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RESEARCH ARTICLE

Two-compartment detector for radon and thoron gases in El-Missikat and El-Erediya uranium exploratory tunnels, Central Eastern Desert, Egypt.

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Abstract

Two-compartment detector containing CR-39 SSNTD was employed to measure the concentrations of the two isotopes of radon gas; radon (^{222}Rn) emanating from the ^{238}U series and thoron (^{220}Rn) which emanates from the ^{232}Th series. This detector was tested inside the uranium exploratory tunnels at El Missikat and El Erediya, central eastern Desert, Egypt. Several detectors were distributed to cover the locations at different concentrations of ^{238}U and ^{232}Th in the granitic rocks and different conditions of ventilation in the two tunnels.

The activity concentration of ^{238}U inside El Missikat tunnel ranged between 305 and 684 (Bq/kg) with an average of 506.8±135.2 (Bq/kg) while it varied in El Erediya tunnel from 293 to 549 (Bq/kg) with an average of 374.6±79.44 (Bq/kg). In El Missikat tunnel ^{232}Th obtained an activity concentration in the studied granites ranging between 206 and 366 (Bq/kg) with an average of 247±49.75 (Bq/kg) and in El Erediya tunnel it varied from 159 to 265 (Bq/kg) with an average of 193.5±34.06 (Bq/kg).

In El Missikat tunnel, the average activity concentration of radon gas was 13.9±5.5 (kBq/m^3) at the studied non-venilated locations and 1.69±1.07 (kBq/m^3) at the ventilated locations while in El Erediya tunnel the average radon concentration was 5.77±2.59 (kBq/m^3) at the non-ventilated area and 1.19±0.4 (kBq/m^3) at the ventilated area. Thoron gas concentration got an average value of 3.83±2.3 (kBq/m^3) at the non-ventilated locations inside El Missikat tunnel and 247±49.75 (kBq/m^3) at the ventilated locations while in El Erediya tunnel this gas got an average concentration of 0.61±0.26 (kBq/m^3) over the non-ventilated area and 0.3±0.2 (kBq/m^3) over the ventilated area.

Indeed, the concentrations of radon and thoron gases obtained by the two-compartment detector responded well to the concentrations of ^{238}U and ^{232}Th in the studied granitic rocks and they differentiated precisely between the ventilated and non-ventilated locations. On another hand, the detector showed linear response of accepted correlation between uranium and thorium concentrations and the effective doses due to the inhalation of radon and thoron gases and their decay products inside the studied tunnels. This, along with the easy use, light weight and small dimensions qualify the proposed detector as an individual monitor of radon and thoron gases for the workers in uranium mines.

Introduction:-

Natural radiation sources are the main exposure of human where, the sources are extraterrestrial; the earth has been bombarded by a high energy particles originating from cosmic rays and terrestrial; the earth's crust contain on radionuclides, (UNSCEAR, 2008). Radon is a noble gas emitted from ^{238}U decay series with half-life 3.82 days. Thoron is derived from ^{232}Th decay series and has a relatively short half-life 55 sec and it represents the largest natural sources of radiation contributing to the exposure, (La Brecque, 2002 and Yang et al. 2005). Radon comes from a decay of radium, present in all soils and rocks, water, and building materials. ^{222}Rn spontaneously breaks down into its fourrelatively short-lived progenies (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) which mix with room air, then are inhaled by human lung, they emit alpha particle, and may strike sensitive cells in the bronchial tubes and increase the risk of lung cancer. The alpha emitters from radon can be cause the lung cancer, (Wang et al, 2002). Inhalation of radon is responsible for 50% of the average effective dose, (UNSCEAR, 1994). It becomes a problem when released into a closed or poorly ventilated enclosure like dwellings, buildings, caves and mines (Diab and Abd El-Hafez 2011).

Various techniques are used to evaluate and monitor the concentrations of radon-thoron gases, (Abdel-Monen et al., 1998; Abd El-Hafez et al. 1999; Eappen and Mayya 2004; Papastefanou 2007; Pereira et al. 2010; Kumar et al. 2013). Solid state nuclear track detectors (SSNTDs) for radon-thoron measurements is widely accepted technique (Beck and Gingrich 1976; Gingrich and Fisher 1976; Abd El-Hafez et al 1996; 1998a,b, Abdel-Monem et al., 1999) because these detectors aren't affected in the atmosphere when exposed in open environments (Tommasino 1990). LR-115 detectors were used in the twin cup dosimeter for measuring radon-thoron concentrations and their decay products, (Eappen and Mayya, 2004; Al-Azmi, 2009; Sathish et al, 2011; Verma et al, 2012). Klein et al,1999, developed a new passive detectors using two solid nuclear detectors; thermo-luminescent detectors (TLDs) (gamma measuring) and solid nuclear track detectors (SSNTDs) (alpha measuring) for measuring in different soil depths.

The mining is a form of industries for extracting radioactive ores in number of countries where, the inhalation of radon, thoron and their respective progenies, the inhalation and ingestion of ore dust and external irradiation with gamma rays are the main potential sources of occupational exposure in most mining operations are the natural radionuclides arising from the radioactive decay the ^{238}U and ^{232}Th series.

In this present study, we used a new two-compartment dosimeter for evaluating the occupational exposures in the mining due to radon, thoron and their decay products.

