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EFFECTIVE ATOMIC NUMBERS, ELECTRON DENSITIES, AND TISSUE EQUIVALENCE OF SOME GASES AND MIXTURES FOR DOSIMETRY OF RADIATION DETECTORS

by

Vishwanath P. SINGH[*] and Nagappa M. BADIGER

Department of Physics, Karnatak University,
Dharwad, Karnatak, India

Total mass attenuation coefficients, μ_m, effective atomic number, Z_{eff}, and effective electron density, N_{eff}, of different gases – carbon dioxide, methane, acetylene, propane, butane, and pentane used in radiation detectors, have been calculated for the photon energy of 1 keV to 100 GeV. Each gas has constant Z_{eff} values between 0.10 to 10 MeV photon energies; however, these values are way far away from ICRU tissue. Carbon dioxide gas shows the closest tissue equivalence in the entire photon energy spectrum. Relative tissue equivalences of the mixtures of gases with respect to ICRU tissue are in the range of 0.998-1.041 for air, argon (4.5%) + methane (95.5%), argon (0.5%) + carbon dioxide (99.5%), and nitrogen (5%) + methane (7%) + carbon dioxide (88%). The gas composition of xenon (0.5%) + carbon dioxide (99.5%) shows 1.605 times higher tissue equivalence compared to the ICRU tissue. The investigated photon interaction parameters are useful for exposure and energy absorption buildup factors calculation and design, and fabrication of gaseous detectors for ambient radiation measurement by the Geiger-Muller detector, ionization chambers and proportional counters.

Key words: effective atomic number, gamma detector, tissue equivalent, reactor, hydrocarbons, inert gases

INTRODUCTION

The interaction of radiation with the sensitive medium of a detector produces the state of ionization and the ions detected are the principle of radiation measurement. The detector provides measurable parameters which yield information on the amount of energy deposited within the detector medium. When the medium of interaction is gas-filled, the detectors are classified as gaseous detectors. Ionization chambers, proportional counters and Geiger-Muller (GM) detectors are widely used for measuring the ambient gamma radiation level and estimation of radioactivity at nuclear power reactors, research reactors, accelerators, research laboratories, nuclear medical centers, pharmaceutical industries, cancer treatment facilities and for the identification of trace quantity of radioactivity of gases, smoke detection, remote sensing, micro-dosimetry, *etc*. Ambient gamma dose rate measurement inside nuclear facilities is one of the measure aspects

for radiological protection of the workers engaged in operation and maintenance and healthiness of nuclear systems operation. The workplace gamma equivalent dose rate in nuclear facilities is a parameter for the design of reactors and accelerator shielding, and for planning their operation and maintenance. The equivalent dose rate measured by radiation detectors is a direct indication of occupational risks/hazards from gamma radiation in nuclear facilities. The tissue equivalent (TE) gas medium of a detector represents the individual absorbed gamma dose by multiplication of the workplace dose equivalent rate and the duration of availability. The personal dose equivalent measured by a personal dosimeter is related to the equivalent dose measured by radiation detectors.

Radiation measurement by detectors is acceptable when the measuring medium/material is a tissue substitute for photon interaction, radiation absorption, and scattering processes. Suitable ways of comparing the radiation characteristics of human body tissue and TE substitutes are the photon mass attenuation coefficient, mass energy absorption coefficient or the effective atomic number. The equivalence of the detector to human body tissue is achieved by employing TE mate-

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[*] Corresponding author; e-mail: kudphyvps@rediffmail.com
Permanent address: Health Physics Section, Kaiga Atomic Power Station-3&4, NPCIL, Karwar, 581400, Karnatak, India

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rials like detector walls and gaseous mediums. Gaseous detectors are filled with a variety of gases and different compositions of hydrocarbon, inert gases, *etc.* Noble gases and pure or binary mixtures like 90% argon and 10% methane gas (P-10) and a mixture of 95% argon and 5% methane (P-5), are widely in use in proportional counters. Many other hydrocarbons, such as methane and ethylene, are also suitable for proportional counters. Gamma-ray exposure measurement is carried out by air-filled ionization chambers with the walls air-equivalent made of plastic, aluminum or stainless steel. Ionization chambers are also filled with methane for 1.836 MeV and 3.26 MeV photon, argon/propane [1, 2] and other mediums, such as acetylene. GM detectors use inert gases such as helium, argon, and xenon with common quenching agents ethanol, propane, butane, ethyl formulate and halogens to prevent continuous ionization. In addition, GM detectors are also filled with methane, carbon dioxide, and a mixture of methane and argon for special purposes.

