Journal of Sustainable Mining 18 (2019) 31–37

Contents lists available at ScienceDirect

Journal of Sustainable Mining

journal homepage: www.elsevier.com/locate/jsm

Research paper

Discharges of dust from NORM facilities: Key parameters to assess effective doses for public exposure

Christian Kunze[a,*], Hartmut Schulz[a], Eckard Ettenhuber[a], Astrid Schellenberger[a], Jörg Dilling[b]

[a] IAF-Radioökologie GmbH, Wilhelm-Rönsch-Str. 9, D-01454, Radeberg, Germany
[b] Bundesamt für Strahlenschutz (Federal Office for Radiation Protection), Köpenicker Allee 120-130, D-10318, Berlin, Germany

ARTICLE INFO

Keywords:
NORM
Dust discharge
Public exposure
High temperature processes
Atmospheric dispersion model

ABSTRACT

In transposing Directive 2013/59/Euratom (European Basic Safety Standards or EU BSS) into national law, it was necessary to identify industrial sectors which involve naturally occurring radioactive materials (NORM) which may lead to public exposure that cannot be disregarded from a radiation protection point of view. A research project was implemented that resulted in a comprehensive survey of all potentially relevant industrial sectors operating in Germany. Major efforts were made to determine source terms of airborne discharges, atmospheric dispersion models, and dose calculations.

The study arrived at the conclusion that the discharge and the settlement of dust in agricultural and horticultural areas is the most relevant dispersion and exposure pathway, while discharges of radon are of minor importance.

The original study used a number of rather complex models that may distract from the fact that very few key parameters and assumptions determine the effective dose of members of the public. This paper revisits the study and identifies those parameters and assumptions and provides a simplified, generic, yet sufficiently reliable and robust assessment methodology to determine the radiological relevance of dust discharges from NORM industries under the typical geographical and meteorological conditions of Germany.

This paper provides examples of dose estimates for members of the public for selected industries operating in Germany. Due to its simplicity and robustness, the methodology can also be used to assess effective doses resulting from discharges in other industries in Germany, and it can be adapted to conditions in other countries in a straightforward way.

1. Introduction

Council Directive 2013/59/Euratom (European Council, 2013, pp. 1–73), commonly referred to as European Basic Safety Standards or EU BSS, has removed the previous distinction between practices and work activities. Henceforth the dose limits for public exposure shall apply for the sum of the annual exposure for members of the public resulting from all authorized practices, according to Art. 12 of the EU BSS. In transposing BSS into national law, Art. 23 requires Member States, *inter alia*, to identify classes or types of practice involving naturally-occurring material (NORM), i.e., industrial sectors commonly but not entirely correctly referred to as “NORM industries” that may need to be regulated because they lead to exposure to members of the public that cannot be disregarded from a radiation protection point of view. Discharges are an aspect of practices and, therefore, may be subject to regulatory control.

In transposing the EU BSS into national law, the Federal Office for Radiation Protection in Germany launched a research project to identify the industrial sectors involving NORM covered by Art. 23. This project resulted in a comprehensive survey (Kunze, Ettenhuber, & Schellenberger, 2018) involving source terms of airborne discharges, atmospheric dispersion models, and dose calculations. Its approach and main findings are briefly summarised in Section 2. It should be noted that the exposure of workers due to practices involving NORM, which is also covered by Art. 23 of the EU BSS, is beyond the scope of the survey (Kunze, Ettenhuber, & Schellenberger, 2018) and, hence, this paper.

It is important to note that the study (Kunze, Ettenhuber, & Schellenberger, 2018) deliberately avoided a site-specific analysis, but adopted a generic approach, i.e. covering a wide range of situations that may typically be encountered in Germany, in terms of source terms and environmental dispersion conditions. The dose estimates for the industrial sectors from Annex VI of the EU BSS that are operating in

---

[*] Corresponding author.
E-mail addresses: kunze@iaf-dresden.de (C. Kunze), jdilling@bfs.de (J. Dilling).

https://doi.org/10.1016/j.jsm.2019.02.002
Received 24 December 2018; Received in revised form 5 February 2019; Accepted 7 February 2019

Germany serves as guidance to lawmakers and regulatory authorities on whether regulatory control of those sectors would, in principle, be warranted within a graded approach, and whether any of those sectors should be included in a “White List” of potentially relevant industrial sectors, similar to Annex VI of the EU BSS, referred to in Art. 23 of the EU BSS.

Concerning the dust pathway, the study (Kunze, Ettenhuber, & Schellenberger, 2018) employed rather complex models that may distract from the fact that very few key parameters and assumptions dominate the results. More details on this study have been published elsewhere (Kunze, Ettenhuber, Schellenberger, & Dilling, 2018). The present paper revisits the study and summarises key parameters and assumptions.

