Transportation Safety Aspects of Ore and Related Material – Inconsistencies in Current Exemption Values

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ABSTRACT

The IAEA's system for exemption of material from the transport regulations is based on the fundamental principle that exemption values should be commensurate with the risk posed by the material, as represented by effective dose and skin dose. Important departures from that principle as well as inconsistencies between exemption values for different radionuclides have resulted from special provisions for natural materials that depend on their intended use, and from exposure scenarios and other assumptions and rules used in the derivation of exemption values. This paper examines the sources and extent of inconsistencies in exemption values for transport, particularly as they relate to naturally occurring radionuclides, and suggests ways to achieve greater internal consistency in exemption values as well as greater consistency with the fundamental principle underlying the current system.

1. BACKGROUND

Prior to 1996, the International Atomic Energy Agency (IAEA) "Regulations for the Safe Transport of Radioactive Material" [1] defined radioactive material as any material having a specific activity greater than 70 Bq g^{-1}. This provided a convenient guideline for exemption of radioactive material from regulatory control but was not justifiable from the standpoint of radiation protection, because dose from a radioactive source depends not only on its activity concentration but also on the particular radionuclides that it contains.

In the early 1990s the Commission of the European Communities (CEC) developed a dose-based system for exemption of radioactive material from regulation on the basis of its activity concentration or total activity [2]. The guiding principle was that exemption values should be based on the maximum radiation dose that might be incurred from routine or accidental exposure to the material. Exemption values were based on the following dose criteria: the effective dose should not exceed 10 μSv per year and the dose to the skin should not exceed 50 mSv per year for the most exposed individual, and the collective dose commitment should be below 1 man-Sv per year of the practice. Dose calculations underlying the exemption values were based on scenarios addressing exposures to workers at a fixed installation or to members of the public at a landfill site containing discarded radioactive sources. The scenarios and computational methods are described in a CEC report referred to as RP-65 [2].

The principles and exemption values developed by the CEC were adopted by the IAEA in its Basic Safety Standards (BSS, IAEA Safety Series No. 115) [3]. As part of the periodic revision of the transport regulations for radioactive material (TS-R-1) [4], researchers examined whether the exemption values in the BSS were suitable for transport of radioactive material [5]. Using specific transport scenarios, they applied the methods of RP-65 to develop comparative values for a set of representative radionuclides. The transport-specific values were generally lower than the BSS exemption values, but it was concluded that the differences did not warrant a second set of exemption values. Thus, the BSS values were adopted for application to transport.

For many naturally occurring radionuclides the BSS exemption values are considerably more restrictive than the threshold specific activity of 70 Bq g^{-1} formerly applied. For example, the exemption value for U-238 in secular equilibrium with its radioactive progeny corresponds to an activity concentration of about 14 Bq g^{-1} for the full chain, and the exemption value for Th-232 corresponds to about 10 Bq g^{-1} for its full chain. It was recognized that these more restrictive values could have important economic implications because they would bring huge quantities of materials handled in mining and petroleum industries, and previously defined as non-radioactive, into the scope of transport regulations. As a result, the IAEA provided a further exemption for "natural material and ores containing naturally occurring radionuclides which are not intended to be processed for use of these radionuclides provided the activity concentration of the material does not exceed 10 times the values specified in [the table of exemption values]" (Paragraph 107(e), TS-R-1) [4].

While the original intent was to produce exemption values that are commensurate with the radiogenic risk posed by a radioactive material, the exemption system as eventually formulated in the Transport Regulations reflects some important departures from that original principle. This paper discusses the methods and assumptions underlying current exemption values for transport of radioactive material and some resulting inconsistencies in exemption values. Attention is focused on naturally occurring materials because of their industrial importance and because of some particularly large and important inconsistencies in their exemption values. The discussion is restricted to exemption values for activity concentration (rather than total activity) because activity concentration is often the relevant quantity for consideration of natural materials.

