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Comparison of Lead and WC–Co Materials against Gamma Irradiation

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According to RoHS (Restriction of Hazardous Substances) directive of European Union it is restricted using lead in many equipment and applications. It is possible to enlarge the restriction of lead usage in some other applications which is including some of nuclear applications in the future. Therefore new materials or systems need to be developed instead of lead as radiation shielding materials and/or collimators. In this study pure tungsten, tungsten carbide-cobalt (WC–Co) materials were investigated against gamma radiation. For gamma radiation Cs-137 and Co-60 gamma radioisotope sources were used. The linear and mass attenuations were calculated. The experimental results were compared with XCOM computer code. Usage possibilities of WC–Co instead of lead in nuclear applications as gamma shielding material were discussed. It has been investigated that the linear gamma attenuation coefficients of lead and WC–Co are very close to each other. Therefore it could be said that WC–Co materials is an alternative promising material which could be used instead of lead as gamma shielding material and/or collimator.

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1. Introduction

Lead is the most used material in nuclear technology as shielding material and collimator. Beside the good properties of lead such as relatively very cheap and easy to get and having high linear and mass attenuation coefficients, it is hazardous material for the people and environment [1]. In addition the main physical properties of lead such as hardness, strength are not good for the hard environments [2].

European Union (EU) accepted a directive in 2002 (and recast it in 2011) on the restriction of the use of certain hazardous substances, including lead, in electrical and electronic equipment [1]. Although there is an exception of using lead on nuclear and medical equipment, in future it is possible to enlarge restriction to these applications if there are some substituting materials which would be used instead of lead [3]. Therefore some other materials have to be researched against lead related with its radiation shielding properties.

In this study, gamma radiation attenuation behaviors of pure tungsten and tungsten carbide-cobalt (WC–Co) have been investigated and compared with the lead. Gamma transmission technique was used in the experiments. Cs-137 and Co-60 gamma radioisotopes were used as gamma radiation sources. The linear and mass attenuation coefficients of the samples were carried out. As a consequence pure tungsten, WC–Co and lead were compared by the view of gamma attenuation.

2. Experimental

Experiments were applied according to gamma transmission technique in which radiation source and detector were set up on the both sides of the sample material on the same axis [4]. The attenuation of gamma radiation could be calculated from the formula [5]:

$$I = I_0\,\mathrm{e}^{-\mu x}, \tag{1}$$

where I and I_0 are transmitted and incident gamma intensity, respectively. μ is the linear attenuation coefficient of the sample at a specific gamma ray and x is the thickness of the sample. Then gamma radiation intensities were measured with/without sample and results were evaluated and interpreted. In Fig. 1 general view of gamma transmission technique and information of experimental setup geometry could be seen.

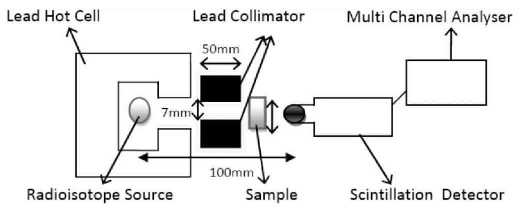

Fig. 1. Schematic view of gamma transmission technique and studied geometry.

The distance between source and detector is 10 cm for Cs-137 and 14 cm for Co-60 gamma radioisotopes and collimator hole diameter is 0.7 cm where the collimator length is 5 cm. In the experiments Cs-137 and Co-60 gamma radioisotopes were used as gamma source where their half lives are 30.1 and 5.23 years, respectively [5]. Cs-137 gamma source has 0.662 MeV energy peak and 8.9 μCi activity. Co-60 gamma source has two main energy peaks at 1.17 and 1.33 MeV which was accepted average energy peak at 1.25 MeV [6, 7]. The studied Co-60 gamma radioisotope has 14.1 μCi activities. In addition PM1401K model scintillation detector and multi channel analyzer were used in the experiments.