Methods and Experimental techniques:-

Field Works:-

The Egyptian Nuclear Materials Authority (NMA) established some of projects to explore the radioactive elements in Egypt. One of them was established at the 85 k Qena-Safaga Road. This project operated in the exploration tunnels at El-Missikat and EL-Eradiya. So, the radioactive exposure arises for a lot of workers in this projects from terrestrial radioactive elements such as uranium, thorium, potassium and radon. El-Misssikat tunnel located at 3 km south of the 85 km post on Qena-Safaga Road, it composed of the main adit D (958.85 m) and two drifts; DI (256.3 m) and DII (589.5 m), which show in Fig (1). DII is open to the outer atmosphere, causing natural ventilation. EL-Eradiya tunnel is located 35 km south of the 85 km post on Qena-Safaga Road. It composed of the main adit D (751.3 m) and thirteen drifts, which show in Fig. (2). DVIII drift is open the outer atmosphere, causing the ventilation in the area. The dimensions of these tunnels are 2x-2.2 m^2 wide and 2.2 m height. The explored rocks in this tunnel include younger granite and altered and brecciated varieties. These tunnels extended in sub surface parallel with shear zone which include silicification, ferrugination, sericitization, kaolinization and Mn-Oxides. The siliceous veins that include the uranium mineralization are abundant in the main shear zones along the drifts DI, DII in El-Missikat tunnel (Abu Deif, 1985). In each tunnel, ten monitoring stations were chosen to test the proposed dosimeter as shown in Figs. (1&2). These stations were chosen to cover different concentrations of uranium and thorium and different ventilation conditions. The dosimeter was hanged at a height of 1.5 m and distant 10 cm from the surface of the granitic walls; Fig (3).

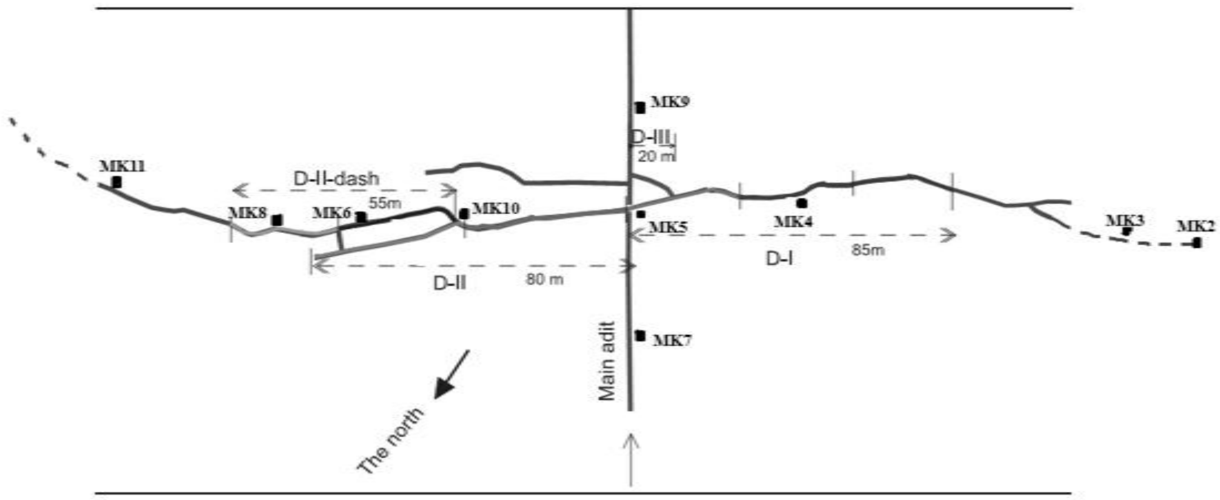

Fig (1): Plan of El-Missikat mining work (Abu Deif, 1985).

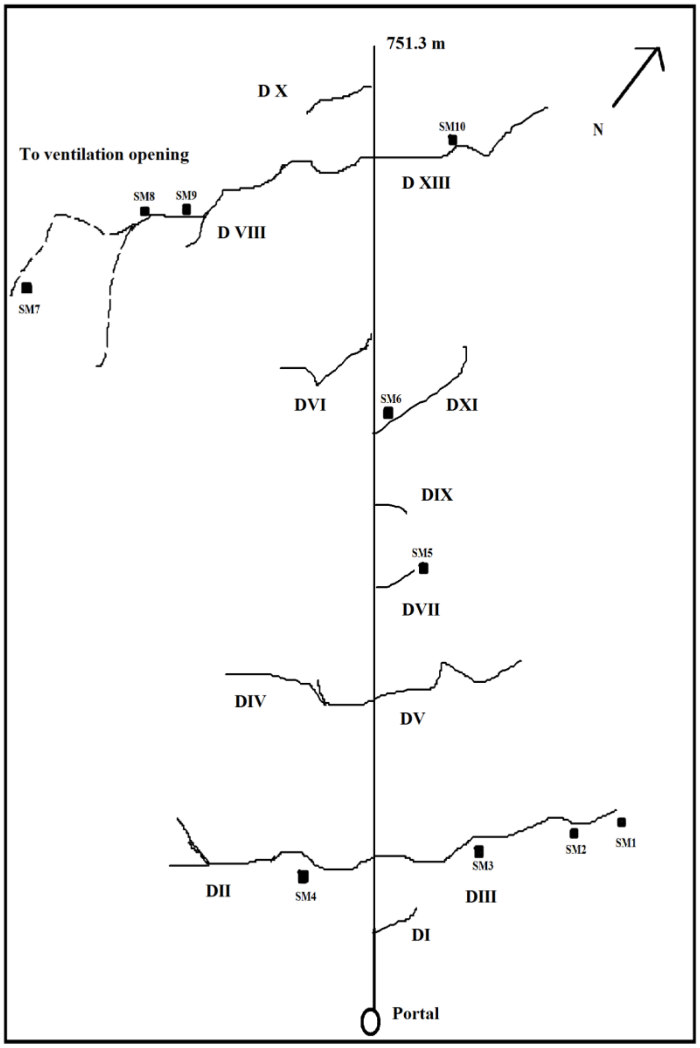

Fig (2): Plan of El Erediya exploratory mine work (El Taher, 1985).

