EUROPEAN COMMISSION

NUCLEAR SAFETY AND THE ENVIRONMENT

Natural Radionuclide Concentrations in Materials Processed in the Chemical Industry and the Related Radiological Impact

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Abstract

Subject of this study is the potential radiation risk that can result from the presence of naturally occurring radioactive materials in raw materials usually considered as not radioactive and used in the manufacturing of chemical products.

In a review concerning such raw materials (phosphate ores, Zirconium, various metal ores) basic information on major companies involved, quantities produced, range of radionuclide concentration, chemical processes, products and by-products has been compiled for EU member states.

Typical radiation exposure scenarios such as radiation exposure of staff due to direct radiation, dust inhalation and dumping of various materials as well as the exposure of the public due to dumping and use of products have been investigated. The results show that the inhalation of dust is the major source of dose uptake which may require limiting dust concentrations.

In a survey concerning the current legislation in the European Union and its member states the problems radon at workplaces, testing and remedying existing workplaces, controlled and supervised areas and protection against exposure from natural sources are discussed. Regarding the regulation and classification schemes identified and taking into consideration the exposure estimates derived, it can be concluded that the dust inhalation situation of staff should be carefully and specifically re-considered before any additional regulatory measures are taken.

Summary

Subject of this study is the potential radiation risk that can result from the presence of naturally occurring radioactive materials (NORM) in raw materials usually considered as not radioactive and used in the manufacturing of chemical products. The concentrations of naturally occurring radioactive substances in the earth's crust vary widely. There are some materials that are extracted for industrial use and contain radioactive substances at concentrations which cannot be disregarded. In some cases industrial processing can lead to even further enhancement of the concentrations in the product, by-product or in the waste materials.

A literature review has been performed concerning raw materials commonly used in the chemical industry and containing a remarkable content of naturally occurring radionuclides. The respective information (major companies involved, quantities produced, range of radionuclide concentration, processes) has been compiled.

The use of relevant raw materials in the chemical industry has been identified, and the corresponding chemical processes are described in detail. The amounts and radiological properties of products and by-products resulting from such processes are evaluated.

The techniques of using NORM have not at all been stopped since the moment when the observation from the outside or the production sites gained the impression that the concerned radioactivity can induce certain harm to the public and the engaged operators. Intensive adaptations and amelioration of the procedures have been executed to reduce the possible contacts with the materials which were already described about 15 years ago. The following ten years were used successfully to leave the main quantities of radionuclides outside of Europe and to adapt the processes for the imported materials in such a way that products and by-products could mainly be taken out of any dose concern. In many cases such concerns had to be taken so seriously that production sites were closed in Europe what transferred the problems to places outside of Europe, however. In other continents the radiation protection aspects could be maintained with less costs.

These aspects show clearly the differences in the treatment of NORM between the chemical industry and the water supply industry. This supply is limited to European sources and this necessitates the consequent treatment of NORM in the member countries of the EU.

Typical radiation exposure scenarios have been identified based on this information. They include the radiation exposure of operating personnel due to direct radiation, dust inhalation and dumping of various materials as well as the exposure of the public due to dumping and use of products (fertilizers). The results show that the inhalation of dust is the major source of dose uptake which may require limiting dust concentrations. The conservative algorithms to be applied according to German regulations predict a considerable dose uptake of the public via the ingestion path as a consequence of the widespread and repeated use of fertilizers.

A survey has been performed concerning the current legislation in the European Union and its member states. In particular the problems radon at workplaces, testing and remedying existing workplaces, controlled and supervised areas and protection against exposure from natural sources are addressed. The approach adopted in some countries is described in detail.

Regarding the regulation and classification schemes identified and taking into consideration the exposure estimates derived, it can be concluded that the dust inhalation situation of staff should be carefully and specifically re-considered before any additional regulatory measures are taken. Nevertheless, a few simple measures facilitating the situation of the staff should be introduced anyway. They can reduce the radiation exposure essentially and will certainly help to a healthier environment even in case of no radiation hazard at all.

It does not make much sense to reduce the allowable concentrations at which radionuclides naturally may occur. The limits currently in use and recommended by international expert organisations are doses of radiation exposure or hazard to health originating from radiation. Whether or not these limits have any impact on the use of materials depends on a variety of technical parameters and process details. These are the items which can be adapted.

The other concern is beyond this study and refers to long term enrichment processes in the environment caused by the use of such natural materials like zirconium sands and others, and by the consequences which can be expected from such processes. Is it advantageous to let the material where mother nature put it, or make intelligent beneficial use of it.

Concerning means and ways of harmonisation, it is our recommendation to use the approaches already applied in a few member states in a manner which adapts the reasoning behind these decisions to the situation in the respective other member states.

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1 Introduction and Objective of the Study

The domain of radiation protection and the corresponding national and international regulation have evolved to ensure safety in the use of radioactive materials. Less attention had been given to radiation exposures that can result from the presence of naturally occurring radioactive materials (NORM) in raw materials usually considered as not radioactive and used in the manufacturing of chemical products. Such radioactive materials belong to the decay chains of long lived nuclides thorium 232, uranium 235 and uranium 238. The main constituents of those decay chains are shown in Table 1 together with their characteristic radiation and half-life data. The concentrations of naturally occurring radioactive substances in the earth’s crust vary widely. There are some materials that are extracted for industrial use and contain radioactive substances at concentrations which cannot be disregarded. In some cases industrial processing can lead to even further enhancement of the concentrations in the product, by-product or in the waste materials.

Effects and consequences shall be investigated that arise from processing those materials or from the treatment of the wastes generated in such processes:

- the processing of raw material generating increased radionuclide concentration in the products, wastes or equipment; the accumulation and concentration of radionuclides in the equipment (like collection on filters and in sludge, precipitation to layers at walls of pipes or process vessels) and/or in the rooms of the process or application buildings during processing;
- the corresponding personnel to handle and treat those products, wastes and equipment (maintenance) or to dispose it of;
- the respective handling, shipment, and disposal or re-use actions taken for the equipment and the by-products/wastes as to the possible exposure pathways opened by those actions which may affect members of the general public;
- the radiation exposure of staff working in the chemical process facilities, at the waste and maintenance departments as well as at the disposal sites;
- the radiation exposure possibly affecting members of the public and caused by activities in shipment of wastes and equipment as well as recycling of materials if applied.

The process industry uses large amounts of raw materials like ore, marl or clay which contain natural radionuclides. These radionuclides, present in the releases into air and water, may establish a risk to the population residing near an industrial site. In the Netherlands, a system of reporting and licensing such emissions has been under development for the last years. An industrial activity becomes subject of this regulatory when a so-called basic dose criterion is exceeded. Thereby the process industry is classified by a limited set of reference situations. For each situation the dose criteria are set as operation emission criteria per radionuclide. Emissions that result in a maximum individual dose of 10 µSv/a and a collective dose of 1 manSv/a [30] are indicated.

The International Commission of Radiological Protection (ICRP) published the basic recommendations regarding principles for protection from ionising radiation [1]. Based on these recommendations Euratom published the Council Directive 96/29 laying down the Basic Safety Standards (BSS) for the protection of the health of the workers and the general public against the dangers arising from ionising radiation [2]. The member states of the European Union are now engaged in the implementation of this Directive. The status of adapting former national regulations varies from country to country, but the governmental institutions are obliged to demonstrate compliance with the Euratom Directive by May 2000. The situation in some Member States is discussed as part of this report.

As foreseen by the BSS Directive, competent national authorities are requested to determine those industrial activities which may require control for the protection of workers and the public from sources of ionising radiation. However, there is a need to harmonise such approaches in the EU. NRPB (National Radiological Protection Board) in UK and CEPN (Centre d´Evaluation de la Protection Nucléaire) in France established reference levels for the regulation of various materials. The levels corresponding to different dose criteria and, hence, to different levels of regulatory control that could form a draft common proposal for the European Union. The need for harmonisation also is an urgent demand of those who use or handle such naturally contaminated materials. They could adapt their process design in a way that meets all requirements or even avoids the need of control [24].

Nuclide	Half-life	Type of radiation	Remark
K-40	$1{,}28 \cdot 10^9$ a	β,γ	
U-238	$4{,}47 \cdot 10^9$ a	α,γ	uranium 238 - radium decay chain
U-234	$2{,}5 \cdot 10^5$ a	α	
Th-230	$7{,}54 \cdot 10^4$ a	α,γ	
Ra-226	1600 a	α,γ	
Rn-222	3,825 d	α	
Pb-210	22 a	β,γ	
Po-210	138,4 d	α,γ	
U-235	$7{,}04 \cdot 10^8$ a	α,γ	uranium-235 decay chain
Pa-231	$3{,}3 \cdot 10^4$ a	α,γ	
Ac-227	22 a	α,γ	
Th-232	$1{,}41 \cdot 10^{10}$ a	α,γ	thorium 232-decay chain
Ra-228	5,75 a	β	
Th-228	1,91 a	α	
Ra-224	3,64 a	α,γ	

Table 1: Physical data of relevant naturally occurring radionuclides [29]

2 Review of Raw Materials

Materials commonly used in the chemical industry and containing a remarkable content of naturally occurring radionuclides have been intensively discussed in a variety of reports and papers. References are indicated together with the material details below. The respective information can be used as a basis for an appropriate classification of materials may possibly be of radiological importance. To meet this target the following data is derived for each type of industrial activity concerned:

- The quantities of material used or produced.
- The range of concentrations of radionuclides in materials throughout the processes, including information on radionuclide chains together with concentrations and total activity in the material.
- Details of processes in use and typical working procedures.

The data is provided in Table 2. As far as possible, it is tried to give a complete set of materials that are processed within the chemical industry in such a way that assessments of radiological exposures may be necessary. The fact that a process is listed does not imply that it will always lead to significant doses. If details of the process change, a review of exposure scenario may be desirable.

2.1 Phosphate ores

Economically interesting deposits contain between 4 and 38 % P_2O_5. The world's most important phosphate mining nations are the USA with e little less than 40%, corresponding to an annual production of 40 million tons of phosphate ore, Marocco with 20% corresponding to 20 million tons, ex-USSR about 10% corresponding to 10 million tons, and Jordan with 5 %, corresponding to about 5 million tons of phosphate ore. This results in a world-wide extraction of about 100 million tons per year. Phosphate ores are normally in the form of calcium phosphates $Ca_3(PO_4)_2$ (phosphorites) which are very old marine deposits associated with fossils. This form represents 85% of the world-wide production. The materials are often calcined by heating to 950 ^oC before dispatch in order to decompose calcium carbonate and organic matter. The second type of phosphate material is apatite $Ca_5[(PO_4)_3(F)]$ that is of igneous origin.

Roughly 75% of the world-wide extracted raw phosphates is used for the production of phosphorous containing fertilizers. (Superphosphates, ammonium phosphates and triple superphosphate, all produced from phosphate ore by processes that are described on a flowsheet, see Appendix 1) [43 and 44]. The ore imports of the EU have decreased by a factor of about two between 1985 and 1993. Almost 60% of these imported material is consumed by countries in the EU. The production rate of phosphoric acid by EU countries follows the same trend. The reasons are economic ones (imported P_2O_5 is cheaper than manufactured one) as well as ecological ones (management of the produced phosphogypsum). Actual data in Table 2 and taken from the two most recent references suggest an accumulated value for Europe of about 2,5 million Mg P_2O_5. Other sources published by the International Commission for the

Protection of the Rhine state that no phosphoric acid was produced in Germany in 1994. A value of 2 million Mg is given for the total European production of P_2O_5 . For France, a much lower value of 200 thousand Mg is mentioned as a consequence of shutting down some phosphoric acid production capacity. For the Netherlands, an annual production rate of 380 thousand Mg is indicated which to our knowledge seems to be overestimated due to closures of fabrication. The highest values are mentioned for Spain where 550 thousand Mg are being produced. These somehow mutually contradicting differences in the data basis are the results of temporary production stops during adaptation of processes due to enhancement of economic or ecological parameters. The latter parameters are mainly an effect of the necessity to reduce heavy metal emissions, especially the cadmium content. The reduction of radionuclide emissions is also mentioned as an advantageous side-effect [35].

2.2 Zirconium

The most common ores of zirconium are Zircon ($ZrSiO_4$) and Baddeleyite (ZrO_2). Most of the economic useful deposits of zirconium ore are found as beach sands which represent secondary detrital masses of heavy minerals (density > 2,9 g/ccm). Zircon is often an accessory constituent of the mineral and is therefore disregarded in its classification. Such secondary deposits are formed by sedimentation of eroded, transported and later precipitated remnants of primary or magmatic rocks. The components of such heavy mineral sands are separated by means of mechanical, physical or chemical treatment to obtain pure zircon, rutile, monazite or ilmenite. The premium grade of zircon sand is typically analysed as 66 % of ZrO_2 plus HfO_2, 32 % of SiO_2, 0,1 % TiO_2, 0.5 % Al_20_3 and 0,05 % Fe_2O_3 [41].

The world consumption of zircon was 890 000 t in 1994. This market is dominated by two companies, namely RGC (Rension Goldfields Consolidated, Australia) and RBM (Richards Bay Minerals in South Africa).The first one delivered about 300.000t per year, its output probably neared peak delivery, the second one about 225.000 t annually. 34 % of the total consumption or more than 300.000 t are consumed in Western Europe. Italy is a major producer of ceramic tiles. Thus, the Italian ceramics industry is probably the largest consumer of zircon in Europe. There are more than 300 manufacturers of ceramic wall and floor tiles besides producers of glazed sanitary ware in Italy. Besides Italy, Spain is a major manufacturer of similar products. In Germany, the main demand for zircon formerly came from the foundries, but the demand from the refractory and ceramic industry has grown. Data of the use of zirconium ores in different EU- countries is given in Table 2.

There has been a considerable increase in the proportion of the total zircon market accounted for by the ceramics industry. In 1980, ceramics accounted for approximately one-quarter of all zircon demand. The level of consumption of zircon in ceramics has increased at an average annual rate of about 7%, and accounts for approximately 50% of zircon demand in 1994.

2.3 Processing of metal ores: Aluminium, copper, iron, tin and niobium

([42], see table 3 for production rates)

Aluminium: Aluminium is the most abundant metal in the earth's crust where it is found in combination with oxygen, fluorine and silica, but never in metallic state. The principal source of aluminium is Bauxite, $(Al, Fe)_2O_3$. Bauxite is the richest form of weathered ores containing up to 55 % alumina. They are extracted by open-cast mining. The production of the aluminium metal comprises two basic steps of refining (production of alumina from bauxite) and reduction (production of aluminium metal from alumina).

Copper: Copper is widely distributed in all continents and is generally mined as sulphide or as oxide ores. Copper is normally extracted by underground or open-pit mining. Native copper, which is remarkably pure, is processed by grinding, washing, melting and casting. The metal is produced from its ores by reduction. Oxides and carbonates can be leached by dilute sulphuric acid and copper may be electrolysed from this solution.

Iron: Iron is most widely found in the form of various minerals such as oxides, carbonates, sulphides or silicates. Iron ores are prepared and processed by washing, crushing and screening, by calcining, sintering and pelletising in order to render the ores smeltable and to obtain iron and steel. The essential feature of iron production is the blast furnace where iron ore is smelted to produce pig iron. The furnace charged from the top with iron ore, coke and limestone is heated by hot air from the bottom, and the carbon monoxide transforms the iron ore into pig iron, the limestone acting as flux. The pig iron melts at a temperature of about 1600 ^oC and collects at the bottom of the furnace.

Tin: Tin containing ores are oxides or sulphides. The successive washing and separation options produce a 70% tin final concentrate. This concentrate is then mixed with charcoal and introduced in a furnace where reduction takes place at about 1.000 ^oC.

Niobium: Niobium is found together with other elements including titanium, zirconium, tungsten, thorium and uranium in ores like Pyrochlore $(Na, Ca, Ce)_2Nb_2O_6F$ in so-called heavy mineral sands. Treatment of the ore includes melting with sodium hydroxide and processing with chlorine at 800 ^oC.

Process	**P_2O_5 Production**		**Phosphate Fertilizer Production**		**Zirconium Ores**
Country	thousand tons per year	% of total EU	thousand tons per year	% of total EU	tons per year [41]
Austria	55	3			
Belgium / Luxemb.	270	14	340	15	3.000 (80% of NL)
Finland	240	12			
France	(200 -) 250	13	930	42	40.000
Germany	0	0	220	10	45.000
Greece	200	11	120	5	
Italy	(150 -) 250	13	330	15	98.000
Netherlands	120	6	290	13	
Spain	(450 -) 530	28	180	8	52.000
Poland	500	-			
Total EU	1900	100	2.200	100	≈ 300.000

Table 2: Phosphate production and use of zirconium ores in the countries of the EU

Process	**Aluminium Production**		**Refined Copper Production**		**Iron ore Production**		**Tin Production**	
Country	thousand tons per year	% of total EU	thousand tons per year	% of total EU	thousand tons per year	% of total EU	thousand tons per year	% of total EU
France	460	22	60	5	1.000	50		
Spain	360	17	180	14	980	49	2	36
Germany	550	26	630	48	15	1	0,1	2
Netherlands	230	11					0,2	4
United Kingdom	240	11	50	4			2,8	50
Total EU	2.150	100	1.300	100	2.000	100	5,6	100

Table 3: Production of various metals in EU countries

2.4 Conclusion of chapter 2

Production and refining processes do not increase the content of NORM in the product, by-product, refuse, or equipment except for a few such items in the zirconium, aluminium and phosphate processing. The reasons are the necessity of addition of large amount of other materials to the process (as for instance in the blast furnace additives in the iron ore processing (resulting in a dilution of the radionuclides in the slag), and the purification of the product resulting in the deviation of the radionuclides into the by-product and refuse streams (as for instance the off-gas).

Thus, the further consideration concentrates on zirconium, aluminium, and phosphate ore treatment. In these instances, enhanced concentrations are found in the products or the by-products.

3 Review of Chemical Processes

3.1 Zirconium

In the zirconium metal extraction process zircon ore (sand) is dressed with coke in a ball mill to a very fine consistency. The coke-zircon mixture is introduced into a chlorination reaction chamber, and chlorine gas reacts with the mixture at 1200 ^{o}C. A first distillation process separates Zr- and Si-chlorides, then hafnium is separated from zirconium. The thereby formed Zr- hydroxide being calcined to form the dioxide is remixed with coke and sent through a pure chlorination to yield zirconium chloride pure without hafnium. The condensed Zr-chloride then goes to a magnesium reduction to form Zr- sponge (process details see Figure 1) .

It is reported that several mining companies beneficiate the mined raw material on spot. E.g. the tailings of a developed copper deposit are used to extract uranium and thorium. The separated concentrate forms the basis for a zirconia plant which uses the sulphuric acid from the copper operation to produce baddeleyite of high grades. Such installations are qualified to produce chemically purified (advanced) zirconium sulphate tetrahydrate (AZST). This is also used to feed another plant on spot that manufactures high-purity hafnia-free zirconia powder (HPZO), used for nuclear industry applications. Other companies are reported to beneficiate their material by manufacturing metal-stabilised zirconias by the installation of a fusing technology for the treatment of zircon as raw material. Furthermore chloride-routing technologies are installed where appropriate raw material is found as deposit [41].

