Jurnal Sains Nuklear Malaysia, 2011, 23(2): 19 – 25
ISSN: 2232-0946

MASS ATTENUATION COEFFICIENTS, EFFECTIVE ATOMIC AND ELECTRON NUMBERS OF STAINLESS STEEL AND CARBON STEELS WITH DIFFERENT ENERGIES

Md Fakarudin Ab Rahman[1, 2a], M. Iqbal Saripan[1], Nor Pa'iza Mohamad Hasan[2] and Ismail Mustapha[2]***

[1]Department of Computer and Communication System,
Faculty of Engineering, Universiti Putra Malaysia (UPM)

[2]Plant Assessment Group (PAT), Industrial Technology Division (BTI),
Malaysian Nuclear Agency, Bangi

ABSTRACT

The total mass attenuation coefficients (μ/ρ) of stainless steel (SS316L) and carbon steel (A516) that are widely used as petrochemical plant components, such as distillation column, heat exchanger, boiler and storage tank were measured at 662, 1073 and 1332 keV of photon energies. Measurements of radiation intensity for various thicknesses of steel were made by using transmission method. The γ-ray intensity were counted by using a Gamma spectrometer that contains a Hyper-pure Germanium (HPGe) detector connected with Multi Channel Analyzer (MCA). The effective numbers of atomic (Z_{eff}) and electron (N_{eff}) obtained experimentally were compared by those obtained through theoretical calculation. Both experimental and calculated values of Z_{eff} and N_{eff} were in good agreement.

Keywords: Mass attenuation coefficients (μ/ρ), effective atomic number (Z_{eff}), effective electron number, Hyper Pure Germanium (HPGe) detector, Multi Channel Analyzer (MCA)

INTRODUCTION

Photon technology has been widely used in different areas such as in physical, technological and engineering as well as in medical fields. The beauty of γ-ray principle application lies in the fact that it can be absorbed by dense materials and heavy atoms such as lead, high density concrete and barium. Knowledge on the radiation absorption mechanism in materials is necessary for keeping radiation hazards within the desired limit. Quantities of materials that need to be known include mass attenuation coefficients (μ/ρ), effective atomic number (Z_{eff}) and effective electron density (N_e).

Attenuation coefficient was defined as the probability of a radiation interacting with a material per unit path length [Woods, 1982]. The incident photon energy, the atomic number and the density of material contribute to values of linear attenuation coefficient of material [Akkurt et al., 2005a]. The atomic number in composite materials cannot be represented by a single number. Thus, a parameter called the ‘‘effective atomic number’’ was introduced for such materials. Additionally, the effective atomic number is a convenient parameter for evaluation of photon interaction with a material [Hine, 1952], and it can provide an initial estimation of the chemical composition of the material. Generally, the effective atomic number is large for inorganic compounds and metals and relatively smaller for organic substances. The other important quantity to be determined is the effective electron number or electron density and it is defined as the electrons per unit mass of the absorber [Shivalinge et al., 2005].