Fig (3): Radon- thoron dosimeter.

Measurements of radionuclidesactivity concentrations:-

A portable RS-230 BGO (Bismuth Germanate Oxide) spectrometer used to wide range application during the uranium exploration process. It provides readout the concentration of uranium, thorium with ppm and the percentage of potassium in the medium through 30 sec (used in this work). For example, the measurement with the RS-230 BGO handled provides comparable quality, as the same measurement using the much larger 21 in^3 (390 cm^3) NaI portable detector. The spectrometer is auto-stabilizing on the naturally occurring (K, U, &Th) radioactivity and does not require any test sources (Terraplus, 2013). These measurements were carried out at different points on the surfaces of the rocks around the location of the dosimeter.

Dosimeter system:-

Radon and thoron concentrations:-

The radon, thoron discriminator is shown as in Fig.4. The dosimeter consisting of two compartments, each compartment has a radius 1.5 cm and height 4.2 cm.CR-39 sheet with thickness 750 µm obtained from TASTRAK were cut into small detectors1×1 cm^2. The detector 1 placed in the membrane compartment M to detect radon only, which diffuses into it from the ambient air through a semi permeable membrane has permeability constant in range 10^{-8}-10^{-5} $cm^{-2}.s^{-1}$ and suppress thoron gas (Jonsson, 1981, Ramachandran, 1987 and Arafa, 2002). The detector 2 placed in the glass fiber filter of thickness 0.56 mm in the compartment F, the glass fiber allows to radon and thoron diffuses into it.

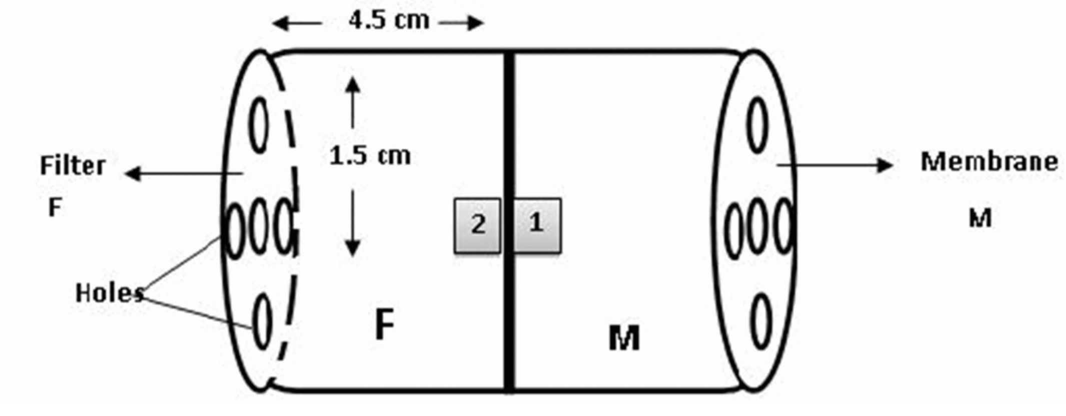

Fig (4): Design of the radon-thoron dosimeter.

The radon, thoron concentrations and their decay products are calculated by the following Equations, (Mayya et al, 1998):

$$\mathbf{C_{Rn}(Bq.m^{-3}) = \frac{T_1}{dS_m}} \qquad \textbf{(1)}$$

$$\mathbf{C_{Tn}(Bq.m^{-3}) = \frac{T_2 - dC_{Rn}S_{rf}}{dS_{tf}}} \qquad \textbf{(2)}$$

where C_{Rn} is the radon concentration and C_{Tn} is the thoron concentration (Bq/m^3), T_1 is the track density of the detector in the compartment M, d the period of exposure (days), S_m the calibration factor of the compartment M, T_2 the track density of the detector in filter compartment, S_{rf} the calibration factor of radon in the compartment F and S_{tf} is the sensitivity of thoron in the compartment F.

Calibration Facility:-

Calibration factors defined as the quantities which are used for converting the observed track density rates to the activity concentrations. A natural radioactive source was used with ^{226}Ra and ^{228}Ra activity concentrations of 120 Bq/kg and 178 Bq/kg, respectively. The source was placed in a powder form at the bottom of a calibration chamber. Radon gas emanates from the source grains was left to build up in the air inside the chamber under ambient conditions of temperature, 25^{o}C, and humidity, 25–50%. The dosimeter suspended in the central of calibration chamber which has a radius 13 cm and a height 30 cm. The chamber was tightly closed for one month to reach the equilibrium between radon and decay products. At the end of exposure time, the detectors removed and subjected to a chemical etching process in 6.25N at 70^o for 8 hours. The detectors were washed and dried and the alpha tracks were counted under an optical microscope at 400X.

