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Findings and future work of the International Working Group on review of A_1 and A_2 values

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Abstract

The A_1 and A_2 values described in the advisory material SSG-26 have been developed to provide the maximum allowable contents in packages not designed to survive accidents, with the objective of limiting the exposure of individuals to an effective dose of less than 50 mSv and a skin dose equivalent of less than 500 mSv.

Current A_1 and A_2 values were determined in 1996. Since then, the ICRP has published revised radiological data. In addition, progress in computer hardware and software allows the implementation of new methods of calculation, which are more complete and more precise.

In September 2013, NRA, PHE, GRS and IRSN agreed to exchange findings and proposals about methods of calculation of A_1 and A_2 and to create an international working group. The review of following issues 1 and 2 had been completed when the abstract was submitted; discussion of issues 3 to 8 is pending on further work to be completed in the future.

1. Use of new data in new ICRP publications (ICRP 107, ICRP 116) for radionuclide emission spectra and dose coefficients.
2. Use of calculation models based on Monte-Carlo (MC) methods (probabilistic approach for a sampling of particle histories) in order to take into account the new radiations not explicitly

considered in the current Q system (beta particles of more than 400 keV, or spontaneous fission neutrons).

3. Selection of the irradiation field geometry.
4. Selection of the calculation model for beta radiation.
5. Selection of the method of calculation of progeny radionuclides.
6. Development of a specific irradiation scenario for the lens of the eyes and the associated dose objective.
7. Reviewing Q_C (inhalation) and Q_D (contamination) values: firstly to take into account new ICRP inhalation dose coefficients that are presently in the process of publication; secondly to check the possible significant influence on Q_D from ingestion. Tritium scenarios should also be reviewed.
8. Finally, methods to aggregate the different contributions to effective dose or to skin equivalent dose are to be confirmed, as well as the multi-path cumulative dose principle where simultaneous exposures may occur, for instance by direct external irradiation and internal contamination (inhalation, ingestion) in the evaluation of Q eff or by direct external irradiation and contamination in the evaluation of Q skin.

This paper will indicate the status of work that has been performed, explain the main changes in the calculation methods, show the preliminary results and describe the actions that are not yet completed.

Introduction

The A_1 and A_2 values tabulated in the IAEA transport regulations SSR-6 [1] have been determined to limit the contents of packages so that "*the radiological consequences […] are deemed to be acceptable, within the principles of radiological protection, following failure of the package after an accident*" (para. 402.1 in SSG-26 [2]) where the package has lost its safety and radiation protection functions. These values had been derived from the "Q system" radiological model, based on 5 different exposure scenarios and described in the advisory material SSG-26, using reference doses of 50 mSv (effective dose) and 500 mSv (equivalent dose to skin). It is considered that exposures below these limits would not lead to significant health detriment, either deterministic or stochastic.

A_1 and A_2 values are also often used to express the package standard performances required in the different transport situations, as they represent equivalent radiological consequences whatever radionuclide is involved.

The current Q system is the heir of, successively, the radiotoxicity classification system used in the 1961, 1964 and 1967 editions of the Regulations, and the "A_1/A_2 system" derived in the 1973 edition. The Q system was first introduced in the 1985 edition No. SS6, using a similar method to the "A_1/A_2 system", taking into account the latest changes in ICRP recommendations (ICRP 26) at that time [3]. The A_1 and A_2 values were then updated with the 1996 edition of the Regulations No. ST-1 to take into account the new IRCP 60 recommendations and ICRP latest data at that time. Since then, they have remained unchanged in the following editions.

However, ICRP has published updated and more complete data that supersede the previous data sets. New means of calculation are also available. Furthermore, there was a need in some countries to have A_1/A_2 values for additional radionuclides. Unfortunately, simple calculations of additional A_1/A_2 values or recalculation of existing values only using Appendix I of SSG-26 are not possible: inconsistencies and the unavailability of required information to do this task or to interpret the basic radionuclide values fixed in the transport regulations were identified by several organizations.