Section 3 explores whether a simple, multiplicative approach using a few key parameters could be developed in order to estimate the order of magnitude of effective doses for members of the public, resulting from dust-borne discharges from NORM facilities.

In Section 4, dose estimates using the generic approach are carried out for four industrial sectors with significant dust emissions operating in Germany:

- Cement production
- Primary iron production
- Lead smelters
- Coal-fired power plants.

In addition to a base case that reflects the average plant size and dust discharges typical for the respective sector, a plausible distance of the receptors from the source of the discharge (chimney) and average meteorological conditions prevailing in Germany, Section 4 also provides the results of sensitivity analyses under very conservative assumptions.

Section 5, finally, summarises the findings and puts them in perspective with respect to the provisions adopted in the new Radiation Protection Law of 2017 that implements the EU BSS in the German legal and regulatory framework.

It is noted that discharged dust from material storage and handling, maintenance of boilers, dust filters etc., and of radon were found in (Kunze, Ettenhuber, & Schellenberger, 2018) to be of minor importance in the overall picture of NORM industries operating in Germany, and therefore will not be considered further in this paper. The remainder of this paper focuses on discharges from high-temperature processes.

2. Summary of the approach and main findings of the dose estimate for discharges from NORM industries in Germany

2.1. Overview

The survey of discharges from NORM industries in (Kunze, Ettenhuber, & Schellenberger, 2018) was structured as follows:

- Determination of the source term of the discharges, expressed in Bq per year, and identification of the typical radionuclide vector of the discharges.
- Development of a numerical, Lagrangian particle trajectory model.
- Development of a dose model that links the deposition rate of the radionuclides to the effective dose of the representative person.

The following sub-sections will summarise the approach to each of these steps.

2.2. Source terms of the discharges

Based on the “White List” of industrial sectors in Annex VI to the EU BSS and a tentative list of additional industrial sectors that were known to be operating in Germany, a survey was carried out to identify those sectors that are currently using, or in the foreseeable future may be expected to use, raw materials of increased natural radioactivity, so that significant discharges may be predicted.

For sectors that passed an initial screening stage with respect to their discharges, attempts were made to estimate activity source terms in more detail. In the case of dust-borne discharges of natural radionuclides, the estimates of source terms were based on one of the following or a combination thereof:

- Data on emissions of natural radioactivity, either from published sources or using company information. However, such data was very hard to obtain.
- Data in the public domain on dust settling rates ($g/m^2/s$) or activity deposition rates ($Bq/m^2/s$) from environmental monitoring programs. Emission rates were estimated using a reverse modelling approach. If only dust settling rates were known, assumptions on the activity concentration of the dust particles had to be made.
- Raw material input and activity concentration of the raw material, under the assumption that in high-temperature processes all input activity of volatile nuclides such as Po-210 is transferred to dust. This approach requires knowledge on the retention rate of the dust filter. Dust retention rates between 95 and 99% are realistic in modern filters: for lead smelters (European Commission. European IPPC Bureau, 2014), for cement production (European Commission. European IPPC Bureau, 2013), for primary iron production (European Commission. European IPPC Bureau, 2012), and for coal-fired power plants (European Commission. European IPPC Bureau, 2016).

As will be shown in sub-section 2.4 below, the most dose-relevant nuclides are Po-210 and, to a lesser extent, Pb-210. This is due to the high dose conversion factors of these two nuclides and the fact that the NORM industries with significant dust discharges all involve high-temperature processes in which nuclides of volatile elements, such as polonium and lead, are preferentially redistributed from the combustible or raw materials into the dust stream.

Table 1 shows the results of the survey in (Kunze, Ettenhuber, & Schellenberger, 2018) for selected sectors involving high-temperature processes.

Table 1
Estimated source terms for Po-210 and Pb-210 from high-temperature processes, average plant capacity.

Sector	Production/generation capacity	Discharge of Po-210, GBq/a
Cement production	0.7 Mt/a	1.0
Power plants (hard coal)	1 GW_{el}	2.4
Primary iron production	5 Mt/a	7.5
Lead smelting	0.1 Mt/a	0.5

2.3. Atmospheric dispersion model

For the numeric modelling of the atmospheric transport of dust and radon the code ARTM (Atmospheric Radionuclide Transport Model (Federal Office for Radiation Protection, 2018)) was used. ARTM is based on Lagrange trajectories of unit air volume elements. It includes dry and wet deposition and takes into account radioactive decay along the trajectory. A comprehensive description of the ARTM code can be found in (Hettrich, 2017). The model requires time-resolved meteorological data and, unless flat topography is assumed, a digital topographical model (DTM).

The survey of NORM industry sectors was deliberately generic, i.e., not site-specific. The key question was to identify industry sectors whose discharges may lead to effective doses for the public, which cannot be disregarded from a radiation protection point of view, under a wide range of typical topographical and meteorological conditions prevailing in Germany. The German Meteorological Service (DWD) provides so-called TRY (Test Reference Year) model datasets that represent average weather conditions over the course of one year in 1-h time steps (German Meteorological Service, 2017). At the time of writing, TRY datasets were available for 15 characteristic regions in Germany.

