A comparative photon shielding properties of protective Window materials by using EGS5 code

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Abstract. For an X-ray room, there is a special window for radiation workers to monitor the patient during an irradiation procedure. Lead glass commonly used as protective window materials for diagnostic X-rays even it is known for its toxicity due to the lead oxide in the air which could be inhaled either during manufacturing or recycled process. Monte Carlo simulation (EGS5 code) was used to study several other types of available protective windows for its radiation shielding efficiency. In this study, the practicability of acrylic glass, plate glass and Pyrex glass systems with respect to lead glass were studied for protective window materials. The photon attenuation coefficients (μ), the percentage of transmitted and reflected photon energy spectra and half-value layer (HVL) were investigated by using simulation. Three photon source energies of 59.5 keV, 150 keV, and X-ray 150 kVp were calculated via EGS5 code to study the capability of these four glass systems as low energy photons radiation shielding materials. A thickness of 7 cm plate glass, 8 cm pyrex glass and more than 10 cm acrylic glass are adequate as a non-lead shielding material for 150 kVp X-ray to have a similar lead-glass equivalency. The use of plate glass as radiation protecting material to replace lead glass can reduce expenses as plate is way cheaper than lead but the increase thickness of plate will need special framing and concerns of its increased weight needs to be considered. However, given that the X-ray primary beam will not be directed towards the protective windows, therefore the findings are appropriate, with less thickness of plate glass could be used.

1. Introduction
Radiation protection is a specialised area and important in the radiation and radioactive sources related working environment. Its application is not just for the patient but more importantly for the staff or personnel who works daily with radiation. Functionally, radiation shielding materials are used to reduce radiation dose exposed to staff or personnel that outside of an irradiation room [1, 2, 3, 4, 5]. The designing and construction of effective radiation shielding materials requires an in-depth knowledge regarding the types of interaction between radiation and the target material [6, 7, 8, 9, 10, 11, 12].
Apart from doors and walls, protective windows are installed in a control room near the control panel for viewing. All of them must have the same lead equivalence. Referring to Standards & Industrial Research Institute of Malaysia [13], lead equivalence is defined as the protective value of a specified thickness of any materials expressed in terms of the thickness of the lead which would provide an equivalent value, where the protective material concerned is not lead on its own or a lead compound for example PbO\(_2\). It is stated that for general radiographic X-ray systems capable of operating at potentials above 100 kVp, the lead glass observation window required minimum thickness of 1.5 mm lead equivalence while for the size, minimal dimensions of 75 cm of width by 45 cm of height.

In this study, lead glass, acrylic glass, plate glass and Pyrex glass are used for radiation shielding materials. Lead glass has many exceptional properties for instance high density, excellent infrared transmission, high non-linear optical susceptibility and high refractive index [14]. However, the lead glass is easily damaged during handling due to its soft structure, consequently increasing the amount of repairs required [15]. Concerning the standard lead glass, it is interesting to know the required thickness for other types of glass for low energy photons. As elemental composition (Table 1) for each glass is different, the type of photon interactions such as photo electric absorption, Rayleigh scattering and Compton scattering within the material could be examined by using simulation. Lead material is relatively very expensive. As the area of protective windows is large, the study of other glass materials with reasonable thickness is beneficial, without degrading the radiation shielding effect. Lead glass due to its weakness of easily damaged, would lead to more expenses for the repairs needed.

| Element | Lead | Acrylic | Plate | Pyrex |
|---------|------|---------|-------|-------|
| H\(^1\) | 0.0805 | | | |
| B\(^5\) | | | | 0.0401 |
| C\(^6\) | 0.5998 | | | |
| O\(^8\) | 0.1565 | 0.3196 | 0.4598 | 0.5396 |
| Na\(^{11}\) | | 0.0964 | 0.0282 | |
| Al\(^{13}\) | | | 0.0116 | |
| Si\(^{14}\) | 0.0809 | | 0.3366 | 0.3772 |
| K\(^{19}\) | | | | 0.0033 |
| Ca\(^{20}\) | | | 0.1072 | |
| Ti\(^{22}\) | 0.0081 | | | |
| As\(^{33}\) | 0.0027 | | | |
| Pb\(^{82}\) | 0.7519 | | | |