The effective atomic number, Z_{eff}, of ICRU tissue, 7.46 [3]; water, 7.9; PMMA phantom, 6.56 [4]; $Li_2B_4O_7$, 7.23 [5], A-150 plastic [6], and a bio-molecule present in DNA, RNA, and retina showed significant variations in the photon energy range of 0.001-20 MeV [7]. The underestimation of the personal dose equivalent of radiation detectors has been investigated in the high energy bremsstrahlung radiation near the 450 MeV electron storage ring [8] and tissue equivalent proportional counters (TEPC) have been studied in detail [9-12]. Therefore, the Z_{eff} of the gaseous interacting medium of detectors is a vital parameter characterization for various radio-nuclides emitting gamma radiation.

The photon interacts with the medium by photo-absorption, Compton scattering and the pair-production process which depend on photon energy, and the constituent element atomic number. Photo-absorption and pair-production are a complete photon removal process, whereas the Compton interaction slows down photon energy and is then removed by the photo-absorption interaction. Theoretical values for mass attenuation coefficients and cross sections of various elements, compounds and mixtures have been tabulated by Berger, *et al.* and given in the form of the XCOM program at energies of 1 keV to 100 GeV [13]. A similar program, the XmuDat, also calculates the mass attenuation coefficient, mass energy transfer, mass attenuation coefficients for elements, compounds and mixtures in the energy range from 1 to 50 MeV photon energy range for medical physics purposes [14].

Several authors have investigated photon interaction parameters such as the effective atomic number and electron densities for various composite materials at photon energies from 1 keV to 1 GeV [15], phosphate glass containing Bi_2O_3, PbO, and BaO at 662 keV [16], total mass attenuation coefficients, ef-

fective atomic and electron numbers for PbO, barite, colemanite, tincal, and ulexite at 80.1, 302.9, 356.0, 661.7, and 1250.0 keV photon energies [17], the effective atomic number of composite materials such as bakelite, nylon, teflon *etc.*, in the photon energy region from 280-1115 keV, by measuring the incoherent scattering cross-section [18], photon interaction parameters of common solvents [19], effective atomic numbers and electron densities of solid state detectors [20], mass attenuation coefficients, effective atomic numbers, and electron densities of thermoluminescent dosimetric compounds [21], as well as photon attenuation coefficients and the effective atomic number of cement [22]. The stopping power of electrons in gases [23] and beta-efficiency of the gas-flow ionization chamber have been reported in [24], however, photon interaction parameters of commonly used gases and gaseous mixtures in detectors which are needed for photon spectrum abundance in the range of 0.10--10 MeV in a reactor and 4-40 MeV in accelerator operations, have not been investigated. The characteristics of gamma photon interaction with gases are crucial as far as the radiation equivalent dose rate measurement and their tissue equivalence are concerned.

TE gases based on methane (64.4% CH_4, 32.5% CO_2, and 3.1% N_2) and propane (55% C_3H_8, 39.8% CO_2, and 5.4% N_2) are commercially available for use in radiation detectors [25, 26]. However, gamma radiation measurement by detectors which contain hydrocarbons and inert-hydrocarbon are not available in literatures for complete understanding and detailed study. In the present paper, we have studied the interaction of the gamma photon, effective atomic numbers and tissue equivalence of CO_2 (carbon dioxide), CH_4 (methane), C_2H_2 (acetylene), C_3H_8 (propane), C_4H_{10} (butane), C_5H_{12} (pentane), and their gaseous mixture compositions with inert gases and the like, at an atmospheric pressure of 1 [27]. Our study highlights the suitable composition of gases for the tissue equivalence for gamma radiation detectors based on Z_{eff} simulations. Recently, the effective atomic numbers and electron densities of several gases in the range from 1 keV to 1000 MeV have been studied [28].