Atmospheric dispersion models were run to obtain dust deposition rates, expressed in g/(m^2 a), in each of the 15 TRY regions. The activity deposition rate is simply calculated by multiplying the nuclide-specific activity concentration of the dust particles.

2.4. Dose model

In order to estimate doses resulting from discharges of dust (in addition to the exposure to the natural background, including as radon and direct radiation), the following exposure pathways were considered:

- Ingestion of food impacted by dust settlement, including the following:
  - Dust settlement on plants that are consumed directly, including:
    - Crops (including cereals),
    - Fruits and vegetables (including juices),
    - Leafy vegetables (salad).
  - Dust settlement on plants used as fodder by dairy and beef cattle,
- Transfer from milk into dairy products and into breast milk, and consumption of milk, dairy products and breast milk.

The activity concentration a_n of a plant resulting from dust settlement has been calculated according to the following formula (Federal Office for Radiation Protection of Germany, Department of Radiation Protection and Environment, 2011):

$$a_{n,p} = D_n \frac{1 - \exp(\lambda_{n,p}\, t_p)}{Y_p \lambda_{n,p}} \tag{1}$$

where

a_n is the activity concentration of nuclide n in Bq/kg,
D_n is the activity deposition rate in Bq/(m^2 s) of nuclide n,
Y_p is the yield of plant species in kg/m^2 per vegetation period, see (Federal Office for Radiation Protection of Germany, Department of Radiation Protection and Environment, 2011) for numerical values,
$\lambda_{n,p}$ is the effective residence coefficient of a nuclide n on a plant of species p, which can be approximated by 5.7E-7 s^{-1} for the food and fodder plants considered,
t_p is the time over which dry or wet deposition takes place during a vegetation period (2.6E6 s or 5.2E6 s, depending on plant species p).

Using age-specific consumption rates of various foodstuffs that are typical for nutrition habits in Germany (Federal Office for Radiation Protection of Germany, Department of Radiation Protection and Environment, 2011), Fig. 1 shows the effective dose resulting from the ingestion of various foodstuffs linked with food and fodder plants, assuming the deposition of dust with a unity activity concentration of each nuclide of the U-238 series of 1 Bq/g, at a deposition velocity of 1 cm/s. The representative person is an infant (age group < 1 a), since dose conversion factors of the relevant nuclides are higher than in all other age groups, which also outweighs the lower food consumption rates. The dose coefficients of the nuclides considered here for infants are shown in Table 2 below.

Deposition of dust in agricultural and horticultural areas and the subsequent consumption of vegetables, fruit, milk and dairy products are the most relevant pathways that dominate over other dispersion and exposure pathways that are usually taken into account in dose calculation guidelines (Federal Ministry of the Environment and Reactor Safety, Germany, 2012; Federal Office for the Radiation Protection of Germany, the Department of Radiation Protection and Environment, 2011), by at least one order of magnitude, such as inhalation of dust, soil contamination by dust and uptake of radionuclides by plant roots, ingestion of contaminated soil, exposure to gamma and beta emitting dust particles deposited on the soil or in the dust cloud.

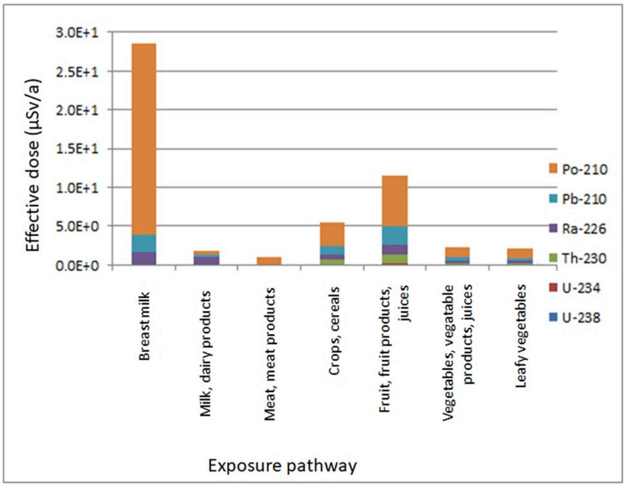

Fig. 1. Nuclide-specific contributions to the effective dose resulting from the direct or indirect ingestion of various foodstuffs contaminated at a unit deposition rate of 1 Bq/(m^2 a).

Table 2
Ingestion dose coefficients of relevant nuclides for infants (age group < 1 a).