Radon gas inside the buckle builds up according to the relation:

$$\mathbf{C_g=C_{Ra}(1-e^{-\lambda t})} \qquad \textbf{(3)}$$

where,
C_g activity concentration of C_{Rn} or C_{Tn} (Bq/m^3),
C_{Ra} and C_{Rn} are the respective activities (Bq) of the ^{226}Ra and ^{228}Ra.
λ is the radon decay constant = $0.693/(T_{1/2})_g$.
t is the elapsed time in days.

Accordingly, the calibration factors S_k in the air inside the buckle is obtained using the relation:

$$\mathbf{S_k = ThA/C_{Ra}T_eM} \qquad \textbf{(4)}$$

where:
S_k calibration factor, k=m, rf and tf,
T= Track density (Tracks.cm^{-2}),
h= Height of radon chamber (cm),
A= Area of the bottom of radon chamber (cm^2),
C_{Ra}= Activity concentration of ^{226}Ra or ^{228}Ra (Bq/kg),
T_e= Effective time, (d),
M= Mass of the sample (= 0.9 kg).

Effective dose due to radon and thoron:-

The effective doses due to the inhalation of radon gas Rn, thoron gas Tn and their decay products are calculated assuming an occupancy time of 2000h/y and the conversion factors to obtain the effective dose from radon and thoron are 9 nSv.(Bq.h.m^{-3})$^{-1}$ and 40 nSv(Bq.h.m^{-3})$^{-1}$ respectively. Accordingly, the annual effective doses E_{Rn} and E_{Tn} (mSv) received by the workers in the studied tunnels due to the inhalation of, respectively, radon Rn and thoron Tn gases and their decay products are calculated as follows:

Radon:-

$$\mathbf{C_{Rn}\ (Bq.m^{-3}) \times F_R \times 2000h \times 9nSv\ (Bq\ h\ m^{-3})^{-1}} \qquad \textbf{(5)}$$

Thoron

$$\mathbf{C_{Tn}\ (Bq.m^{-3}) \times F_{Tn} \times 2000h \times 40nSv\ (Bq\ h\ m^{-3})^{-1}} \qquad \textbf{(6)}$$

where, F_R and F_T are the radon and thoron equilibrium factors which it calculated at the same locations by Abdel-Monem et al (1998).

Results and discussion:-

Uranium and thorium activity concentrations:-

From Table 1, the activity concentrations A_U ranged from 305 to 733 $Bq.kg^{-1}$ with average 528 ± 212 $Bq.kg^{-1}$, and the activity concentrations A_{Th} ranged from 236 to 366 $Bq.kg^{-1}$ with average 290 ± 56 $Bq.kg^{-1}$ for non-ventilation section at Missikat tunnel, while the activity concentrations A_U ranged from 415 to 623 $Bq.kg^{-1}$ with average 492 ± 73 $Bq.kg^{-1}$ and the activity concentrations A_{Th} ranged from 206 to 235 $Bq.kg^{-1}$ with average 219 ± 11$Bq.kg^{-1}$ for ventilation section.

Table 1: Activity concentrations of A_U and A_{Th} ($Bq.kg^{-1}$) for non-ventilation and ventilation sections at Missikat tunnel.

Non – ventilation			Ventilation		
St.no	**A_UBq/kg**	**A_{Th}Bq/kg**	**St.no**	**A_UBq/kg**	**A_{Th}Bq/kg**
MK2	**684**	**236**	**MK5**	**623**	**227**
MK3	**305**	**265**	**MK6**	**513**	**208**
MK4	**391**	**293**	**MK7**	**415**	**235**
MK9	**733**	**366**	**MK8**	**488**	**215**
			MK10	**440**	**206**
			MK11	**476**	**219**
Ave	**528**	**290**	**Ave**	**492**	**219**
SD	**212**	**56**	**SD**	**73**	**11**
SE	**53**	**14**	**SE**	**18**	**3**

From Table 2, the activity concentrations A_U ranged from 308 to 465 $Bq.kg^{-1}$ with average 372 ± 69 $Bq.kg^{-1}$ and the activity concentrations A_{Th} ranged from 163 to 265 $Bq.kg^{-1}$ with average 216 ± 42 $Bq.kg^{-1}$ for non-ventilation section at Eradiya tunnel, while the activity concentrations A_U ranged from 293 to 549 $Bq.kg^{-1}$ with average 376 ± 92 $Bq.kg^{-1}$and the activity concentrations A_{Th} ranged from 159 to 212 $Bq.kg^{-1}$ with average 178 ± 19 $Bq.kg^{-1}$ for ventilation section.

Table 2: Activity concentrations of A_U and A_{Th}, A_K, ($Bq.kg^{-1}$) for non-ventilation and ventilation sections at Eradiya tunnel.

