in impure explosive

No. of dynamite columns / Thickness □cm□	Measure time and counting rate						average □n□	transmissivity □n/n_0□
	1	2	3	4	5	6		
background	17.9	16.2	14.8	18.5	16.3		16.7	
Without column	141.0	146.6	135.7	140.5	143.3		124.7	
5#□2.124□	114.4	116.9	110.6	116.5	113.0	113.4	97.4	0.781
5# 6#□4.258□	95.8	98.2	96.3	100.0	97.0	96.8	80.7	0.647
5# 6# 7#□6.383□	78.3	81.6	82.6	78.0	83.3	83.9	64.6	0.518
5# 6# 7# 8#□8.501□	71.1	71.6	65.7	69.2	69.3	68.2	52.5	0.421

Remarks : Data shown as average is net counting rate and contains no background count

a = -1.007 b = 4.8132 σa = 0.0022 σb = 0.0207

$$y = -1.007 \cdot x + 4.8132$$

Table 5 measured data for γ-ray penetrating in explosive column with aluminium plate

Serial number / Thickness(cm)	Measure time and counting rate				average □n□	transmissivity □n/n0□
	1	2	3	4		
background	15.8	16.7	15.3	15.6	15.5	
With out dynamite column	138.9	140.9	150.0	135.0	124.5	
Al□0.216□	142.6	138.7	127.4	132.9	119.9	0.963
5# Al	116.9	115.4	117.4	111.9	99.9	0.803
5# Al 6#	96.2	94.2	95.8	92.6	79.2	0.636
5# Al 6# 7#	80.4	88.7	77.3	86.2	67.65	0.543
5# Al 6# 7# 8#	73.9	70.6	68.2	69.9	55.15	0.443
5# 6# Al 7# 8#	68.0	70.6	70.1	72.4	54.78	0.440
5# 6# 7# Al 8#	69.5	75.9	71.9	74.5	54.34	0.436
5# 6# 7# 8# Al	69.3	63.9	68.8	68.7	52.18	0.419

Remarks :Data showed as average is net counting rate not contains background count

a = -0.0945 b = 4.81644 σa = 0.0020 σb =0.0317

Table 6 measured data for γ-ray penetrating in explosive column with iron plate

Serial number / thickness□x cm□	Measure time and counting rate				average □n□	transmissivity □n/n_0□
	1	2	3	4		
background	15.8	16.7	15.3	15.6	15.5	
With out column	138.9	140.9	150.0	135.0	124.5	
Fe□0.218□	128.3	128.5	125.1	126.3	111.55	0.896
5# Fe	110.3	111.6	110.7	110.5	95.28	0.765
5# Fe 6#	95.6	91.9	89.6	88.7	75.95	0.610
5# Fe 6# 7#	80.9	82.3	76.0	80.9	64.53	0.518
5# Fe 6# 7# 8#	68.2	70.7	63.2	63.3	50.85	0.408
5# 6# Fe 7# 8#	68.8	66.9	70.0	64.5	52.05	0.418
5# 6# 7# Fe 8#	67.9	66.4	65.1	68.9	51.58	0.414
5# 6# 7# 8# Fe	71.3	66.1	68.7	69.4	53.38	0.429

Remarks :Data shown as average is net counting rate and contains no background count

a = -0.0948 b = 4.7773 σa = 0.0028 σb =0.0448

Table 7 measured data for γ-ray penetrating in explosive column with copper plate

Serial number / Thickness(cm)	Measure time and counting rate				average (n)	transmissivity (n/n0)
	1	2	3	4		
background	15.8	16.7	15.3	15.6	15.5	
Without dynamite column	138.9	140.9	150.0	135.0	124.5	
Cu(0.200)	128.9	132.3	137.2	132.1	117.13	0.941
5# Cu	111.2	113.9	107.4	102.0	93.13	0.748
5# Cu 6#	88.3	91.4	86.9	93.2	74.45	0.598
5# Cu 6# 7#	74.9	80.6	74.5	76.1	61.03	0.490
5# Cu6# 7# 8#	65.0	64.6	68.6	62.4	49.65	0.399
5# 6# Cu7# 8#	61.3	64.8	61.2	63.2	47.13	0.379
5# 6# 7# Cu8#	68.37	58.85.	65.7	61.4	48.08	0.386
5# 6# 7# 8# Cu	66.9	68.1	67.4	69.0	52.35	0.420

Remarks : Data showed as average is net counting rate and contains no background count

a =-0.1034 b = 4.7924 σa = 0.0032 σb =0.0524

Table 8 measured data for γ-ray penetrating in explosive column with lead plate

Serial number / thickne(xcm)	Measure time and counting ratio 1	2	3	4	average (n)	transmissivity (n/n0)
15.8	16.7	15.3	15.6	14.2	15.8	
With out column(0)	138.9	140.9	150.0	135.0	124.5	
Pb(0.218)	118.5	120.5	126.1	119.3	105.6	0.848
5# Pb	97.8	105.6	107.3	103.4	88.03	0.707
5# Pb6#	88.7	90.6	83.4	83.3	71	0.570
5# Pb6# 7#	75.9	73.9	78.6	74.5	60.23	0.484
5# Pb6# 7# 8#	63.4	62.9	66.6	65.3	49.05	0.394
5# 6# Pb7# 8#	62.1	64.7	66.3	65.4	49.13	0.395
5# 6# 7# Pb8#	61.4	62.9.	63.7	67.4	48.35	0.388
5# 6# 7# 8# Pb	61.4	66.9	66.3	62.1	48.68	0.391

Remarks : Data showed as average is net counting rate and contains no background count

a =-0.0978 b = 4.7354 σa = 0.0041 σb =0.0666

Do the least square fitting according to measured data: fitting curve for γ-ray penetrating in pure explosive columns is shown in figure 3, that for γ-ray penetrating in impure explosive columns is shown in figure 4