COMPUTATIONAL WORK

In the present work, inorganic, hydrocarbon gases and mixtures of these gases with inert and other mediums whose chemical compositions are given in tab. 1 have been chosen. Table 1 also contains ICRU tissue, A-150 plastic, methane/propane based TE gases, the PMMA phantom, water, and air. Computational work on photon interaction with gases for the mass attenuation coefficient, μ_m, effective atomic number, Z_{eff} and electron densities, N_{eff}, are based on the basic Lambert-Beer law as,

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Table 1. Elemental compositions of tissue substitutes, gases and other interacting mediums

Serial number	Description	Percentage composition of elements						
		H	C	N	O	F	Ca	Ar
1	ICRU tissue	10.10	11.10	2.60	76.20	–	–	–
2	A-150 plastic	10.20	76.80	3.60	5.90	1.70	1.80	–
3	PMMA phantom	8.05	59.98	–	31.96	–	–	–
4	Water	11.20	–	–	88.88	–	–	–
5	Air	–	0.01	75.52	23.17	–	–	1.30
6	Methane bases TE gas	10.20	45.60	3.50	40.70	–	–	–
7	Propane bases TE gas	10.30	56.90	3.50	29.30	–	–	–
8	CO_2	–	27.29	–	72.71	–	–	–
9	CH_4	25.13	74.86	–	–	–	–	–
10	C_2H_2	7.74	92.26	–	–	–	–	–
11	C_3H_8	18.29	81.71	–	–	–	–	–
12	C_4H_{10}	17.34	82.66	–	–	–	–	–
13	C_5H_{12}	16.76	83.24	–	–	–	–	–

$$I \quad I_0 \exp(\quad \mu_m x) \qquad (1)$$

where, I and I_0 are photon intensities of the transmitted and incident photon of energy E, medium thickness, and μ_m, the mass attenuation coefficient.

Computation of mass attenuation coefficient

The mass attenuation coefficients for elements ($Z = 1$-92) and some additional dosimetric calculations are provided by Hubbel, *et al.*, [29]. Using the mixture rule, the mass attenuation coefficient of different gases has been obtained using the following relation

$$\mu_m \quad \frac{\mu}{\rho}_{GAS} \quad {}^n_i w_i \frac{\mu}{\rho}_i \qquad (2)$$

where, w_i is the fractional weight and $(\mu/\rho)_i$ is the mass attenuation coefficient of the ith constituent element. The quantity w_i is given by,

$$w_i \quad \frac{n_i A_i}{\Sigma_j n_j A_j} \qquad (3)$$

under the condition ${}^n_i w_i \quad 1$ and A_i being the atomic weight of the ith element, with n_i as the number of formula units.

Effective atomic number

The effective atomic number of gas for photon can be obtained by mass attenuation coefficient values. The total molecular cross-section, σ_m, of the gas is determined by the formula

$$\sigma_m (\mu_m) \frac{\Sigma_i n_i A_i}{N_A} \quad [\text{barn}^* \text{ per molecule}] \qquad (4)$$

where, n_i is the total number of atoms (with respect to mass number) in the molecule, A_i – the atomic weight of the ith element in a molecule, and N_A – the Avogadro number (atom/g).