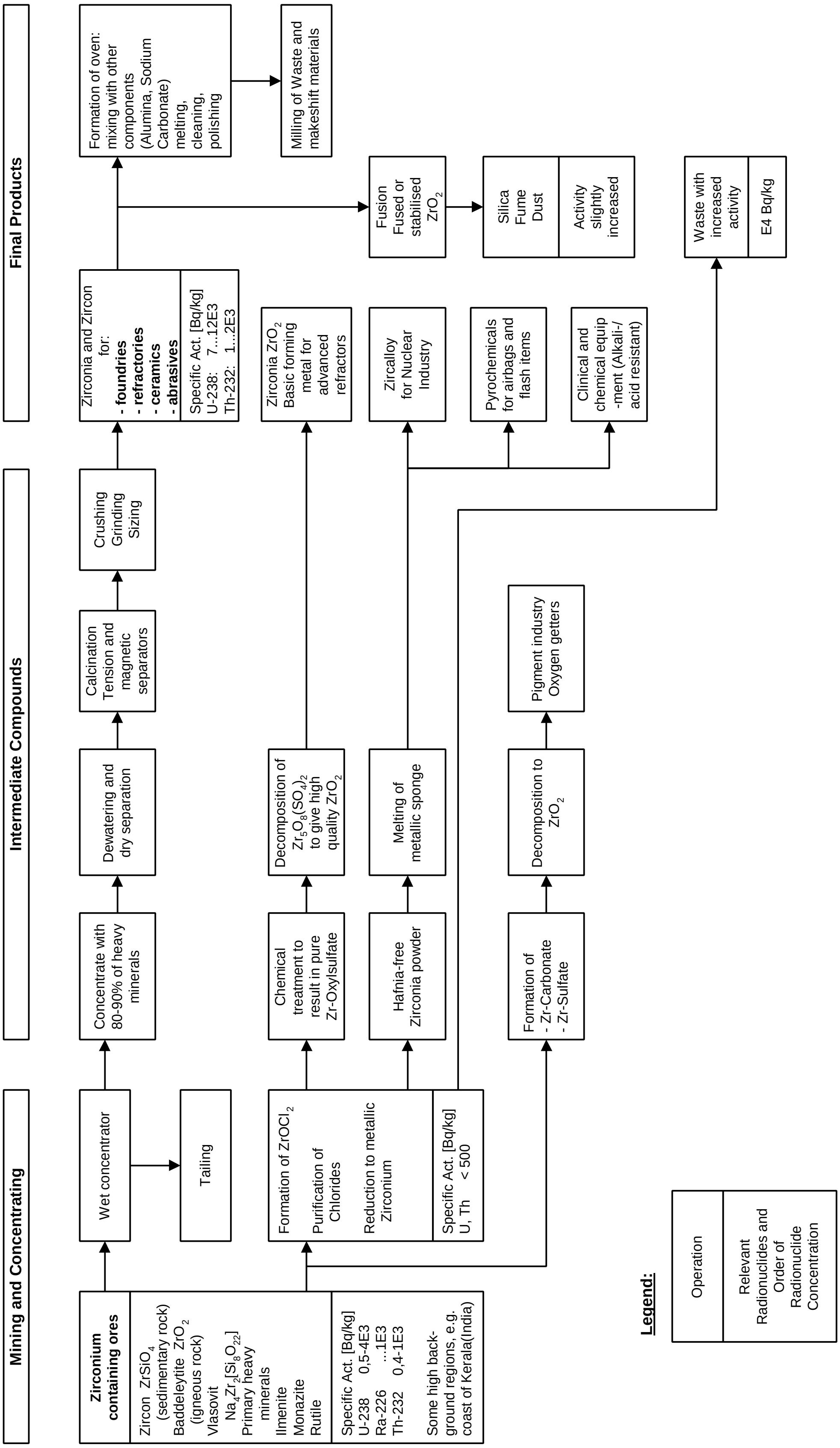


Figure 1
Production of zircon and zirconia material with special respect to natural radionuclides ([36], [43], [41])

3.2 Phosphate industry

The phosphate processing operations comprise the mining and milling of phosphate ore and then the manufacture of phosphate products by either the wet or the thermal process. More than 70% of the ore being beneficiated in several process steps to increase the P_2O_5 concentration before delivery to Europe are wet processes. The main route for more than 90% is then acidulation with sulphuric acid (besides nitric and hydrochloric acid in minor extent [45]) with the main by product of gypsum sulfate (phosphogypsum) of which 4-5 tonnes are received when 3 tonnes of ore are turned into 1 ton of P_2O_5 (process details see Figures 2 to 4) .

The reaction of calciumphosphate with sulphuric acid leads to different products depending upon the relative amount of sulphuric acid added to the phosphate ore. The first reaction giving single superphosphate (SSP) as product is described as follows, the product representing a combination of phosphoric acid and phosphogypsum:

$$Ca_3(PO_4)_2 + 2\ H_2SO_4 \rightarrow Ca(H_2PO_4)_2 + 2\ CaSO_4$$

The second reaction describes the formation of phosphoric acid H_3PO_4. Sulphuric acid reacts with the phosphate to yield a pulp of orthophosphoric acid and gypsum which is filtered:

$$Ca_3(PO_4)_2 + 3\ H_2SO_4 \rightarrow 2\ H_3PO_4 + 3\ CaSO_4$$

Another reaction produces the P(phosphate)-fertilizer with the largest amount of P_2O_5-units, namely triple superphosphate (TSP):

$$Ca_3(PO_4)_2 + 4\ H_3PO_4 \rightarrow 3\ Ca(H_2PO_4)_2$$

If phosphoric acid is neutralised by ammonia, another type of fertilizer can be produced, namely NP(nitrogen/phosphorus)-fertilizers. Principally the neutralisation process can lead to mono-, di- or polyammoniumphosphate. The formation of MAP (monoammoniumphosphate) is given as an example:

$$NH_3 + H_3PO_4 \rightarrow NH_4H_2PO_4$$

With the production of these NP-fertilizers the basis for mixed fertilizers is laid. As can be seen from the reaction equations, the fertilizer industry produces considerable amounts of phosphogypsum, namely about 10 million tonnes for the European countries alone, only a small fraction of which is used in agriculture, in the manufacture of building materials or in road construction. In the main, phosphogypsum is therefore regarded as a waste which is either stored on land in waste heaps or discharged into aquatic media (estuaries and the marine environment).

Nowadays a “crude green acid“ is quite often delivered to European companies because of their need to minimise wastes or products containing naturally occurring radionuclides. From this follows that the reduction in discharges in the OSPARCOM (OSlo-PARis-COMmission) region is compensated by an increase in such discharges in other parts of the world [46]. For example, it is reported from one company in Morocco that pumps three quarters of a million tons into the Atlantic Ocean per year. Experience in the use of this “green acid“ demonstrates that the treatment of the ore with sulphuric acid preferentially separates the thorium into the phosphogypsum waste stream and the uranium into the “green acid“ [47]. A preferred alternative of the discharge of phosphogypsum is given by qualified storage on land with the aim of limiting discharges not only of natural radionuclides, but also, and most importantly, of metals (with priority being given to cadmium) [45].

Since 1990 the US EPA (Environmental Protection Agency) requires that all phophogypsum is to be placed in stacks or mines. Environmental contamination resulting from phosphogypsum storage may occur from: (i) atmospheric contamination with fluoride or other toxic elements; (ii) groundwater pollution with mobile anions, acidity or radionuclides; (iii) radon gas; (iv) inhalation of radioactive dust; (v) direct exposure of gamma radiation. Several proposals to reduce these possible contaminations are described [45,46].

As an alternative to the wet processing of phosphate ores with acid, a dry thermal process was developed. In this process the phosphate ore is crushed, mixed with silica (SiO_2 gravel) and coke, and finally heated to 1500 ^{o}C in an electric furnace. (Process details see Appendix 4) At this temperature phosphorus vapour and carbon monoxide are produced by the following mechanisms:

$$Ca_3(PO_4)_2 + 3\ SiO_2 \rightarrow 3\ CaSiO_3 + P_2O_5$$

and

$$P_2O_5 + 5\ C \rightarrow 5\ CO + 2\ P$$

The phosphorus is condensed and removed as a liquid or solid, and quickly submerged in oil in order to prevent reaction with moisture in the air. The elemental phosphorus is often converted into phosphoric acid, H_3PO_4, using nitric acid HNO_3, for later use in the manufacture of artificial fertilizers. As a by-product a large amount of calcium silicate $CaSiO_3$ slag is produced.

EFMA, the European Fertilizer Manufacturers' Association, published a series of booklets titled "Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry". Booklet No. 4 of 8 deals with the production of phosphoric acid [34]. The booklets were prepared by EFMA member companies in response to the EU Directive on integrated pollution prevention and control (IPPC Directive), Council directive 96/61 EC of 24 September 1996. Among others, the implementation of this Directive will bring forward BAT (Best Available Technique) reference documents (BREFs) with descriptions of what is considered as BAT for a specific sector. Furthermore, descriptions of the marine conventions, like

OSPARCOM, will be developed. Principles for the assessment of a proposed waste strategy are provided, like preference for waste prevention, promotion of re-use and recycling. As to the preparation of the booklets, the EFMA member companies have asked their experts to publish their highly experienced technologies in order to improve the situation of pollution control amongst the European fertilizer industry.

If re-use is intended, several qualifications have to be fulfilled by the by-product: Only smallest traces of acid are allowed to remain within the product and the amount of natural radionuclides has to be minimised. However, the basic problem is that the consumption rate for these uses is normally many times smaller than the production rate of the by-product. Dumping the gypsum on land is only possible if sufficient space or area of land is available where the soil meets certain recommended qualities. The pile on which the dry gypsum is collected has to be completely surrounded by a ditch which collects the run-off water including any rain water. If the filter cake is slurried with recycled pond water and pumped to a special storage stack for drying, the leak water must be collected in adjacent cooling ponds. By recycling the water the system keeps contaminants within the plant. Furthermore, the height of the stacks depends on the engineering properties of the underlying soil which sets a limit. In order to prevent the pond water to reach the ground water system, intercepting barriers are to be installed.

Another important aspect in the selection of the best process is to adapt the production process to the origin of the rock, being sedimentary or igneous. The most easily mined phosphate deposits are found in the great sedimentary basins. These deposits are generally associated with substances of organic origin and casual gangue minerals. These circumstances result in variations of the finished ore concentrate due to different techniques during the beneficiation stage. Thus, the re-adaptation of the acidulation process is unavoidable.

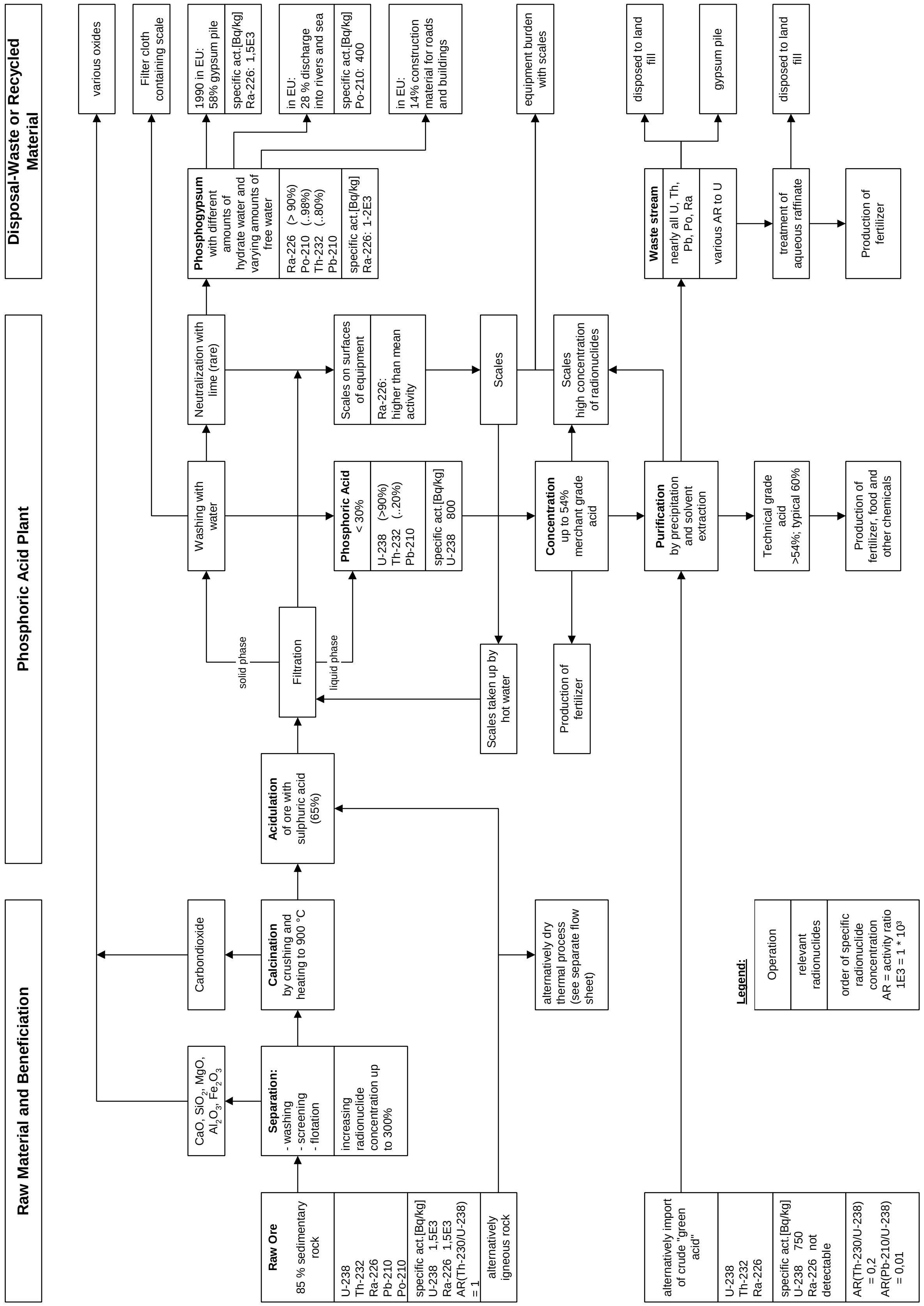


Figure 2
Flow of radionuclides in phosphate containing material (wet process) ([9], [46], [47])

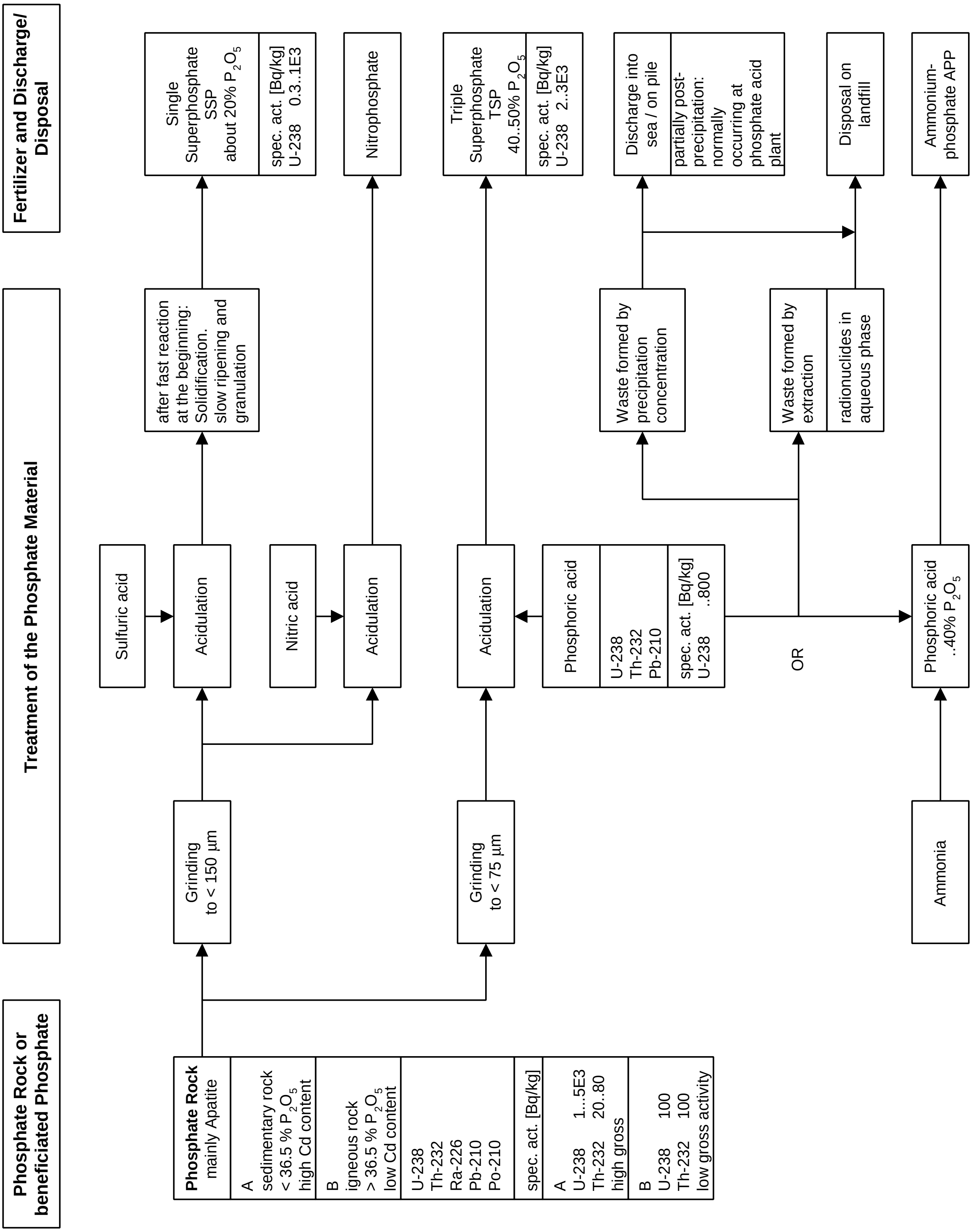


Figure 3
Survey of phosphate fertilizer production with special respect to natural radionuclides ([43])