Correspondence author: fakarudin@nuclearmalaysia.gov.my

Jurnal Sains Nuklear Malaysia, 2011, 23(2): 19 – 25
ISSN: 2232-0946

Similar works have also been performed by other physicists and engineers on the μ/ρ, Z_{eff} and N_e but for different types of materials [Akkurt et al.,2004; Akkurt et al., 2005b; Akkurt et al., 2007; Içelli et al., 2005; El-Kateb et al., 2000; Murty et al., 2000]. The linear attenuation coefficient of for steels almost equivalent to the material under investigation and the effect of boronizing have been measured [Akkurt et al., 2008]. Berger and Hubbell [1987], on the other hand have tabulated the values in the energy range from 1 keV to 100 GeV for all elements in the atomic range 1 < Z < 92 and 48 additional substances for the dosimetric purposed. Baltas et al. [2007] have also performed similar works on the μ/ρ and N_e for MgB_2 superconductor. Baltas and Cevik [2008], evaluated values of Z_{eff} and N_e for YBaCuO superconductor in the range 59.5–136 keV from the other work. Celik et al. [2008], have obtained values of effective atomic numbers and electron densities for $CuGaSe_2$ semiconductor in the energy range 6–511 keV. Meanwhlie, Manjunathaguru and Umesh [2007] have performed other works to obtain Z_{eff} for some compounds containing H, C, N and O in the energy range 6.4–136 keV. At the same time, Han and Demir [2009], have established values for the mass attenuation coefficients, effective atomic and electron numbers in some alloys such as Cr, Fe and Ni at different energies. The same author [Demir et al., 2009], have also established mass attenuation coefficients, effective atomic numbers and electron densities of undoped and differently doped GaAs and InP crystals. In addition, Kaewkhao et al. [2008] have also determined the effective atomic numbers and effective electron densities for some other alloys. The most recent study on Z_{eff} and N_{eff} for some steels at different energies has been performed by Akkurt [2009], by using the scintillation detector.

In conclusion, the general objective of this study is to compare the values of μ/ρ, Z_{eff} and N_e of stainless steel AISI 316L and carbon steel A516 at photon energies of 662, 1173 and 1332 keV with those obtained from calculation.

MATERIALS AND METHODS

The mass attenuation coefficients (μ/ρ) of two different types of steel, namely carbon steel (516) and stainless steel (316L) were calculated using the XCOM code. The code requires input of chemical composition of these steels to allow it to compute the total cross sections as well as partial cross sections for various interaction processes at photon energy of 662, 1073 and 1332 keV [Berger et al., 1987]. In this work the linear attenuation coefficients (μ) for two different identified steels were measured at photon energies of 662 obtained from ^{137}Cs and 1173, 1332 keV obtained from ^{60}Co. Table 1 shows values chemical compositions of the investigated steels. These values were verified by an optical emission spectroscopic technique.

Table 1: Chemical Compositions of the steels

	Density (g/cm^3)	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
SS316L	8.0	0.03	0.53	1.85	0.04	0.005	16.00	2.12	10.77	68.27
CS516	8.1	0.31	0.19	0.98	0.01	0.005	-	-	-	98.39

Detection of gamma rays has been comprehensively performed using a gamma spectrometer that consists of a HPGe detector connected to the Multi-Channel-Analyzer (MCA). A schematic diagram of the detection system is shown in Fig. 1. The mass attenuation coefficients $(\mu/\rho)_{material}$ were obtained via

Jurnal Sains Nuklear Malaysia, 2011, 23(2): 19 – 25
ISSN: 2232-0946

measuring the linear attenuation coefficients (μ) of a material with known density (ρ). The calculated μ/ρ values for the present steels have been precisely acquired by XCOM program.

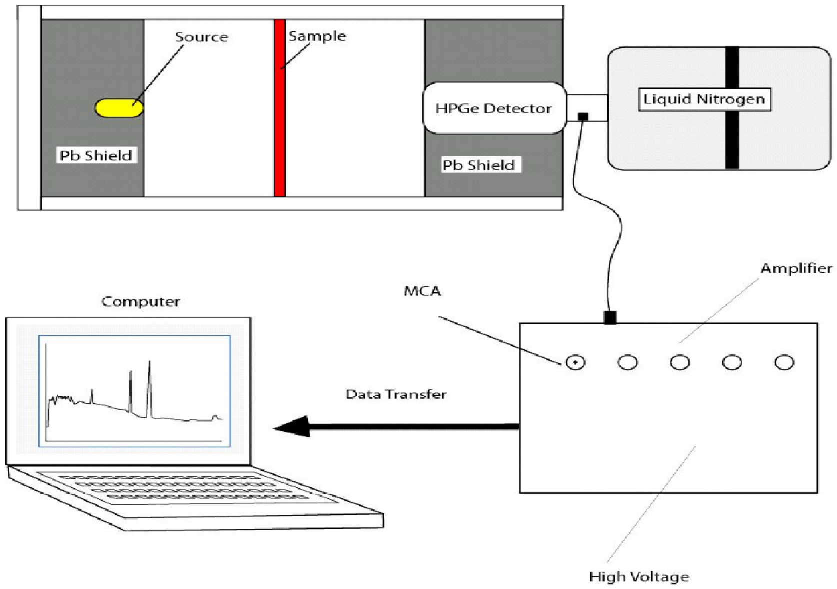


Fig.1: Illustration of the gamma spectrometry system

If I and I_o are the measured count rates in detector with and without the absorber of thickness x (cm) respectively, the linear attenuation coefficients (μ) can be determined by Lambert law equation:

$$\mu = \frac{1}{x}\ln\frac{I_\circ}{I} \qquad (1)$$

A plot of $\ln\frac{I_\circ}{I}$ versus x would present a straight line and the value of μ can be taken from the value of the slope. A γ-ray spectrum acquired from ^{137}Cs and ^{60}Co sources is displayed in Fig. 2, where attenuated and unattenuated gamma ray at 662, 1073 and 1332 keV can be obviously identified.

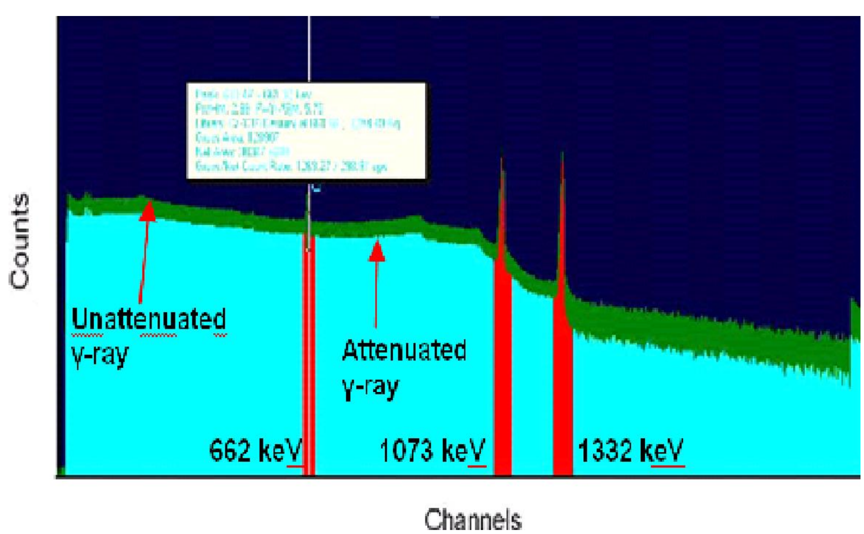


Fig. 2: Typical spectrum of Caesium-137 and Cobalt-60

This means that if values of μ/ρ for materials that consist of different elements are known, then its Z_{eff} can be calculated by the following formula [Gagandeep et al., 2000]:

$$Z_{eff} = \frac{\sigma_a}{\sigma_{el}} \quad (2)$$

where σ_a is the total atomic cross section while σ_{el} is the total electric cross section. The total atomic cross section can be calculated by using values of total $(\mu/\rho)_{material}$ [Prasad et al., 1998], utilizing the following formula:

$$\sigma_a = \frac{1}{N}\frac{(\mu\frac{}{\rho})_{material}}{\sum\frac{w_i}{A_i}i} \quad (3)$$

where μ/ρ is total mass attenuation coefficients, N is the Avogadro's number A_i and w_i are atomic weights (in gram) and fractional weights of the component of material respectively. Furthermore, the total electric cross section σ_{el} can be obtained by the following formula:

$$\sigma_{el} = \frac{1}{N}\sum_i \frac{f_i A_i}{Z_i}\left(\frac{\mu}{\rho}\right)i \quad (4)$$

where f_i is the number of atoms of element *i* relative to the total number of atoms of all elements in the mixture, Z_i is the atomic number of the *i*th elements in a mixture, and $(\mu/\rho)_i$ is the total mass attenuation coefficients of the *i*th element in mixture. The effective electron number (N_{eff}) can be estimated using following expression

