A Model for the Derivation of New Transport Limits For Non-Fixed Contamination

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1. Introduction

The IAEA Regulations for the Safe Transport of Radioactive Material [1] contain requirements for contamination limits on packages and conveyances used for the transport of radioactive material. Current contamination limits for packages and conveyances under routine transport conditions have been derived from a model proposed by Fairbairn more than 40 years ago [3]. This model has proven effective if used with pragmatism, but is based on very conservative as well as extremely simple assumptions which is in no way appropriate any more and which is not compatible with ICRP recommendations regarding radiation protection standards. Therefore, a new model has now been developed which reflects all steps of the transport process. The derivation of this model has been fostered by the IAEA by initiating a Co-ordinated Research Project (see section 2). The results of the calculations using this model could be directly applied as new nuclide specific transport limits for the non-fixed contamination.

2. IAEA Co-ordinated Research Project

The IAEA has initiated a Co-ordinated Research Project (CRP) in 2001 which had the task to develop a new model for the exposure by non-fixed contamination and to give advice to the IAEA TRANSSC on the appropriateness of the old Fairbairn model [3], on needs for changes of transport regulations in this respect and on guidance on the implementation. This international group combined members from regulatory bodies, expert groups, research and industry.
The model (as described in section 3) has been developed by four working groups within the CRP and has been refined and agreed upon in combined meetings. It is therefore based on consensus among the participants of the CRP and can be regarded as the present expert opinion on which exposure situations caused by non-fixed contamination on packages during transport to include, which steps to include in the transport process and on how to model the exposure in an enveloping and conservative way.
The CRP has finished its work in 2003. It came to the conclusion that the “Fairbairn model was limited and outdated and that a new comprehensive model (the Basic Model) should be produced to provide the basis for eventually deriving new contamination limits for transport situations”. As the result of this model is a set of radionuclide specific surface contamination levels (instead of integral values 0.4 / 4 Bq/cm²), the CRP also gave advice on how to deal with such a set of levels in practice (see section 4.5 below). A report of the CRP will be published soon [4].

3. Description of the Model

3.1. Overview of the model

The starting point of the model development within the CRP has been formed by WNTI proposal which reflected common steps in the transport process in Germany. This proposal was refined to be commonly applicable to all types of packages, represented by four package types (see section 3.2), as well as all types of nuclear installations and industrial or medical application of radioactivity. The model is divided into the 5 major steps which are in turn further divided into sub-steps (see section 3.3) to cover all exposure conditions. Exposure scenarios have been designed for exposure of the personnel during handling and transport of the packages as well as exposure of the general public. Using appropriate dose constraints, the model has finally been used to calculate radionuclide specific surface contamination limits as described in section 4 below.
More details of the model including figures of package types, exposure conditions etc. can be found in another presentation of this conference [5]. The following description is therefore limited to a basic outline of the model allowing the reader to assess the relevance of the results presented in section 4 and the changes to the TS-R-1 regulations proposed in section 5.

3.2. Package types

Separate exposure conditions (times, distances, frequencies of exposure etc.) were set up independently for the four generic package types:

- small manually handled packets,
- small remotely handled objects like 200 l drums,
- large remotely handled containers and
- fuel flasks.

By finally taking the maximum dose contribution from the scenarios for all four package types, it is ensured that the results of the model calculations This approach ensures that the overall results are valid for all package types while still allowing to distinguish between the radiological relevances of the individual package types.

3.3. Transport steps

The transport process is broken down into the following 5 steps:

1. final inspection of the package,
2. transfer of the package to the vehicle,
3. movement of the vehicle (the actual transport phase),
4. change of transport mode (e.g. unloading the package from conveyance #1 on conveyance #2),
5. receiving inspection of the package,

each of which is further divided into sub-steps. This covers the entire range of work and workplaces during the transport process, beginning from the point when contamination of the package (if applicable, depending on the package type) has been completed and ending after receiving inspections have been completed. The model contains appropriate assignment of workers to tasks as well as a separate part on the exposure of the public.

3.4. Exposure scenarios

Detailed exposure conditions are defined for each sub-step and each package type. Each scenario takes into account the following exposure pathways:

- External exposure
- Inhalation of radionuclides from the non-fixed surface contamination which are (re-)suspended into the air,
- Ingestion of radionuclides from the non-fixed surface contamination via a hand-to-mouth pathway,
- Skin contamination.