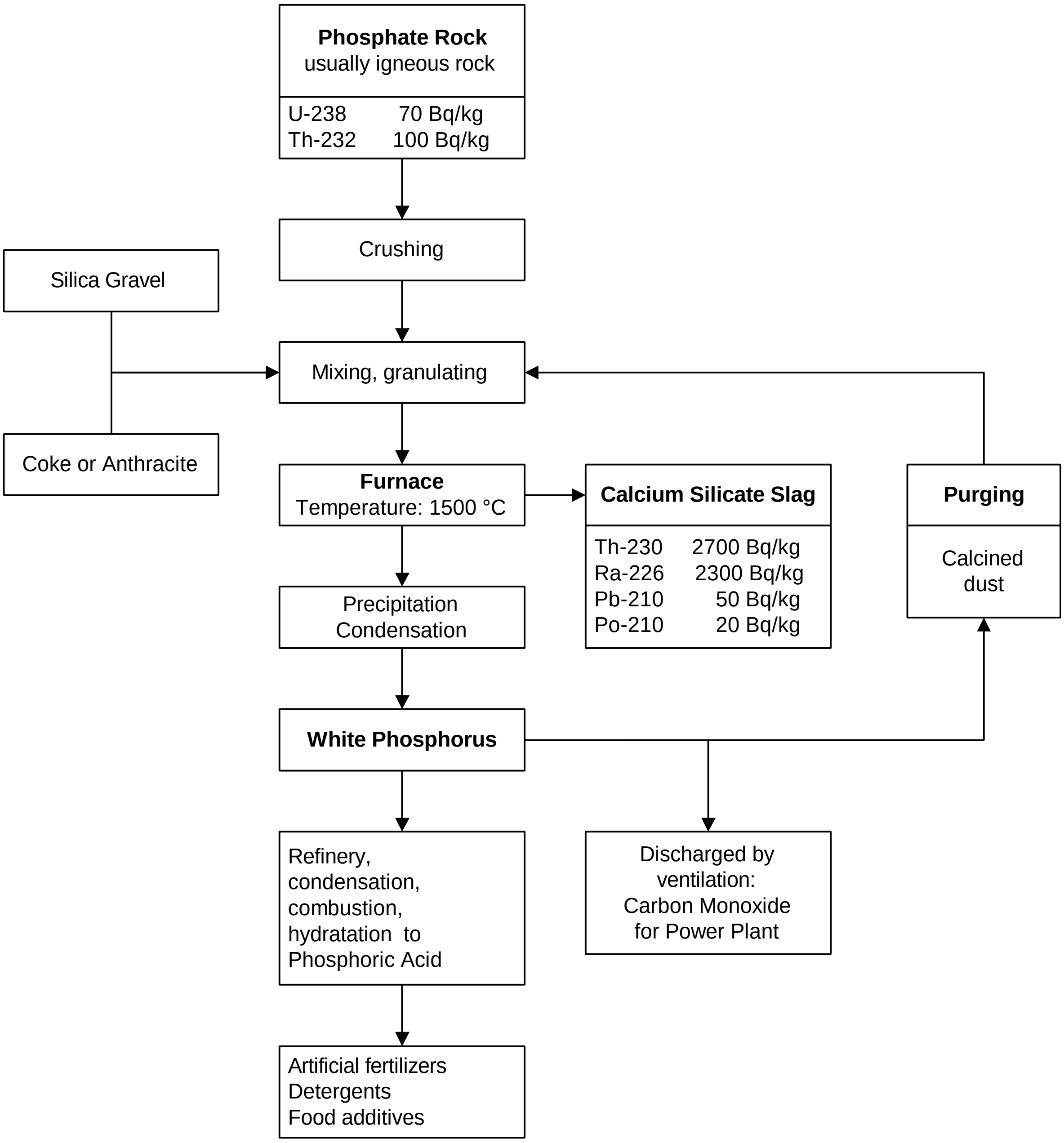


Figure 4a
Flow of radionuclides in thermal process of phosphorus production ([9], [42])

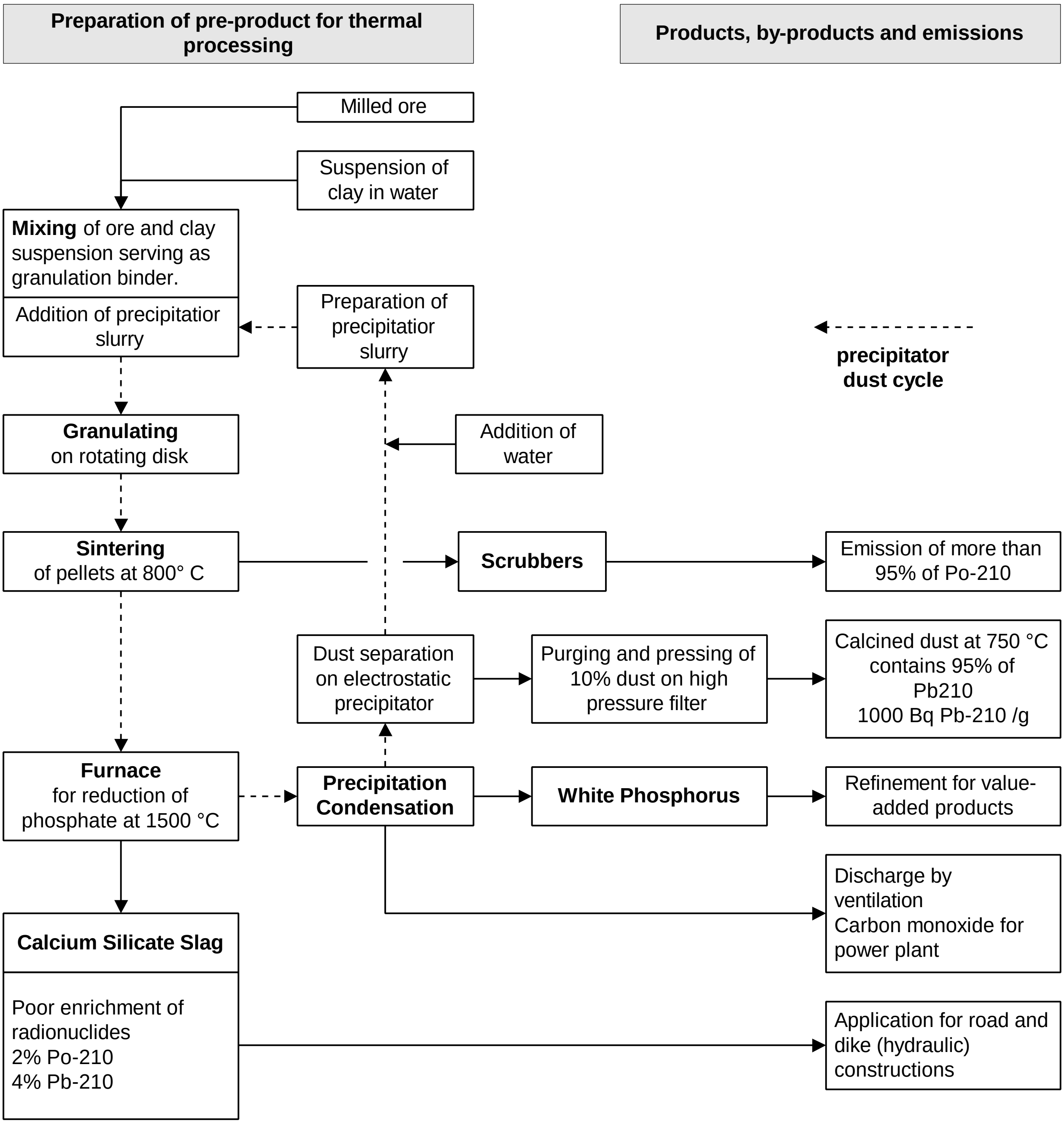


Figure 4b
Flow of radionuclides in thermal process of phosphorus production ([9], [42])

3.3 Aluminium

The production of aluminium metal comprises two basic steps of refining, which consists of alumina production from bauxite by treating (dissolving) the raw material with caustic soda, and reduction, i.e. production of aluminium metal from alumina by an electrolytic process.

The bauxite ore, containing up to 55% of alumina, is red-coloured by its iron content (10 to 25%) and contains various amounts of crystalline water and silicon dioxide, as well. When the ore is treated with aqueous caustic soda, the amphoteric aluminium hydroxide and the acidic silicon dioxide will be dissolved leaving the precipitations of iron and titanium oxides as so-called red sludge. This sludge contains the essential parts of uranium, thorium and their decay products.

3.4 Conclusion of chapter 3

In the zirconium processing, the wet concentrator process results in a slight increase of NORM concentration in the product. These products are then used for surface treatment of ceramics or glass constituent of glasses and others. In these final products the concentrations of NORM are again reduced down to quantities below those found in the ore. The other zirconium processes result in products which are directly reduced in their NORM concentrations. The concentration of NORM in the wastes are very similar to those in the ore. As a conclusion, zirconium is not considered a matter of concern with respect to NORM.

The production of aluminium transfers the radionuclide content of the bauxite ore into the so-called red sludge. Its NORM concentration is about that of the raw material (see tables 5 and 6). The refining process of the sludge and the extraction of copper, iron and tin do not change the situation.

The processing of phosphate and the production of ammonia based fertilisers as well as of phosphorus are facing NORM concentration problems. The wet process of phosphate production releases most of the radionuclides with the phosphogypsum and the rest with the effluents and road construction additives. Uranium remains in the phosphoric acid at a reduced concentration (more than 90 % of U in phosphoric acid ! - see Fig. 2) . A problem in this context is the scales inside the equipment where radionuclide concentrations considerably pile up. The decontamination procedures are mentioned in the flow diagram (figure 2). The dry process of producing ‘white phosphorus’ releases the NORM in the slag off-gas. Equipment contamination was not explicitly reported. Finally, there is the ammonia used in the fertiliser. The NORM concentration in the main products is generally less than in the raw material. Some of the by-products and wastes show enhanced concentrations.

These data form the basis of the definition of the exposure scenarios and the corresponding estimates of doses.

4 Supplementary Information

4.1 Management of wastes and by-products

In this chapter the management of wastes and by-products or waste is reviewed in more detail. The common result of several contacts with the concerned industry is that many changes were performed with regard to the intention of avoiding large quantities of such materials containing radionuclides in a concentrated form.

It has been a primary aim of the European companies to import minimised quantities of material containing such radioactive components. Since about 1985 the eventual impacts which result from the management of these material by stacking them on open-air piles or dumping them into rivers or the sea have been discussed by the concerned industry when institutions like the Dutch National Institute of Public Health and Environmental Hygiene (RIVM) have guided the public to put interest on the environmental impact or individual consequences of these activities [50].

In 1985 about 2.000.000 Mg of phosphogypsum were disposed into the Rhine only by Dutch companies. As we could confirm meanwhile such amounts of gypsum result from the production of about 400.000 Mg of P_2O_5. The up-to-date inquiries repeated a very short time ago assure that all such activities have been stopped in the Netherlands meanwhile. This information confirms that the report of L. H. Baetsle [51] continuously cited during the last ten years in several reports is not relevant any more as a basis for throughput considerations because so many activities have been stopped during this time all over Europe. Instead co-operations and joint ventures with companies owning the mining capacities have overtaken to produce pre-products or even purified products of the mentioned materials. As result of this procedure much less NORM reached Europe leaving these behind in the exploiting countries. This description is ascertained by the actualised Table 2.

It is confirmed that per Mg of P_2O_5 produced the phosphate consumption ranges from 2,7 to 3,5 Mg, depending on the content and process used. For the wet process almost 5 Mg of calcium phosphate are received. As mentioned this goes to deposit, river or sea. The Belgium company which was inquired a short time ago is selling their by-product gypsum in the plaster and cement industry. More than 80% of the received gypsum are used for this purpose mainly or go partially to road constructions. About 15 % of the material remain as waste. Investigations on gypsum plasters and mortars influencing dose considerations of inhabitants or stucco-workers resulting from indoor living or working seem to be in the range of several micro-Sv which is well below the 1 mSv/y concept of the Euratom directive [53]. General good information is received by EFMA the actual information of which was used in this report.

The preferred method to avoid harm for the groundwater if gypsum is dumped on land is to produce a dry by-product. Some plants transport such a product by belt conveyors to the gypsum storage pile. Such a pile should be surrounded completely by a ditch which collects the run-off water including any rain water. In other plants the filter cake is slurried with recycled pond water and pumped to special storage areas where the phosphogypsum eventually dries in stacks. The area receiving the phosphogypsum slurry is sub-divided into small areas, with each section being used in rotation. Slurry is discharged on top of the storage pile and the phosphogypsum rapidly settles out of solution. Clear water runs off and drains to the adjacent cooling ponds. The water is recycled within the system to ensure that the contaminants are kept within the plant. The phosphogypsum stack is completely surrounded by a ditch with the function as described above.

The more important considerations in the design and construction of phosphogypsum disposal areas are:

- Site selection
  The height of the stacks depends on the engineering properties of the underlying soil and its load bearing strength, if there are no legal restrictions.
- Cooling ponds
  The cooling pond surfaces will have to be adapted to local climatic conditions and the water balance in the plant.
- Percolation control
  The process water associated with phosphogypsum is highly acidic and contains high levels of contaminants. Some of the following options may be necessary to prevent this water reaching the surrounding ground water system: seepage collection ditches, intercept wells, natural barriers, lining systems (natural or synthetic) and fixing of soluble P_2O_5 and trace elements by neutralisation.
- Monitoring of discharges
  Phosphogypsum discharges on land are regularly monitored. Parameters are typically the P and F content and the ground water quality. With regard to radioactivity any requirements were not seen as necessary due to 84/467/EURATOM Directive. Any excess of contaminated water is to be treated with lime before being discharged as the most serious effect of discharging improperly treated pond wastes is rapid change in pH, which can effect most species of fish, aquatic life and vegetation.

The best P_2O_5 recovery efficiencies that are generally expected are between 90 and 96%. The P_2O_5 losses are retained in the filter cake and this can create problems with disposal or use of the by-product gypsum. Some of this loss of P_2O_5 passes into solution and can be recovered when the calcium sulphate is finally separated if it is made to recrystallise to its other hydrate (as result from the installed dihydrate or hemihydrate processes, respectively). This procedure does not only raise the overall efficiency of the process but also gives a much cleaner calcium phosphate.

New proposals for the use of cleaned phosphogypsum are:

- Exchange of natural gypsum (primary origin) by phosphogypsum. This new attitude is supported by the environmental (movement) specialists and is also favoured by the industry, e.g. Knauf. This development corresponds to the intention of the Commission (OSPARCOM)
- Servers as sulphur addition for the agriculture.
- Street construction for roads, together with fly-ash to immobilise.

4.2 Radiological situation

At the time around 1985 the phosphogypsum disposed in the Rhine had consequences by an increase of the U-238 chain radionuclides expected in sea food [50]. A maximum increase of the individual dose of 150 µSv / y was predicted by this fact based on the radionuclide Po-210 as the main contributor. Further research was executed to study the reality of such predictions at various places in the member states of the EU.

The above mentioned Dutch institute could find clear enhancements of Po-210 in mussels and shrimps due to effluents from phosphorous plants in operation. In France the Laboratory for Radiological Studies of the Atlantic Seaboard (LERFA) carried out a special study of the impact of the mentioned wastes on the levels of Po in the marine environment. Until 1993 the data did not enable a recognition of an industrial impact on levels of PO-210 in the Seine estuary. Similar investigations were performed in Spain (A. Travesi, M. Garcia-Leon), Ireland and Denmark (Dahlgaard). These investigations were organised in the context of the OSPARCOM activities mentioned in the draft final report under [35] and [44]. British members of the OSPARCOM/RAD group quantified this dose estimation in 1997 [44] with the result that doses received in the critical group are in the order of magnitude of 100 and 300 µSv per year due mainly (75%) to Po-210.

The OSPAR Convention for the Protection of the Marine Environment of the North-east Atlantic has initiated the formation of a working group on radioactive waste: this group distributes information to the to the phosphoric acid industry under the elements of an integrated approach to prevent and control the marine pollution by this industry. This group is known in the interested public as OSPARCOM/RAD. The main interest is the development of BAT (= Best Available Techniques) as described already in chapter 3.2. A key factor is the specification of imported material which can help to minimise or even avoid the imports of materials with high NORM content which can lead to the production of TENORM (NORM containing technically enhanced radionuclides) by a sequence of processes as described for a variety of ores and subsequent products. Further key issues to avoid marine or any other pollution like the underlying soil of a gypsum pile, are the more efficient extraction of phosphoric acid from the gypsum or its cleaning to enable recycling as a product for e.g. civil constructions.

4.3 Thermal process improvements

Details were received about the thermal process for phosphorus production by Thermphos International BV (TIBV) in Vlissingen (Netherlands). Essential data of the entire process have been improved with the intention to reduce the emissions to air and water and to reduce the specific radioactivity of the silicate slag in order to render it to a valuable and saleable by-product of the phosphorus production. The advantage of the improved process is that there is no enhancement of radionuclides within the silicate slag in comparison to the used ore. It is reported that the phosphate ores used for the process contain altogether only 1 Bq per g uranium-238 with daughter nuclides in near equilibrium. When the company TIBV looked into more details of the process in 1995 and measured the activity of all phosphate ores these measurements gave higher concentrations of radionuclides than assumed in the years before. With respect to the general information we received and to the information of TIBV giving the origin of the imported ores a magnitude of 10 to 50 Bq per g uranium does not seem to be unrealistic.

As mentioned by TIBV the added amounts of silica gravel and of a specially prepared clay suspension which is specified afterwards in the process description are so huge that the radionuclides are not enriched in the silicate slag. This means that per Mg phosphate ore used in the process 1 Mg of silicate slag is received which essentially contains all radionuclides the atomic number of which are greater than that of radon. Its content of lead and polonium is comparatively low at the end of the furnace process. Having these data in mind the flow of the radionuclides of Figure 4a does not correspond to these up-dated figures. A separate flow is therefore taken into the report as Figure 4b. The elemental phosphorus leaves the furnace as gas together with the carbon monoxide formed during the reaction. Entrained dust is separated from the gases in an electrostatic precipitator. This dust is collected in the slurry tanks where it is mixed with water. The resulting precipitator slurry is pumped to the slurry station where it is re-used in the granulator binder, an aqueous suspension of clay.

This mixed binder is brought onto a rotating granulator where the milled phosphate ore is added as a fine powder. Due to the rotation of the disk pellets are formed which are then transported onto the front end of a slowly rotating sintering grid roaster. After passing through a drying zone at about 300 ^{o}C the pellets are then sintered to hard spheres at temperatures around 800 ^{o}C. After cooling they are conveyed to an intermediate storage facility where they are stored in large silos before being fed into the electric furnaces.

The radionuclides with an atomic number less than that of radon escape from the melt and end up in the precipitator dust cycle, while radon itself as an inert gas escapes along with the carbon monoxide. The short-lived nuclides of the dust with the atomic numbers 214 and 218 decay within a few hours. The problem nuclide is Pb-210 which has a half-life of 22 years and is therefore relatively long-lived. This precipitator dust is trapped in one of the electrostatic precipitators and is recycled via the clay suspension into the pellets as described. When they reach the furnace the volatile inorganic substances, metals and radionuclides evaporate again. But before in the sintering roaster Po-210 with a half-life of 138 days being more volatile than Pb-210 leaves the pellets during the sintering process. Despite the installation of several scrubbers about 95% of the Po-210 are emitted into the environment. Consequently the activity of Po-210 in the phosphate pellets is lower than the activity of Pb-210. High concentrations of volatile inorganic matter as metals and nuclides cause instability in the operation of the furnaces. To control the concentration the system is purged thereby producing calcined dust in a rotating calcining kiln at 750 ^{o}C after being filtered on a high-pressure filter with an activity of Pb-210 of 1.000 Bq/g.