Non - ventilation			Ventilation		
St.no	**A_UBq/kg**	**A_{Th}Bq/kg**	**St.no**	**A_UBq/kg**	**A_{Th}Bq/kg**
SM1	**465**	**212**	**SM4**	**354**	**171**
SM2	**379**	**265**	**SM5**	**293**	**187**
SM3	**308**	**163**	**SM6**	**403**	**167**
SM10	**336**	**224**	**SM7**	**342**	**159**
			SM8	**549**	**175**
			SM9	**317**	**212**
Ave	**372**	**216**	**Ave**	**376**	**178**
SD	**69**	**42**	**SD**	**92**	**19**
SE	**17**	**10**	**SE**	**23**	**5**

Radon and thoron concentrations:-

Table 3 showing the results of track densities which induced from the radon, thoron and their decay products where, the radon concentration ranged from 8934 to 19419 $Bq.m^{-3}$ with average 13897 ± 5520 $Bq.m^{-3}$ and the thoron concentration ranged from 1369 to 5426 $Bq.m^{-3}$ with average 3833 ± 2304 $Bq.m^{-3}$for non-ventilation section at Missikat tunnel while the radon concentration ranged from 924 to 3828 $Bq.m^{-3}$ with average 1686 ± 1069 $Bq.m^{-3}$ and the thoron concentration ranged from 291 to 2417 $Bq.m^{-3}$ with average 668 ± 865 $Bq.m^{-3}$ for ventilation section.

Table 3: Radon track density T_1 (tr.cm^{-2}) and radon and thoron track density T_2 (tr.cm^{-2}), concentration of radon C_{Rn} (Bq.m^{-3}) and thoron C_{Tn} (Bq.m^{-3})for non-ventilation and ventilation sections at Missikat tunnel.

Non – ventilation					Ventilation				
St.no	T_1 tr.cm^{-2}	T_2 tr.cm^{-2}	C_{Rn} Bq.m^{-3}	C_{Tn} Bq.m^{-3}	St.no	T_1 tr.cm^{-2}	T_2 tr.cm^{-2}	C_{Rn} Bq.m^{-3}	C_{Tn} Bq.m^{-3}
MK2	6994	7512	17867	2405	MK5	1498	2326	3828	-
MK3	3666	5766	9366	6131	MK6	362	461	924	291
MK4	3497	3966	8934	1369	MK7	457	566	1167	319
MK9	7602	9460	19419	5426	MK8	576	635	1472	173
					MK10	579	674	1480	276
					MK11	488	670	1246	533
Ave	5440	6676	13897	3833	Ave	660	889	1686	247
SD	2161	2354	5520	2304	SD	419	709	1069	49.75
SE	540	588	1380	576	SE	70	118	178	144

Table 4 showing the results of track densities which induced from the radon, thoron and their decay products where, the radon concentration ranged from 3136 to 9336 Bq.m^{-3} with average 5770 ± 2588 Bq.m^{-3} and the thoron concentration ranged from 312 to 928 Bq.m^{-3} with average 610 ± 210 Bq.m^{-3} for non-ventilation section at Eradiya tunnel, while the radon concentration ranged from 836 to 1946 Bq.m^{-3} with average 1192 ± 397 Bq.m^{-3} and the thoron concentration ranged from 64 to 1221 Bq.m^{-3} with average 455 ± 415 Bq.m^{-3} for ventilation section.

Table 4: Radon track density T_1 (tr.cm^{-2}), radon and thoron track density T_2 (tr.cm^{-2}) and radon and thoron decay products T_3 (tr.cm^{-2}), concentration of radon C_{Rn} (Bq.m^{-3}) and thoron C_{Tn} (Bq.m^{-3}) for non-ventilation and ventilation sections at Eradiya tunnel.

Non – ventilation					Ventilation				
St.no	T_1 tr.cm^{-2}	T_2 tr.cm^{-2}	C_{Rn} Bq.m^{-3}	C_{Tn} Bq.m^{-3}	St.no	T_1 tr.cm^{-2}	T_2 tr.cm^{-2}	C_{Rn} Bq.m^{-3}	C_{Tn} Bq.m^{-3}
SM1	3654	3972	9336	928	SM4	500	516	1279	64
SM2	2071	2178	5291	312	SM5	422	840	1078	-
SM3	2081	2302	5315	646	SM6	406	570	1037	478
SM10	1228	1416	3136	551	SM7	327	403	836	221
					SM8	884	916	1946	533
					SM9	381	453	973	211
Ave	2258	2467	5770	610	Ave	487	616	1192	301.4
SD	1013	1077	2588	255	SD	203	212	397	197.4
SE	253	269	647	64	SE	34	35	66	69

Equilibrium factor and annual effective dose:-

Table 5 indicates that the equilibrium factor F_R ranged from 0.321 to 1 with average 0.654 ± 0.042 and the equilibrium factor F_T ranged from 0.07 to .469 with average 0.271 ± 0.026 at the non-ventilation section at Missikat tunnel. The radon annual effective dose E_{Rn} ranged from 54 to 329 mSv.y^{-1} with average 190 ± 156mSv.y^{-1}, while the thoron annual effective dose E_{Tn} ranged from 22 to 187mSv.y^{-1} with average 74 ± 15mSv.y^{-1} at this section. The wind speed W_S ranged from 0.24 to 0.73 m.s^{-1} with average 0.57 ± 0.19 m.s^{-1}, the equilibrium factor F_R ranged from 0.018 to 0.940 with average 0.236 ± 0.053 and the equilibrium factor F_T ranged from 0.0003 to 0.158 with average 0.039 ± 0.0003. The radon annual effective dose E_{Rn} ranged from 0.4 to 45 mSv.y^{-1} with average 10 ± 3 mSv.y^{-1}, while the thoron annual effective dose E_{Tn} ranged from 0.01 to 31 mSv.y^{-1} with average 5 ± 1 mSv.y^{-1} for ventilation sections.