Organization of the review

The first meeting was held in September 2013 in Cologne, Germany, with participants from UK (PHE, formerly HPA), Japan (JNES), France (IRSN), Germany (GRS, BfS), and WNTI, to share their understanding of these issues. However, as no complete proposal was available, the TRANSSC committee concluded at its November 2013 meeting (TRANSSC 27) that no change to the SSR-6 Safety Standard could be provided. It was, however, identified that further meetings were needed to exchange views and conclusions about possible improved methods and associated results. Up to now a total of 7 meetings have been held about these issues between 2013 and 2016, gathering participants from UK (PHE), Germany (GRS and BfS), Japan (NRA – formerly JNES, NMRI, MHI NS ENG), France (IRSN and ASN), USA (US DOT), and WNTI. The participants form the so-called "Working group on review of methods of calculation of A_1 and A_2 values", (A_1-A_2 WG or WG).

As the WG is recognized by TRANSSC, TRANSSC passed some technical questions from proposals for the 2015 review of the IAEA transport regulations to the WG for comment. Furthermore, TRANSSC asked the WG to calculate Q and A values for five new nuclides (^{135m}Ba, ^{69}Ge, ^{193m}Ir, ^{57}Ni, and ^{83}Sr) to be included in the 2015 revision cycle. Calculations were carried out by the group using the current Q system calculation models. Three different calculation tools were used for this task: SEAL [4] by PHE, BerQATrans [5] by GRS, and BRACSS by NRA.

In 2016, TRANSSC has proposed that a coordinated research project (CRP) be undertaken to strengthen the structure of this organization. This CRP would be extended to include future work about exemption values. The IAEA secretariat will initiate the process.

Latest changes in ICRP publications

Previous recommendations and available data (ICRP 38 [7], ICRP 51 [8], ICRP 60 [10]) have been updated (ICRP 103 [13], ICRP 107 [14], ICRP 116 [15], ICRP 118 [16] and ICRP 119 [17]). In these new publications, the existing data (radionuclide emission spectra and dose coefficients) have been updated and new kinds of data have been included such as extended energy range, spectra for delayed beta / prompt and delayed gammas / neutrons, and skin dose coefficients for photons and for neutrons, as well as effective dose coefficients for beta and for neutrons. Coefficients based on an updated computational phantom are tabulated for different radiation fields. Higher incidence of eye cataract than previously expected was also considered.

Improved calculation tools and use of full set of data

The updated ICRP data can be used within the current Q system with similar analytical calculation methods. However, the current dose calculation model is not adapted to process these new data in entirety. Some of the new data correspond to radiations, the dose contributions of which were previously not explicitly considered in the Q system, and for which new calculation methods are necessary. For that purpose, the WG agreed to use calculation models based on Monte Carlo (MC) methods (probabilistic approach for sampling of particle histories). By using this MC method and including all kinds of new data provided by ICRP, it is now possible to calculate contributions from all radiations, e.g. bremsstrahlung or neutrons.

The results of calculations performed by the WG with MC methods appear consistent with the results obtained with the analytical methods of current Q system and with the same radiological data. From the calculations performed by the WG for a shortlist of 20 nuclides and progeny with ICRP 38 data and with same data as revised in ICRP 107, results have shown some limited differences on non-constraining Q values, resulting in no change to A_1 values.

In addition, calculations using the current calculation method of the Q system were also performed for all radionuclides listed in SSR-6. These calculations were executed to verify the influence of only new data from ICRP 107 instead of ICRP 38 onto the Q and A values. Results have shown some changes in Q values for a few radionuclides. However, there would be no significant change for A_1 and A_2 values except for 3 radionuclides (^{114m}In, ^{102}Rh, ^{102m}Rh). The changes in the last two radionuclides (^{102}Rh, ^{102m}Rh) seem to arise because of switching the properties assigned to them from ICRP 38 to ICRP 107.

Furthermore, calculations have been performed by members of the WG with MC methods and all data from ICRP 107 (including neutrons), instead of considering only beta and gamma doses and neutron arbitrary activities (Q_F – considered equal to 1 000 times Q_C, except for ^{252}Cf), on a short list of 20 radionuclides[1] that are considered to be representative of the transport of radioactive materials.