2. METHOD OF DERIVATION OF EXEMPTION VALUES

2.1. Exposure scenarios

The authors of RP-65 [2] considered different ways in which non-radiation workers or members of the public are likely to be exposed to small radioactive sources and attempted to establish a manageable set of exposure scenarios that would cover the most common modes of exposure. Attention was narrowed to three general situations: (1) Normal use of sources in the workplace, i.e., use of small amounts of radioactivity in the manner intended, giving rise to chronic exposure. (2) Accidental exposure to a source in the workplace. (3) Exposure to members of the public, either in a normal situation or an accident, after disposal of the source at a landfill.

Several specific scenarios were used to describe potential exposures in each of these three general situations. Scenarios representing normal exposure in the workplace included external exposure from handling a small source or being near a 1-m^3 source or gas bottle, inhalation of dust, or ingestion from contaminated hands. Scenarios for accidental exposure in the workplace addressed different modes of external or internal exposure due to fires or spillage of material. Scenarios for members of the public addressed external exposure from activity in the soil or from handling a radioactive object, inhalation of dust, or ingestion of a radioactive object.

For most (~77%) of the 300 radionuclides addressed, the limiting scenario for activity concentration was external exposure to a worker from a nearby source, either a 1-m^3 cubic source or a gas cylinder. For about 17.5% of the radionuclides, the limiting scenario was chronic inhalation of activity by a worker. For the remaining ~5.5% of radionuclides, the limiting scenario was ingestion of radioactive material by members of the public. The radionuclides limited by inhalation or ingestion scenarios consisted largely of alpha emitters, including the naturally occurring U-238 and Th-232 chains. Neither the inhalation scenario nor the ingestion scenario as formulated in RP-65 is directly relevant with regard to evaluation of hazards from transport of radioactive materials.

2.2 Assumptions concerning radioactive progeny

Many of the radionuclides considered in RP-65 have radioactive decay products (daughters) that need to be taken into account when estimating dose from a source containing the parent radionuclide. In a number of cases, exemption values for parent radionuclides were derived under the assumption that radioactive progeny are in secular equilibrium with their parents. This assumption usually was made in cases where the half-lives of the daughters were sufficiently short relative to that of the parent that equilibrium would be likely within the timescales of the exposure scenarios. Long-lived radioactive progeny were included in some but not all cases, and the reasons for inclusion are not always evident. For some decay series occurring in nature, including the U-238 chain and the Th-232 chain, the exemption value is based on the assumption that the parent is in secular equilibrium with all radioactive progeny, regardless of half-life.

Additionally, the transport regulations use a very different approach for determining when and how progeny are considered in calculating activity limits (the Q system). Footnotes (a) and (b) of Table I in TS-R-1 illustrate the disparity in how the two systems have considered progeny

2.3. Dose calculations

For a given exposure scenario, dose (Sv y^{-1}) to an individual was estimated for an activity concentration remaining at 1 Bq g^{-1} throughout the exposure. Dose was estimated as the product of the exposure time T and a dose coefficient R (dose per unit exposure or per unit intake) taken from published tabulations, with the product TxR scaled by scenario-specific values. For example, in the case of an accident scenario, TxR was scaled to account for the probability of an exposure occurring during the year, with a nominal probability of 0.01 generally applied to limit the worst-case dose to an individual to 1 mSv y^{-1}. The dose coefficients R for inhalation or ingestion used in RP-65 can now be replaced in many cases with values based on updated biokinetic models for radionuclides.

The exemption value for a radionuclide was calculated from the dose estimates for an activity concentration of 1 Bq g^{-1} based on the dose limits described earlier (e.g., effective dose of 10 µSv y^{-1}). That is, the dose limit was divided by the maximum estimated dose from an activity concentration of 1 Bq g^{-1}, considering all scenarios. The calculated exemption values were rounded up or down as follows: If the calculated value fell between 3×10^n and $3 \times 10^{n+1}$, the exemption level was rounded to 10^{n+1}. For example, 6×10^7 rounded to 10^8 and 2×10^5 rounded to 10^5.

Calculated and rounded exemption values for some naturally occurring radionuclides are shown in Table 1, along with the critical scenario for each radionuclide. The radioactive progeny assumed to accompany the parent are listed in a footnote to the table.

Table 1. Dose-based exemption values (activity concentrations) for some naturally occurring radionuclides.