Nuclide	Ingestion dose coefficient, µSv/Bq
U-238	0.34
U-234	0.37
Th-230	4.1
Ra-226	4.7
Pb-210	8.4
Po-210	26

It should be noted that the natural background, such as the radionuclide contents of the soil or the deposition of excess Pb-210 (resulting from the decay of Rn-222 in the atmosphere), is not considered here as this study is only interested in doses that are in addition to the natural background.

From the discussion above, Po-210 can be identified as the key nuclide with the highest relative contribution to public exposure among the natural radionuclides considered. This is due its high dose conversion factor (see Table 2) and to the fact that virtually all relevant dust emissions occur from high temperature processes, such as smelting or coal combustion, in which Polonium with a boiling point of 962 °C is volatilised. Pb-210 is also volatile in high-temperature processes, but to a lesser degree due to its higher boiling point (1744 °C).

It also follows from Fig. 1 that, for the generic approach that is discussed here, Pb-210 is of minor importance in comparison to Po-210, despite the fact that it is also present in the discharges of dust from high-temperature processes. In comparison with Po-210, all other nuclides of the U-238 series can be neglected as far as dust emissions from high-temperature processes are concerned.

Taking into consideration all exposure pathways and the associated consumption rates as described in detail in (the Federal Office for Radiation Protection of Germany, the Department of Radiation Protection and Environment, 2011), a deposition rate of 1 Bq/(m^2 a) of Po-210 in agricultural land leads to an aggregate effective dose of 38

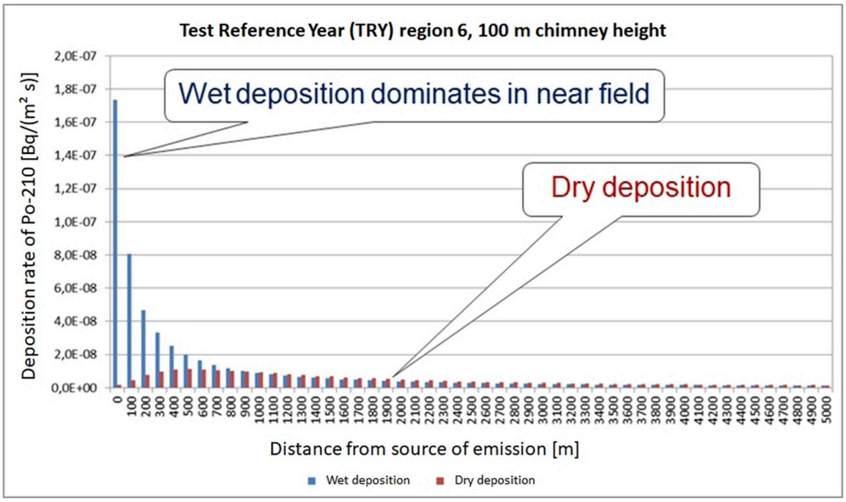

Fig. 2. Example of wet and dry activity deposition rate resulting from a unit source strength of 1 GBq/a. The deposition rates are shown along a radius in the main wind direction.

μSv/a in infants (age group “ < 1 year”) for all exposure pathways involving the ingestion of foodstuffs discussed above. This conversion factor between the deposition rate of Po-210 and effective dose via a series of food ingestion pathways will also be used in the simplified approach described in Section 3.

2.5. *Summary of findings of the survey (Kunze, Ettenhuber, & Schellenberger, 2018)*

The study arrived at a series of conclusions that are summarised below:

- Under typical West European meteorological conditions, the numeric transport model clearly shows that within a distance of five times the chimney height, wet deposition outweighs dry deposition by at least a factor of three (see Fig. 2). Wet deposition is largely independent of the chimney height.
- Extensive sensitivity analyses were carried out in order to determine whether the effective dose depends critically on the meteorological conditions or facility-specific parameters, such as chimney height or topographical setting. Within the typical ranges of meteorological conditions prevailing in Germany, the wet deposition rate of dust does not significantly (i.e., beyond an order of magnitude) depend on wind speed and directional distribution, nor on the chimney height.
- Industrial facilities (power plants, metallurgical plants etc.) are usually located on fenced premises. There is a correlation between the production capacity, the footprint of a facility, and the height of the chimney. A GIS-based survey using a random sample of facilities in the coal combustion, iron smelting, and cement industries has shown that it is realistic to assume that the distance between the source (chimney) and the point of impact (horticultural use, gardens) is at a radius of at least four times the chimney height.
- Therefore, the representative person, i.e., “the individual receiving a dose that is representative of the more highly exposed individuals in the population” (European Council, 2013, pp. 1–73), is an infant (age group < 1 a) living at a realistic minimum distance from the point of discharge, i.e., four times the chimney height, and in the preferential direction of the wind field.

In view of these findings, one may ask whether a simple model using only a few key parameters can be developed as a robust screening tool for discharges of dust from NORM facilities to estimate the order of magnitude of the effective doses for members of the public and thus potential radiological relevance of the NORM industry sector. This question will be addressed in the next section.