4.4 Radiological case studies

From the very start of TIBV in Vlissingen it was known that phosphate ores are classified as NORM. The problem of enrichment of radioactivity and the associated emission was not recognised until 1983, when the monitoring network of the nearby nuclear power station detected activity emitted by TIBV. TIBV meanwhile takes 200 samples of the air and water discharges each year needed to check for compliance with the environmental and workplace regulations imposed by the Nuclear Power Act licence.

After consultation with VROM (the Dutch Ministry of Public Housing, Planning and the Environment) TIBV commissioned KEMA (a Dutch nuclear research institute) to carry out a study for the determination of doses caused by TIBV activities.

The following exposure paths were mainly examined:

- Inhalation of radioactive dust from discharges into atmosphere
- Ingestion of radioactive fall-out from discharges into atmosphere
  - soil – plant – man
  - soil – grass – cattle – milk or meat – man
  - water – fish – man
- Ingestion from radioactivity discharged directly into water
- External irradiation from cloud
- External irradiation from the soil, attributable to radioactive fall-out

It was shown that the individual dose by TIBV in a nearby village 4 km away from the production site does not exceed 30 µSv per year on average. The greatest dose is attributable to the inhalation path which accounts for 96% of the total dose. With regard to the European Directive 96/29 the Dutch VROM affirmed the MTD (maximum tolerable dose) for one practice or work activity at 100 µSv per year and changed the Nuclear Power Act accordingly. VROM based its support of the 100 µSv per year threshold limit by arguing that it is possible that members of the public could be exposed to a maximum of 10 different practices or work activities. Another benefit of this approach is that one practice or work activity does not depend on another not filling up the licensed space to the maximum cumulative dose of 1.000 µSv per year. The following conclusions can be drawn from the legislative situation for the TIBV plant:

- An "urgent remedial action" situation for the TIBV plant for all locations rather close around the phosphorus production and a "remedial action" situation do not exist for the mentioned location 4 km off the plant.
- The ALARA (as low as reasonably achievable; social and economic facts taken into account) considerations must be applied for these locations.

TIBV therefore has continuously investigated the possibilities to reduce the emissions occurring during the phosphorus production and the hereby caused dose. The ALARA analysis which has to be carried out means that the effect of measures, such as the construction of a precipitator dust processing plant, on the reduction of the dose in the surrounding area must be weighed against the consequent investment and operating costs. However due to the absence of any national (Dutch) or international clear indications what costs are defensible in relation to the reduction of any individual or collective dose TIBV referred to a cost-benefit-analysis (CBA) of the British National Radiation Protection Board [54]. In this paper a CBA value of 20,000 Pounds per saved man-sievert is given in order to weigh up the reasonableness of an investment.

Trials were carried out with the aim of improving the scrubber systems of the sintering plant. Recent studies in 1997 and 1998 even showed that more efficient scrubbing could lead to a higher dose as result from Po-210 being fixed on smaller particles than before and leaving the stack by this changed matrix which causes higher dose due to increased lung deposition.

In this situation it was stated after long and comprehensive research that 2 dose-reducing measures were feasible: the construction of a precipitator dust processing plant and a high stack. As described the phosphorus process results in about 1,000 Mg calcined precipitator dust per year with high activity. It is mentioned that only the absolutely necessary amount of precipitator dust is removed because the storage of calcined dust is very expensive. Instead TIBV worked out plans to remove 3,000 Mg precipitator dust which is to be processed in the precipitator dust processing plant. By this process the heavy metals, the radioactive fraction and the other substances are to be separated chemically from each other. A highly active lead sulphate fraction is formed which has to be transported to COVRA (Centrale Organisatie voor Radioactief Afval: The Dutch central organisation that stores radioactive waste). The volume of radioactive waste would be reduced considerably. In early 1993, after consultation with VROM, it was decided that the plant would not be built due mainly to the costs and remaining uncertainties of the effectiveness of the fractional separation to a heavy metal and to a radioactive waste. By this measure it could be supposed that the level of dose in the surrounding area would be reduced by a factor of 2.

The second dose-reducing measure was to build a 140 m high stack which could also have the effectiveness of reducing the dose by half. However the erection of a higher stack would not reduce emissions in absolute terms, so that the benefits would be restricted to the immediate vicinity of the plant. TIBV therefore decided in consultation with VROM not to build the stack.

In this context the use of alternative ores was discussed and tried. However expected improvements could not be realised because of other surprises. Although the heavy metal and radionuclide content was lower the emissions of these substances increased. This effect resulted from the presence of other impurities, notably chloride or calcium carbonate which made the metals more volatile during the sintering process. So when changing the origin or the used ores their influence on emissions has to be checked in advance, because of the altered mobilising or immobilising characteristics. In the end the emission profile belonging to new ore can only be determined after its use in the process during a period of up to several months.

Meanwhile the calcined dust has been kept in an intermediate storage on site for a number of years so that ten to twenty thousand Mg of this radioactive waste with a half-life of 22 years from Pb-210 cannot be disposed of in a chemicals landfill. Leaching tests carried out by KEMA favour the immobilisation of the waste in a cement matrix so that it can be disposed of in an adequate landfill without difficulties. The Po-210 activity will have fallen below 10 Bq per g after 150 years. Additionally TIBV and COVRA have signed a contract to store the calcined precipitator dust in 20-feet containers with plastic lining which will be stacked in a purpose-built storage building. Because of the volume increase by immobilising the precipitator dust in cement which is not desirable at all it was decided to carry out the immobilisation after the decay period of the radionuclides.

Operators being involved in this phosphorus production process are relevantly exposed to radionuclides Pb-210 and Po-210. An intake of these nuclides predominantly occurs by inhaling the dust from the precipitator dust cycle. To obtain the dose received by the concerned operators Personal Air Sample (PAS) measurements were carried out. Specified devices consisting of an air pump and a filter in a filter holder, connected each by a tube, are installed in such a way as to pass a continuous sample of the air surrounding the operator through the filter. On this filter the dust containing radionuclides is separated from the air and collected. The intake of radionuclides can be calculated from the obtained count rate, the flow passed through the filter and a worker's assumed breathing rate. Given the intake it is possible to make a dose assessment together with a Dose Conversion Coefficient /Sv per Bq). As result from these measurements it can be said in general that operators concerned with the production of phosphorus at TIBV site are exposed to an average dose of 1 mSv per year. It is also found that dose rates up to 1 mSv per hour are obtained possibly, if certain parts of the installation are polished in order to remove radionuclides from contaminated surfaces. Contamination has been measured of up to several hundred Bq per cm^2 on the inside of process equipment. This makes preventive measures necessary.

A similar situation is reported from a company that processes mineral sands containing NORM. The combined dust and condensed fume which is released during a high-temperature fuse in an electric arc furnace process is collected by an extraction system. The fine dust typically contains the same radionuclides found in the raw material, but in an enhanced concentration and the fume contains volatile radionuclides that condense and attach to dust particles in the extraction system. This process leads to a substantial increase in the activity concentration of radionuclides such as Po-210 and Pb-210. Behind the extraction system the dust is collected in drums from whereon it is referred to as furnace " dust collector fines (DCF). For many years this furnace DCF had been disposed of to landfill site as controlled (non-radioactive) industrial waste. In 1991 an analysis of the material indicated Po-210 activity concentrations of 600 Bq/g and disposal was immediately suspended. By 1995 over 100 Mg of waste had been accumulated with no viable means of disposal identified. Maximum doses have been calculated from the highest air sampling results, Various measures reduced the doses from the range of 20 to 30 mSv per year during 1990 to 1992 to about 10 mSv in the years after 1993. Again doses could be drastically reduced to less than 5 mSv byy the introduction of a new raw material that has a lower NORM content. This facts support our general observation once more that the import and handling of NORM materials was subject to intensive radiation protection measures about 10 to 15 years ago. Thereby the characteristic data of the imported materials concerning naturally occurring radionuclides have been lowered to an issue of less sensibility.

5 Exposure Scenarios

5.1 General aspects

As a general statement the observation has to be stressed that the values given in the literature for specific activities of several raw materials vary in a wide range, especially if materials of different origin are compared with each other. Another reason for this observation may be that the degree of beneficiation of raw materials close to the place of extraction is not clearly defined. This results in different upgrading processes of the raw material and different specific activities, consequently. It is e.g. well known that companies extracting and beneficiating zircon ores are looking for disposal of tailings with elevated specific activities [49]. Furthermore, the most up-to-date activity data are not always published for economic reasons, and the tabulated older values are not valid any more because materials with comparatively high radiation activities which were processed in former days are avoided by the process industry nowadays.

A number of times a scrap yard discovered a container with an elevated exposure rate, as indicated by the gate monitor. Objects (tubing, valves) in the container originated from the fertilizer industry. The objects were found to be contaminated with scale, appearing in the form of $CaSO_4$ (phosphogypsum). In some cases the scale formed a thin layer (<1 mm) which was less easily removable than thicker layers. The Dutch Inspectorate of the Environment (IMH) who was in charge for this event, reported on the offence for the fertilizer plant originally in possession of the objects. In another event it is reported that the Th-232 decay chain of Baddeleyite was found out of secular equilibrium. Therefore the 100 Bq/kg limit was applied instead of the 500 Bq/kg limit which was to be applied for ore concentrates in secular equilibrium. It is known that ores have already undergone some treatment as grinding or removing of undesired by-products by using separation techniques as shown in Figures 2 and 3. IMH decided to perform additional investigations before implementing the limits as to clarify which process was responsible for the observed disturbance [14].

These excemption levels are formulated in the Euratom BSS Directives 80/84 [3]. As far as non-secular equilibrium observations are concerned it must be emphasised that processes as leaching will influence the equilibrium between nuclides. For instance, the highly soluble Ra is dissolved to a much greater extent and at a far higher rate than U isotopes. As a result, Ra-226 is starting its own decay series independently from the U-238 decay. In addition, the Ra-226 progeny Rn 222 as noble gas can escape into the atmosphere and cause again a break of the decay chain. Such phenomena are not only observed with metal sands, but also with phosphate ores and products for which accumulated radioactivity within stocks was observed [15].

In the context of the above mentioned “green acid” as alternative raw product of the wet phosphoric acid production, the equilibrium is disturbed by the lacking Ra-226 decay nuclides which go with the removed phosphogypsum. This is of importance when consequences of the discharges from production plants are discussed. The production places publish their results in the relevant literature either from North England (Whitehaven),[47] from Sweden [25] or from Southwest Spain [26]. As a consequence of 2 million Mg of gypsum waste annually from the Dutch fertilizer industry, the Health Council of The Netherlands was advised by a special Committee on searching an acceptable destination for this waste. The advice given by this Committee to the Dutch government is discussed in more detail in Chapter 7 [27].

5.2 Specific activities

As a consequence of radionuclides being separated into different streams during the acidulation process, the activity concentrations in the phosphate fertilizers depend on their type. If e.g. the phosphoric acid alone is used as the source of phosphorus in the production of ammonium phosphate fertilizers, the activity of Ra-226 will be relatively low compared to U-238. If phosphorus is supplied from both phosphoric acid and phosphate rocks (TSP), the product will exhibit higher concentration of both Ra-226 and U-238. In the production of normal (single) superphosphate SSP, there are no chemical reaction by-products. The proportions of activity concentrations of natural radionuclides are preserved and characteristic for the phosphate rock used. Radiological data for fertilizers are summarised in Table 4.

The specific uranium activities of phosphate ores differ as a consequence of their origin. The typical value for their activity is 1.500 Bq/kg, ranging between 800 and 2.000 Bq/kg. However, Russian deposits of Apatite come from igneous rock and present a much lower specific activity for uranium of 70 Bq/kg. The Th-232 activities are generally smaller and amount to 20 to 80 and 100 Bq/kg, respectively. These differences are reflected in the specific activities of the phosphogypsa which are mainly dominated by the Ra-226 and Th-232 activities. The Ra-226 contribution ranges between 500 and 2.000 Bq/kg. The Th-232 values vary between 10 and 60 Bq/kg [42]. The radiological data of the calcium silicate slag of the thermal process are results of the high process temperature of 1.500 ^{o}C. Most of the uranium and decayed radium product is retained within the slag, whereas the volatile radionuclides Pb-210 and Po-210 are released to the process gas. The analyses of the process slag confirm these data. Furthermore, the content of both these radionuclides in the slag increases with time as consequence of their reformation. These two nuclides are indeed found in the volatilisation residues. Thus, the radiation protection administration monitored workers close to that installation. The activity concentrations of both nuclides were in the range of 50 to 500 Bq/kg.

The specific activities of various raw materials and of several side-products formed by certain chemical or physical processes are summarised in Tables 5 and 6. The data of Tables 4 to 6 clearly shows that the indicated specific activities of several materials differ distinctly. In order to prepare for the calculations of exposure scenarios, a mean and maximum value are selected, respectively (Table 7). Taking the maximum values into account, a first result is obtained for the upper dose expected. A recalculation with the mean value is executed in case that the dose resulting from the maximum specific activity is essentially higher than a dose of 1 mSv corresponding to the lower regulatory limit as described in Chapter 5.

Fertilizer	**Concentration**			**Specific activity**	
	N	**P_2O_5**	**K_2O**	**U-238 decay**	**Th-232 decay**
	%	**%**	**%**	**[Bq/kg]**	**[Bq/kg]**
Single Super Phosphate, SSP	20				
Germany				300-500	15-40
Belgium				900-1100	20
Triple Super Phosphate, TSP	40-50				
Germany				200-800	15
Belgium				800-2000	15
PK[1]-Fertilizer	0	15	20	400	10
NPK[1]-Fertilizer	15	15	15	600	10-20
[1] N : nitrogen, ammonia P: phosphorus, phosphate K: potassium					

Table 4: Specific activities of fertilizers ([31, 42, 48])

Raw Material	**U-238 decay [Bq/kg]**	**Th-232 decay [Bq/kg]**
Phosphate rock		
• Sedimentary origin	up to 5.000	up to 80
• Igneous origin	up to 100	up to 100
Zircon sands	up to 60.000	up to 10.000
Aluminium ore	40 - 500	50 - 400
Copper ore	30 - 70	5 - 50
Ferro-niobium	17.000	

Table 5: Specific activities of raw materials ([10, 33, 42])

Processing by-products	**Specific activities**		
	U-238 [Bq/kg]	**Th-232 [Bq/kg]**	**Ra-226 [Bq/kg]**
Phosphogypsum from phosphate wet processing :			
• Observation of a French Company	14 %	30 %	80 %
• Central Florida rocks			˜ 1.100
• Average values of various measurements	100 - 200	10 - 40	500 - 1.700
Phosphate thermal process / calcium silicate slag	˜ 5.000	2.700	2.300
Aluminium / Red sludge	300	400	250
Copper / slag		100 - 200	300 - 1.500
Iron slag		100	
Tin slag	250 - 5.000	250	1.000

Table 6: Radiological data of by-products ([42])

Dose initiating material	**Appr. density [Mg/m^3]**	**Nuclide**	**Mean specific activity [Bq/kg]**	**Maximum specific activity [Bq/kg]**
Raw materials				
Phosphate ore	3	Th-232→Tl-208	50	100
		U-238→Po-210	2.000	5.000
		K-40	100	250
Zircon sands	5	Th-232→Tl-208	700	4.000
		U-238→Po-210	4.000	30.000
Aluminium ore	3	U-238→Po-210	300	500
		Th-232→Tl-208	100	400
Copper ore	4,6	U-238→Po-210	40	80
		Th-232→Tl-208	30	100
Pyrochlore (Ferro-niobium)	5,3	U-238→Po-210	17.000	
Products				
Fertilizer, SSP	2,4	Th-232	20	40
		Ra-228→Ac-228	10	
		Th-228→Tl-208	10	
		U-238	500	1.100
		Th-230	670	800
		Ra-226	300	850
		Pb-210→Po-210	300	500
		K-40	140	170
Fertilizer, TSP	2,4	Th-232	45	50
		U-238	800	2.000
		Th-230	500	
		Ra-226	200	230
		K-40	30	50
PK-fertilizer	2,4	Th-232	10	20
		Ra-228→Ac-228	10	20
		Th-228→Tl-208	8	10
		Ra-226→Po-210	200	350
		K-40	5000	6200
By-products				
Phosphogypsum	2	U-238→Th-230	200	500 (Spain: 900)
(Ra-enrichment)		Ra-226→Po-210	600	2.000 (Spain: 2.700)
		Th-232	20	60
		Ra-228→Ac-228	70	100
		Th-228→Tl-208	20	60
Calcium silicate slag (Phosphate thermal process-Pb-volatilization	2,5	U-238→Po-214	2.000	4.000
		Pb-210→Po-210	200	400
		Th-232→Tl-208	400	1.000
Red sludge (Iron-sludge from aluminium refining)	1,5	U-238→Po-210	250	500
		Th-232→Tl-208	300	500
Copper slag	3,5	U-238→Po-210	800	1.500
		Th-232→Tl-208	80	200
Tin slag	3,5	U-238→Po-210	500	4.000
		Th-232→Tl-208	250	5.000

Table 7: Mean / maximum values of specific activities [32, 42, 48]

5.3 Exposure scenarios

Based on the materials and their mean activities summarized in Table 7, model calculations have been performed in order to assess the radiological consequences of typical scenarios and to identify the materials most dose relevant. These scenarios include:

- dose uptake of operating personnel due to direct gamma radiation
- dose uptake of operating personnel due to dust inhalation
- dose uptake resulting from material transport
- dose uptake of operating personnel and public resulting from material dumping
- dose uptake of public resulting from use of fertilizer products
- dose uptake of public resulting from use of Phosphogypsum in wall covering plates

An overview of materials and scenarios considered is shown in Figure 5.