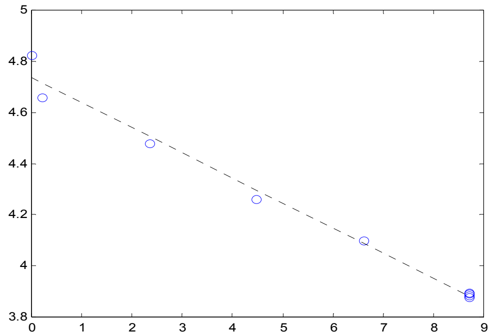

Figure 3

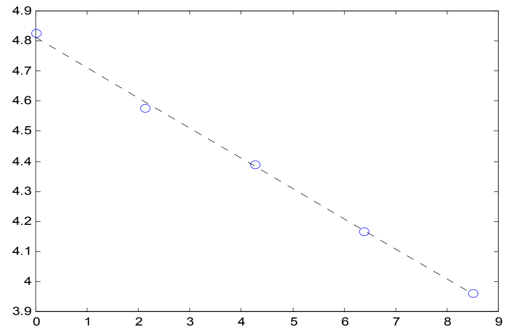

Figure 4

It can be seen from figure 3: the fitting curve in semi-logarithm coordinate paper is linear. In other words, attenuation rule of ray penetrating in pure explosive submits to exponential rule. Being consistent with theory, its characteristics for impure explosive with lead plate is shown in figure 4.

Also as shown in figure 4: the fitting curve in semi-logarithm coordinate paper is linear. That is to say, the attenuation rule of γ-ray in impure explosive column with lead plate is also submitted to exponential rule.

Using M-C method, adopting MCNP-4B program to simulate and trace γ photon of 60Co irradiation source, considering the effect of Compton scattering, optic galvanic effect, duplet effect, recording how many γ-ray beam emitting form the back end face (its radius is 0.35cm) and confine the separation angle of this γ-ray beam and normal direction of the end face within 0~5º. Then figure out the individual penetration coefficient for γ photon of 60Co irradiation source penetrating in different explosive columns with different thickness. The result is shown in table 9.

Table 9 : characteristics of γ-ray penetrating in pure explosive by M-C method

Number of columns	thickness□cm□	Transmissivity n/n0
1	2.124	0.809
2	4.248	0.655
3	6.372	0.530
4	8.496	0.428
5	10.620	0.346
6	12.744	0.280
7	14.868	0.227
8	16.992	0.184
9	19.116	0.149
10	21.240	0.121

Adopting the attenuation coefficient μ, reckon out from the fitting result by least square method according to experimental data into equation (1), then figure out the transmissivity and compare it with the result deduced from M-C method:

Table 10: compare the experimental result with M-C method

thickness □cm□	Experiment (n/n0)	M-C method(n/n0)	From Fitting μ (n/n0)	Relative error for experiment to M-C method (%)	Relative error for fitting to M-C method (%)
0.218	0.781	0.809	0.807	3.46	0.247
0.436	0.647	0.655	0.652	1.22	0.195
0.654	0.518	0.530	0.526	2.26	0.755
0.872	0.421	0.428	0.425	1.64	0.701

1.090	0.346	0.343	0.867
1.308	0.280	0.276	1.428
1.526	0.227	0.224	1.322
1.744	0.184	0.181	0.163
1.962	0.149	0.146	2.013
2.180	0.121	0.118	2.479

Discussion: As shown in table 3, on the condition of different voltage there is error between the theoretical and experimental linear attenuation coefficient. The reason is that the theoretical result is detected on the condition of γ-ray fountain only generate homogeneous γ-ray, but the experimental data is on the condition that X-ray generator produces multi-spectrum rays. Moreover, even if the tube current and voltage of the X-ray generator is kept immovable, the generated rays are instable. Considering the measurement error, the error between theoretical and experimental value are unavoidable.

There are two kinds of γ-ray generated by 60Co γ source with energy 1.33MeV and 1.17MeV individually. Each shares 50% of the total energy. In the table5~8, the transmissivity change trend for rays transmitting in explosive column with different attenuating metal whose thickness is variable in different places is presented: the higher the interlayer thickness is, the lower transmissivity the rays penetrating in it will be. If the thickness of the attenuating plate does not change, the difference of its position in the column (with constant thickness) has no effect on ray transmissivity, Pay attention to the latter 4 columns in tables 5~8.

Looking at the table 10 we can draw conclusions as follows:

The most relative error for four groups experimental data to the M-C method deduced data is 3.46%□the least is 1.22%, they are fitting well. Comparing the transmissivity reckoned out by least squares method according to experimental data and that by M-C method, the most relative error is 2.48%, the least is 0.20%. Especially for the former data group, the most is only 0.76%. The former four data group (the thickness of explosive column is: 2.124~8.496cm) have it experimental data, so the relative error is smaller. For the experimental condition, the latter six group (the thickness of explosive column is 10.620~21.240cm) haven't experimental data. The error for fitting μ to M-C methods is relatively larger.

Conclusions: If the tube current and voltage of X-ray source is kept steady, theoretically, the dose rate of the ray penetrating in explosive column will reduce exponentially according to the change of column thickness. However, for the same material, the scattering effect of the X-ray will became apparent as the thickness of penetrated material increases. The once fitting curve for logarithmic transformation of dose rate does not tally with the attenuation rule deduced from experiment, but the cubic fitting curve can do. Attenuation character of γ-ray penetrating in pure or impure explosive columns tallies with the exponential rule. It is feasible to use X-ray and γ-ray to detect the flaws of explosive parts.

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