Nuclide[a]	Exemption value (Bq g^{-1})		Limiting scenario in RP-65		
	Calculated (RP-65)	Rounded (RP-65 & IAEA)	Group	Exposure mode	Exposure time
Ra-226+	4.7	10	Public	Ingestion	Acute
Ra-228+	15	10	Worker	External (at 1 m)	100 h y^{-1}
Th-232N	0.85	1	Worker	Inhalation	2000 h y^{-1}
U-238N	1.8	1	Worker	Inhalation	2000 h y^{-1}

[a]Ra-226+ = Ra-226 in secular equilibrium with all radioactive progeny
Ra-228+ = Ra-228 in secular equilibrium with Ac-228
Th-232N = Th-232 in secular equilibrium with all radioactive progeny
U-238N = U-238 in secular equilibrium with all radioactive progeny

2.4. Comparisons with values derived from transport-specific exposure scenarios

As part of the revision of the IAEA transport regulations [4], Carey and coworkers [5] examined whether exemption values derived in RP-65 were suitable for application to transport of material. They developed an alternate set of scenarios, starting with a few RP-65 scenarios judged to be relevant for transport and adding several transport-specific scenarios. The relevant RP-65 scenarios addressed external exposure from relatively small sources and various accident scenarios involving external exposure or intake of radionuclides due to spillage or fires. Additional transport-specific scenarios included a driver transporting bulk material in a truck or van, a worker loading bulk material into a truck or van, a worker cleaning a truck in which bulk material had been carried, a postman or courier delivering a package after carrying it during a delivery round, and a traveler externally exposed from material carried in the hold of an aircraft.

For 20 representative radionuclides, Carey and coworkers [5] compared exemption values based on the transport scenarios with values derived in RP-65. As illustrated in Table 2, the transport scenarios yielded more restrictive exemption values in most (18/20) cases, usually due to longer exposure times and/or larger masses and volumes of material in the transport-specific scenarios. For example, for many gamma emitters the limiting scenario for activity concentration in RP-65 is external dose to a person assumed to be exposed for 100 h at a distance of 1 m from a source with volume 1 m^3. For these same radionuclides, the truck-driver scenario may yield a 10- to 20-fold higher dose estimate due to a combination of a four times greater exposure time (400 h) and a much larger mass of material (21 m^3) presenting a wider angle of exposure. However, when compared with some values reported in the literature [6], these assumed parameters may be very conservative.

The transport-specific dose estimates were dominated by three scenarios. External dose to a truck driver transporting bulk material was the limiting scenario for 60% (12/20) of the radionuclides addressed. For 20% (4/20) of the radionuclides, the activity concentration was limited by multiple-pathway exposure (external, inhalation, and ingestion) to a worker cleaning a truck used to haul bulk quantities. For the remaining 20% (4/20), the activity concentration was limited by external exposure from being close to and handling packages. For naturally occurring radionuclides, the truck-driver scenario is the critical scenario except in the case of Th-232N, for which the truck-cleaner scenario gives a marginally lower unrounded exemption value (Table 3).

Table 2. For selected radionuclides, comparison of exemption values (activity concentrations) based on transport-specific scenarios with exposure scenarios applied in RP-65 (values from [5]).

Radionuclide	Exemption value (Bq g^{-1})		Ratio
	RP-65 scenarios	Transport scenarios	RP-65:Transport
C-14	18,000	33,000	0.55
K-40	100	5.4	19
I-131	54	2.5	22
Cs-137+	30	1.7	18
Ra-226+	4.7	0.50	9.4
Th-232N	0.85	0.31	2.7
U-238N	1.8	0.49	3.7

Table 3. Comparison of exemption values (activity concentrations) for naturally occurring chains, derived from truck driver and truck cleaner scenarios (values from [5]).

Radionuclide	Derived exemption values (Bq g^{-1})	
	Truck driver	Truck cleaner
Ra-226+	0.496	5.15
Th-232N	0.344	0.313
U-238N	0.493	0.780

3. DISCUSSION

The current IAEA system for exemption of material from regulatory control was originally intended to produce a uniform and consistent dose basis for exemption of materials. Between its conception and its eventual application in the Transport Regulations, however, a number of inconsistencies crept into the system. Two sources of inconsistency are particularly important for naturally occurring materials.