The average atomic cross-section, σ_a, is obtained by dividing the molecular cross-section by the total number of formula units as

$$\sigma_a \quad \frac{\sigma_m}{\Sigma_i n_i} \quad [\text{barn per atom}] \qquad (5)$$

Similarly, the average electronic cross-section σ_e, for the individual elements is given by

$$\sigma_e \quad \frac{1}{N_A} {}_i \frac{f_i A_i}{Z_i} \frac{\mu}{\rho}_i \quad [\text{barn per electron}] \qquad (6)$$

where, $f_i = n_i / {}_j n_j$ and Z_i are the fractional abundance and atomic number of constituent elements, respectively; n_j is the number of atoms of constituent elements, $\Sigma_j n_j = n$ is the total number of atoms present in the molecular formula. The effective atomic number, Z_{eff}, atomic cross-section and electronic cross-section are related as

$$Z_{eff} \quad \frac{\sigma_a}{\sigma_e} \quad [\text{dimentionless}] \qquad (7)$$

Effective electron density

The effective electron density or electron density, N_{eff} (electron per cm^3), is related to the effective atomic number as

$$N_{eff} \quad \frac{N_A}{N} Z_{eff} {}_i n_i \frac{\mu_m}{\sigma_e} \qquad (8)$$

RESULTS AND DISCUSSION

We have calculated the μ_m, σ_a and σ_e, for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12} at energies from 1 keV-100 GeV using the XCOM program. Based on

* 1 barn = 10^{-28} m^2

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these results, we have estimated the effective atomic number, Z_{eff} (*i. e.* ratio of the atomic cross-section and electronic cross-section) and effective electron density, N_{eff}, at different photon energies, as explained in eqs. (1) to (8). The simulation of gaseous compositions for tissue equivalence, *i. e.* the tissue equivalent effective atomic number ($^{TE}Z_{eff}$) of various compositions of the gases with argon, xenon, nitrogen, and hydrocarbons, are analyzed by the XmuDat program. The percentage compositions of the gases are found to vary, so as to achieve the effective atomic number of gas closest to the tissue equivalent.

Pure gases of radiation detectors

Mass attenuation coefficient

From fig. 1, we have found that the variation of the mass attenuation coefficient, μ_m, can be explained by basic radiation interaction principles in terms of three energy regions: low, intermediate and high photon energy. In the low photon energy region, it undergoes photoelectric absorption where the cross-section is proportional to the atomic number, Z^{4-5}, and inversely proportional to photon energy, $E_\gamma^{7/2}$, where E_γ is the energy of the photon. The atomic number of the constituents (carbon and hydrogen) of all gases such as CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12} are the same, except for CO_2 and, therefore, the μ_m values of the gases are near to similar within the photoelectric absorption region. In the intermediate energy region, the Compton scattering is the dominant interaction and the cross-section is proportional to Z and inversely proportional to energy E_γ . Finally, in the high photon energy region, the pair-production process plays a dominant role and its cross-section is proportional to Z^2. The μ_m values of the gases reduce gradually in energies from 0.1 to 10 MeV, whereas they begin to grad-
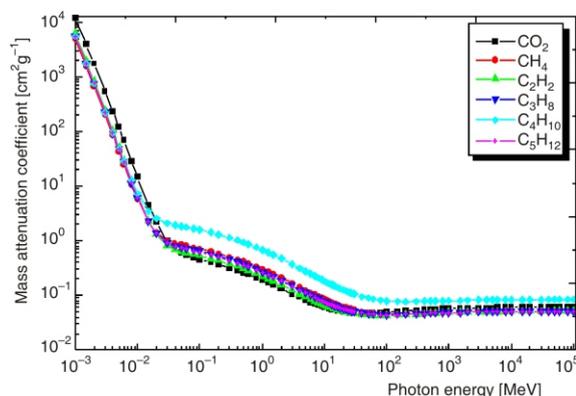
ually rise and become invariable in the high photon energy region.

Effective atomic number

We have estimated the Z_{eff} for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12} by calculating the total atomic cross-sections, σ_a, and electronic cross-sections, σ_e, at energies from 1 keV to 100 GeV, shown in fig. 2. The figure shows that the Z_{eff} of the gases is approximately constant in the low-energy photon region, reaching the minima at the intermediate photon energy. The Z_{eff} for CO_2 gas is comparatively high at all energies of the photon region, whereas the minimum for CH_4, the Z_{eff} of CO_2 gas, is more or less constant above 100 keV, without a significant reduction exhibited by other gases. We found that the Z_{eff} of CO_2 for the entire photon energy region nearly equals the human tissue equivalent, *i. e.* that it is between 7 and 8. Other hydrocarbon gases show a sharp reduction of the Z_{eff} at the photon energy of 10 keV and constant Z_{eff} values between 100 keV to 10 MeV. Also, in the intermediate photon energy region, these hydrocarbon gases are lesser Z_{eff} ($\approx$1.65 to 5), which is far from the ICRU tissue value.