Table 5: Wind speed W_S ($m.s^{-1}$), equilibrium factors F_R, F_T, radon annual effective dose E_{Rn} ($mSv.y^{-1}$) and thoron annual effective dose E_{Tn} ($mSv.y^{-1}$) for non-ventilation and ventilation sections at Missikat tunnel.

Non - ventilation						Ventilation					
St.no	W_S $m.s^{-1}$	F_R	F_T	E_{Rn} $mSv.y^{-1}$	E_{Tn} $mSv.y^{-1}$	St.no	W_S $m.s^{-1}$	F_R	F_T	E_{Rn} $mSv.y^{-1}$	E_{Tn} $mSv.y^{-1}$
MK2	Considered zero speed	1	0.114	322	22	MK5	0.72	0.656	0.1581	45	31
MK3		0.321	0.070	54	34	MK6	0.45	0.120	0.0036	2	0.08
MK4		0.353	0.469	57	51	MK7	0.73	0.018	0.0003	0.4	0.01
MK9		0.940	0.432	329	187	MK8	0.24	0.135	0.0034	4	0.05
						MK10	0.59	0.112	0.0670	3	1
						MK11	0.67	0.371	0.0030	8	0.13
Ave		0.654	0.271	190	74	Ave	0.57	0.233	0.041	10	5
SD		0.042	0.026	156	15	SD	0.19	0.063	0.002	3	1
SE		0.011	0.007	39	4	SE	0.03	0.016	0.0005	0.5	0.16

Table 6 indicatethe that the equilibrium factor F_R ranged from 0.394 to 1 with average 0.721 ± 0.062 and the equilibrium factor F_T ranged from 0.016 to 0.405 with average 0.191 ± 0.088. The radon annual effective dose E_{Rn} ranged from 38 to 168 $mSv.y^{-1}$ with average 78 ± 9 $mSv.y^{-1}$, while the thoron annual effective dose E_{Tn} ranged from 1 to 10 $mSv.y^{-1}$ with average 7 ± 4 $mSv.y^{-1}$for non-ventilation section at Eradiya tunnel. The wind speed W_S ranged from 0.64 to 1.16 $m.s^{-1}$ with average 0.83 ± 0.19 $m.s^{-1}$,the equilibrium factor F_R ranged from 0.098 to 0.281 with average 0.183 ± 0.033 and the equilibrium factor F_T ranged from 0.002 to 0.048 with average 0.012 ± 0.002. The radon annual effective dose E_{Rn} ranged from 2 to 10 $mSv.y^{-1}$ with average 4 ± 3 $mSv.y^{-1}$, while the thoron annual effective dose E_{Tn} ranged from 0.04 to 0.81 $mSv.y^{-1}$ with average 0.16 ± 0.14 $mSv.y^{-1}$ for ventilation section.

Table 6: Wind speed W_S ($m.s^{-1}$), equilibrium factors F_R, F_T, radon annual effective dose E_{Rn} ($mSv.y^{-1}$) and thoron annual effective dose E_{Tn} ($mSv.y^{-1}$) for non-ventilation and ventilation sections at Eradiya tunnel.

Non – ventilation						Ventilation					
St.no	W_S $m.s^{-1}$	F_R	F_T	E_{Rn} $mSv.y^{-1}$	E_{Tn} $mSv.y^{-1}$	St.no	W_S $m.s^{-1}$	F_R	F_T	E_{Rn} $mSv.y^{-1}$	E_{Tn} $mSv.y^{-1}$
SM1	Considered zero speed	1	0.11	168	8	SM4	0.66	0.227	0.010	5	0.05
SM2		0.58	0.40	55	10	SM5	0.88	0.106	0.003	2	0.32
SM3		0.39	0.02	38	1	SM6	0.85	0.165	0.006	3	0.22
SM10		0.91	0.23	51	10	SM7	0.64	0.220	0.002	3	0.04
						SM8	0.81	0.281	0.002	10	0.09
						SM9	1.16	0.098	0.048	2	0.81
Ave		0.72	0.19	78	7	Ave	0.83	0.183	0.012	4	0.16
SD		0.06	0.09	9	4	SD	0.19	0.033	0.002	3	0.14
SE		0.02	0.02	2	1	SE	0.03	0.008	0.0004	1	0.03

The ratio between F_R at Missikat tunnel to F_R at Eradiya tunnel for ventilation section equal 1.28. This is due to the difference in ventilation rate in the two tunnels, where the ratio between W_S at Eradiya tunnel to W_S at Missikat tunnel for ventilation section equals 1.46. This is consistent with the ratio between the radon concentrations C_{Rn} in Missikat tunnel and in Eradiya tunnel which is 1.41.

Figures 5, 6, 7 and 8, clarify the good correlation between the radon annual effective dose E_{Rn} and activity concentration A_U in the two sections; ventilation and non-ventilation at Missikat and Eradiya tunnels. Also, from Figures 9, 10, 11 and 12, it is obvious the good correlation between the thoron annual effective dose E_{Tn} and activity concentration A_{Th} in two sections; ventilation and non-ventilation at Missikat and Eradiya tunnels. Generally, we can conclude that the proposed radon-thoron dosimeter or the two-compartment detector is sensitive to the environmental conditions.

