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# The Effect of Shielding on A1 and A2 values

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## Abstract

Over the last 5 years, an international group of experts has reviewed and update the methodology to calculate the $A_1$ and $A_2$ values included in IAEA Transport regulations. The methodology known as the Q system, is described in IAEA SSG-26 [1].

This update has involved a review of input values and methods of calculation. As part of this, the Q system pathway scenarios that involve external radiation have moved from equations using attenuation and build-up factors to using Monte Carlo method particle transport codes such as MCNP.

The use of MCNP has proved particularly useful in the review of calculation methods for the values of $Q_A$ (external doses from gamma radiation) and $Q_B$ (skin equivalent doses from beta radiation) and to resolve inconsistencies between the two methods. In particular, along with new dose coefficient data, Monte Carlo method calculations allowed the change from calculating effective dose and skin dose for single particles to assessing the effect of all radiations.

Another area where the use of MCNP proved to be very useful was in the calculation of the impact of shielding from the source material or the capsule around it. This paper describes how MCNP was used to investigate the shielding effect of different materials and thicknesses on both external doses and doses to the skin. In the current Q system, a shielding factor of 150 mg $cm^{-2}$ is used only in the calculation of skin equivalent doses from beta emissions to account for auto-absorption. The paper also illustrates how the effect of shielding of gamma ray radiations was also assessed, allowing the effective and skin equivalent dose pathway scenarios to be harmonized and for bremsstrahlung to be directly accounted for.

The effects of the changes of the methodology on the $Q_A$ and $Q_B$ values and on the $A_1$ values for a number of key radionuclides are also presented.

## Introduction

Table 2 of the IAEA transport regulations includes the activity limits for Type A packages, called $A_1$ and $A_2$ values and are given in IAEA SSG-26 [1]; $A_1$ is the maximum activity allowed in a Type A package for special form material (either an non-dispersible solid or a sealed capsule), $A_2$ for non-special form material.

The $A_1$ and $A_2$ values are calculated via a methodology known as the Q-system. The values are determined on the basis of the dose received by a person near a package that is broken open in a transport accident via 5 different exposure pathways. The values thus calculated are called Q values running from $Q_A$ to $Q_E$. A radionuclide's $A_1$ value is the minimum of $Q_A$ (external effective dose from gamma radiation) and $Q_B$ (external skin equivalent dose from beta radiation).

Over the last 5 years a special working group of international experts under the IAEA Transport Safety Standards Committee (TRANSSC) has carried out a thorough review of the Q-system. This paper presents the work we carried out as members of this group on how the inclusion of shielding affects the calculations of $Q_A$ and $Q_B$ values.

**Figure 1: Type A Packages**

It should be noted that the new methodology developed by the working group of experts is based on the use of Monte-Carlo transport programs to calculate the external dose-rates necessary in the determination of $Q_A$ and $Q_B$ instead of the analytical method adopted in the current methodology. Monte Carlo programs, such as MCNP [2], which is the code we use at PHE, simulate particle movement using random numbers to determine scattering events and trajectory. These simulations can often take a long time to converge on a result with acceptable precision; however Monte-Carlo particle transport codes have several advantages compared to the old Q-system methodology. One advantage is they can simulate secondary particles such as bremsstrahlung photons produced from beta radiation. The current Q-system methodology can only account for the possible effects of bremsstrahlung with an arbitrary upper limit of 40 TBq on A values. These upper limits are no longer required if Monte Carlo techniques are used. Another advantage is that Monte Carlo programs allow a detailed comparison between results obtained using different configurations in the methodology, such as the shielding of the exposed person from the source by different materials of different thicknesses as explored in this paper.

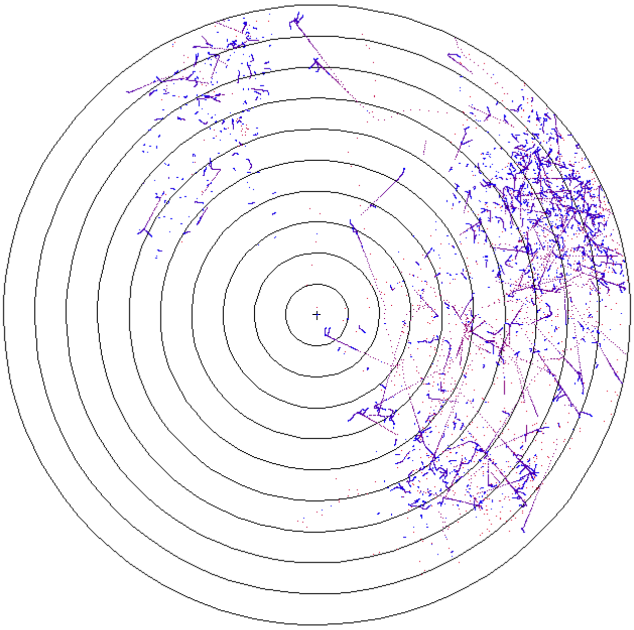

**Figure 2: Simulated Collisions in MCNP**

## Method to calculate $Q_A$ and $Q_B$ values

In the Q system, the $Q_A$ value for a radionuclide is the activity in a package corresponding to an external effective dose 50 mSv received by a person standing at 1 metre for half an hour from a package which is assumed to be completely destroyed with no residual shielding. $Q_A$ values can be calculated from the equation [3]:

$$Q_A = \frac{D/t}{DRC_\gamma} C \quad (1.1)$$

Where D is the reference effective dose of 50 mSv, t is the exposure time of 0.5 hours, $DRC_\gamma$ is the effective dose rate coefficient for the radionuclide (Sv $Bq^{-1}$ $h^{-1}$) and C is a unit conversion factor (TBq $Bq^{-1}$). Equation 1.1 can be rearranged as:

$$Q_A\,(\mathrm{TBq}) = \frac{1\times10^{-13}}{\dot{e}_{pt}} \quad (1.2)$$

Where $\dot{e}_{pt}$ is the effective dose rate coefficient for the radionuclide at 1 metre (Sv Bq$^{-1}$ h$^{-1}$). This dose rate coefficient is calculated analytically in the current methodology and by Monte-Carlo program calculation in the revised method.

In the current methodology $Q_A$ values have been calculated using only the X and gamma emissions of a radionuclide, but the use of Monte Carlo methods has enabled the working group to extend the calculations to an effective dose from all radiations and to include the contribution of bremsstrahlung and other secondary particles.

$Q_B$ values are calculated by comparing the skin equivalent dose at 1 metre for half hour to a reference dose of 0.5 Sv. Although the package is assumed to be destroyed, a shielding factor is included, unlike in the calculation of $Q_A$ values where no shielding is considered. $Q_B$ values can be calculated from the equation [3]:

$$\mathrm{Q_B}(\mathrm{TBq}) = \frac{1\times 10^{-12}}{\dot{e}_\beta} \tag{1.3}$$

Where $\dot{e}_\beta$ is the equivalent skin dose rate coefficient for beta emission at 1 metre given by:

$$\dot{e}_\beta = \frac{J_{\mathrm{air}}}{\mathrm{SF}} C \tag{1.4}$$

Where $J_{air}$ is the dose at 1 metre per disintegration (MeV g$^{-1}$ Bq$^{-1}$ s$^{-1}$), $C$ is a conversion constant (TBq Bq$^{-1}$) and SF is the shielding factor. The shielding factor SF is given by:

$$\mathrm{SF} = e^{\mu d} \tag{1.5}$$

Where $\mu = 0.017 \times E_{\beta_{\max}}^{-1.14}$ and $d$ is the thickness of the absorber. $E_{\beta max}$ is the maximum beta energy of the source while the value of $d$ was assumed to be 150 mg cm$^{-2}$ and is equivalent to 0.2 mm of iron. The shielding factor for beta emitters which was first included in the 1985 Edition of the Transport regulations is associated with materials such as the beta window protector, package debris or self-shielding of the source. Figure 3 shows how the shielding factor varies with $E_{\beta max}$. The shielding factor is always higher than 1 and converges to 1 at high energies, therefore the shielding factor always reduces the dose and hence increases the $Q_B$ value.