We have found the Z_{eff} of CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12} values for the photon energy range of 1-10 keV to be 7.61-7.67, 5.95-4.23, 5.98-5.39, 5.96-4.66, 5.99-5.69, and 5.99-4.76. The Z_{eff} of the gases sharply goes down as the photon energy exceeds 10 keV and reaches the minima of 7.33, 1.65, 2.87, 1.92, 5.0, and 1.99 for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12}, respectively. The value of Z_{eff} from 10 keV to 1.22 MeV is invariable and increases as the photon energy exceeds 1.22 MeV because of the dominant pair-production interaction process. We have also found that the Z_{eff} values of all gases become constant above 100 MeV. The Z_{eff} of the above cited gases has also been compared with the average single value, $<Z_{eff}>$ by the XmuDat program and was found to be 7.58, 5.19, 5.74, 5.41, 5.43, and 5.45 for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12}, respec-
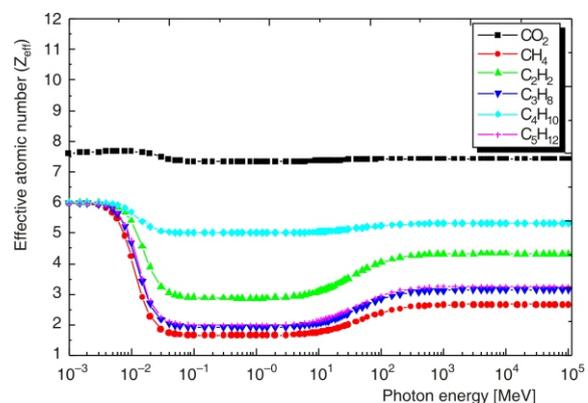

Figure 1. Mass attenuation coefficient *vs.* photon energy for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12}

Figure 2. Variaton of effective atomic number *vs.* photon energy for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12}

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tively. Therefore, CO_2 is the most suitable gas for gamma radiation detection, as far as tissue equivalence is concerned.

Effective electron density

The variation of electron density, N_{eff}, of the selected gases with photon energy is linearly dependent on Z_{eff}, and therefore follows the variations of the Z_{eff}. The N_{eff} of the gases is shown in fig. 3 which shows that the N_{eff} of the CO_2 gas is observed approximately invariable and lower compared to others. The N_{eff} of CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12} in the photon energy range of 1 to 10 keV are $11.15 \ 10^{23}$-$7.93 \ 10^{23}$, $5.53 \ 10^{23}$-$4.99 \ 10^{23}$, $8.95 \ 10^{23}$-$7.00 \ 10^{23}$, $8.68 \ 10^{23}$-$8.24 \ 10^{23}$, and $8.64 \ 10^{23}$-$6.75 \ 10^{23}$, respectively. The N_{eff} value of the gases reaches the minima above the photon energy of 50 keV. We have also found that the effective electron densities of all hydrocarbon gases gradually increase above 10 MeV and become stable afterwards. The N_{eff} of the gases calculated by the XmuDat program were found to be $3.55 \ 10^{20}$, $2.50 \ 10^{20}$, $3.52 \ 10^{20}$, $1.63 \ 10^{20}$, $8.78 \ 10^{20}$, and $2.20 \ 10^{23}$ for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12}, respectively.