Radiation field geometry

The existing Q_A (external radiation dose due to photons) values were calculated using the dose coefficients for irradiation, published in ICRP 51, based on an isotropic irradiation field (called ISO

[1] ^{3}H, ^{18}F, ^{60}Co, ^{85}Kr, ^{90}Sr-^{90}Y, ^{99m}Tc, ^{106}Ru, ^{134}Cs, ^{137}Cs, ^{154}Eu, ^{192}Ir, ^{222}Rn, ^{237}Np, ^{241}Am, ^{244}Cm, ^{252}Cf, natural U and Th, chemically-separated U and Th.

geometry), homogeneous in any spatial direction. Such geometry approximates the exposure in a large homogenous cloud of radioactive gas or in a highly scattered radiation field. The use of the other possible geometries, namely AP (antero-posterior, for a person facing the source), ROT (rotational, for a person standing up walking around a contaminated field) or the average of AP, PA (postero-anterior), RLAT (lateral from the right side) and LLAT (lateral from the left side), leads to lower the Q_A values (with a degree depending on the geometry chosen) for all radionuclides. The choice of the ISO geometry is not well documented, to the knowledge of the participants, and its definition seems inconsistent with the use of a "point source", thus many WG participants questioned its use.

All participants eventually agreed that the irradiation field should average the exposure from a severe transport accident (where a type A package would lose its contents) and that ICRP 116 defined dose coefficients for a parallel beam of ionising radiation, which is unrealistic for a point source only 1 m away from a person. It was decided to retain ISO and ROT fields as reasonable field candidates; investigating the dose coefficients, it was confirmed that the difference in Q_A values should be less than 30 %. No decision on recommended field geometries will be taken until the new calculation method has been considered.

The use of irradiation field geometries will also be extended to calculate external irradiation due to beta and neutrons, which is currently not considered in the Q system.

Calculation methodology

At the beginning of the WG project, it was decided to directly calculate the Q_A (external dose due to photons) and Q_B (external dose due to beta emitters) using MC- calculation tools; the dose coefficients were directly encoded in the input files. Because of the issue related to the field geometry and the desire to compare different calculation tools, it was decided to evaluate surface flux through a detector located at 1 m from the point source, for the same energy bins (or with a better resolution) in ICRP 116, then to process the results using the dose coefficients agreed upon (ISO or ROT field). The flux is based on the physical processes and interaction cross-sections used in the corresponding code, and is therefore well-suited for validation procedures.

The model geometry is simple: a surface of a sphere of 1 m radius with a point source at the centre of the sphere. Considering that backscattering was taken into account when deriving the ICRP 116 dose coefficients, it was decided that the 1-m-radius sphere would be the boundaries of the calculation universe.

Calculation model for beta radiation

The Q system considers a 150 $mg \cdot cm^{-2}$ absorber for the calculation of Q_B. It is an arbitrary figure originally chosen to simulate either residual shielding between the radioactive source and the bystander [2] (due to package debris or because of the capsule containing the source), or auto-shielding of the source itself [3]. This value is not properly documented in SSG-26 and was mentioned as a simple derivation of an assumption made in the 1973 edition of the IAEA Regulations [3].

Discussions are ongoing in the WG about restricting the use of shielding factors to radionuclides that are always in gaseous form in order to allow for the containment necessary for a 30-minute exposure without dispersion of the gas. Also it is being discussed within the WG whether to expand the model of remaining shielding to all external radiation for consistency purposes, to withdraw the absorber model from all or to adapt the current model with MC calculations. It was underlined that, while it would be acceptable to assume a minimum thickness for remnant shielding when calculating A_1 values for special form materials which integrate a robust metallic sheath, it is more difficult to imagine an absorber model in calculating the external irradiation component of the A_2 values of radionuclides, which can be in powder or liquid form. After breaching of the package (containment and shielding), these radionuclides would have no shielding except self-absorption, but thickness of material including the radionuclides can be very low so that self-absorption could be considered negligible. Proper considerations relating to modelling of shielding should be debated before the end of the year.

Eye lens irradiation

A new limit for the equivalent dose to the eye lens has recently been recommended by ICRP 118 for workers. It was decreased from 150 mSv per year to 20 mSv per year averaged on 5 years with a maximum of 50 mSv per year. This reduction by a factor of 3 to 7.5 may call into question the appropriateness of the statement in SSG-26, para. I.28, that "*the dose to the skin is always limiting for maximum beta energies and that specific consideration of dose to the lens of the eye is unnecessary*".

Accordingly, dose to the eye lens will be explored first using the same scenario and the parameters considered in deriving Q_A and Q_B. The 50 mSv equivalent dose limit is taken into account on the same basis as the 50 mSv effective dose limit (maximum of 50 mSv for a single year). Initial investigations on beta emitters led the WG to conclude that changes in A_1 values are expected for radionuclides with high beta energies (mean energy higher that ~700 keV).