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WC–Co samples which include 15% cobalt by weight were produced by hot pressing method and they have $5 \times 5 \times 1$ cm^3 dimensions. Standard lead samples were used in the examples which have 5 cm diameter at different thicknesses. Finally, pure tungsten (> 99.95% purity) was used which has 5 cm diameter at different thickness values [8].

In the experiments, firstly background radiation was measured to reduce it from the all other measurements to indicate net intensities. Then I and I_0 gamma intensities for different sample thicknesses were measured by 300 s accumulation time. Afterwards relative intensity values (I/I_0) were calculated for all sample thicknesses. Finally relative intensity–thickness graphs were drawn for all materials and their gamma attenuation properties were evaluated.

3. Results and discussion

The experimental results for Cs-137 and Co-60 gamma sources were carried out. Experimental results of tungsten (W), WC–Co and lead (Pb) against Cs-137 and Co-60 gamma sources were given in Table I.

TABLE I

Experimental results for tungsten, WC–Co and lead against Cs-137 and Co-60 gamma source.

Material (code)	Thickness [cm]	1. count	2. count	3. count	Av. count	Std. deviation	Relative count	R. std. deviation (±)
Cs-137								
Tungsten (W)	0	2643	2639	2647	2643	4	1.0000	0.0030
	0.2272	1760	1759	1767	1762	4	0.6667	0.0027
	0.3228	1522	1530	1531	1528	5	0.5780	0.0027
	0.4541	1219	1229	1229	1226	6	0.4637	0.0029
	0.55	1047	1048	1053	1049	3	0.3970	0.0018
	0.7769	707	701	702	703	3	0.2661	0.0016
WC–Co	0	6236	6216	6223	6225	10	1.0000	0.0033
	1.0271	2030	2041	2044	2038	7	0.3274	0.0017
	2.0592	761	758	765	761	4	0.1223	0.0008
	3.0861	266	265	259	263	4	0.0423	0.0007
Lead (Pb)	0	3059	3062	3072	3064	7	1.0000	0.0044
	0.0913	2852	2843	2829	2841	12	0.9272	0.0058
	0.17	2625	2611	2616	2617	7	0.8541	0.0042
	0.2613	2398	2412	2398	2403	8	0.7841	0.0044
	0.318	2172	2183	2187	2181	8	0.7116	0.0041
	0.6608	1503	1496	1489	1496	7	0.4882	0.0034
	0.8308	1298	1288	1280	1289	9	0.4205	0.0039
	0.9788	1076	1073	1068	1072	4	0.3499	0.0021
	1.2401	812	816	804	811	6	0.2645	0.0026
Co-60								
Tungsten (W)	0	2500	2491	2509	2500	9	1.0000	0.0072
	0.2272	1990	2005	1996	1997	8	0.7988	0.0059
	0.3228	1807	1801	1811	1806	5	0.7225	0.0046
	0.4541	1577	1576	1560	1571	10	0.6284	0.0061
	0.55	1430	1415	1425	1423	8	0.5693	0.0051
	0.7769	1112	1115	1105	1111	5	0.4443	0.0037
WC–Co	0	3313	3290	3304	3302	12	1.0000	0.0070
	1.0271	1701	1697	1692	1697	5	0.5138	0.0032
	2.0592	877	884	885	882	4	0.2671	0.0023
	3.0861	436	434	432	434	2	0.1314	0.0011
Lead (Pb)	0	3324	3311	3319	3318	7	1.0000	0.0040
	0.0913	3081	3074	3072	3076	5	0.9270	0.0033
	0.17	2965	2978	2977	2973	7	0.8961	0.0040
	0.318	2673	2700	2678	2684	14	0.8088	0.0059
	0.6608	2205	2202	2186	2198	10	0.6623	0.0044
	0.9788	1811	1802	1804	1806	5	0.5442	0.0025
	1.2401	1433	1438	1437	1436	3	0.4328	0.0017

From Table I the relative intensity–material thickness graphs were drawn for WC–Co, lead and tungsten which are given in Fig. 2.