Dedicated model assumptions are used for calculating the radionuclide concentration in the air around the packages. They are based on a conservative assumption on the resuspension rate, i.e. the percentage of contamination which is released from the surface into the air per unit time. Each sub-step is linked to one scenario which in turn comprises all exposure pathways.

Exposure scenarios are linked to specific workplaces in the model in an enveloping way. That means that e.g. the same health physicists may be involved in various sub-steps of steps 1 and 2. If such a workplace would exceed the normal annual working time, appropriate corrections are made.

Additional scenarios are designed for exposure of the general public.

3.5. Radionuclide specific approach and calculation method

The doses from each scenario are evaluated for the standard suface contamination of 1 Bq/cm² and separately for each radionuclide. The radionuclides are taken from Table I of TS-R-1 [1] and include progeny as indicated in footnote (b) of that table (see also the excerpt of the new proposed Table I below in section 4.3 of this paper). Doses are summed for each workplace which is part of the model. This finally yields a list of doses per unit activity for each radionuclide, for each package type and for each workplace (as well as each exposure scenario for the general public). The last step is then to take the maximum dose contribution of all workplaces for each radionuclide and to use this value as the dose conversion factor between surface activity and annual dose.

4. Results and Discussion

4.1. Overview

Calculation of radionuclide specific dose conversion factors as described in section 3 above has been the last step in the calculations the IAEA CRP has taken in [4]. The WNTI working group went one step further and actually derived radionuclide specific surface contamination limits. The radionuclide specific approach is absolutely necessary because the dose conversion factor (Sv/a per Bq/cm²) strongly depends on the properties of the radionuclide. This

requires to abandon the two groups of nuclides as currently used in TS-R-1, linked to the surface contamination limits of 0.4 Bq/cm² and 4 Bq/cm² and to replace them with a radionuclide specific approach.
Calculations have been made for all radionuclides listed in Table I of TS-R-1 using the model described in section 3 above. They have started from the dose constraints discussed in section 4.2 and have led to the results shown in Table I in section 4.3.

4.2. Dose constraints

In order to carry out the calculations of radionuclide specific surface contamination limits, it is first necessary to define dose levels or dose constraints from which the calculation starts. One dose constraint is required for worker scenarios, a second dose constraint for scenarios for members of the general public.
Although the IAEA CRP has not calculated surface contamination limits of its own, the question of suitable dose constraints have been discussed in the CRP. There was consensus of the broad majority of participants (though not unanimity) that dose constraints of of 2 mSv/a for workers and 0.3 mSv/a for the public would be appropriate. These values have been used for the calculations.
When assessing these dose constraints, it must be kept in mind that a value of 2 mSv/a is only 10 % of the annual dose limit for workers, as laid down in Basic Safety Standards of IAEA [6] and EU [7]. On the other hand, the old Fairbairn approach [3] which is still in effect today in the form of the current surface contamination limits of TS-R-1 [1], is based on a dose value of 50 mSv/a or 100 % of the then dose limit and did not take into account any scenarios for the general public. In this respect, the new approach proposed in this paper can be regarded as a major step forward!

4.3. Calculation results

Calculation of surface contamination levels have been carried out for all radionuclides listed in Table I of TS-R-1 [1]. When comparing the dose contributions from worker scenarios and scenarios for the general public, worker scenarios generally give higher doses, compared to their respective dose constraints. The most restricting scenarios are those for workers dealing with small manually or remotely handled packages because here it is assumed that they have the longest contact with any surface contamination combined with the shortest exposure distances.
The results (in the unit Bq/cm²) for the proposed radionuclide specific contamination limits span several orders of magnitude ranging from below 0.1 Bq/cm² for highly radiotoxic alpha emitters to 10^5 Bq/cm² for radiologically insignificant nuclides. A system of introducing a lower and upper boundary (0.1 to 1000 Bq/cm²) as well as a rounding procedure (logarithmic rounding to half-decades):

$$0.563 \cdot 10^x \ldots 1.77 \cdot 10^x \rightarrow 1 \cdot 10^x$$
$$1.78 \cdot 10^x \ldots 5.62 \cdot 10^x \rightarrow 3 \cdot 10^x$$