Parent and progeny radionuclides

Considering the lack of traceability in the evaluation of existing basic values for some parent and progeny radionuclides, the WG will recalculate them using the following principles:

- general assumption of a transport period of 1 year, during which a transient equilibrium may take place, when the progeny activity reaches its maximum during this period (it is especially true for progeny with half-lives longer than their parents', cf. para. I.57 of SSG-26);
- radionuclides in naturally occurring radioactive material (NORM) are in secular equilibrium with their progeny;

- very short lived progeny are taken into account (e.g. ^{137}Cs-^{137m}Ba, ^{106}Ru-^{106}Rh, ^{110m}Ag-^{110}Ag);
- specific materials with complex decay chains such as thorium, uranium, uranium (enriched) and uranium (depleted) should be calculated and presented separately according to appropriate mixtures, such as full secular equilibrium, 100-year build-up, freshly produced.

It was discussed whether the consignor should use the mixture law for all kinds of material; for example, applicants for certificate of approval already use the mixture law for safety reports. Further, footnotes (a) and (b) of Table 2 (SSR-6) are sources of confusion (there are many proposals to TRANSSC to clarify them). However, while participants agreed to continue using the aforementioned principles, they stressed that introducing A values (and, possibly, exemption values) for all progeny radionuclides would overcomplicate Table 2 and confuse the users of the Regulations.

It was underlined that, whatever the decision regarding this matter, the Q values will have to be determined for all parent and progeny radionuclides. The final decision will, therefore, be postponed, although the participants would prefer to keep the current system with clarifying footnotes (a) and (b).

Previous Q system simplifications, cut-off energy and emission rate cut-off

Calculation cut-offs

Cut-off values for energy and emission rate were considered in view to shorten computation time. It was recognised that cut-off values for energy need to be consistent with the cut-off of the dose coefficient considered by ICRP 116.

After comparison of different calculations with or without emission rate cut-offs, it was found that computation time was not significantly affected, but that some Q_B values could be affected by this technique. Therefore, no calculation cut-offs were retained.

Upper cut-off of 40 TBq for A_1 and A_2 values due to bremsstrahlung

In the current Q system, an upper cut-off of 40 TBq for A_1 and A_2 values is used to take bremsstrahlung into account. Using MC methods allows implementing bremsstrahlung into the calculation for each radionuclide explicitly. Further, for Q values related to intakes of radionuclides, the WG agreed to proceed with the same method as in the current Q system, i.e. using the ICRP data for intakes to be updated in the coming years (cf. ICRP 130 [18] introducing this update). Therefore, it was agreed that this 40 TBq cut-off could be discarded.

Upper cut-off of 1 000 TBq for Q values

The upper cut-off of 1 000 TBq for Q values is not documented in the current Q system; the WG considers that cut-off arbitrary. Therefore, it was agreed that this 1 000 TBq cut-off could be discarded.

Upper cut-off of 10 mg for intakes (Q_C values) and “unlimited” values

The current Q system considers an upper cut-off of the mass of radionuclide that can be absorbed (inhalation or ingestion). This corresponds to a physical limitation of the human body. So the WG is considering applying such an upper cut-off.

The mass limit is used to define the “unlimited value” in both deriving the Q and A values. As such, it explains why natural uranium has unlimited A_1 and A_2 values while its Q_A and Q_B values are not unlimited: the point source assumption cannot be used here since those Q_A and Q_B values represent tonnes of uranium, strongly decreasing the exposure, so that it is never possible to reach 50 mSv in 30 minutes at 1 m, whatever the mass of material involved; this is not explicit in SSG-26. The WG is considering applying such a mass limit.

External irradiation cumulative dose principle

The majority of participants of the WG consider that the principle of considering only one kind of radiation to determine either the effective dose or an equivalent dose, and not allowing for all kinds of emissions, should be improved since ICRP recommendations now provide coefficients for all radionuclide emissions, and new calculation techniques (MC methods) are now available that allow precise evaluation of the associated total exposure of persons. For example, effective dose coefficients now exist for beta, neutron and gamma emissions meaning that the Q_A value for ^{137}Cs should take into account effective dose due to both its gamma and beta emissions.

In addition, the arbitrary Q_F value for alpha emitters (replacing Q_A) will be discarded: e.g. a Q_A value for ^{244}Cm can now be calculated. However, for alpha emitters, discussions are still ongoing, essentially regarding the (alpha, n) reactions occurring in matrices containing the radionuclides (oxygen mainly; then beryllium, fluorine, magnesium, etc. for the transport of specific sources).