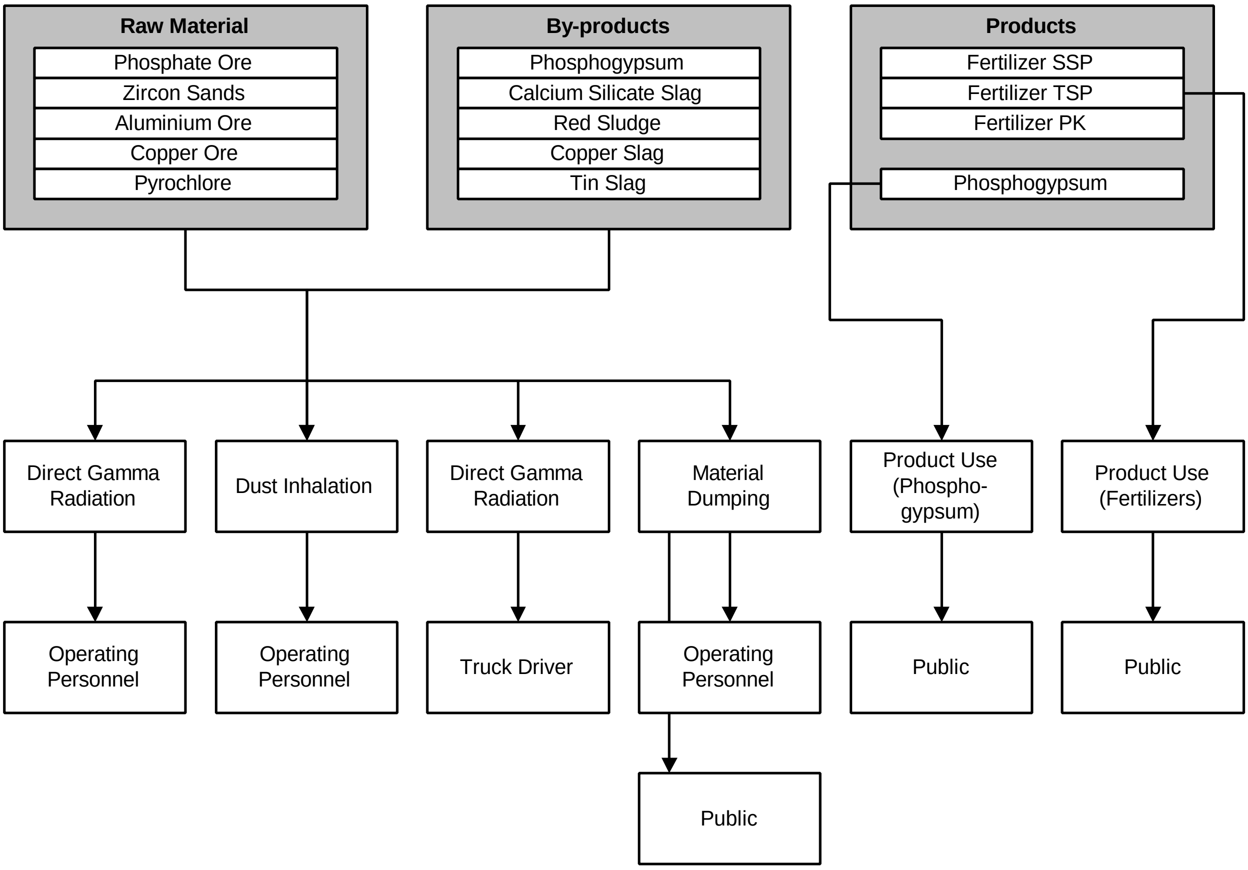


Figure 5
Overview of materials and scenarios considered for the assessment of radiological impact

5.3.1 Radiation exposure of operating personnel due to gamma-radiation

Gamma radiation from various materials handled or stored in chemical plants can cause dose uptake to the operating personnel.

The dimensions and locations of corresponding stockpiles or vessels containing natural radioactive substances vary considerably and cannot be modelled in detail.

Normalised dose rates in µSv/h*Bq at 1m, 2m and 5m distance from a standard model vessel were therefore derived for specific radionuclides on the basis of a cylindrical source (1m diameter and 1 m high, approx. 0.75 m^3), taking account of zero and 5 mm vessel wall thickness. This model is also conservative for larger vessels or stockpiles with the same activity. Thus it covers all sizes of accumulated material in a conservative way.

In the model calculations performed it is assumed that a worker spends 2000 hours per year in a distance of 2 m from a volume of 10 m^3 unshielded material with the mean activity concentrations as specified in Table 7. Mean activity concentrations were taken because during the long observation period of 1 year possible fluctuations will averaged.

The results can be scaled according to the particular conditions. The are:

- proportional to the exposure time (2000 hours are an upper annual limit)
- proportional to the material mass (this is a conservative approach)

The nuclide specific results are presented in Table 10.1 in the Appendix. Those radionuclides showing extreme low γ-intensities in their spectra are not taken into account.

A graphical representation of the total effective doses resulting from the considered materials is given in Figure 6.

Even under the selected unfavourable conditions the resulting effective dose does not exceed 100 µSv/a.

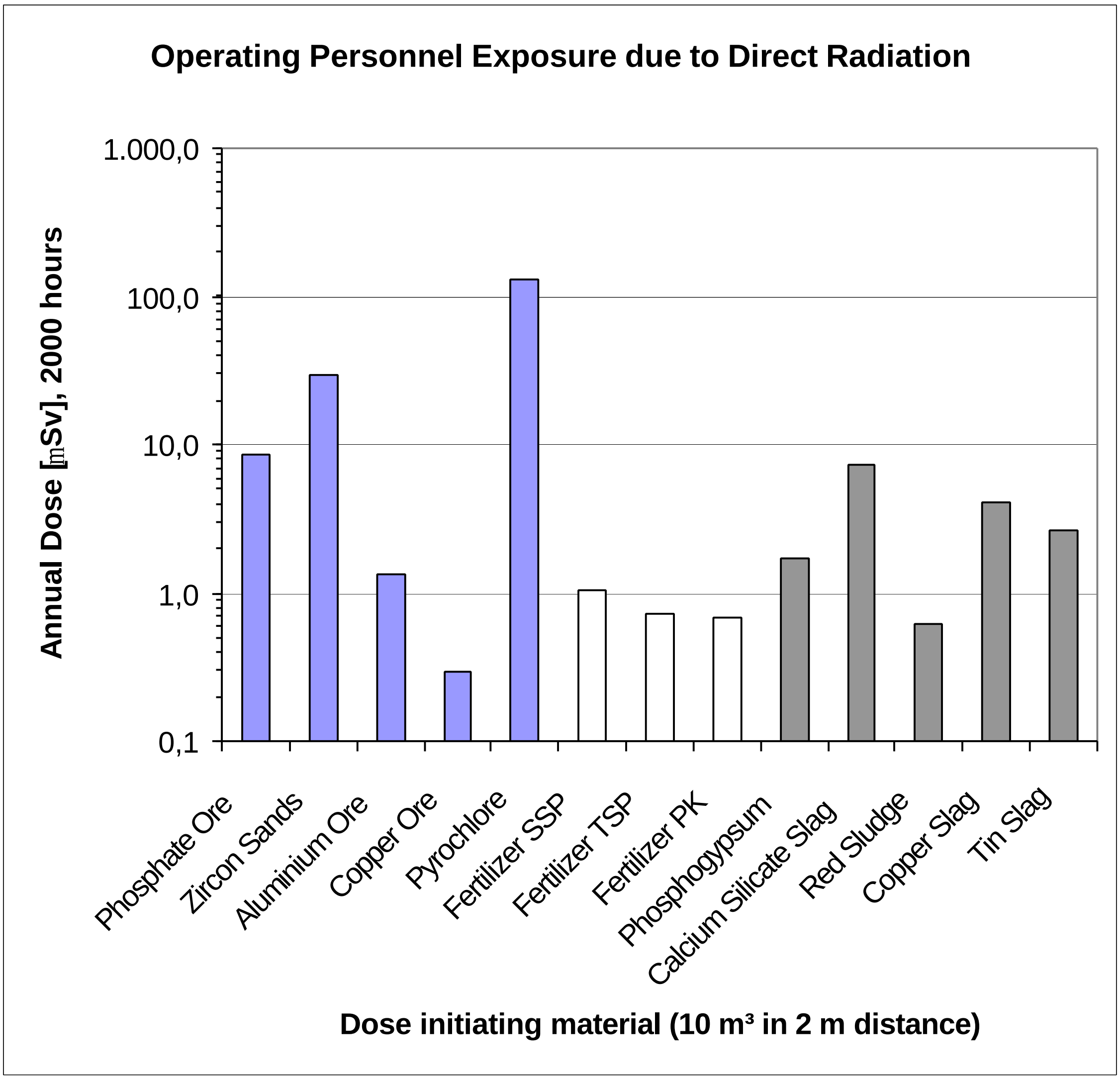


Figure 6
Annual effective doses for operating personnel resulting from direct gamma radiation of various materials

5.3.2 Radiation exposure of operating personnel due to dust inhalation

As a consequence of mechanical treatment of materials or other dry processes in a chemical plant, small particles are created which are released into the atmosphere of rooms in the chemical plant. The fine fraction of such particles can form stable aerosols which are inhaled by the operating personnel leading to a corresponding radiation dose uptake.

The concentration of such dust depends on the ventilation and conditioning of the air. According to German regulations, a general upper limit of 6 mg/m³ exists for the concentration of fine dust at workplaces, much lower limits exist for dangerous or toxic substances.

In the scenario considered here it is assumed that the operating personnel is exposed to a mean dust concentration of 0,1 mg/m³ during 2000 hours per year.

The results can be scaled according to the particular conditions. The are:

- proportional to the exposure time (2000 hours are an upper annual limit)
- proportional to the dust concentration

The nuclide specific results are presented in Table 10.2 in the Appendix. A graphical representation of the total effective doses resulting from the considered materials is given in Figure 7.

The results show that inhalation of dust can lead to a considerable dose uptake by the operating personnel. Depending on the material, the values vary between 1 and 100 mSv per year and exceed 100 mSv in the case of Pyrochlore.

Even though the used annual exposure time of 2000 hours represents an upper limit, the dust concentration of 0,1 mg/m³ can be considered realistic.

Dose uptake by dust inhalation is the major potential contributor to radiation exposure caused by natural radioactive material in the chemical industry.

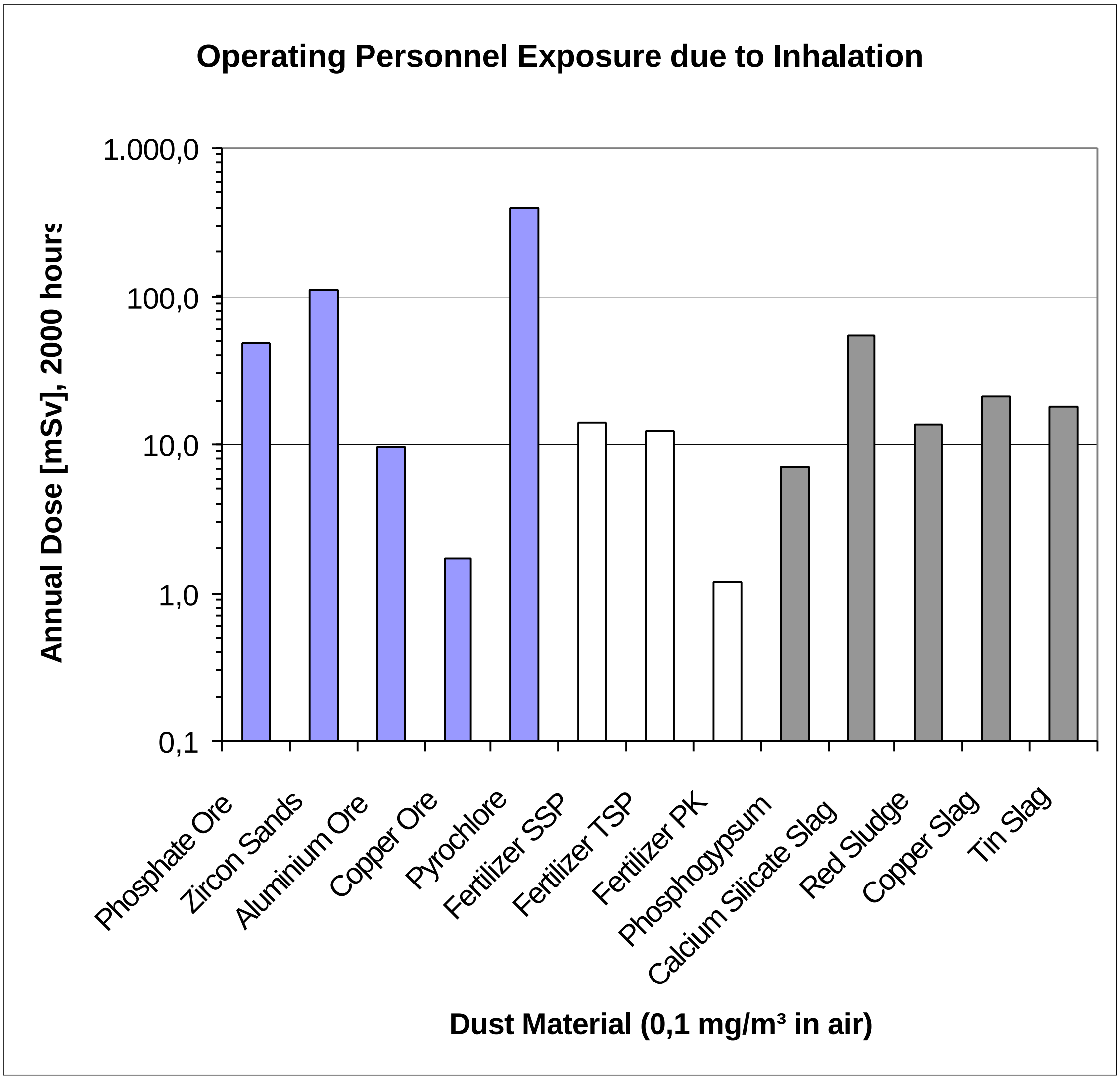


Figure 7
Annual effective doses for operating personnel resulting from inhalation of dust consisting of various materials

5.3.3 Radiation exposure due to transport of material

The various raw materials, by-products and products need to be moved either to the disposal site or to other facilities where they are further processed or used. In the selected scenario it is assumed that this transport will be performed by trucks.

Dose uptake due to material transfer includes:

- dose uptake by the driver due to external gamma-irradiation
- dose uptake by members of the public living alongside the transport route due to external gamma-irradiation.

Driver dose uptake

It is assumed that the driver undertakes 200 transports per year, whereby each transport covers an average distance (one direction) of 100 km taking roughly 2 to 3 hours. This would result in an exposure duration of approximately 600 hours per annum. A typical load would be 20 Mg of material per truck transport.

The nuclide specific results are presented in Table 10.3 in the Appendix. A conservative dose uptake estimate of maximal 15 µSv/a for transporting various materials is indicated. This estimate is based on an assumed 2 m distance between the driver and the radiation source, any shielding effects between the driver and source being ignored.

The results of the exposure calculations are shown in Fig. 8 for the different materials under consideration.

Public dose uptake

Assuming that the truck transporting the material moves past an individual stationary member of the public at 10 m/s (36 km/h), then an exposure time of approximately 1 second per transport results for a truck length of 10 m. It is further assumed that the individual stationary member of the public is at an effective distance of 5 m from the tanker and any shielding effects between the sludge and person are ignored.

Assuming again 200 such transports per annum, the maximum exposure time for an individual member of the public from these transports would be 200 seconds per annum.

This exposure time is by a factor of 10.888 lower than the driver’s exposure time. Taking also into account the higher effective distance (5 m assumed instead of 2 m), the resulting dose to a person of the public is very small (<< 1 µSv/a) and can safely be neglected.

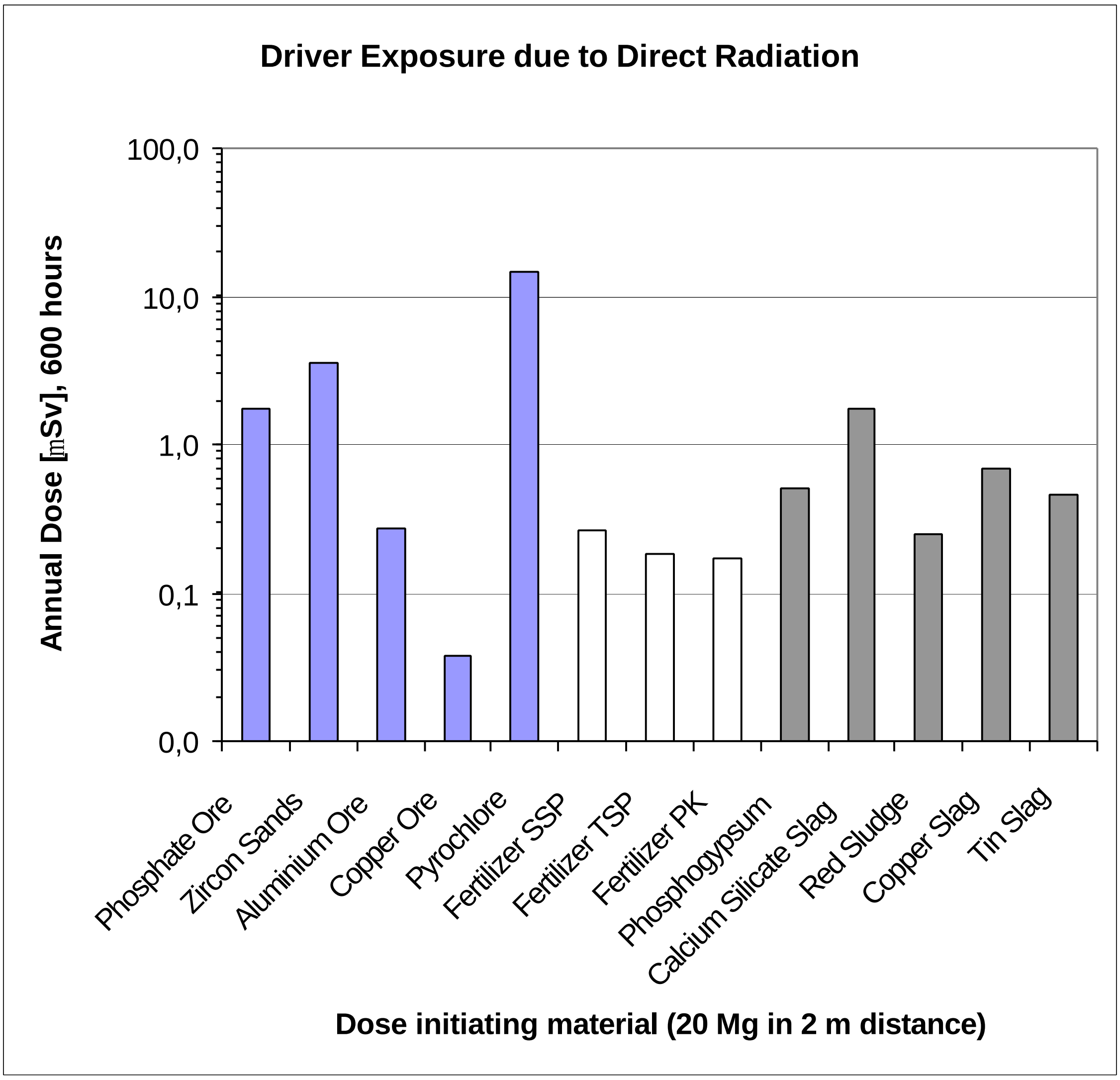


Figure 8
Annual effective doses for truck driver personnel resulting from direct gamma radiation during the transport of various materials

5.3.4 Radiation exposure resulting from material dumping

For intermediate or final storage, materials are unloaded at storage sites which are supposed to be located outside the chemical plants.