which leads to steps 0.1, 0.3, 1, 3, 10, 30, etc. has been used to make the calculated contamination limits applicable in practice. The calculation results from this model are suitable for direct use as new radionuclide specific surface contamination limits for the non-fixed contamination and for application in a revised version of TS-R-1. They are therefore part of a proposal for changing TS-R-1 which has been fed into the current revision cycle and which is summarized in section 5 of this paper.
A selection of results have been given in the following table (which is part of the proposed changes to TS-R-1) for some relevant radionuclides in the 6th column. The results are presented here as part of a revised Table I to show that they could easily be implemented into the current structure of the Transport Regulations. In cases of decay chains (i.e. where a footnote (a) or (b) is present), the value refers to the head of the decay chain (parent nuclide) only. There is one exception to this rule for uranium which needs special consideration (see section 4.4 below).

TABLE I BASIC RADIONUCLIDE VALUES

Radionuclide (atomic number)	A_1	A_2	Activity concentration for exempt material	Activity limit for an exempt consignment	Limit for surface contamination
	(TBq)	(TBq)	(Bq/g)	(Bq)	(Bq/cm²)
Am-241	1E+01	1E-03	1E+00	1E+04	3E-1
C-14	4E+01	3E+00	1E+04	1E+07	1E+3
Cl-36	1E+01	6E-01	1E+04	1E+06	1E+3
Cm-240	4E+01	2E-02	1E+02	1E+05	1E+1
Cm-241	2E+00	1E+00	1E+02	1E+06	3E+2
Co-60	4E-01	4E-01	1E+01	1E+05	1E+2
Cs-134	7E-01	7E-01	1E+01	1E+04	1E+2
Cs-137 (a)	2E+00	6E-01	1E+01	1E+04 (b)	3E+2

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Radionuclide (atomic number)		A_1	A_2	Activity concentration for exempt material	Activity limit for an exempt consignment		Limit for surface contamination
		(TBq)	(TBq)	(Bq/g)	(Bq)		(Bq/cm²)
Eu-152		1E+00	1E+00	1E+01	1E+06		3E+2
Eu-154		9E-01	6E-01	1E+01	1E+06		1E+2
Eu-155		2E+01	3E+00	1E+02	1E+07		1E+3
Fe-55		4E+01	4E+01	1E+04	1E+06		1E+3
Fe-59		9E-01	9E-01	1E+01	1E+06		3E+2
I-129		Unlimited	Unlimited	1E+02	1E+05		1E+2
I-131		3E+00	7E-01	1E+02	1E+06		3E+2
K-40		9E-01	9E-01	1E+02	1E+06		1E+3
Ni-59		Unlimited	Unlimited	1E+04	1E+08		1E+3
Ni-63		4E+01	3E+01	1E+05	1E+08		1E+3
Np-237		2E+01	2E-03	1E+00	1E+03		1E+0
Np-239		7E+00	4E-01	1E+02	1E+07		1E+3
Pa-231		4E+00	4E-04	1E+00	1E+03		1E-1
Pb-210	(a)	1E+00	5E-02	1E+01	1E+04	(b)	3E+0
Po-210		4E+01	2E-02	1E+01	1E+04		1E+1
Pu-239		1E+01	1E-03	1E+00	1E+04		3E-1
Pu-240		1E+01	1E-03	1E+00	1E+03		3E-1
Pu-241	(a)	4E+01	6E-02	1E+02	1E+05		3E+1
Ra-226	(a)	2E-01	3E-03	1E+01	1E+04	(b)	3E+0
Sr-90	(a)	3E-01	3E-01	1E+02	1E+04	(b)	3E+2
H-3		4E+01	4E+01	1E+06	1E+09		1E+3
Tc-97		Unlimited	Unlimited	1E+03	1E+08		1E+3
Tc-99		4E+01	9E-01	1E+04	1E+07		1E+3
Th-232		Unlimited	Unlimited	1E+01	1E+04		1E+0
Th-nat		Unlimited	Unlimited	1E+00	1E+03		3E-1
Th-234		3E-01	3E-01	1E+03	1E+05		1E+3
U-238 F	(d)	Unlimited	Unlimited	1E+01	1E+04	(b)	3E+1
U-238 M	(e)	Unlimited	Unlimited	1E+01	1E+04	(b)	1E+1
U-238 S	(f)	Unlimited	Unlimited	1E+01	1E+04	(b)	3E+0
U-sec		-	-	1E+00	1E+03	(b)	3E-1
U-nat		Unlimited	Unlimited	1E+00	1E+03	(b,h)	5E+0
U-enr-5%		Unlimited	Unlimited	1E+00	1E+03	(b,h)	3E+0
U-enr-20%		Unlimited	Unlimited	1E+00	1E+03	(b,h)	2E+0
U-dep		Unlimited	Unlimited	1E+00	1E+03	(b,h)	7E+0