3. Simplified methodology to estimate the effective doses to members of the public from dust emissions

Based on the results of Section 2 that show that the wet deposition of the dust dominates the deposition rate, the three-dimensional numerical model of the transport of dust in the atmosphere can be reduced to a two-dimensional analytical expression, see Fig. 3.

The wet deposition rate D of dust-borne at a point is proportional to the areal activity concentration $\hat{c}$ (in Bq/m^2) at that point (i.e., the total amount of dust in a vertical column of air from the ground into infinite height, divided by the cross section of the column), and to the annual precipitation I (in mm/a). The proportionality factor is an empirical quantity that depends on rainfall duration characteristics. In the case of Germany, the proportionality factor is equal to $0.19\,\mathrm{mm}^{-1}$, see Appendix 7 of (the Federal Ministry of the Environment and Reactor Safety, Germany, 2012):

$$D\ [\mathrm{Bq/(m^2a)}] = \hat{c}\ [\mathrm{Bq/m^2}]\ I\ [\mathrm{mm/a}]\ \ 0.19\ \mathrm{mm}^{-1} \tag{2}$$

In a wind field of homogeneous angular distribution of wind

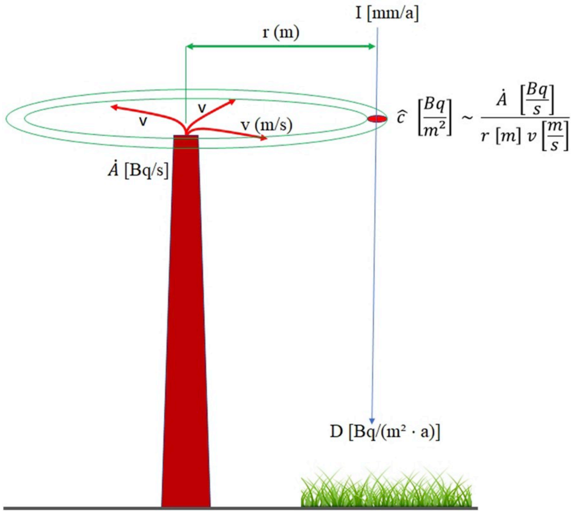

Fig. 3. Schematic of the simplified two-dimensional model of dispersion and wet deposition.

Table 3
Estimated source terms for Po-210 and Pb-210 from high-temperature processes for an average plant capacity, and effective doses calculated from the 2d model. Results from the ARTM model (last column) for comparison.

Sector	Production or generation capacity of an average facility	Simplified approach using a 2d dispersion model				For comparison: source term and effective dose according to (Kunze, Ettenhuber, & Schellenberger, 2018)	
		$\dot{M}$ [kg/s]	C_{raw} [Bq/kg]	$\dot{A}$ [Bq/s] $\dot{M}\, C_{raw}$	H_{eff} [µSv/a]	$\dot{A}$ [Bq/s]	H_{eff} [µSv/a] ARTM
Cement production	0.7 Mt/a	22	40	26.4	17	8.9	9.9
Power plants (hard coal)	1 GW_{el}	42	25	31.5	20	43.1	52
Primary iron production	5 Mt/a	158	50	237	146	270	350
Lead smelting	0.1 Mt/a	1.6[a]	100	4.8	3	9.5	12

[a] For an annual production of 0.1 Mt of lead, 50,000 t of ore concentrate with 60% Pb content and 100,000 t of recycled lead are processed. Only ore concentrate contributes substantial radioactivity of 100 Bq/kg, while the recycled lead is virtually free of radioactivity.

directions, the areal density of dust $\bar{c}$ follows from mass conservation. The source strength of the activity emission $\dot{A}$ [Bq/s] must be equal to the mass flow rate of dust that is radially "torn apart" by the wind field into concentric rings of radius r around the source:

$$\hat{c} = \bar{c}\,[\mathrm{Bq/m^2}] = \dot{A}\,[\mathrm{Bq/s}]\ \frac{1}{2\pi\, r\ [\mathrm{m}]\ v\ [\mathrm{m/s}]} \tag{3}$$

where v is the average wind speed at the altitude of the chimney tip.

In an inhomogeneous statistical distribution of wind directions, the areal activity concentration $\hat{c}$ in the preferential wind direction is higher than the average $\bar{c}$. For this study, we carried out statistical evaluation of wind fields in the 15 TRY regions of Germany. In conclusion it could be shown that $\hat{c} = 1.4\bar{c}$ and $\hat{c} = 2.3\bar{c}$ hold for regions with the most even distribution of wind directions, and those with a pronounced preferential wind direction, respectively (Kunze, Ettenhuber, & Schellenberger, 2018). Therefore, $\hat{c} = 2\bar{c}$ is a reasonable approximation for the purposes of a generic assessment.