### 2. Calculated transmitted photons of the elements for 150 keV photon

EGS5 code has been developed at High Energy Accelerator Research Organization, Japan. EGS5 code is a general purpose package for the Monte Carlo simulation to transport electrons and photons in an arbitrary geometry with energies above a few keV up to several hundred GeV. For verification of our Monte Carlo (EGS5 code [16]) input model with theory and literature data, we calculated the percentage of transmitted photon after the glass for single-photon energy of 150 keV photons. The density and atomic compositions of each glass were based on NIST database [17].
Figure 1 shows the materials geometry was modelled as rectangular shape with a pencil beam of mono-energy photons was incident to the center of element. The number of histories is set at 100000 of source particles to have the statistics error less than 3 %. The distance was set at 20 cm from the surface of material. All the main photon’s interaction, such as photoelectric absorption, Compton scattering (including Rayleigh scattering), and pair productions were considered in our calculation. The scattered photons that penetrate the material were ignored for comparison with the attenuation coefficients generated by XCOM.

![Simulation geometry modelled in EGS-CG view for calculation of photons attenuation.](image1)

**Figure 1.** Simulation geometry modelled in EGS-CG view for calculation of photons attenuation.

| Photon Energy  | Photon Energy | EGS5 | XCOM | % of difference |
|----------------|---------------|------|------|-----------------|
| 150 keV       | Acrylic glass | 0.174| 0.17 | 0.56            |
|                | Lead glass    | 9.612| 9.64 | 0.29            |
|                | Plate glass   | 0.346| 0.34 | 1.75            |
|                | Pyrex glass   | 0.315| 0.31 | 1.60            |

**Table 2.** The percentage difference of linear attenuation coefficient for glasses at 150 keV.

Figure 2 shows the calculation of transmitted photons as a function of material thickness for a pencil beam of 150 keV photon for each type of glass. From this graph, it can be seen that the percentage of calculated transmitted photon decreased exponentially with increasing thickness of material. Then, the data were fitted with an exponential equation to obtain the value of the linear attenuation coefficient (μ; cm$^{-1}$). Overall, the calculated μ value has a good agreement, within 2 % with the XCOM as in Table 2. This indicates that the μ value calculated by the simulation was reliable and verified to be used for the study of photon interactions between radiations and energy within the material.

![Graph showing the calculation of transmitted photons as a function of material thickness for each type of glass.](image2)
Figure 2. The calculated transmitted photons of lead glass (a), acrylic (b), plate (c) and Pyrex (d) glasses for photon of 150 keV. Calculated $\mu$ values were deduced from exponential fitting of the graph data and were compared to XCOM values.

3. The glasses attenuation coefficient for X-ray of 150 kVp

The calculation for X-ray of 150 kVp was done to see the impact of transmitted and reflected photon spectra of the same shielding glass compound. Report 78 Spectrum Processor of IPEM 1997 software [18] was used to obtain the unfiltered X-ray spectra as a source input for EGS5 code as shown in Figure 3.

Figure 3. X-ray photon spectra of 150 kVp as a source input in the calculation. The average energy is 49.8 keV. The X-ray spectra was adopted from Report No. 78.