The WG members checked the influence of the additional emissions on the doses, without changing the current dose limits (effective dose of 50 mSv and equivalent skin dose of 500 mSv, per accident), on a few radionuclides. For the first 20 radionuclides of interest, the following observations and assumptions could be drawn:

- while, as expected, Q_A decreases for radionuclides with high beta energies and Q_B decreases for radionuclides with significant γ energy fraction, the A_1 value remain unchanged (also due to the rounding method);
- Q_A values for neutron emitters will drastically change (the values calculated until now being either higher or lower than the former Q_F).

Application to the calculation of A_1 value for each radionuclide

The new calculation methods herein described should be applied to determine new A_1 values for each radionuclide. Depending on whether progeny are to be considered together with parent nuclide, there will be either 388 or about 700 nuclides to calculate.

Eventually, more radionuclides may need to be addressed in order to be consistent with the list of radionuclides considered in the IAEA GSR Part 3 [19].

Review of methods of calculation of Q_C, Q_D and Q_E

The Qc (inhalation) and Q_D (skin contamination or ingestion) values warrant future review for at least two reasons: firstly to take into account new ICRP inhalation dose coefficients that should be included in a ICRP series for occupational intakes of radionuclides, beginning with ICRP publication 130 replacing ICRP publications 30 [6], 61 [11] and 68 [12]; and secondly to check the possible significance of ingestion on Q_D (it is currently not determined in the Q system because it is considered that it would be lower than the Q_C due to inhalation, cf. para. I.50 of SSG-26).

With regard to Q_D, there are no ICRP publications related to dose coefficients due to contamination (only ICRP 59 served as a basis to determine equivalent dose limitation to the skin; ICRP 118 completed that work for the eye lens). It was suggested that MC method could be used; one model of calculation with 3 cases (^{90}Sr-^{90}Y, ^{60}Co and ^{14}C) showed results similar to Q_D values currently listed in the SSG-26.

For Q_E (submersion dose due to gaseous isotopes), current dose coefficients due to submersion are taken from the Federal Guidance Report No. 12 for both external and internal exposure. For internal exposure, they are consistent with dose coefficients listed in ICRP 119 (compendium of dose coefficients based on ICRP 60 recommendations, including those of ICRP 68 and some updates); they will be updated by ICRP (cf. above). For external exposure, it was suggested to use a MC method. No example calculation has been provided so far but this proposal will be considered in due time.

Other issues, such as tritium scenarios[2], will be reconsidered if necessary.

Multi-path cumulative dose principle

The current SSG-26 explains in para. I.86 that multiple exposure pathways were not retained because the "*examination of table I.2 shows that this consideration applies only to a relatively small number of*

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[2] The specificity of tritium is that it may undergo complete phase change (i.e. liquid to gas when in form of tritiated water), even in absence of fire, which warrants a specific scenario for exposure pathway. It has also been noted that it should be clarified why the limit of 1 TBq/litre for the concentration of ^{3}H in water mentioned in SSG-26 has not been stated in SSR-6.

radionuclides". Since no further element was presented to support this assertion, this consideration will also be questioned in due course; for the same reason the principle of aggregating doses from all emissions from a point source located at 1 metre distance was accepted, the majority of WG participants have also agreed to study simultaneous exposures by all calculated pathways in the Q system, i.e. all Q values for a radionuclide.

From the first review using the current Q values of 20 radionuclides, allowing for multiple exposure pathways, it was generally concluded that:

- changes in A_2 values are expected for β/γ-emitters driven by both their A_1 and Q_D;
- no change in A_2 values is expected for actinides driven by their Q_C (i.e. most of them);
- "unlimited" values will probably remain so (considering the limitations stated in para. I.68 and I.70, that all participants agreed to keep, at least in a similar form, cf. cut-off issue above).

Application to the calculation of A_2 value for each radionuclide

The new calculation methods herein described should be applied to determine new A_2 values for each radionuclide. These calculations will be postponed until new dose coefficients are published by ICRP.

Conclusion and further steps

As mentioned throughout this paper, some parameters still need to be fixed before final calculations are performed. TRANSSC agreed to request a CRP on this topic in order to complete the work and to document the new methods and results obtained in a TECDOC.

Some time should then be reserved for a special group to analyse the requirements to change the A_1 and A_2 values regarding the safety and radiation protection benefits versus potential impacts on transport activities.

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