However, all figures indicate a threshold value for the activity concentrations of uranium or thorium (x-intercepts) below which the effective doses due to radon or thoron gas can't be estimated. This limits the use of the studied detector for higher concentrations of uranium and thorium, i. e. restricts the detector for uranium mines exclusively.

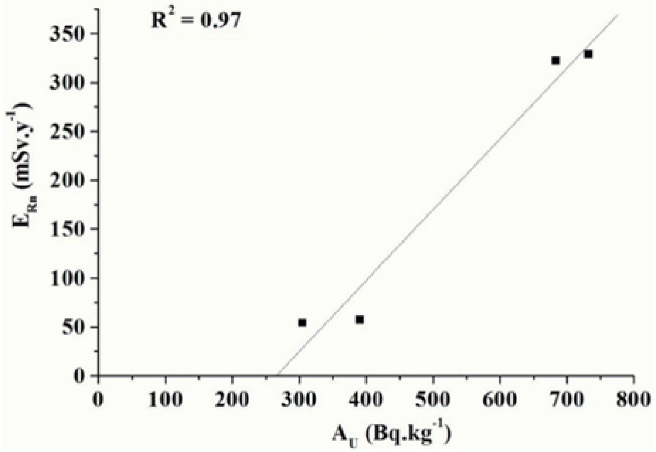

Fig (5): The relation between uranium activity concentration A_U (Bq.kg^{-1}) and radon annual effective dose E_{Rn} (mSv.y^{-1}) for non-ventilation section at Missikat tunnel.

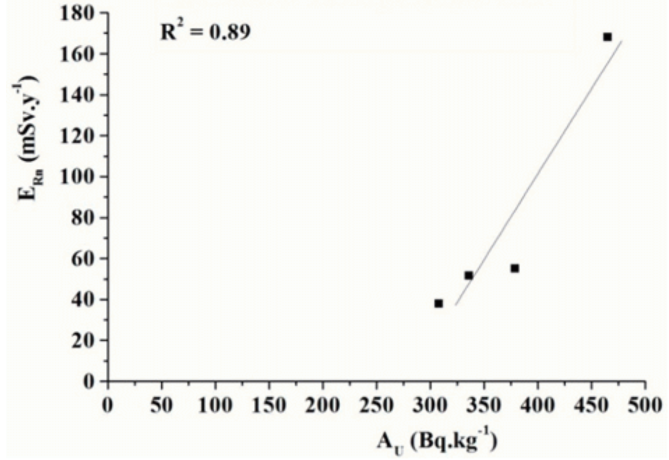

Fig (6): The relation between uranium activity concentration A_U (Bq.kg^{-1}) and radon annual effective dose E_{Rn} (mSv.y^{-1}) for non-ventilation section at Eradiya tunnel.

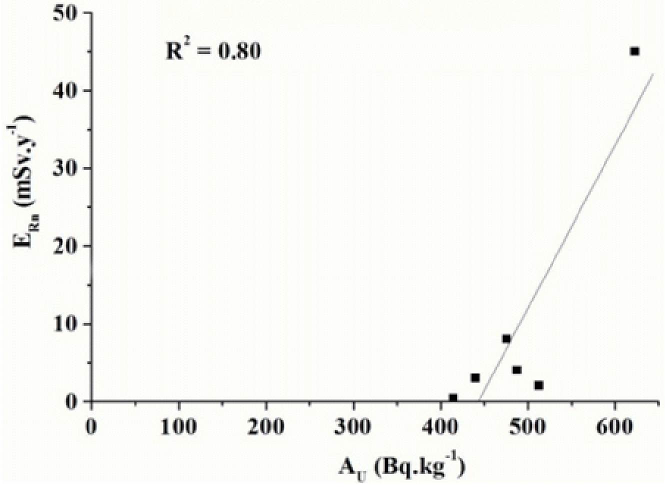

Fig (7): The relation between uranium activity concentration A_U (Bq.kg^{-1}) and radon annual effective dose E_{Rn} (mSv.y^{-1}) for ventilation section at Missikat tunnel.

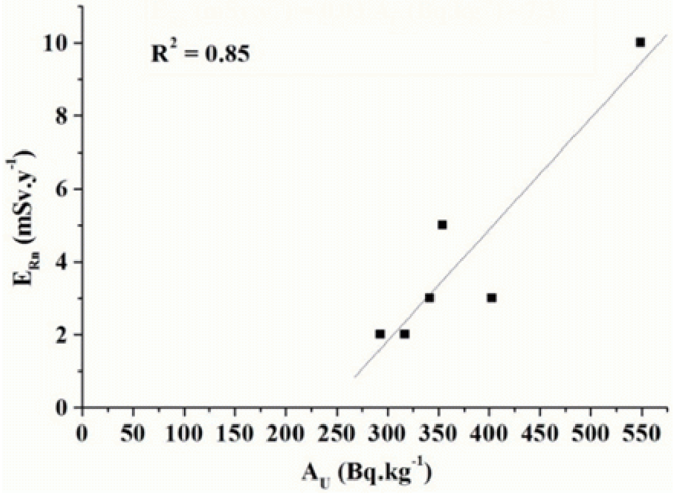

Fig (8): The relation between uranium activity concentration A_U (Bq.kg^{-1}) and radon annual effective dose E_{Rn} (mSv.y^{-1}) for ventilation section at Eradiyatunnel.