First, TS-R-1 [4] includes a special provision that increases the exemption value by an order of magnitude for naturally occurring materials, provided they are not intended to be processed for recovery of radionuclides. Dependence of the exemption value on the anticipated use of the material is an important departure from the principle that values should be exempted on the basis of the hazard they pose. In the case of transport of bulk quantities of uranium- or thorium-bearing materials, for example, the most exposed individual is typically a truck driver, and the truck driver's dose is unrelated to the expected use of the material being transported.

Second, relative exemption values for different radionuclides often do not reflect the relative potential doses associated with actual transport practices because the values are limited by exposure scenarios that are not relevant to transport. Use of specific transport scenarios such as those described by Carey and coworkers [5] for derivation of exemption values would provide a more consistent set of values as well as an improved technical basis for derived values because they are based on observations of common tasks and situations actually encountered in transport of radioactive material. For example, the scenario involving a truck driver transporting bulk quantities of material is based in reality, and theoretical estimates of the external dose rate to a truck driver transporting bulk quantities of U-238N or Th-232N are consistent with measured values [6].

Other factors have contributed to inconsistencies or technical weaknesses in exemption values. For example, the practice of rounding calculated exemption values to a power of 10 may lead to order-of-magnitude differences in values for radionuclides with similar estimates of dose. The basis for inclusion or exclusion of radioactive progeny from the derivation of an exemption value for a parent radionuclide is not always apparent. Finally, the technical basis for exemption values can now be strengthened by the application of updated dose coefficients that are generally based on more consistent and realistic models and assumptions than those applied in RP-65.

As an illustration of the sources and potential magnitude of inconsistencies in exemption values, we consider a hypothetical situation in which two companies transport different materials containing naturally occurring radionuclides:

> Company A transports material containing Ra-226+ (Ra-226 in equilibrium with its daughters) to be dumped in a landfill. Company B transports material containing U-238N (U-238 in equilibrium with its daughters) to be used for recovery of its radionuclides. The derived exemption values based on the methods of RP-65 together with the transport scenarios described by Carey and coworkers [5] are virtually identical for the two materials (0.493 Bq g^{-1} for U-238N and 0.496 Bq g^{-1} for Ra-226+) because, in both cases: (1) the limiting scenario is external exposure to the truck driver, and (2) nearly 100% of the external dose to the truck driver is from Ra-226+, which is also present in U-238N. In a uniformly dose-based system, the exemption value for activity concentration would be the same for both materials.
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> The actual exemption values, i.e., those given in TS-R-1 [4], are based on the scenarios in RP-65 rather than transport-specific scenarios. The calculated exemption values in RP-65 for Ra-226+ and U-238N are not far apart: 4.67 Bq g^{-1} for Ra-226+ based on ingestion by a member of the public, and 1.83 Bq g^{-1} for U-238N based on inhalation by a worker. However, application of the rounding rule described earlier leads to upward rounding to 10 Bq g^{-1} for Ra-226+ and downward rounding to 1 Bq g^{-1} for U-238N.
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> Because the material transported by Company A is not intended to be processed for recovery of its radionuclides, the rounded exemption value of 10 Bq g^{-1} is further increased by a factor of 10, to 100 Bq g^{-1}. The exemption value for material transported by Company B remains at 1 Bq g^{-1} due to the intended use of the material.

Thus, in the above illustration, exemption values differing by two orders of magnitude would be applied to two materials that emit the same types and energies of radiation and deliver the same dose per unit activity concentration to the person presumed to receive the highest dose.

4. CONCLUSIONS

The combination of using RP-65 based exemption values, applying the rounding rules, and limiting the exemption in paragraph 107(e) of TS-R-1 [4] to only certain materials, creates a significant inconsistency in the exemption provisions. If the exemption provisions are to be risk-informed, they should be based on dose implications, not on the intended use of the material being transported. Consequently, allowing a 10-fold increase in the exemption values for natural material and ores containing naturally occurring radionuclides should be applied to all such material regardless of their intended purpose.

The inconsistent way in which progeny are taken into account in the transport regulations deserves further consideration. Consistent, transparent rules for inclusion of radioactive progeny should be applied in both the Q system and the derivation of exemption values.

4. REFERENCES

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