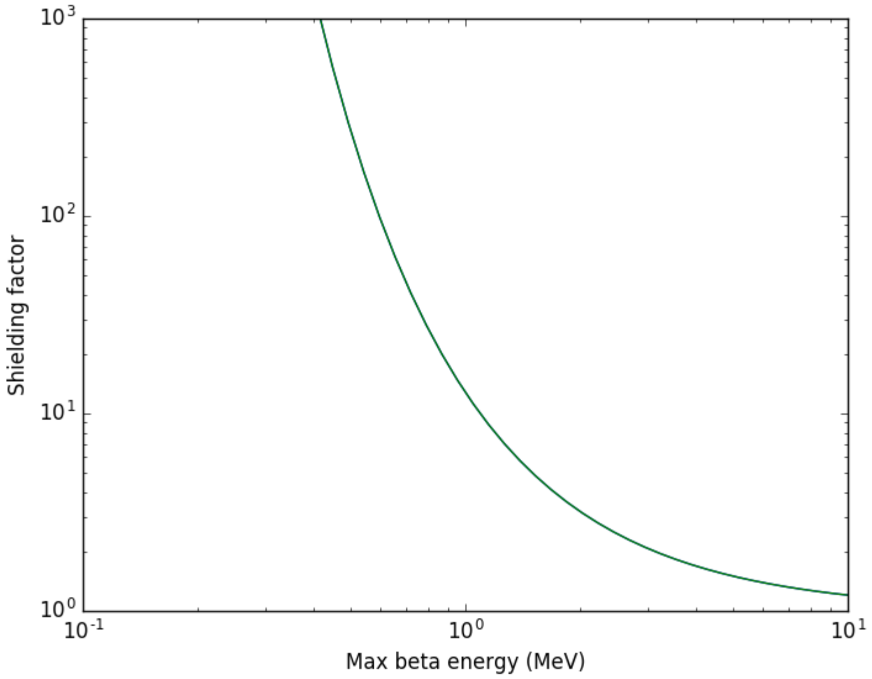

**Figure 3: Shielding as a function of beta energy**

## Work done on the effect of shielding

The working group conducted a thorough review of the actual shielding afforded to radioactive sources during transport to see if the current shielding factor was required in the Q-system.

To explore the effect of shielding on $Q_B$ values and $A_1$ values, we calculated $Q_B$ values using a software program called SEAL, which implements the current Q-system methodology [4] with and without the shielding factor. The results for a limited number of radionuclides are presented in Table 1. The table shows that for some radionuclides such as $^{60}$Co, there is no difference in the $A_1$ value as it relies on the shielding free $Q_A$ value. However for $^{85}$Kr, there is a significant increase as the removal of shielding means a higher dose and therefore a lower activity limit. Overall, we found that removing the shielding from $Q_B$ decreased the $A_1$ value of about a third of the 400 radionuclides listed in Table 2 of the IAEA regulations. The working group decided that removing the shielding, thus causing significant reductions in $A_1$ values, would not be acceptable by TRANSSC.

**Table 1 - The effect of removing shielding on $Q_B$ calculated using the current Q system**

| **Radionuclide** | $Q_A$ (TBq) | $Q_B$ (TBq) | | $A_1$ (TBq) | | $A_1$ ratio |
|---|---|---|---|---|---|---|
| | | **Shielding** | **No shielding** | **Shielding** | **No shielding** | |
| **$^{18}$F** | 1.10E+00 | 2.90E+01 | 4.00E-01 | 1.00E+00 | 4.00E-01 | 2.5 |
| **$^{60}$Co** | 4.50E-01 | 5.00E+02 | 9.80E+01 | 4.00E-01 | 4.00E-01 | 1 |
| **$^{85}$Kr** | 4.70E+02 | 1.40E+01 | 2.80E-01 | 1.00E+01 | 3.00E-01 | 33.3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **$^{90}$Sr** | 1.00E+03 | 3.20E-01 | 1.00E-01 | 3.00E-01 | 1.00E-01 | 3 |
| **$^{99m}$Tc** | 9.60E+00 | 1.00E+03 | 1.00E+03 | 1.00E+01 | 1.00E+01 | 1 |
| **$^{106}$Ru** | 5.30E+00 | 2.20E-01 | 1.20E-01 | 2.00E-01 | 1.00E-01 | 2 |
| **$^{134}$Cs** | 6.90E-01 | 3.60E+00 | 6.80E-01 | 7.00E-01 | 7.00E-01 | 1 |
| **$^{137}$Cs** | 1.80E+00 | 7.90E+00 | 9.40E-01 | 2.00E+00 | 9.00E-01 | 2.2 |
| **$^{154}$Eu** | 8.90E-01 | 1.60E+00 | 4.50E-01 | 9.00E-01 | 5.00E-01 | 1.8 |
| **$^{192}$Ir** | 1.30E+00 | 4.40E+01 | 8.20E-01 | 1.00E+00 | 8.00E-01 | 1.3 |

## Inclusion of shielding factor in the revised Q-system

To harmonize the methodology used to calculate $Q_A$ and $Q_B$ values the working group agreed to include shielding in the $Q_A$ calculation. As the current $Q_B$ shielding factor (equation 1.5) was based on the shielding of electrons it could not be reused for gamma rays. The working group also wanted to include the effect of all primary radiations from a source and also secondary radiations such as bremsstrahlung. MCNP allowed this and to the inclusion of a shielding material in directly in a calculation.

Information from industry on the type of material that could be used for shielding indicated that a shield of 0.2 mm thickness of iron is only appropriate for a $^{90}$Sr source. For other radionuclides, the minimum thickness generally used for transport purposes is 0.5 mm of stainless steel. This value is more consistent with the smallest possible size of sources; for example a spherical source of $^{60}$Co with activity equal to its $A_1$ value, 0.4 TBq, would have a radius of 0.6 mm. Additionally radioisotopes are often not in this compact form, but are either distributed over a substrate or in larger molecules such as $^{18}$F in fluorodeoxyglucose.