Mixture of gases in radiation detectors

A biological tissue equivalence gas composition mixture consisting of 64.4% methane, 32.9% carbon dioxide and 3.2% nitrogen is recommended for dosimetric purposes [30]. Monatomic gases operating at a high value of gas multiplication require a quench gas for stabilizing the additive. Noble gases, viz. argon, krypton and xenon, are useful proportional gases which require additional polyatomic quench gases to reduce instabilities and proportionalities losses. High atomic number gases are utilized for obtaining a high efficiency of detectors for gamma-ray photon measurement. We have, therefore, studied different compositions of these gases, so as to establish suitable compositions for gamma radiation measuring detectors based on the tissue equivalent effective atomic number.
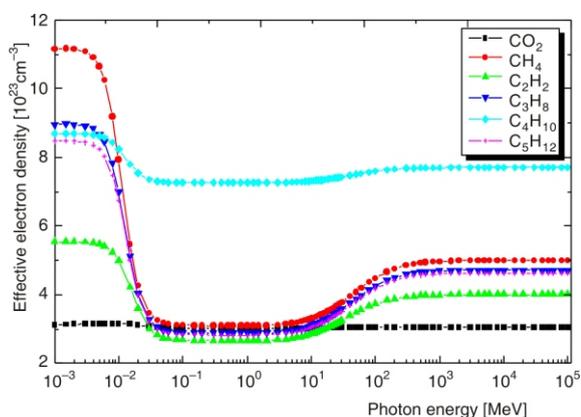

Figure 3. Variation of effective electron density *vs.* photon energy for CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12}

Effective atomic number of the gaseous mixture

The average effective atomic number $<Z_{eff}>$ values for methane, acetylene, propane, butane and pentane were found to be 5.19, 5.74, 5.40, 5.43, and 5.45, respectively. The $<Z_{eff}>$ of the mixtures of: (a) argon and methane, (b) argon and carbon dioxide, (c) xenon and carbon dioxide, and (d) methane and pentane, are shown in fig. 4 (a-d). In fig. 4, the percentage composition of a gas has been plotted on the abscissa and the $<Z_{eff}>$ value on the ordinate. Figure 4 (a) shows that the $<Z_{eff}>$ of a mixture of argon with methane increases with the increase in the percentage composition of argon in the mixture. Similarly, in fig. 4 (b), and fig. 4 (c), the value of $<Z_{eff}>$ increases with the increase in the percentage of xenon and argon in the composition. In all three cases, $<Z_{eff}>_{min}$ is close to the TE value and, hence, the minimum value of the inert gas is suitable for composition. However, a mixture of hydrocarbons such as methane with pentane shows that $<Z_{eff}>$ decreases from 5.45 to 5.20 as the percentage composition of the methane increases, if only slightly. As the percentage composition of a noble gas increases in the mixture, the $<Z_{eff}>$ drifts further away from tissue equivalence. The Z_{eff} of mixtures of argon (4.5%) + methane (95.5%), 7.44; argon (0.5%) + carbon dioxide (99.5%), 7.76; xenon (0.5%) + carbon dioxide (99.5%), 11.98; and methane (0.5%) + pentane (99.5%), 5.45 were observed. We have found that a minimal percentage contribution of noble gases is suitable for the TE gas mixture and that the reduction of hydrocarbon contents increases the average effective atomic number of the mixture.

We have also investigated the composition of more than two gases for nitrogen, methane and carbon dioxide gases. The $<Z_{eff}>$ of the mixture of nitrogen (5%) + methane (7%) + carbon dioxide (88%) and nitrogen (3.2%) + methane (64.4%) + carbon dioxide (32.4%) was found to be 7.41 and 6.16, respectively. The mixture of nitrogen (5%) + methane (7%) + carbon dioxide (88%) is a suitable combination of the gases for radiation detectors. Relative tissue equivalence of the gases with respect to the ICRU tissue shows that air, argon (4.5%) + methane (95.5%), argon (0.5%) + carbon dioxide (99.5%) and nitrogen (5%) + + methane (7%) + carbon dioxide (88%) are within the range of 0.998-1.041. Therefore, these gases are suitable for gamma radiation detectors in radiation protection. The gas composition of xenon (0.5%) + carbon dioxide (99.5%) shows a 1.605 times higher tissue equivalence as compared to the ICRU tissue.