The dust-borne activity source strength $\dot{A}$ of a high-temperature process can in good approximation be derived from the mass flow $\dot{M}$ of raw material or fuel, multiplied by its activity concentration C_{raw}, and adjusted by the retention F of the dust filters. This is justified by the fact that the temperature of most industrial combustion and smelter processes is considerably higher than the boiling point of inorganic Polonium compounds (962 °C), so that virtually all Po-210 is volatilised. It should also be noted that in most raw materials, the nuclides along the decay chains are in equilibrium, so that the activity concentration of U-238 can be used as proxy for the activity concentration of Po-210.

From the range of retention rates (95–99 per cent, see above), $F = 97\%$ was found to be a reasonable assumption for generic estimates (Kunze, Ettenhuber, & Schellenberger, 2018), unless specific retention rates are available.

The radioactivity source term can be written as

$$\dot{A}\,[\mathrm{Bq/s}] = \dot{M}\,[\mathrm{kg/s}]\ C_{raw}\,[\mathrm{Bq/kg}](1 - F) \tag{4}$$

If the representative person is located from the source at a distance of four times the height of the chimney h [m], which is discharging the dust-borne activity, as explained above, i.e., $r = 4\,\mathrm{h}$, and using the above-mentioned effective dose of the representative person per unit activity deposition rate of 38 µSv/a per Bq/(m^2 a) that was derived in Section 2.4 above, the effective dose H_{eff} is finally obtained:

$$H_{eff}\,[\mu Sv/a] \cong \dot{M}\,[\mathrm{kg/s}]\ C_{raw}\,[\mathrm{Bq/kg}](1 - F)\frac{0.19\ \mathrm{mm^{-1}}}{4\,\pi\, h\ [\mathrm{m}]\ v\ [\mathrm{m/s}]} I\ [\mathrm{mm/a}]\ \frac{38\ \mu Sv/a}{\mathrm{Bq/m^2a}} \tag{5}$$

If the activity source term of the Po-210 discharge is known, e.g., from emission or source monitoring, the first three factors can be replaced by the activity discharge in Bq/s.

It should be noted that due to the fact that wet deposition is the dominating deposition mode, the effective dose estimated in (4) is independent of many parameters that are relevant for dry deposition rates but may often be hard to come by, including the following:

- Particle deposition velocity which is strongly dependent on particle size.
- Topographical setting, shading effects by buildings and other geometrical obstacles.
- Distribution of the meteorological stability class.

4. Results

In order to estimate the effective dose for facilities in industrial sectors listed in Annex VI of the EU BSS and involving dust emissions from high temperature processes that are operational in Germany, Formula (4) is applied using typical plant sizes in terms of raw material or fuel consumption. The input data and results are shown in Table 3. For simplicity, the chimney height was assumed to be 100 m for facilities of all sectors, the filter retention rate was uniformly assumed to be 97%, and the average annual precipitation in Germany to be 850 mm. At a 100 m chimney height, the average wind speed is approximately 4 m/s.

Comparing the last two pairs of columns of Tables 3 and i.e., the effective doses calculated from the simplified 2d model presented in this paper, and the full 3d Lagrange model used by ARTM, it can be concluded that both results are in the same order of magnitude.

The differences between the results of the detailed study (Kunze, Ettenhuber, & Schellenberger, 2018) and the simplified approach presented here result mainly from using different source terms of the radioactive discharges, and to a certain extent from differences of the 2d and 3d atmospheric dispersion and dust deposition models:

The survey (Kunze, Ettenhuber, & Schellenberger, 2018) used literature data on the discharges of Pb-210, Po-210 and, occasionally, other natural nuclides, from NORM industries. As well as the general scarcity of published information, some of the literature data was inconsistent and/or incomplete, and therefore had to be complemented by plausible assumptions where necessary. For atmospheric dispersion and deposition modelling, generic meteorological datasets were used in a Lagrangian particle trajectory model.

By contrast, the simplified model presented in this paper starts from the assumption that Po-210 dominates both the discharges (due to its lower boiling point) and the dose calculations (due to its high ingestion dose coefficient). Neglecting the contribution of Pb-210 and other nuclides leads to a minor underestimation of the effective dose. The simplified model also assumed that the entire activity of Po-210 entering an industrial process with raw materials or fuel is volatilised by the high process temperatures and held back by filters with a defined retention rate. This leads to an overestimation of the effective doses.

Note that the dose model itself, linking the deposition rate of radionuclides in agricultural areas to the effective dose in the ingestion pathway, is the same in both approaches.