It could be said that lead and WC–Co have nearly same attenuation properties for both Cs-137 and Co-60 gamma sources, where tungsten has more high attenua-

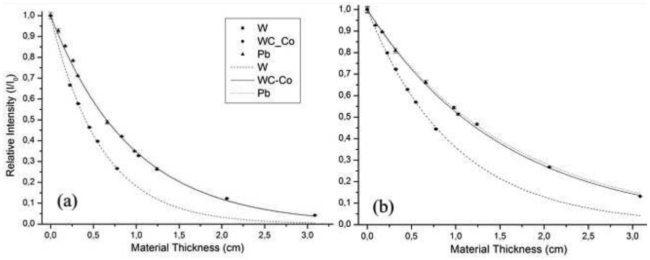

Fig. 2. Cs-137 (a) and Co-60 (b) gamma attenuation curves of tungsten, WC–Co and lead.

tion properties. From the graphs the linear attenuation coefficients of the samples were carried out by using origin program and given in Table II.

Experimental mass attenuation coefficients of the samples were calculated and compared with theoretical values which were taken from XCOM computer code [9]. The experimental and theoretical mass attenuation coefficients of the materials were given in Table III.

For all the samples, the experimental and theoretical mass attenuation coefficients are close to each other. The difference percentages of the results are between 4.74 and 9.67%.

Finally, the half value layers (HVLs), which means the material thickness to reduce initial radiation intensity to its half, of the samples were calculated by using the formula [10]:

$$HVL = 0.693/\mu. \quad (2)$$

TABLE II

Linear gamma attenuation of tungsten, WC–Co and lead for Cs-137 and Co-60 gamma sources.

Material	Linear attenuation coeff. [cm^{-1}]			
	Cs-137	Std. deviation [cm^{-1}]	Co-60	Std. deviation [cm^{-1}]
W	1.7043	0.0139	1.0252	0.0074
WC–Co	1.0627	0.0187	0.6476	0.0036
Pb	1.0507	0.0180	0.6252	0.0095

HVLs of the materials for Cs-137 and Co-60 gamma radiation were listed in Table IV. As seen in Table IV, HVLs for tungsten are the smallest values for both Cs-137 and Co-60 gamma radiations. In addition, WC–Co and lead have almost equal HVL values for both studied gamma radiations.

TABLE III

Mass gamma attenuation of tungsten, WC–Co and lead for Cs-137 and Co-60 gamma sources.

Material	Mass attenuation coefficient [10^{-2} cm^2/g]					
	Cs-137			Co-60		
	Experi- -mental	Theoret- -ical (XCOM)	Differ- -ence [%]	Experi- -mental	Theoret- -ical (XCOM)	Differ- -ence [%]
W	8.831	9.776	9.67	5.312	5.576	4.74
WC–Co	8.416	9.290	9.40	5.129	5.536	7.35
Pb	9.267	10.01	7.43	5.514	5.875	6.15

TABLE IV

HVLs of tungsten, WC–Co and lead against Cs-137 and Co-60.

Material	Cs-137		Co-60	
	HVL	Std. deviation	HVL	Std. deviation
W	0.407	0.003	0.676	0.005
WC–Co	0.652	0.011	1.070	0.006
Pb	0.660	0.011	1.109	0.017

4. Conclusion

The linear and mass attenuation of pure tungsten, tungsten carbide (WC–Co) and lead materials were carried out against Cs-137 and Co-60 gamma radiation. Pure tungsten has the biggest linear attenuation coefficient of the all studied samples. Both WC–Co and lead have nearly same linear attenuation coefficients. The HVLs of both lead and WC–Co are nearly the same which are of the following values: 0.652 and 0.66 cm for Cs-137. Furthermore, HVLs of WC–Co and Pb are close to each other and the values are 1.07 and 1.109 cm for Co-60 gamma radiation. Pure tungsten has the smallest HVLs which are 0.407 and 0.676 cm against Cs-137 and Co-60, respectively. On the other hand, it is known that WC–Co materials have better physical properties such as hardness, strength than lead and pure tungsten. Therefore tungsten based materials are promising shielding and collimator materials for the future gamma radiation applications.

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