Electron densities of gaseous mixtures

The average effective electron density, $<N_{eff}>$, of the mixture of selected gases is given in tab. 2. Electron densities of gas mixtures examined were noted in

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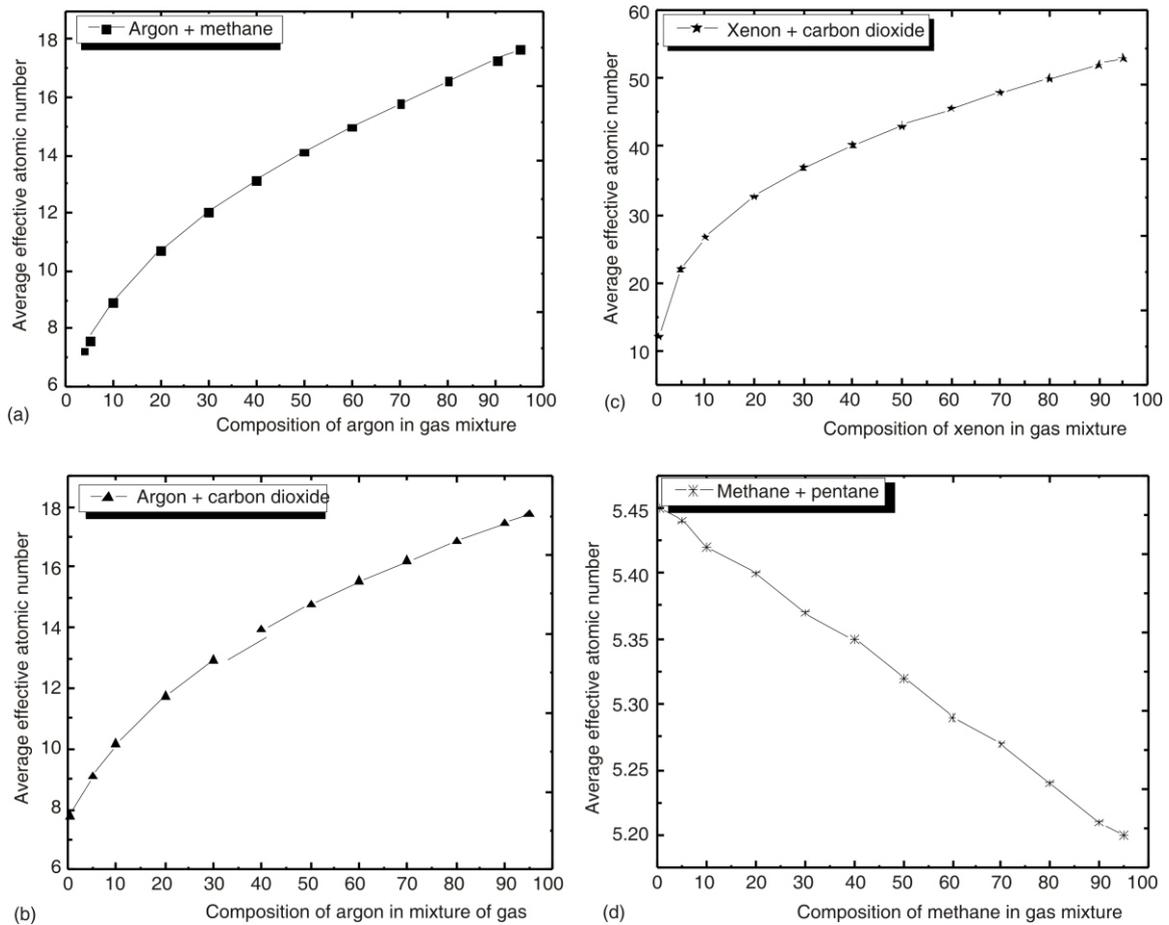**Figure 4(a-d). Variation of average effective atmic number with varying gas compositions (only one composition percentage is shown in the graphs)**

Table 2. Electron densities and relative tissue equivalence of various mixtures of gases