$$N_{eff} = \frac{(\mu/\rho)_{material}}{\sigma_{el}} \quad (5)$$

RESULTS AND DISCUSSION

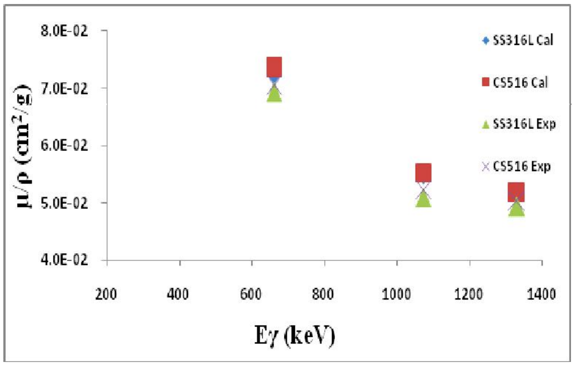
The mass attenuation coefficients $(\mu/\rho)_{material}$ for steels have been calculated at photon energies of 662, 1073 and 1332 keV and the results were compared with those measured experimentally for gamma-ray photon energies of 662 and 1173 and 1332 keV. The calculated and experimental results were in good agreement for the selected steels as demonstrated in Fig. 3 (a). Values of $(\mu/\rho)_{material}$ depend on photon energies, where different photon energies result in different values of $(\mu/\rho)_{material}$ when it interacts with matter in accordance with the Eq. (1). As indicated in Fig. 3b, the increase in photon energies resulted in decrease experimental values of $(\mu/\rho)_{material}$.

The value of effective atomic number (Z_{eff}) is closely related to many characteristics of the material. In this study, the Z_{eff} values were calculated from Eq. (2) – (4). The results were then compared with those obtained through experiments. The variations of Zeff versus photon energy both obtained by calculation and through experiment are shown graphically in Fig. 3 (c). The Figure shows that interaction (absorption and scattering and pair production) of γ rays and is closely related to material composition and values of photon energies. Hence, these interactions involved the energy transfer from photon to matter. It is also clearly evident that the Z_{eff} decreased with increasing photon energy. Such an observation is in good agreement with Akkurt et al [2009] for range of energies between 500 keV to 1 MeV.

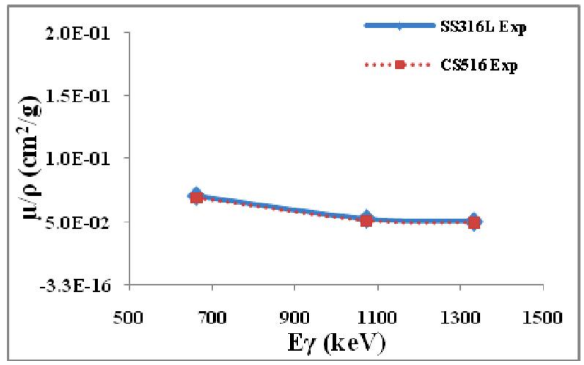
Jurnal Sains Nuklear Malaysia, 2011, 23(2): 19 – 25
ISSN: 2232-0946

Values effective electron density number (N_{eff}) were determined by using Eq. 5 and these values were plotted versus photon energy as indicated in Fig. 3 (d). It can be seen that values of N_{eff} are not significantly varies with photon energy. Finally, the calculated and experimentally determined values of Z_{eff} and N_{eff} were correlated and presented in Fig. 3 (e).

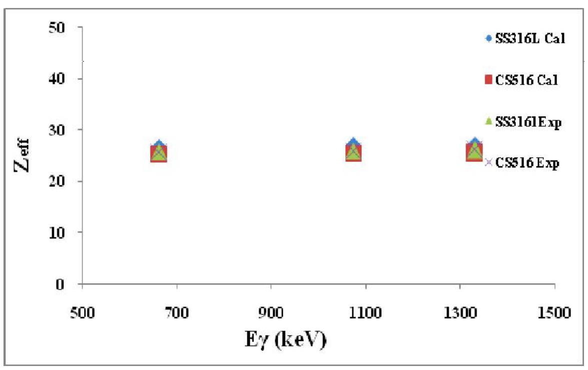
(a)