The pathway for dose uptake (workers and public) from the radioactive content of materials considered here is the re-suspension during unloading (dumping) of the transport vehicle at a disposal site.

It is assumed that unloading causes the generation of aerosols within the respirable range AMAD (aerodynamic median activity diameter) 10 µm or less. For a conservative drop height of 3 m a release factor of 1E-4 is considered appropriate.

The release source term per unloading event is based on the radioactive content of 10 m^3 dry substance. Radiological exposure is due to inhalation and ingestion of the released activity.

It is assumed that a disposal site worker in a distance of 10 m from the unloading vehicle is exposed to the radioactive aerosols generated during unloading, and that a person of the public (adult and infant) is located at the fence of the facility which is assumed to be in a distance of 100 m.

The duration of the unloading is considered to be less than 0,5 h, in which period the whether conditions can be assumed to be constant. Both worker and persons of the public are assumed to be located in the wind direction. As already mentioned above, the emission altitude is assumed to be 3 m.

The exposure paths considered are β-/γ-submersion, ground radiation, and inhalation. For the evaluation of the exposure of the public, the ingestion path has in addition been considered. More details of the dispersion and exposure models used are presented in appendix, chapter 10.2.

The results of the dispersion and exposure calculations are shown in Table 10.4 and in Fig. 9 for the different materials under consideration.

These results show that the exposure resulting from one unloading event does not exceed the order of magnitude of 100 µSv for all types of materials and for all exposure groups even under the very conservative assumptions made.

In the case of the public, it is not reasonable to assume that the same persons will attend all unloading events at the point of worst case dispersion conditions, and therefore the worst case single event dose can be assumed to represent the annual exposure due to unloading.

The worker, however, can in principal be the same person attending many unloading events, and the maximum dose for him is then given by the product of single event dose and the number of unloadings per year. This value then needs to be modified for taking into account average whether conditions (probability for the wind direction and wind velocity). Considering this, the annual dose of a disposal site worker can be expected to amount to less than 1 mSv.

Resuspension of dumped material could also lead to radiation exposure of members of the public. This material, however, is likely to be covered with other materials on disposal sites, thus reducing the resupension probability considerably. As average weather conditions are to be used in this case, additional significant reduction of the resulting radiation exposure to the public can be expected, compared with the dumping scenario. The same effect will result from the fact that members of the public will stay or live at higher distances from the dumping site. This scenario has therefore not been evaluated in detail.

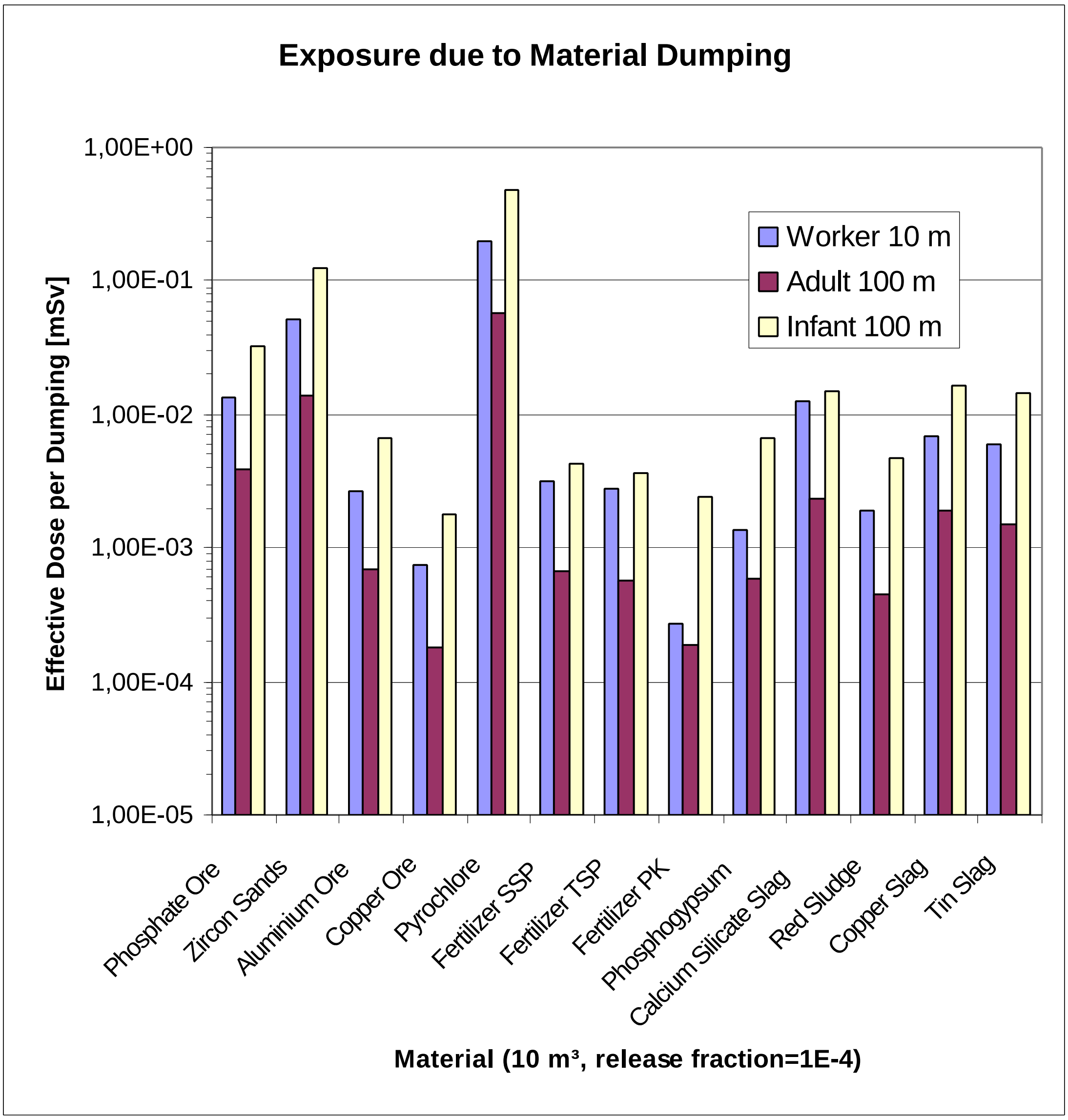


Figure 9
Effective doses for operating personnel and public resulting from dumping of various materials

5.3.5 Radiation exposure due to fertilizer use

In order to gain a general overview, the radiological impact resulting from the intended use of the fertilizer products has also been studied.

In this scenario, the fertilizers are spread on land thus leading to a surface contamination which depends on the radionuclide concentration in the fertilizer and on the thickness of the layer on the land. The use of this land for agricultural production (vegetables, animal products) will then lead to an exposure of the public via the ingestion path. In this scenario, spreading 0,02 kg of fertilizer per m^2 is assumed according to the recommendations of the manufacturers (200 kg/ha).

The results of the exposure calculations are shown in Table 10.5 and in Figure 10 for mean radionuclide concentrations of the 3 fertilizers under consideration.

It can be seen that the resulting doses are in the range of 0,1 to 1 mSv per fertilizer application and do not vary very much for the different fertilizer types.

The dose values given are accumulated over 50 years of exclusive nourishment from products grown on the fertilized land. This is a very conservative assumption. But since fertilizers are applied to most of the agriculturally used land every year, the results may be not far from reality.

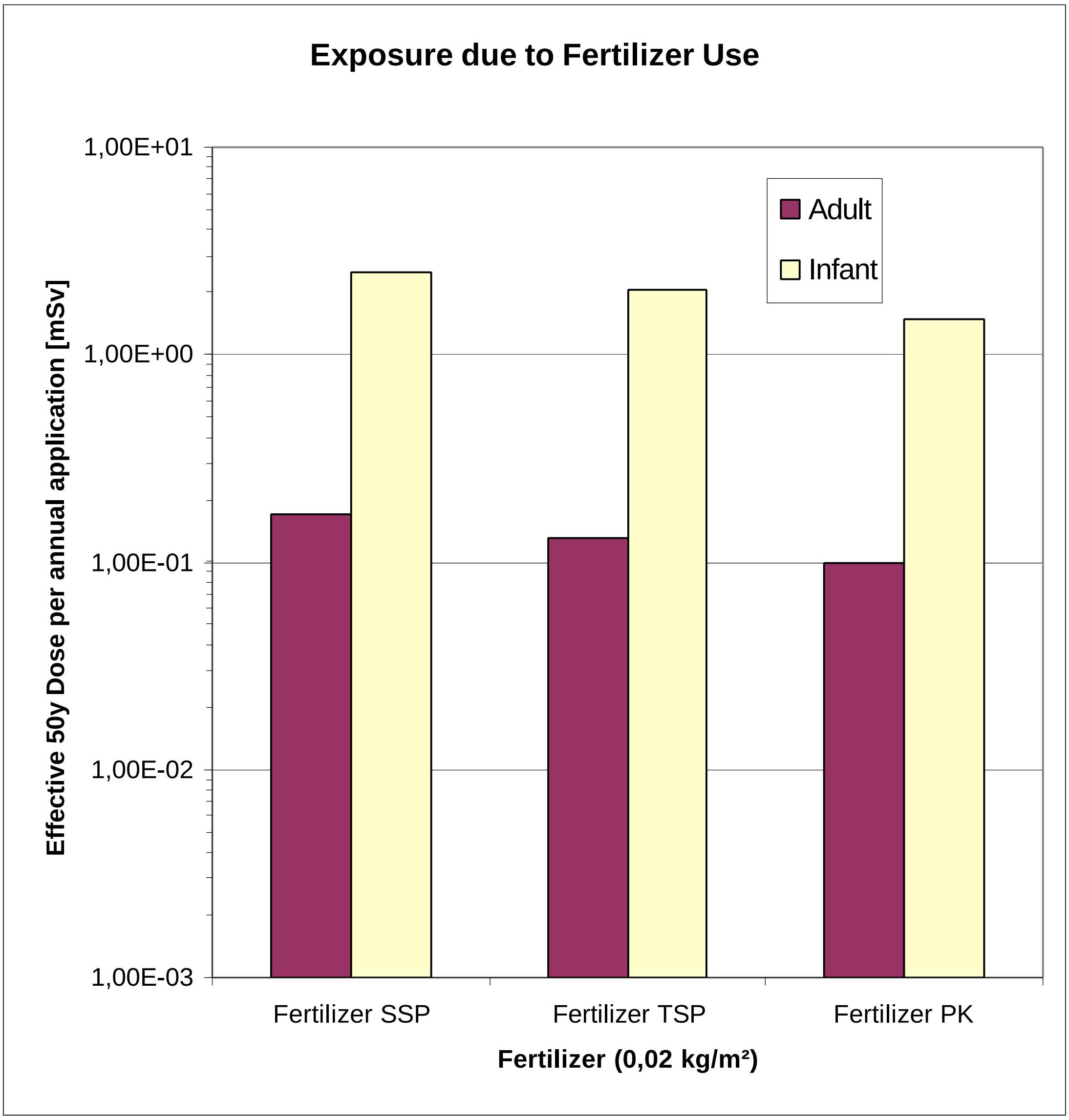


Figure 10
Effective doses (50 years ingestion) for the public resulting from the use of different fertilizers

5.3.6 Radiation exposure due to Phosphogypsum use

Phosphogypsum may be used as wall covering plaster material in homes and thus cause radiation exposure to the public by direct gamma radiation. In order to obtain a conservative estimate of this exposure, the following scenario has been studied:

- all walls and the ceiling of a room with an area of 4 m * 5 m = 20 m² and a height of 2,5 m is covered with Phosphogypsum plaster of 1 cm thickness, resulting in a total mass of 1,3 Mg (density 2 Mg/m³)
- a person stays permanently in this room (8760 hours per year)
- the average distance of the person to the surface (radiation source) is 2 m

Under these conservative assumptions, the resulting radiation dose is 0,5 µSv per year. The nuclide specific detailed results are presented in Table 10.6.

The radiation risk resulting from the use of Phosphogypsum therefore can be considered negligible.

5.4 Conclusion of chapter 5

The advantage of the very simple scenarios chosen is the direct comparability of the results across the various industries (see results overview given in Fig. 11) . A few conclusions can be made here:

- Staff exposure is dominated by inhalation of material dusts, mainly in stores, with a maximum of about 400 mSv per year in case of Pyrochlore. Contributions by external irradiation or material dumping activities are lower by roughly a factor of 1,000 and do not need any further consideration or concern. This includes the decontamination of equipment as well as the external irradiation from contaminated equipment. The reason is that there is no dry decontamination used, i.e. no dust inhalation possible, and the equipment walls provide some shielding.
- Comparing the inhalation exposure across the industries and process ranges, it is apparent that the raw materials and the residues are the main contributors to staff exposure. However, their contributions are at least five times smaller than the main exposure cause ‘Pyrochlore’. The products themselves do not contribute at all but for the fertilisers. Reasons are that most of the other products (metals) do not generate powder or dust.
- It is to be mentioned that a more specific and less generic approach to scenario modelling and exposure estimating would certainly result in more realistic and lower exposure assessments.
- Even the largest exposures (effective dose per year) resulting from dumping are by a factor of 1,000 smaller than the staff inhalation exposure data. The highest value are, again for Pyrochlore residue dumping, for infants in the general public at 0.4 mSv, for staff at 0.2 mSv, and for adult members of the general public at 0.06 mSv.
- The use of phosphate based fertilisers causes – in the considered scenario – an effective 50 y dose equivalent to the indivdual member of the public of maximally 1.5 mSv for infants and of 0.1 mSv for adults.
- The use of Phosphogypsum as wall covering plaster material in homes leads to a relatively low annual exposure of the member of the public of 0,5 µSv.

An overview of the annual radiation exposures derived for the particular scenarios is given in Fig. 11. The values shown represent the maximum and minimum values for the considered materials. In the case of dumping, it is assumed that the annual exposure to a worker is 10 times the value of one dumping since the worker will avoid the dust cloud in the wind direction. A member of the public will attend only one dumping per year. The fertilizer use results are divided by 50 in order to obtain annual values.

Concern is caused almost exclusively by the dust inhalation dose of staff. This, however could considerably be reduced by dust prevention measures as well as by the use of efficient respirator masks and by reduced time of presence in the storage rooms.

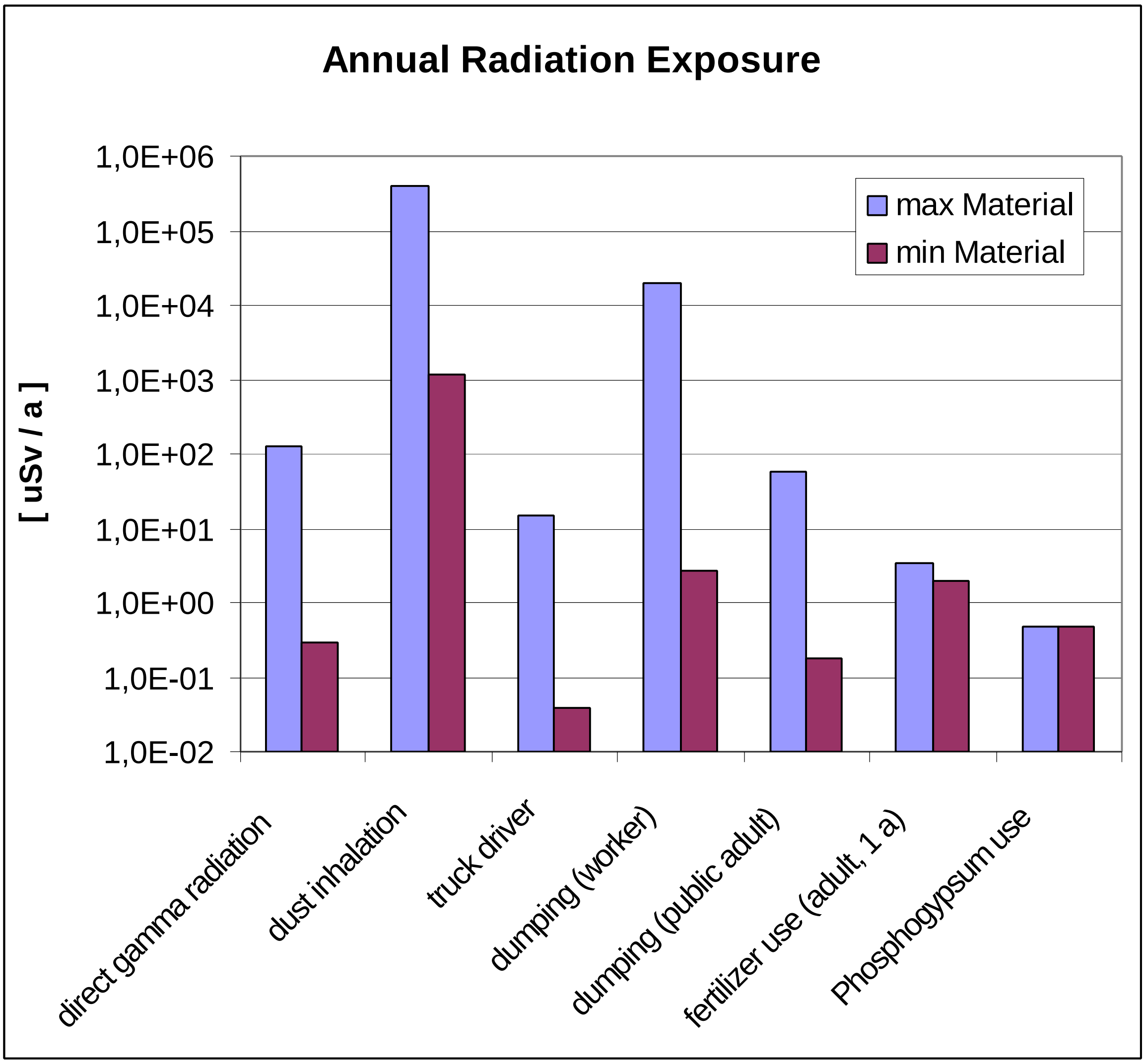


Figure 11
Overview of exposures in the studied scenarios

6 Assessment of Radiological Consequences

Reference levels for the regulatory control of workplaces involved exposed to NORM radiation were proposed by a joint expert working group of the UK National Radiological Protection Board (NRPB) and the French Centre d´Evaluation de la Protection Nucléaire (CEPN). In order to meet this objective, a method had to be developed for the generic assessment of workplace exposure caused by materials containing the elevated levels of naturally occurring radionuclides as described in the previous chapters. The method was used to predict doses from different materials in different industries. Furthermore, it formed the basis to determine a classification system and reference levels for a regulatory control scheme related to the annual effective dose criteria given by the BSS Directive and explained in Chapter 7 [42].