Serial number	Gas mixture composition	$<Z_{eff}>$	$<N_{eff}>$ (electron/cm^3)	Relative tissue equivalence with ICRU tissue ($Z_{eff} = 7.46$)
1	Air	7.77	$3.62\ 10^{20}$	1.041
2	Argon (4.5%) + methane (95.5%)	7.45	$2.54\ 10^{20}$	0.998
3	Argon (0.5%) + carbon dioxide (99.5%)	7.76	$5.54\ 10^{20}$	1.040
4	Xenon (0.5%) + carbon dioxide (99.5%)	11.98	$5.56\ 10^{20}$	1.605
5	Methane (0.5%) + Pentane (99.5%)	5.45	$386\ 10^{20}$	0.730
6	Nitrogen (5%) + methane (7%) + carbon dioxide (88%)	7.41	$4.90\ 10^{20}$	0.993
7	Nitrogen (3.2%) + methane (64.4%) + carbon dioxide (32%)	6.16	$2.99\ 10^{20}$	0.826

the range of $4.90\ 10^{20}$ to $5.54\ 10^{20}$ electron per cm^3, except for the mixture of pure hydrocarbon gases, amounting to $3.86\ 10^{22}$. The relative tissue equivalence of various mixtures of gases shows that the mixture of argon (4.5-5%) with methane and carbon dioxide (95.5%) is the best possible combination of gases for radiation detectors known at present.

CONCLUSIONS

The mass attenuation coefficient of the selected gases decreases with the increase in the incident pho-

ton energy. Effective atomic numbers of CO_2, CH_4, C_2H_2, C_3H_8, C_4H_{10}, and C_5H_{12} show a sudden decrease within the 10 keV-10 MeV photon energy range, afterwards gradually becoming constant in the high energy photon region. CO_2 gas shows the closest tissue equivalent in the entire photon energy spectrum of 1 keV to 100 GeV. The average effective atomic number of a mixture of argon (4.5%) + methane (95.5%), argon (0.5%) + carbon dioxide (99.5%) and nitrogen (5%) + methane (7%) + carbon dioxide (88%) showed tissue equivalence. It is, therefore, safe to conclude that the said mixtures are a suitable combination for gamma radiation detectors, as far as dosimetry is concerned.

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Вишванат П. СИНГ, Нагапа М. БАДИГЕР

ЕФЕКТИВНИ АТОМСКИ БРОЈЕВИ, ГУСТИНЕ ЕЛЕКТРОНА И ЕКВИВАЛЕНТНОСТ ТКИВА НЕКИХ ГАСОВА И СМЕША ПРИ ДОЗИМЕТРИЈИ ДЕТЕКТОРА ЗРАЧЕЊА

Тотални масени коефицијент атенуације μ_m, ефективни атомски број Z_{eff}, и ефективна густина електрона N_{eff}, различитих гасова: угљендиоксида, метана, ацетилена, пропана, бутана, и пентана, који се користе у детекторима зрачења – срачунати су за енергије фотона од 1 keV до 100 GeV. Сваки гас има константну вредност за Z_{eff} на енергијама од 0.1 до 10 MeV; међутим, ове вредности доста одступају од вредности ICRU ткива. Гас угљендиоксид показује највећу сличност ткиву у целом опсегу енергија фотона. Релативне ткивне еквивалентности мешавине гасова у односу на ICRU ткиво су у опсегу од 0.998 до 1.041 за ваздух, аргон (4.5%) + метан (95.5%), аргон (0.5%) + угљендиоксид (99.5%), и азот (5%) + метан (7%) + угљендииоксид (88%). Смеша ксенона (0.5%) + угљендиоксида (99.5%) даје 1.605 пута већу вредност ткивне еквивалентности у поређењу са ICRU ткивом. Испитивани параметри интеракције фотона су корисни за прорачуне фактора излагања фактора нагомилавања гасних детектора за мерење амбијенталног зрачења Гајгер-Милеровим бројачм, јонизационом комором и пропорционалним бројачем.

Кључне речи: ефективни атомски број, гама детектор, ткивна еквивалентност, реактор, угљоводоници, инертни гасови