Footnotes have the same meaning as in Table I of TS-R-1 [1]:
(a) A_1 and/or A_2 values include contributions from daughter nuclides with half-lives less than 10 days.
(b) Parent nuclides and their progeny included in secular equilibrium are listed in the following: [list follows]
(d) These values apply only to compounds of uranium that take the chemical form of UF_6, UO_2F_2 and $UO_2(NO_3)_2$ in both normal and accident conditions of transport.
(e) These values apply only to compounds of uranium that take the chemical form of UO_3, UF_4, UCl_4 and hexavalent compounds in both normal and accident conditions of transport.
(f) These values apply to all compounds of uranium other than those specified in (d) and (e) above.
(h) The values of the contamination limit for the non-fixed surface contamination (col. 6) are given for the total surface activity and are rounded to one siginificant digit

If more than one nuclide needs to be considered, a summation rule like the one in § 404 of TS-R-1 [1] needs to be applied to the proposed surface contamination limits. That means that the sum $\sum_{i=1}^{n} \frac{c_i}{C_i}$ should not exceed the value 1, where c_i is the actual concentration of radionuclide i and C_i is the limit concentration of the same nuclide according to Table I.

4.4. Values for uranium

Uranium takes a special role in transport regulations because of the large number of transport and the great variety of forms and degrees of enrichment in which it is transported. Table I of TS-R-1 therefore containts a large number of different entries which also have been used when calculating the proposed surface contamination limits.
There is, however, a substantial contradiction between the definition of "natural uranium" in para. 246 of TS-R-1 [1] and the inclusion of daughter nuclides in footnote (b) of Table I of TS-R-1. Para. 246 defines "natural uranium" as chemically separated uranium, i.e. without the daughter nuclides below U 234:

> *246. Natural uranium shall mean chemically separated uranium containing the naturally occurring distribution of uranium isotopes (approximately 99.28% uranium-238, and 0.72% uranium-235 by mass). ... In all cases, a very small mass percentage of uranium-234 is present.*

while the list of progeny which is to be included with the parent nuclide in footnote (b) of Table I of TS-R-1 defines U-nat (which is supposed to be equal to "natural uranium") as the complete decay chain in secular equilibrium:

> U-nat: Th-234, Pa-234m, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210

This contradiction has been resolved by introducing U-sec (including all progeny down to Po 210) and U-nat in the sense of para. 246, i.e. chemically separated U. In addition, two cases for enriched U (5 % and 20 %), denoted by U-enr-5 and U-enr-20, as well as depleted U, denoted by U-dep, have been defined because the surface contamination limits would be different. For U-nat, U-enr-5, U-enr-20, and U-dep, the total surface contamination is given (as is current practice of U transport), not just the value for the head of the decay chain. This has been done to provide harmonization with the current practice in U transports to always state the total contamination.