6.1 General aspects of regulatory control

Classification system

A classification scheme presented graphically in Figure 12 of Chapter 7 can be used to define five distinct regions by four reference points. The reference points are, in turn, defined by four criteria:

- the dose criterion for effective dose under normal conditions,
- the dose criterion for effective dose under unlikely conditions,
- the dose criterion for skin dose under normal conditions and
- the dose criterion for skin dose under unlikely conditions.

It is possible to use the four reference points and associated dose criteria evaluated by IRCP recommendations and revised BSS definitions (Title VI, Article 21) together with exposure scenarios to derive nuclide concentrations in various materials that correspond to the four reference points. A first set is called “reference levels”. They are indicator levels that correspond to the four reference points. These reference levels take into account the contributions of other nuclides present in the material. A second set is called “screening levels”. These are nuclide concentration levels that correspond to the four reference points and hence they make no allowance for any other nuclides present in the material. These reference levels and screening levels are obtained by selecting the minimum of the four concentrations that correspond to the four reference point criteria.

It is envisaged that screening levels are used to give a first estimate of the classification of a particular workplace. This would then be followed by an analysis of the radionuclide composition of the material used at the workplace and a more precise classification of the workplace using the reference levels. Screening levels are the easiest to use as it is only necessary to compare the concentration of the screening nuclide segment in the material with the values given in the corresponding table. Screening levels contain generic assumptions about the relative abundance of the natural decay chains and their state of equilibrium. Therefor, the classification of specific individual workplaces must take into account specific assumptions which reflect the actual particular circumstances. Hence, the need for such recalculation may arise if the national authority finds that the activity concentrations used in a study do not adequately reflect the types of raw materials or by-products characteristic in that country.

Derived levels as basis for the description of reference levels

Before describing the derivation of reference levels, it is necessary to introduce the concept of derived levels. A derived level for a particular material is the radionuclide concentration that gives rise to a certain dose, the dose criterion. The derived level always refers to the concentration of a single radionuclide or the concentration of the head of a decay chain segment, but the actual value may or may not allow for the contributions from other radionuclides that are present in other chains or chain segments. Different types of derived levels can, therefore, be obtained from information on the dose per unit activity of radionuclides and chain segments and the typical states of equilibrium of the natural decay chains for different materials and industries.

There are three different types of derived levels that can be used:

Derived nuclide level

The fundamental derived nuclide level relates the activity concentration of a single nuclide or head of chain segment to a dose without taking into account any radionuclides in other chains or chain segments. It should be noted that the derived nuclide level for members of the segment is equal to the derived level for the parent nuclide of the segment, multiplied by the appropriate factor taking into account the state of equilibrium within the segment.

The derived nuclide levels are very useful when only a single radionuclide or chain segment is present in a material, but they do not take into account contributions from other radionuclides (segments) or other chains.

For natural radionuclides it is normal that the entire decay chain is present. It is made up of several nuclides (segments) each having a particular activity and these need to be taken into account.

Derived chain level

The contribution of other radionuclides in a decay chain can be incorporated directly by defining a derived chain level. This is done by incorporating an appropriately realistic state of equilibrium between the segments of the chain. The state of equilibrium is expressed by the activity of a nuclide (segment) relative to the activity of the head of the chain.

To facilitate application, it is focussed on three chain levels, one for the head of each of the three natural decay chains. They are expressed in terms of the concentration of the corresponding parent nuclide, uranium 238, thorium 232 and uranium 235. In some materials these parent nuclides are not present. So it is stated in terms of the head of the part of the chain that remains. The derived chain level DL_{ch} applies to the head of the segment and every nuclide in the segment, multiplied by the appropriate factor taking into account the state of equilibrium within the segment. The derived chain level for any other nuclide (segment) can be obtained by multiplying the relevant DL_{ch} by the activity of the nuclide (segment) relative to the activity of the head of the chain in the considered state of equilibrium. By this calculation any radionuclide (segment) in a decay chain can be compared with its derived chain level. Other radionuclides present in the decay chain are automatically taken into account. In other words, if the Th-232 chain is in the assumed state of equilibrium then it is only necessary to compare the Th-232 concentration with the Th-232 chain level to see if the dose criterion will be exceeded. However the contributions from the two other natural decay chains will still need to be considered, correspondingly.

Derived indicator level

The derived indicator level takes into account the contributions from radionuclides in all natural decay chains, considering a particular state of equilibrium in each chain, and a particular state of ratio of activities between chains. The contributions of radionuclides in all the natural decay chains can be taken into account in such a derived indicator level. Each radionuclide (segment) is assumed to have a given activity relative to the head of the reference chain.

The derived indicator level is expressed in terms of a particular nuclide (segment) and it is focussed on a few nuclides (segments). A derived indicator level for any nuclide segment may be used as an indicator for all the radionuclides present. As only a single nuclide needs to be compared to its derived indicator level these values are the most simple ones to refer to for regulatory purposes.

Reference levels and exposure scenarios

Reference levels are derived by considering particular combinations of derived levels obtained by using different dose criteria and assumptions. They are expressed in terms of nuclide levels (screening levels) or indicator levels (reference levels). In order to define the reference levels for materials with enhanced quantities of naturally occurring radionuclides, a set of exposure scenarios and pathways is to be prepared which describe the situations in which an individual could receive a significant radiation dose.

The U-238, Th-232 and U-235 decay chains each contain a number of radionuclides, giving a total of approximately 40 radionuclides over the 3 chains. A number of these radionuclides are very short-lived, with half lives of less than one year, and these can be considered to be in secular equilibrium with their parent radionuclide. This means that the chains can be simplified into a smaller number of key radionuclides and chain segments.

It is necessary to identify situations in which a worker receives the highest exposure from each material that poses a radiological hazard in each industry. In general the highest doses from concerned pathways occur when a person is in one of the following situations:

Pathway	**Most exposed situation**
Inhalation of dust:	In dusty conditions with little respiratory protection
External irradiation:	Close to large amounts of material with little shielding
Inhalation of radon:	In a room with large amounts of the material and little ventilation

Such considerations identify the work task or situation which would likely lead to the highest dose from a particular material. Although it can be attempted to base data on actual working practices, this information may be difficult to obtain and often unreliable. Therefore, in most cases appropriate generic scenarios are used and modified in some way to reflect specific conditions. These scenarios are developed by considering the likely work activities that may occur with three broad categories of material: stockpiles, residues and material in vessels or pipes.

- Stockpiles of material

  A worker is exposed to the radiation emanating from the material whilst working in a storage facility containing a very large quantity of the material. The worker spends most of his time in the facility, close to the material, breathing and taking in dust generated during loading or unloading the material.

- Residues and scales

  The worker is exposed when removing residues, i.e. cleaning pipes or vessels. The worker performs this operation infrequently for almost regular periods (for instance a day per week or an hour per day), but is exposed to high concentrations of dust in the handling procedure. The quantity of material present is usually between a few kg and a few t. Any quantity of residues larger than this could be treated as a stockpile. Some respiratory protection was assumed in the normal set of assumptions.

- Process material in vessels and pipes

  Workers are quite likely to be “incidentally” exposed to radiation from material in pipes and vessels for a significant fraction of their working year. However, the only exposure pathway is by external irradiation, and there is some shielding from the pipe or vessel walls.

The value of applying such reference levels can be seen in the quick availability of guidance. Thereby an ad-hoc decision can be made which is later followed by a more precise and specific calculation based on the individual character of the concerned material. For this purpose, a table of such reference levels is compiled to give an impression of the values forming the basis of the regulatory classification system presented in Figure 12. For an easy understanding of Table 8 the five regulatory levels are used from low level – no intervention necessary(1) - to the highest level – continuation of work interdicted (5).

Doses and important pathways

Using a variety of typical exposure scenarios and a range of activities as presented in Table 7 the dose to a worker from the different discussed materials can be estimated. Under the general assumptions the results cover a wide range of doses, between a few hundred μSv/a and a few hundred mSv/a. In all concerned industries the estimated exposures for unlikely assumptions and maximum concentrations might be above 1 mSv/a, the dose limit for members of the general public. Typically the materials which give rise to the lowest doses are lead and polonium precipitates. The highest doses arise from exposure in warehouses storing materials with high concentrations of Th-232 decay series radionuclides.

In general, the most important exposure pathway is radon and thoron (the radon nuclide Rn-220 from the Th-232 decay chain) inhalation from storage in a warehouse. This is because materials are often in a crushed or powdered form, which allows the radon to escape more easily, and stored in poorly ventilated spaces that allow radon and thoron (the radon nuclide Rn-220 from the Th-232 decay chain) concentrations to build up. However, it must be noted that the radon concentration in room atmospheres may substantially vary as it very strongly depends on a wide range of parameters (emanating fraction, dose equilibrium factor, dose conversion factor, ventilation rates, room size, surface to volume ratio, diffusion coefficients).

In cases where there is a dusty atmosphere the exposure pathway via inhalation of dust is also a major contributor to the total dose. This is evident in scenarios where dusty residues are being removed, or the general working environment is quite dusty due to the type of processing (such as any process where dry, fine particles are handled and dispersed).

The external irradiation pathway may be important if there are large amounts of material or if the material contains radionuclides which have high yield high energy gamma emissions, such as the short-lived decay products of Ra-226. A particularly important case is residues in which radium had precipitated.

Typically, all these derived levels, derived nuclide and derived chain levels, are in the range of a few tenths of Bq/g to 10 Bq/g. Certain exceptions exist, such as the exposure to lead/polonium precipitate. Two points are worth noting. Firstly, when all the different materials are taken into account there is a wide range of derived nuclide levels for the same nuclide. This means that it is important to produce material specific derived or reference levels. Secondly, skin doses are never the limiting factor in determining the derived levels.

These two sets of derived levels have been used to obtain derived indicator levels using the activity concentrations of the corresponding material. Where either the state of equilibrium in a radionuclide chain or the relative activities of the three chains is markedly different, the results may afford recalculation of the derived indicator levels to suit the particular type of material.

The purpose of the classification system is to provide a clear link between an activity concentration of radionuclides in a material and the degree of regulatory intervention needed to provide adequate protection of workers from the radiological hazard. Levels of regulation are based on both the limiting dose values and the assumptions made in calculating them: is it a “normal” or an “unlikely” situation.

6.2 Standards and other recommendations

ICRP Recommendations and revised EU Basic Safety Standards

The latest ICRP recommendations, ICRP 60 published in 1991, provide a framework for the protection of workers and members of the public from ionising radiation. There are three main principles: justification, optimisation and dose limitation. Dose limitation is of direct relevance for the derivation of reference levels and a classification system. Justification and optimisation are not relevant in this context. ICRP recommends effective dose limits (to reduce the risk of stochastic effects to tolerable levels): these are 1 mSv/a for members of the public and 100 mSv/a over a 5 year period for workers, with a limit of 50 mSv in any one year. ICRP also recommends skin equivalent dose limits (to prevent deterministic effects) of 50 mSv/a for members of the public and 500 mSv/a for workers. When discussing the classification of workplaces, ICRP recommends the designation of work areas into controlled areas and supervised areas. It recommends that the designation should be based on the expected level of individual annual dose and also that it should take into account likely variations and the potential for accidents. However, ICRP 60 does not recommend a particular value of dose at which a controlled area should be defined.

The revised BSS adopts the dose limits recommended by ICRP. Again, it does not rigidly define controlled and supervised areas in terms of expected dose but it defines two categories of workers: Category A who may receive an effective dose above 6 mSv per year or an equivalent dose greater than 3/10 of the organ dose limits for workers, and Category B who are exposed to lower doses (Title VI, Article 21). More details of IRCP recommendations and the revised BSS are given in Chapter 7.

Existing regulation systems can be helpful in illustrating the types of classification system that are feasible. An analogue may be found in the system of classifying workplaces in the nuclear industry from the radiation protection viewpoint. Four fundamental classes of workplace are considered, all defined by the dose that is received under normal conditions.

If the normal dose received is less than the public dose limit, there will be no additional regulatory requirements placed on the workplace. If the dose is between the dose limit for the public and 3/10 of the worker limit, the area will be designated a “supervised” area requiring some degree of regulation. More complex regulatory control will come into force if the dose, under normal conditions, is greater than 3/10 of the worker limit. Work practices giving rise to doses above these levels are forbidden as they are deemed to give rise to an unacceptable level of risk.

The proposed classification system for natural radionuclides in the non nuclear industry must be based upon dose criteria which are received under certain types of conditions. As typical for several EU countries, four fundamental effective dose criteria (1, 6, 20 and 50 mSv/a) and two skin equivalent dose criteria (50 mSv/a and 500 mSv/a), together with two sets of conditions (normal and unlikely) are used. There are many possibilities to combine these criteria. However, a classification system works best with only a few reference levels. Therefore, simplification is needed. To be consistent with the nuclear industry approach, “normal” assumptions should be compared with the dose criterion. However, a further level of safety could be afforded if “unlikely” assumptions are also compared with the dose criterion. This gives the first three points in the scheme (Figure 12, Chapter 7):

- Conservative lower limit to regulation:

  Unlikely assumptions $D \leq 1$ mSv/a, $H \leq 50$ mSv/a

  (D: effective Dose, H: skin dose)

  If the exposure of a worker is very unlikely to exceed the dose limits for members of the public, there is clearly no need for regulating work activities. No account is taken of any benefit from the practice.

- Lower limit to regulation based on normal assumptions:

  Normal assumptions $D \leq 1$ mSv/a and $H \leq 50$ mSv/a and unlikely assumptions $D \leq 6$ mSv/a, $H \leq 500$ mSv/a

  If the effective dose to a worker is normally below 1 mSv/a, but may be slightly higher in unlikely situations then there is probably no need for regulatory control. The dose is below the public dose limit in almost all situations, but could exceed it in some cases. Similar arguments may be made in the case of the skin equivalent dose. The flexibility to allow the possibility of doses slightly higher than the dose limit for members of the public may be viewed as taking account of the workers benefit from his work, which involves radiation. Conversely, once doses normally exceeded 1 mSv/a, some degree of regulation would be expected.

- Upper limit to classification:

  Normal assumptions $D \geq 20$ mSv/a and unlikely assumptions $D \geq 50$ mSv/a, $H \geq 500$ mSv/a in both cases

  If the effective doses are greater than 20 mSv/a under normal conditions or a maximum of 50 mSv/a in unlikely conditions, and the skin equivalent dose limit is exceeded, the practice will clearly be unacceptable in its current form as it implies unacceptable risks. The practice would need to cease unless it was possible to derive factory specific reference levels or do detailed dose assessments that showed that the doses were indeed below the worker dose limits for that specific case. In other words, the level would require a thorough review of working practices and local particularities.

  Whilst helpful in defining the “top” and “bottom” of the scheme, these classification points do not address interim levels in between. A graded classification scheme has the advantage of allowing regulation that is more closely related to the actual hazards, thus guiding the optimisation process. The nuclear industry has two levels of regulation, separated by a dose criterion of 1/3 of the effective dose limit and the revised BSS uses a dose criterion of 6 mSv/a.

- Lower level of regulation:

  Normal assumptions D between 1 and 6 mSv/a and unlikely assumptions D $\leq$ 20 mSv/a, H $\leq$ 500 mSv/a in all cases

  As stated above, if the effective dose to a worker in normal conditions is above 1 mSv/a or the skin dose is above 50 mSv/a, then some level of regulation of the workplace is necessary as the person receives more than the public dose limit. However, it can be argued that if effective doses do not exceed 6 mSv normally and do not exceed 20 mSv/a even in unlikely situations, then a lower level of regulation may be acceptable as long as the skin equivalent dose is below 500 mSv/a. This corresponds to a “supervised area” in the nuclear industry scheme and Category B workers.

- Upper level of regulation:

  Normal assumptions D between 6 and 20 mSv/a and unlikely assumptions D $\leq$ 50 mSv/a, H $\leq$ 500 mSv/a in all cases

  If the effective dose to the worker is above 6, but below 20 mSv/a (under normal conditions) and the skin dose is below 500 mSv/a, then a higher level of regulation is needed to more carefully ensure that the radiation protection principles are being applied to the practice. This corresponds to the “controlled area” in the nuclear industry and Category A workers.

Interaction with other standards and recommendations

- ICRP recommendations

  ICRP is currently addressing the issue of exposure to enhanced levels of natural radionuclides in the non-nuclear industry. They identify the U-238 and Th-232 decay chains and note that certain components of the decay chains may also be important, notably isotopes of radium and Pb-210.

  ICRP recommends that the policy for control is based on the activity concentration of these radionuclides in materials. Using general assumptions it is suggested that activity concentrations of 1 to 10 Bq/g of each member of either the U-238 or Th-232 decay chain, or Ra-226 or Pb-210 and their short-lived progeny, would lead to an effective dose of 1 or 2 mSv/y each from dust inhalation and external exposure pathways, under general working conditions. It has been recommended that regulatory agencies choose values of 1 to 10 Bq/g to determine whether these exposures are deemed occupational (and are therefore subject to regulation).

- Exemption levels

  The Basic Safety Standards exemption levels are the levels at which the doses from the use and disposal of small quantities of radioactive material are trivial, i.e. less than or equal to 10 µSv/y. However, the BSS state that the exemption levels are not directly applicable to material containing natural radionuclides that are not processed for their radioactive properties. It is worth noting that exemption levels for these radionuclides are of a similar order of magnitude to the screening levels. It is therefore very important that care is taken to distinguish between the two sets of levels.

The BSS state that a national authority may declare that exemption levels apply to the natural radionuclides. The relation of exemption levels and screening/reference levels therefore requires clear and careful consideration by the authority in charge.

- Transportation

  The interaction of screening/reference levels with transport regulations requires addressing, as it would be advisable that any material regarded as unregulated during processing should not require regulation when transported. However, current exemption levels for materials containing natural radionuclides in transportation are simply 10 times the exemption level for natural radionuclides and were not based on a detailed assessment of the radiological implications of transportation scenarios. There are, however, some cases where the transport exemption level is more restrictive than the lowest two reference levels.

6.3 Conclusion of chapter 6

Regarding the regulation and classification schemes presented in this paragraph and taking into consideration the exposure estimates derived in chapter 5, it can be concluded that the dust inhalation situation of staff should be carefully and specifically re-considered before any additional regulatory measures are taken. Nevertheless, a few simple measures facilitating the situation of the staff should be introduced anyway. They can reduce the radiation exposure essentially and will certainly help to a healthier environment even in case of no radiation hazard at all.

7 Review of Current Regulations

7.1 General procedure

Article 2.b of the Euratom Treaty which is further specified in Chapter III, Health and Safety, lays down the obligation to establish uniform safety standards. The first standards were already laid down in 1959, very soon after the signature of the Euratom Treaty in 1957. They have evolved over the past 40 years as scientific knowledge on the effect of ionising radiation has improved and in this context it is important to refer to the internationally recognised work of the ICRP. Another major reason for the repeated revisions of the Basic Safety Standards is to take into account practical experience with operational radiation protection. Throughout these 40 years there has been a continued trend to strengthen regulatory control of radiation exposure. The European Union brought in the latest IRCP recommendations, namely IRCP80, by publishing a new directive in May 1996.