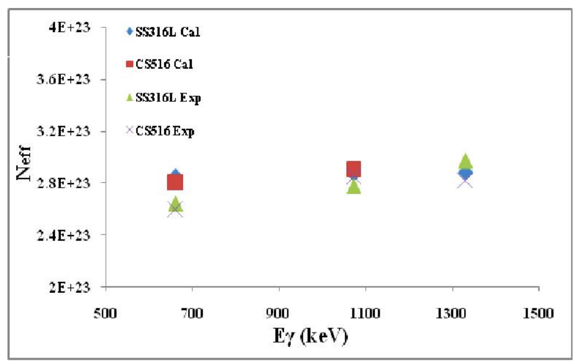
(b)



(c)



(d)



(e)

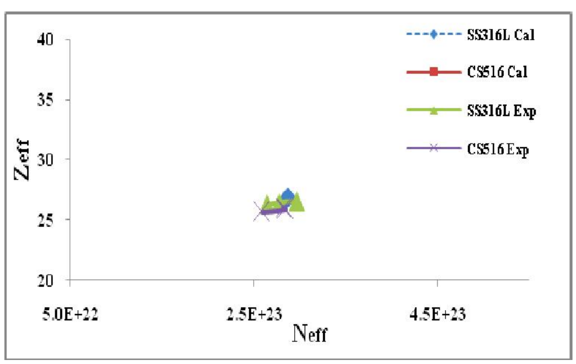


Fig. 3: Typical plot of measured $(\mu/\rho)_{material}$, (Z_{eff}) and (N_{eff}). (a) The calculated photon $(\mu/\rho)_{material}$ of steels at 662, 1073 and 1332 keV and comparisons with experiments, (b) The measured $(\mu/\rho)_{material}$ of steels at selected energy, (c) The Z_{eff} of steels as a function of photon energy, (d) The N_{eff} of steels as a function of photon energy and (e) Correlation between Z_{eff} and N_{eff} of steels for calculated and measured results.

CONCLUSION

The present study has been undertaken to establish values of $(\mu/\rho)_{material}$, effective atomic (Z_{eff}) and effective electron (N_{eff}) number for selected stainless and carbon steel. The results of the work indicated that values of $(\mu/\rho)_{material}$ is highly sensitive physical quantity that determine values of Z_{eff} and N_{eff} in chosen steels. The $(\mu/\rho)_{material}$ values of steels decrease with increasing photon energy. Results of this study will be helpful in recognizing how mass attenuation coefficients vary with variation of the atomic and electronic number for different steel compositions. In short, the conclusion made from this study is that the mass attenuation coefficients (μ/ρ), the effective atomic (Z_{eff}) and electron number (N_{eff}) depend on photon energies and compositions of the materials.

ACKNOWLEDGMENTS

The authors would like to extend their appreciations and sincere thanks to the personnel of the Plant Assessment Technology Group, Malaysian Nuclear Agency for their support and co-operation especially to Mr. Mior Ahmad Khusaini Adnan and Mr. Airwan Affandi Mahmood. Last but not least thanks also go to Dr. Abdul Nassir Ibrahim (Director) and Dr. Muhammad Lebai Juri (Director General) for their support and encouragement.

REFERENCES

Akkurt, I.,Basyigit, C.,Kilincarslan,S. (2004), The photon attenuation coefficients of barite, marble and limra. *Ann.Nucl.Energy 31* (5), 577 - 582.

Akkurt, I.,Mavi, B., Akkurt, A., Basyigit,C., Kilincarslan,S., Yalim,H.A. (2005a), *J. Quant. Spectrosc. Radiat.Trans*. 94 (3 - 4), 379.

Akkurt, I., Basyigit, C., Kilincarslan, S., Mavi, B. (2005b), The shielding of γ-rays by concretes produced with barite. *Prog. Nucl. Energy* 46, 1.

Akkurt, I. (2007), Effective atomic numbers for Fe-Mn alloy transmission experiment. *Chin.Phys.Lett*.24 (10), 2812.