Sensitivity analyses of the results in Table 3 are necessary to cover a range of realistic dose estimates. They may include variations of the following parameters:

- Activity source strength $\dot{A}$: The figures for $\dot{M}$ and C_{raw} of the base case shown in Table 3 may be increased by 50% each to reflect a realistic range of situations, both regarding production capacity and the activity concentration of the raw materials. The retention rate of the dust filters in the sectors discussed above that are commonly used in Germany typically varies between 95 and 99 per cent. The conservative assumption of 95 per cent would result in an increase by a factor of 2 compared to the base case of 97 per cent. A simultaneous increase of $\dot{M}$ and C_{raw} by 50% each and a decrease of the filter retention from 97 to 95 per cent would result in a factor of 3.75 to be applied to the base case results in Table 3.
- The annual rainfall I may be increased by a factor of 1.5 to cover wet regions of German with annual precipitation of 1200–1300 mm, e.g., in parts of highly industrialised North Rhine Westphalia and the Upper Rhine Valley in Baden Württemberg (Federal Ministry of the Environment, Nature Protection and Nuclear Safety, 2018).
- While a minimum distance r of agricultural/horticultural areas of four times the chimney height h was found to be a realistic assumption for most industrial facilities, a conservative approach may suggest a shorter distance of twice the chimney height.

If all parameter variations described above are applied simultaneously, the results from Table 3 increase by a factor of 11.25. A summary of the results for the four industrial sectors considered above is shown in Table 4:

Table 4 shows that even under very conservative assumptions the effective doses for the representative person resulting from the discharge of dust are relatively small, with the possible exception of raw iron production.

Other sources of uncertainty include, but may not be limited to, the following:

- Dry deposition (which in itself carries large uncertainties, such as deposition velocity that depends on particle size) is neglected by the 2d model presented in Section 4. At larger distances from the source, the relative importance of dry deposition increases, as can be seen from Fig. 2.
- In wind fields with a pronounced preferential wind direction, the assumption $\hat{c} = 2\bar{c}$ may not hold.

In summary, applying the uncertainties of all parameters to the dose estimate shows that the generic approach allows the effective dose to the order of magnitude to be determined. This is fully sufficient for the purpose set out in the introduction above, namely to generically identify industry sectors that may potentially subject to further regulatory control, and conversely single out, sectors that can be safely neglected from a radiation protection point of view.

5. Conclusions

In order to estimate the effective dose incurred by the representative person caused by dust-borne emissions of natural radioactivity from high-temperature processes, a relatively simple and robust approach has been developed. It is based on the fact that wet deposition dominates the atmospheric transport in the proximity of a source, i.e., where the highest doses may be expected. Generic examples of four NORM industries listed in Annex VI of the EU BSS (cement production, coal fired power plants, primary iron production and lead smelting) are considered to demonstrate the application of the simplified approach. It was found that in a base case, which describes the average production capacity of a facility under typical meteorological prevailing in Germany, effective doses for any of the sectors considered do not significantly exceed 100 μSv/a or are even well below that mark. The contributions to the effective dose result mainly from dust deposition in agricultural and horticultural areas. Under very conservative assumptions for the source strength, the distance between source and impacted areas, and rainfall, the effective dose for raw iron production reaches values in the order of 1 mSv/a, while it remains well below 200 μSv/a for the other three sectors.

One of the reasons for the relatively low effective doses resulting from discharges of dust is the industry's compliance to strict regulatory limits on air-borne discharges, such as efficiency requirements of dust filters that were introduced into the regulatory framework independent of radio-ecological considerations.

These findings from the generic approach confirm the results of an earlier study (Kunze, Ettenhuber, & Schellenberger, 2018) using a more comprehensive Lagrange trajectory model (ARTM) to describe atmospheric transport of dust-borne natural radionuclides. It must be noted that there are several parameters that may vary, leading to significant overall uncertainty of the model results. As can be seen from Table 4, the range of results varies by a factor of more than 10 if all input parameters are varied within their range of uncertainty.

Referring to the objective of the research, i.e., to provide guidance to lawmakers and the authorities on whether any of the sectors contained in Annex VI of the EU BSS should be included in a “White List” according to Art. 23 of the EU BSS, the results have shown that this is not warranted for any of the sectors considered above. In fact, this finding is reflected by the new German Radiation Protection Law of 2017 (Bundesgesetzblatt, 2017) that transposes the EU BSS into German law, and in the official Explanatory Notes on the Radiation Protection Law (Deutscher Bundestag, 2017) stating that the exposure of members of the public to discharges from NORM activities are below the significance threshold that would warrant regulatory control.

It must be emphasised that the approach presented in this paper and in the more comprehensive study (Kunze, Ettenhuber, & Schellenberger, 2018) is generic and neither considers plant-specific nor site-specific conditions. Topographical or meteorological conditions that deviate significantly from the generic assumptions made above may lead to different results; detailed calculations are required for site-specific considerations, such as permitting.

Finally, it should be noted that this study was prepared for NORM industries in Germany. Other conditions may prevail in other countries,

Table 4
Parameter variations to cover a realistic range of effective doses.