4.5. Implications for measurements

When the proposal of the WNTI working group to introduce radionuclide specific surface contamination limits have been discussed in international working groups (for instance, the IAEA CRP, WNTI meetings etc.), one objection has always been raised which is the question whether adoption of radionuclide specific values would incur higher effort for measurements, e.g. the use of spectroscopic techniques. It has been argued that if one has to satisfy a whole list of surface contamination limits (instead of just two integral values), the authorities could (and probably would) demand measurements for all radionuclides for each transport. This is, of course, a severe misapprehension of the difference between radionuclide specific and integral limits and neglects the fact that even in the case of integral limits, one has to know precisely which radionuclides are present in the contamination in order to give meaningful measurement results. This has already been emphasized in the CRP report [4] where it has been called "*a misconception to think ... that radionuclide specific surface contamination levels might lead to extra effort when performing the measurements, even presuming that this would require spectroscopic measurements every time surface contamination measurements are performed*".
The reasons are as follows: Already now, with the two limits (4 Bq/cm² and 0.4 Bq/cm²) only, a correct interpretation of a measurement is possible only with the knowledge of the present radionuclides and their relative contributions. A typical measuring device calibrated for example with Sr 90 will obviously not give a correct readout for Fe 55. So already now it is necessary to determine the radionuclide mixture and to derive for this mixture the readout of the used measuring device, which has to be in compliance with the limits. The same is true for determining the compliance with the new limits. The actual problem to determine the contamination values of weak beta emitters rightly, will even be lessened. Due to their low radiotoxicity they have higher limits C_i (cf. Table I above) and their fractions in the sum $\sum_{i=1}^{n} \frac{c_i}{C_i}$ decreases.

5. Proposal for Changes to TS-R-1

The results of the model as described in section 4 have been used as the basis to propose a totally new approach for the surface contamination limits in TS-R-1 [1]. This proposal has been submitted into the current IAEA review process for the transport regulations.
The basic elements of the proposal are the following:

- Para. 214 needs to be changed to reflect a new definition of contamination ("Contamination shall mean the presence of a radioactive substance on a surface in quantities in excess of 1/10 of the limits listed in Table I, column 6").
- Para. 246 needs to be changed to resolve the discrepancy between the definitions of U-nat and U-sec.
- The following new text should be introduced in Para. 508a: "The non-fixed contamination on the external surfaces of any package shall be kept as low as reasonably achievable and, under routine conditions of transport, shall not exceed the limits listed in Table I, column 6. If a mixture of radionuclides is present, the summation

rule of para 404a has to be applied. These limits are applicable when averaged over any area of 300 cm² of any part of the surface."

- A new column 6 needs to be introduced into Table I which contains the proposed surface contamination limits, as already shown in the excerpt of Table I above.
- There are collateral effects concerning tanks and intermediate bulk containers used for the transport of radioactive material in para. 504, concerning the summation rule mentioned in section 4.3 above (as a new para. 404a), and on a few other places in TS-R-1 where the two values 0.4 and 4 Bq/cm² need to be replaced appropriately. However, the definition of SCO (surface contaminated objects) of para 241 should remain unchanged because this definition is based on a totally different rationale (the scenarios used for SCO definition are briefly described in the Advisory Material to TS-R-1 [2]).

These changes to TS-R-1, if adopted in this or in a revised form, would put one of its key elements, i.e. surface contamination limits, onto a sound radiological basis and would be in line with concurrent approaches in radiation protection.

6. References

[1] International Atomic Energy Agency: Regulations for the Safe Transport of Radioactive Material; 1996 Edition (Revised) No. TS-R-1, Vienna, 2000

[2] International Atomic Energy Agency: Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, Safety Guide TS-G-1.1 (ST-2), Vienna, 2002

[3] A. Fairbairn: The derivation of maximum permissible levels of radioactive surface contamination of transport containers and vehicles; IAEA, Vienna, STI/PUB/32, 1961, p.79 ff.

[4] International Atomic Energy Agency (publ.): The Radiological Aspects of Package and Conveyance Non-Fixed Contamination - Final report of a co-ordinated research project. (to be published)

[5] S. Hughes, S.M. Warner Jones, M.T. Lizot, M.-L. Perrin, S, Thierfeldt, E. Schroedl, G. Schwarz, R. Rawl, M. Munakata, M. Hirose: "A Model to Determine the Radiological Implications of Non-fixed Radioactive Contamination on the Surfaces of Packages and Conveyances"; PATRAM 2004, Conference Proceedings; Berlin, September 2004

[6] International Atomic Energy Agency: International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Standards, Safety Series No. 115-I, Vienna, 1994, ISBN 92-0-101492-9

[7] Council Directive 96/29/Euratom laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation (Basic Safety Standards); Official Journal of the European Communities, ISSN 0378-6978, L 159, Vol. 39, 29.06.1996