Akkurt, I., Calik Adnan, Akyıldırım Hakan, Mavi Betul. (2008), The effect of boronizing on the radiation shielding properties of steel. *Z. Naturforsch*. 63a, 445 - 447.

Akkurt, I. (2009), Effective atomic and electron numbers of some steels at different energies. *Ann.Nucl.Energy* 36, 1702 - 1705.

Akkurt, I., et al., in press, (2009). Radiation Shielding Measurement of the Concrete Containing *Zeolite. Radiat. Meas*.

Baltas, H., Çelik, S., Çevik, U., Yanmaz, E. (2007), Measurement of mass attenuation coefficients and effective atomic numbers for MgB_2 superconductor using X-ray energies. *Radiat. Meas*. 42, 55 - 60.

Baltas, H., Cevik, U. (2008), Determination of the effective atomic numbers and electron densities for YBaCuO superconductor in the range 59.5 - 136 keV. *Nucl. Instrum. Methods Phys. Res. B* 266, 1127-1131.

Berger, M.J. and Hubbell, J.H. (1987), National Institute of Standards Gaithersburg, MD 20899, USA. http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html.

Celik, A., Cevik, U., Bacaksiz, E., Celik, N. (2008), Effective atomic numbers and electron densities of $CuGaSe_2$ semiconductor in the energy range 6 - 511 keV. *X-Ray Spectrom* 37, 490 - 494.

Demir, L. and Han, I. (2009), Mass attenuation coefficients, effective atomic numbers and electron densities of undoped and differently doped GaAs and InP crystals. *Ann. Nucl. Energy* 36, 869 - 873.

El-Kateb, A.H., Rizk, R.A.M. and Abdul-Kader, A.M. (2000), Determination of atomic cross-sections and effective atomic numbers for some alloys. *Ann. Nucl. Energy* 27, 1333.

Gagandeep, Kaur, Singh, Kulwant, Lark, B.S. and Sahota, H.S. (2000), Photon interaction studies in solutions of some alkali metal chlorides-I. *Radiat. Phys. Chem*. 58, 315.

Han, I. and Demir, L. (2009), Determination of mass attenuation coefficients, effective atomic and electron numbers for Cr, Fe and Ni alloys at different energies. *Nucl. Instrum. Methods Phys. Res. B* 267, 3 - 8.

Hine, G.J. (1952), Use wildcard to add more than one file at a time. *Phys. Rev*. 85, 752.

Içelli, O., Erzeneoglu, S., Karahan, I.H. and Çankaya, G. (2005), Effective atomic numbers for CoCuNi alloys using transmission experiments. *J. Quant. Spectrosc. Radiat. Trans.* 91, 485

Kaewkhao, J., Laopaiboon, J. and Chewpraditkul, W. (2008), Determination of effective atomic numbers and effective electron densities for Cu/Zn alloy. *J. Quant. Spectrosc. Radiat. Trans.* 109, 1260 - 1265.

Manjunathaguru, V. and Umesh, T.K. (2007), Total interaction cross sections and effective atomic numbers of some biologically important compounds containing H, C, N and O in the energy range 6.4–136 keV. *J. Phys. B: At. Mol. Opt. Phys.* 40, 3707 - 3718.

Murty, V.R.K., Winkoun, D.P. and Devan, K.R.S. (2000), Effective atomic numbers for W/Cu alloy using transmission experiments. *Appl. Radiat. Isotopes* 53, 945.

Prasad, S.G., Parthasaradhi, K., Bloomer, W.D. (1998), Effective atomic numbers for photo absorption in alloys in the energy region of absorption edges. *Radiat. Phys. Chem.* 53, 449.

Shivalinge, G., Krishnaveni, S. and Ramakrishna, G. (2005), Studies on effective atomic numbers and electron densities in amino acids and sugars in the energy range 30 - 1333 keV. *Nucl. Instrum. Methods B* 239 (4), 361.

Woods, J. (1982), Computational Methods in Reactor Shielding. Pergamon, New York.