To calculate poly-energy X-ray of 150 kVp in EGS5 code was time-consuming. It has to be noted that practically portable Am-241 gamma source was utilised to check the irradiation room shielding before the installation of an X-ray machine. The average energy of above X-ray photon spectra was 50.7 keV. This average energy was close to Am-241’s 59.5 keV. We therefore include also the calculation of 59.5 keV to estimate the difference between Am-241 and X-ray of 150 kVp.
Table 3. The linear attenuation coefficients values of lead glass, plate glass, Pyrex glass, and acrylic glass obtained by EGS5 and WinXCom for 59.5 keV and 150 kVp

| Glass Materials | Linear Attenuation Coefficients, LAC (cm⁻¹) |
|-----------------|---------------------------------------------|
|                 | 59.5 keV | X-ray 150 kVp |                  |
|                 | EGS5     | XCOM         | EGS5             |
| Lead glass      | 23.82    | 24.41        | 18.84            |
| Plate glass     | 0.72     | 0.71         | 0.66             |
| Pyrex glass     | 0.56     | 0.54         | 0.58             |
| Acrylic glass   | 0.24     | 0.23         | 0.28             |

As for the glass comparison, it could be noted that lead glass had the highest LAC values for both experimental and theoretical values for energy of 59.5 keV while the acrylic glass had the lowest values of linear attenuation coefficients. The LAC results were mainly influenced by the density of material. Lead glass had the highest density while acrylic glass had the lowest density that was obtained from NIST website. The plate glass and Pyrex glass LAC values were close to each other with small amount of difference as the density for both glasses were almost similar.

In case for poly-energetic beam X-ray of 150 kVp, lead glass obviously had the highest LAC values than other three glasses mainly because of its high density, 6.22 g cm⁻³ which contained the element of lead with high atomic number of 82 (NIST). The high Z element contributed 75% fraction by weight in the lead glass chemical composition. According to Mohd et al. (2010, 2014), lead was a strong attenuator which had the property of attenuating X-ray radiation due to its high density which was 11.34 g/cm³. As the density or atomic number of a material increased, the attenuation produced by a given thickness would be increased (McKetty, 1998). Among the three glasses excluding lead glass, acrylic glass had the lowest LAC value because of its lowest density of glass. As shown in the Table 1, the chemical composition of acrylic glass only contained low atomic number elements which were hydrogen, carbon and oxygen. Between plate and Pyrex glass, both had almost similar density which was 2.40 and 2.23 g cm⁻³ (NIST, 2020), respectively. However the LAC value of plate glass was significantly higher more 13.8% than the value for Pyrex glass. It has to be noted that, among the three glasses studied, plate glass contained the high Z element which was Calcium (Ca-20) within 11% in its mixture.

Figure 4. The calculated transmitted dose (Sv/inc./cm²/s) for several glasses.
Among the three glasses, it could be noted that plate was better attenuator for it had less transmitted dose (%) at lower thickness compared to other two glasses, acrylic and Pyrex. It could be concluded from the graph that, 6 cm plate, 7 cm Pyrex, and more than 10 cm acrylic were needed to have the same output of lead glass at 0.02 cm thickness. A thickness of 0.12 cm lead glass, 4 cm plate, 4.5 cm Pyrex and 9.5 cm acrylic glass were adequate to reduce dose up to 90% of the photons from 150 kVp energy source. According to Direct Scientific (2020), acrylic had to be approximately five times thicker than lead glass for the same lead equivalent which significantly decreased observation capabilities. For the same size requirement and lead equivalent, acrylic had almost twice the weight of glass about 1.8 times. Nevertheless, researchers from a previous study stated that plate glass was completely clear rather than lead glass which had a yellowish colour [19].

4. Conclusion

In designing radiation shielding, to explore new element or compound materials, one must consider to account for photon energy spectra and dose whether transmitted or attenuated. The study results were useful for fabricating a lead-free radiation shielding glass in the appropriate energy range to reduce lead toxicity. It could be concluded that a thickness of 7 cm plate glass, 8 cm of Pyrex glass, and more than 10 cm of acrylic glass was adequate as a non-lead shielding material for X-ray 150 kVp in diagnostic and interventional radiology. The use of plate glass as the radiation protecting material to replace lead glass could reduce expenses as plate was cheaper than lead but the increase in weight factor needed to be considered. However, given that the X-ray primary beam would not be directed towards the protective windows, therefore the findings are appropriate, with less thickness of plate glass could be used. Besides of cost, a protective window designer must take into account of other significant factors such as factor of weight, size and the requirement of special framing.

5. References

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