Sector	Factor of conservative variation of parameters			Conservative estimate for H_{eff} [μSv/a]
	Source strength $\dot{A}$	Rainfall I	Distance r	
Cement production	3.75	1.5	0.5	183
Power plants (hard coal)				221
Primary iron production				1630
Lead smelting				32

regarding atmospheric dispersion conditions, exposure pathways (consumption habits) and emissions from industrial operations.

Ethical statement

Authors state that the research was conducted according to ethical standards.

Funding

This work was funded by the Federal Ministry for the Environment, Nature Protection and Nuclear Safety under research contract number 3615S12232 and co-ordinated by the Federal Office for Radiation Protection.

Conflict of interest

None declared.

Acknowledgment

The authors wish to thank Michael Kümmel for his valuable comments on the original study under contract No. 3615S12232.

References

Bundesgesetzblatt (2017). *Radiation Protection Law of 27 June 2017 [Full title in German: Gesetz zur Neuordnung des Rechts zum Schutz vor der schädlichen Wirkung ionisierender Strahlung vom 27. Juni 2017]. Bundesgesetzblatt Jahrgang 2017 Teil I Nr. 42, Bonn, 3 July 2017*.

Deutscher Bundestag (2017). *Official Explanatory Notes by the Federal Government on the Draft Radiation Protection Law [Full title in German: Entwurf eines Gesetzes zur Neuordnung des Rechts zum Schutz vor der schädlichen Wirkung ionisierender Strahlung – Amtliche Begründung der Bundesregierung]. Official Publication of the Bundestag No. 18/11241 of 20 February 2017*.

European Commission. European IPPC Bureau (2012). *Best available techniques (BAT) reference document for iron and steel production.* Retrieved June 30, 2017 from http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf.

European Commission. European IPPC Bureau (2013). *Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide.* Retrieved June 30, 2017 from http://eippcb.jrc.ec.europa.eu/reference/BREF/CLM_Published_def.pdf.

European Commission. European IPPC Bureau (2014). *Best available techniques (BAT) reference document for the non-ferrous metals industries.* Retrieved June 30, 2017 from http://eippcb.jrc.ec.europa.eu/reference/BREF/NFM_Final_Draft_10_2014.pdf.

European Commission. European IPPC Bureau (2016). *Best available techniques (BAT) reference document for large combustion plants, final draft.* Retrieved June 30, 2017 from http://ec.europa.eu/environment/industry/stationary/ied/pdf/LCP_finalDraft_06_2016.pdf.

European Council (2013). *Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. Official Journal of the European Union, OJ L 13, 17.1.2014*.

Federal Ministry of the Environment, Nature Protection and Nuclear Safety (2018). *Hydrological atlas of Germany. Dataset of average annual precipitation.* Retrieved December 10, 2018 from https://www.bmu.de/fileadmin/Daten_BMU/Bilder_Unterseiten/Themen/Wasser_Abfall_Boden/Binnengewaesser/Fluesse_und_Seen/130517_karte_niederschlag.pdf.

Federal Ministry of the Environment and Reactor Safety, Germany (2012). General technical instructions for the implementation of Art. 47 of the radiation protection ordinance "determination of radiation exposure resulting from discharge of radioactive substances from facilities". *Allgemeine Verwaltungsvorschrift zu § 47 Strahlenschutzverordnung: Ermittlung der Strahlenexposition durch die Ableitung radioaktiver Stoffe aus Anlagen oder Einrichtungen* In German:.

Federal Office for Radiation Protection (2018). *Dataset of atmospheric radionuclide transport model (ARTM).* Retrieved March 5, 2018 from https://www.bfs.de/EN/topics/ion/environment/air-soil/emission-monitoring/artm.html.

Federal Office for Radiation Protection of Germany, Department of Radiation Protection and Environment (2011). *Calculation guide for the determination of radiation exposure due to environmental radioactivity resulting from mining*.

German Meteorological Service (2017). *Datasets of test reference years.* Retrieved March 5, 2018 from https://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html.

Hettrich, S. (2017). *Validation and verification of the atmospheric radionuclide transport model (ARTM).* Doctorate Thesisthe Meteorological Institute Munich of the Ludwig Maximilian University of Munich.

Kunze, C., Ettenhuber, E., & Schellenberger, A. (2018). *Determination of potential radiation exposure due to discharges from NORM industries – project 3615S12232 [In German, Ermittlung von potentiellen Strahlenexpositionen durch Ableitungen aus NORM-Industrien - vorhaben 3615S12232], Salzgitter.* Retrieved November 30, 2018 from https://doris.bfs.de/jspui/handle/urn:nbn:de:0221-2018101516404.

Kunze, C., Ettenhuber, E., Schellenberger, A., & Dilling, J. (2018, June). Discharges from NORM industries in Germany: Estimate of doses to members of the public. *International radiation protection association, 5th european IRPA congress, den haag (NL)*.