We carried out three sets of MCNP calculations for a shortlist of key radionuclides for three different configurations: a source at the centre of a sphere of silicon (to simulate glass or similar materials), a source at the centre of a sphere of steel and a source in air (meant to approximate to no shielding). The radius of the silicon was defined to give a thickness of 150 mg cm$^{-2}$ given a silicon sphere of 0.6 mm; a steel sphere of 0.5 mm was also chosen. These spheres are in the centre of nested shells of air, as seen in Figure 2, up to a radius of 1 metre where the dose-rate was calculated.

The results of these calculations, for the shortlist, are shown below in Table 2. As was seen in the calculations in Table 1, removing shielding in MCNP can produce reductions in $Q_B$ values; this can be seen for the air shielding values $^{192}$Ir and $^{137}$Cs in Table 2. However in the case of $^{60}$Co, including the effects of including all radiations and secondary particles in the dose calculation leads to a higher $Q_B$ value with no shielding. For the radionuclides assessed there were only minor differences in the $Q_B$ values between steel and silicon shielding. Therefore the working group chose to use steel shielding in the new Q-system methodology.

**Table 2 - Comparison of Monte-Carlo Calculations of new $Q_A$ and $Q_B$ values with different types of shielding and the current values**

| Radionuclide | Current $Q_A$ values (TBq) | Type of shielding | New $Q_A$ values* (TBq) | New $Q_B$ values (TBq) | Current $Q_B$ (TBq) | Current $A_1$ | New $A_1$ |
|---|---|---|---|---|---|---|---|
| $^{60}$Co | 0.45 | Air | 0.4 | 2.5 | 730 | 0.4 | 0.4 |
| | | Steel | 0.4 | 1.9 | | | |
| | | Silicon | 0.4 | 1.8 | | | |
| $^{90}$Sr | 1000 | Air | 1.4 | 0.08 | 0.32 | 0.3 | 0.1 |
| | | Steel | 5.0 | 0.1 | | | |
| | | Silicon | 5.0 | 0.1 | | | |
| $^{99m}$Tc | 9.6 | Air | 9.6 | 70.4 | 1000 | 10 | 10 |
| | | Steel | 10.1 | 78.6 | | | |
| | | Silicon | 9.7 | 74.4 | | | |
| $^{106}$Ru | 5.3 | Air | 0.7 | 0.09 | 0.22 | 0.2 | 0.1 |
| | | Steel | 1.4 | 0.1 | | | |
| | | Silicon | ** | 0.1 | | | |
| $^{137}$Cs | 1.8 | Air | 1.8 | 0.3 | 8.2 | 2 | 1* |
| | | Steel | 1.8 | 1.3 | | | |
| | | Silicon | ** | 1.5 | | | |
| $^{192}$Ir | 1.3 | Air | 1.4 | 0.4 | 46 | 1 | 1 |
| | | Steel | 1.4 | 4.9 | | | |
| | | Silicon | 1.4 | 4.9 | | | |

*assuming steel chosen as shielding
** value not calculated

For radionuclides with strong gamma and x-ray emissions such that the $Q_A$ value is well below the upper limit in the regulations and the dominant pathway for $A_1$, there is little difference between the dose rate where there is no shielding (air), silicon shielding or steel shielding. For weaker gamma sources, the inclusion of doses from all radiations will reduce the $Q_A$ value but $A_1$ is more likely to be dependent on $Q_B$. This is seen for $^{90}$Sr and $^{106}$Ru in Table 2 which have significant drops in their $Q_A$ values but the $A_1$ value is still dependent on $Q_B$. Where a difference is seen in $Q_A$ values between air and solid shielding, it is not the limiting factor on $A_1$. In general, this new method of calculating shielding does not significantly decrease $A_1$ values like removing the shielding factor in the current Q-system methodology.

## Conclusions

Monte-Carlo particle transport programs were used by the TRANSSC working group reviewing the Q-system to assess the impact of different types of shielding on the calculation of $Q_A$ and $Q_B$ values. This approach has allowed the experts to explore the effects of changes to the shielding calculation used in the Q-system methodology.

The working group is proposing that the Q-system should be modified to include a shield of 0.5 mm stainless steel when calculating both the $Q_A$ (external effective dose) and $Q_B$ (external skin equivalent dose) values. It should be noted that the change in shielding is just one of the factors affecting the calculation of the Q values and that other modifications, such as taking into account all types of radiations can have significant effect on the values.

We are currently finalising the calculation of Q values for all the radionuclides included in Table 2 of the IAEA regulations. Once a complete preliminary set has been produced the new values will be submitted along with the proposals for a revised Q methodology to TRANSSC for review.

## References

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