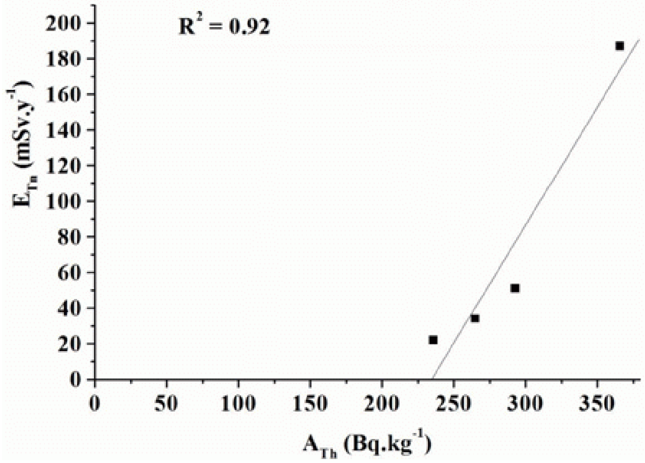

Fig (9): The relation between thorium activity concentration A_{Th} (Bq.kg^{-1}) and thoron annual effective dose E_{Tn} (mSv.y^{-1}) for non-ventilation section at Missikat tunnel.

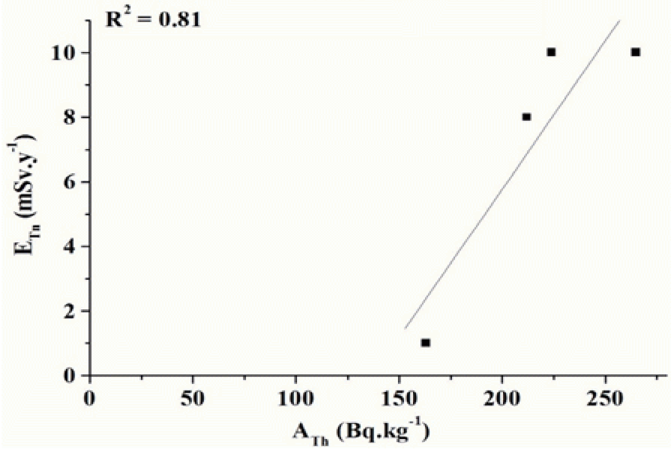

Fig (10): The relation between thorium activity concentration A_{Th} (Bq.kg^{-1}) and thoron annual effective dose E_{Tn} (mSv.y^{-1}) fo rnon-ventilation section at Eradiya tunnel.

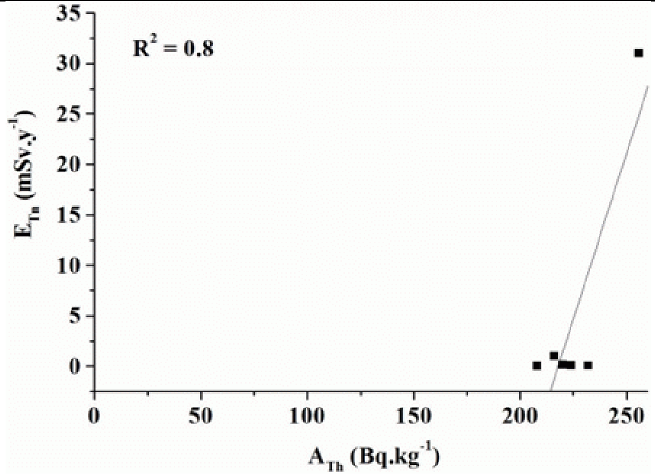

Fig (11): The relation between thorium activity concentration A_{Th} (Bq.kg^{-1}) and thoron annual effective dose E_{Tn} (mSv.y^{-1}) for ventilation section at Missikat tunnel.

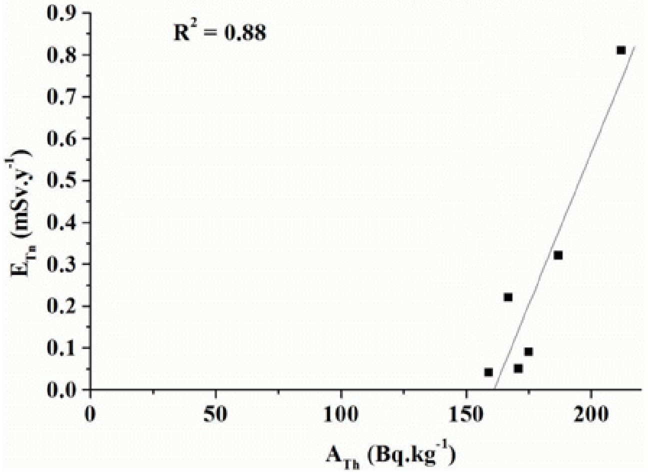

Fig (12): The relation between thorium activity concentration A_{Th} (Bq.kg^{-1}) and thoron annual effective dose E_{Tn} (mSv.y^{-1}) for ventilation section at Eradiya tunnel.

Conclusions:-

The concentrations of radon and thoron gases obtained by the two-compartment detector responded well to the concentrations of ^{238}U and ^{232}Th in the studied granitic rocks and they differentiated precisely between the ventilated and non-ventilated locations. On another hand, the detector showed linear response of accepted correlation between uranium and thorium concentrations and the effective doses due to the inhalation of radon and thoron gases and their decay products inside the studied tunnels. This, along with the easy use, light weight and small dimensions qualify the proposed detector as an individual monitor of radon and thoron gases for the workers in uranium mines.

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