The procedure by which the Basic Safety Standards are established is laid down in the Treaty itself. The Commission receives guidance from a Group of Experts established under Article 31 of the Treaty which then gives rise to a Commission proposal for a Directive. This is submitted first to the Economic and Social Committee. Upon incorporation of all or part of the observations of this Committee, the proposal is published in the Official Journal and forwarded to the Council and to the European Parliament. The European Parliament then proposes amendments to the Commission proposal which are examined by the Commission and taken up as a whole or in part in a revised Commission proposal which is again submitted to the Council. In the end, under the terms of the Euratom Treaty, it is the Council who decides and the Directive is ultimately adopted by a qualified majority at Council. Subsequently, the Directives need to be transposed into national legislation of Member States. For the new Directive an implementation period of 4 years has been laid down in the Directive. Draft legislation is submitted to the Commission under the terms of the procedure laid down in Article 33. The Commission gives an opinion on draft legislation in order to make sure that it is in conformity with the standards.

In February 1998 the Commission of the European Communities published a communication concerning the implementation of the Council Directive 96/29/Euratom laying down basic safety standards for the protection of the health of the workers and the general public against the dangers arising from ionising radiation. The purpose of this communication is to assist the Member States in transposing this Directive into national law. This Directive repeals, with effect from 13th May 2000, the previously established Basic Safety Standards Directives BSS80/84 [3]. There is no explicit treatment of naturally occurring radionuclides in BSS80 which reflected the then current recommendations of IRCP26; its amendment in 1984 was based on ICRP Publication 30. As important general remark it is stated that the Directive sets out requirements designed for the protection of workers and the general public against dangers of ionising radiation without unduly limiting the beneficial uses of the practices giving rise to radiation exposure. The commission recognises that all those concerned with radiation protection have to make value judgements about the relative importance of different kinds of risks and about the balancing of risks and benefits.

It is further stated that the Directive should be regarded as reference document since Member States are bound only by its provisions. The 1996 Directive is based on the ICRP Publication N° 60 that contains the latest recommendations issued by the ICRP to take account of the continuing development in scientific knowledge and administrative experience. This development has been of an evolutionary nature and did not fundamentally change the system of protection recommended by ICRP Publication N°26 on which the 1980/1984 Directive was based. It is well known that ICRP like ICRU are internationally recognised organisations because of their assessments of the state of their respective art.

An important new feature of the 1996 Basic Safety Standards is that in line with ICRP guidance, a clear distinction is now made between, on the one hand, practices, i.e. human activities that can increase the exposure of individuals to radiation from a source, and on the other hand intervention situations, i.e. human activities that aim at preventing or decreasing the exposure of individuals to radiation from sources which are not part of a practice or which are out of control. ICRP has introduced this fundamental distinction between practices and intervention in its 1990 Recommendations (Publication 60) [1]. In the Basic Safety Standards a further distinction is made between practices and work activities, the latter involving the presence of natural radiation sources. Intervention situations are now dealt with much more explicitly than before both for radiological emergencies and in the case of lasting radioactivity or contamination resulting from past practices or work activities, which is an important extension of the previous protective arrangements in the event of an accident laid down in the 1980 Directive.

The extension of the scope of the Directive to include natural radiation sources is very important. In Title VII, consideration is given both to cosmic radiation sources and to terrestrial natural radiation sources, including exposure to radon gas in the workplace and exposure of the population or workers resulting from work activities involving ores or residues containing enhanced levels of natural radioactivity.

The Directive prescribes that for each work activity declared by the Member State's competent authorities to be of concern, the Member State shall require the setting up of appropriate means for monitoring exposure and, as necessary, implement corrective measures pursuant to Title IX, that means the application of the general principles for intervention situations and, as appropriate, the application of all or part of Titles III up to VIII which lay down the radiation protection requirements pertaining to practices.

With respect to the establishment of the Basic Safety Standards by each Member State, arguments are given in order to fully understand the overall philosophy for the establishment of radiation protection standards [4]. It is said to be important being aware of the three major general principles underlying radiation protection. The principle of justification of practices implies that the detriment from exposure should be justified by the benefit resulting from the practice and thus requiring that no frivolous applications of ionizing radiation be permitted. The cornerstone of radiation philosophy, however, is the principle of optimisation of protection which is translated into the principle that doses should be as low as reasonably achievable taking social and economic considerations into account. Finally, the principle of dose limitation ensures an equitable distribution of individual benefits and detriment. These basic principles all reflect the basic working hypothesis in radiation protection, that there is no safe level of radiation. The radiation detriment is a stochastic effect, which means that the detriment, for instance radiation-induced cancer, is never certain to occur but has a certain probability of occurrence which is assumed to be proportional to the radiation exposure. So there is no safe level of radiation and this is reflected by the strict regulatory control of practices involving ionising radiation.

In addition to the extension of the scope of the Directive, the system of dose limitation and the regime of regulatory control have been considerably strengthened. The dose limit for workers is 50 mSv effective dose for one year, but in addition on average, 100 mSv over a period of 5 years or, in practice 20 mSv per year. Member States may specify and decide on an annual amount: This compares to a single effective dose limit of 50 mSv per year for workers in the 1980 Directive, so the reduction in practice down to 20 mSv is more restrictive. For the population the dose limit has been reduced to 1 mSv per year (exceptionally more than 1 mSv may occur as long as the average over 5 years remains less than 1 mSv). The dose limit to members of the public was 5 mSv per year.

Finally the regulatory control of practices has been considerably strengthened through the requirements of reporting of all practices and the explicit requirement of prior authorisation for a list of identified practices . Particularly important is the explicit requirement of prior authorisation for the disposal, recycling or reuse of materials containing radioactive substances arising from practices which themselves are subject to reporting or prior authorisation.

Practices need to be reported except if quantities or concentrations of activity per unit mass are below exemption levels. In terms of activity concentration, for instance, we now have a nuclide-specific list of exempt activity concentrations which is in general much more restrictive than the single value of 100 Bq/g laid down in the 1980 Directive for artificial sources and 500 Bq/g for natural radiation sources. Exemption can also be granted in a number of other cases (sealed sources or electrical apparatus) if the dose rate is less than 1 µSv per hour, at a distance of 0,1 m. The exemption values have been established on the basis of general basic criteria which have been laid down in Annex I of the Directive together with exemption values. Individual risks involved in the exempted practices are required to be below concern, as well as the collective impact expressed in terms of collective doses. It is presumed that these basic criteria are met without further considerations if annual individual doses are about 10 µSv which is 1% of the dose limit or less than 1% of the average level of exposure to natural radiation sources. There is a further requirement that the dose commitment/collective dose should be less than 1 Sv [4].

Title IX dealing with intervention situations addresses lasting exposures resulting either from radiological emergencies (e.g. land contaminated as a result of accidental releases), as a result of past or old practices or work activities which were not subject to a level of regulatory control which would not be acceptable today. The justification principle now reads that the harm and cost of intervention should be justified in terms of the averted or avoided exposure resulting from the intervention situation. The intervention is justified if the net benefit is positive. The optimisation of radiation protection pertains to the form, scale and duration of the intervention. Dose limits do not apply. Intervention down to the limits may, in certain cases cause excessive harm to the individual by comparison to the averted radiation detriment. Indicative intervention levels however need to be laid down by competent authorities for different types of counter-measures.

Under the terms of Article 31 of Euratom Treaty a working party of the Group of Experts was established to prepare a document for technical guidance. This is needed for the identification of work activities and related workplaces that might be concerned by the exposure to natural radiation sources as announced by Title VII of the Directive. Such exposures were not explicitly dealt with before, even though they were implicit within the scope of the Standards. Hence, the introduction of the new provisions may bring a significant change in national legislation. As mentioned, the Member States are challenged to prepare revisions of arrangements as part of their individual acts and regulations. In order to give assistance for these revisions the Group of Experts met on November 14th 1996 and endorsed a document to offer technical guidance [5].

In order to use a systematic procedure the document follows the same general framework as it is used for the BSS. Two articles, namely 40 and 41, are relevant for the work activities by which workers or members of the public may be exposed to natural radiation sources. Each member state will have to ensure the identification of those work activities which may be of concern by means of surveys or by any other appropriate means. These work activities are addressed in more details by nominating such places (a) where workers and, where appropriate, members of the public are exposed to thorium or radon progenies or gamma radiation or any other exposure in workplaces such as spas, caves, mines, underground workplaces and aboveground workplaces in identified areas; (b) where operations are involved with, and storage of materials, not usually regarded as radioactive but which contain naturally occurring radionuclides, causing a significant increase in the exposure of workers and, where appropriate, members of the public; and (c) where activities which lead to the production of residues not usually regarded as radioactive but which contain naturally occurring radionuclides, causing a significant increase in the exposure of the public and, where appropriate, workers.

By this formulation article 40 lays down that Title VII does not apply to exposures from practices as defined before. Following the recommendations of IRCP (Publication 60, paragraph 134 and following) the European BSS Directive limits its validity to exposures to ionising radiation which can reasonably be regarded as amenable to control. The BSS also excludes radon exposure in dwellings. In line with the Commission recommendation 90/143/Euratom on the protection of the public against indoor exposure to radon, Member States may decide to implement a programme of control of domestic exposures. If so, the domestic and occupational programmes are likely to be related. Elevated levels of radon in workplaces and occupational exposure to materials or residues containing natural radionuclides can be regarded as amenable to control. However, since such exposures are ubiquitous it is necessary to have a general system for applying controls selectively. The BSS are consistent with IRCP recommendations that these exposures should be excluded from the scheme of occupational exposure practices and considered separately unless the relevant national authority has determined otherwise. National authorities, thus, need to decide in which parts of their territory and for which activities and working conditions it would be appropriate for doses from natural radioactivity to be regarded as part of occupational exposure or even public exposure. These decisions must be based on a sound review of the patterns and levels of exposure throughout the territory for which the authority is responsible. This will normally require surveys to be conducted, though there are circumstances in which surveys can be complemented by other techniques. For example, geological mapping can help in making maximum use of measurements of radon levels in buildings. Knowledge of activity concentrations in building materials and in sources of water may also provide useful general indications of where levels of natural radioactivity are high.

While the BSS brings exposures to natural radiation sources within the same general framework as other exposures to radiation this does not mean that identical procedures are to be followed in the case of natural and artificial radiation sources. This is because of the special features of some exposures to natural radiation sources, in particular, that some approaches to control may be regarded as interventions and, as such covered broadly by Title IX, rather than practices, broadly covered by Titles III, IV, V, VI and VIII. The sections which follow discuss exposure to radon and to materials containing natural radionuclides. Some similarities in the control schemes for these two classes will be apparent, but they are by no means identical. The control scheme for radon is perhaps the most developed one.

National Authorities may need to consider controlling doses to members of the public as well as those to workers. This applies in particular to work activities giving rise to the release of material containing natural radionuclides in liquid or gaseous effluents or as solid waste.

7.2 Radon at workplaces

For each work activity declared by them to be of concern, the Member States shall require the setting-up of appropriate means for monitoring exposure and as necessary:

a) the implementation of corrective measures to reduce exposure pursuant to all or part of Title IX;

b) the application of radiation protection measures pursuant to all or part of Titles III, IV, V, VI and VIII.

Articles 41 and 42 shall apply to the extent that the Member States have declared that exposure to natural radiation sources due to work activities identified in accordance with paragraph 2 of this Article needed attention and had to be subject to control.

As with other natural radionuclides, exposures to radon and its decay products are ubiquitous. The levels are, however, exceptionally variable and high doses can be incurred. A system is required under which attention can be concentrated on the highest exposures and where action is most likely to be effective. National Authorities must arrange for representative surveys to be undertaken to determine the scale and nature of radon exposures in different types of workplace unless they already have this information.

There are several isotopes of radon. Attention is normally focused on Rn-222 because its relatively long half-life (4 days) facilitates its escape from the matrix which contained its parent Ra-226. Under certain circumstances Rn-220 (thoron (the radon nuclide Rn-220 from the Th-232 decay chain), half-life one minute) can be important. The hazard in high radon environments comes from radon decay products rather than radon gas itself. Nevertheless, for practical reasons control measures should generally be expressed in terms of the concentration of radon gas. Action Levels and Radon Prone Areas are concepts which National Authorities are likely to find useful in controlling radon exposures in the workplace and also in dwellings. Because Action Levels and Radon Prone Areas for occupational and domestic control are interrelated the discussion below necessarily touches on the control of domestic as well as occupational exposures.

Separate investigations should be undertaken of the geographical variation of radon exposures in above as well as in below ground workplaces. Below ground workplaces where radon concentrations may require control, include non-uranium mines, galleries in radon spas, subways, underground installations, show caves and tourist mines, underground water treatment works and stores. Surveys of all types of underground workplace should be carried out; it is not necessarily the case that high levels of radon in below ground workplaces are found, only in areas which also have high levels in buildings.

The atmospheric dispersion of aerosol size distribution has, in principle, the potential to affect doses. Nevertheless, in many circumstances it will be sufficient to just consider the quantity of alpha energy released by the radon daughters. An equilibrium factor of about 0.4 to 0.5 is generally used to provide such a measure. Investigations can be carried out to indicate any circumstances where this is not the case. Radon surveys should be based on reliable long term measurements in workplaces of various kinds in order to average out short-term variations in radon levels.

There may be a role for short-term screening measurements. However, such measurements will require special protocols and very careful interpretation. Measurements should be made with appropriate detectors and equipment which have undergone approved calibration and quality assurance programmes. Geological information may be a useful general guide to identify areas where radon levels in buildings are likely above average. However, there is a complex relation between geological parameters such as uranium concentrations in soil and radon levels in buildings.

A radon Action Level is a concentration of radon gas above which National Authorities require that action is taken. The choice of action level will, in part, be determined by practical consideration in view of the national circumstances. However, the levels chosen for domestic and occupational circumstances should be compatible with the radiological protection point of view (see ICRP Publication 65, paragraph 85). National authorities should define radon Actions Levels for workplaces as they may do for dwellings. Occupational exposures to radon above the Action Level will be subject to Regulatory Control. However, it is expected that the normal response to finding that radon levels in a workplace are above the Action Level will be to undertake remedial measures so that the Regulations need no longer be applied. This should be decisive action to effect a substantial reduction, not just to edge below the Action Level. ICRP recommends that the Action Level for dwellings should fall in the range 200-600 Bq/m^3 (Publication 65, paragraph 73). The 1990 recommendation of the European Communities was for a reference level of 400 Bq/m^3 for existing dwellings and a target of 200 Bq/m^3 for new buildings.

ICRP, in Publication 65, derives a rage of Action Levels for workplaces of 500-1500 Bq/m^3 on the basis of equivalence of doses to the range for dwellings (paragraph 86) and therefore recommends that National Authorities should choose Action Levels for homes and workplaces which are similarly placed within the two ranges (paragraph 86). It is likely that this will also result in a significant but not unmanageable number of workplaces requiring remedial work. This ICRP range of Action Levels is intended as a world wide recommendation.

ICRP recognises that an action level can have two distinct purposes:

a) to define workplaces in which intervention should be undertaken, or

b) to identify where the system of protection for practices should be applied.

It concludes that there are clear advantages in the adoption of the same action level for both purposes. In the context of the BSS Directive, it is the regulatory purpose which is of primary interest.

For this regulatory purpose, it is very desirable for the action level not to exceed the dose level at which special actions are required to protect workers involved in practice – i.e., the criterion for classifying category A workers. It is therefore recommended that, within the European Union, the Action Level for places of work should be set in the range 500-1000 Bq/m^3 time averaged radon gas concentration. This is based on occupational exposure of 2000 hours per year and an equilibrium factor of about 0.4; if there are circumstances where these factors are significantly different then a modified Action Level might be appropriate. National Authorities may also select an Action Level below the specified range if they judge that this is desirable and will not lead to an impractical radon programme. It may be noted that the International BSS specify an Action Level of 1000 Bq/m^3.

National Authorities may find it useful to define **radon prone areas**. It is suggested by ICRP (Publication 65, paragraph 76, 102) that radon prone areas might be those parts of the country where at least 1% of dwellings have radon levels more than ten times the national average as determined by appropriate statistical sampling. It should not be overlooked, however, that high radon concentrations may occur also outside the defined radon prone areas. The definition of radon prone areas is not relevant to the control of radon exposures in below ground workplaces. These should be treated on their merits regardless of whether the workplace falls within a radon prone area or not (ICRP 65, paragraph 85).

7.3 Testing and Remedying Existing Workplaces

National Authorities must decide where employers need to measure radon levels in workplaces. It would be prudent to take action most urgently where radon levels are highest and National Authorities may wish to set priorities for action within radon prone areas. These might be in terms of radon level (ICRP 65, paragraph 76) or the types of workplace. It is likely that measurements will be needed in all underground workplaces of most kinds or at least in a sufficiently large sample for a clear and statistically significant picture to be reached.

Within the specified areas employers should arrange for radon levels to be measured in above ground workplaces. If the measurement time is less than one year and the (seasonal corrected) result approaches the action level it may be appropriate for the result to be verified with repeated measurements in different season. Where the first seasonally corrected results show radon levels well in excess of the Action Level, then action should be taken without awaiting further results. If radon concentrations are found to be below the Action Level then there is no requirement for further action other than re-testing, if the concentrations are marginal or substantial changes are made in the construction or use of the building. Employers may, however, consider undertaking remedial measures if radon concentration approach the Action Level.

ALARA will often indicate that this is appropriate even though it is not within the regulatory requirements of the Member States.

If radon levels are found to be above the Action Level in a workplace or part of a workplace but occupancy is very low then it may be sufficient to monitor and control access to the area. It is emphasised that this is not intended as a substitute for remedial measures when occupancy is a significant fraction of a normal working year. It might, for example, apply to a store room visited for an hour or two per week or a pumping station visited for half a day a month. If radon concentrations are above the Action Level and occupancy is not very low then remedial action to reduce the radon level should be required. This should be decisive action aiming at a substantial reduction in radon concentrations (ICRP 65, paragraph 71, 105). Experience indicates that relatively simple and inexpensive remedial measures are successful in significantly reducing elevated radon levels in the majority of above ground workplaces.

Member States should ensure that advice and assistance is available to employers on how to obtain appropriate radon measurements and, if necessary, on remedial measures appropriate to places of work. If remedial measures are successful in reducing radon concentrations below the Action Level then no further action is needed other than re-testing, if substantial changes are made in the construction or use of the building. Where the reduced radon level relies on active measure, such as a fan, then its efficient operation needs to be checked occasionally. The National Authority may also require periodic re-testing, particularly if radon concentrations approach the Action Level.

If, despite all reasonable efforts, radon concentrations remain above the Action Level, then a scheme of radiological protection should be introduced which follows the principles set out in Titles III, IV, V, VI and VIII where these are appropriate. Application of these principles to protection against radon may vary in some instances from their application to artificial sources. The most important elements are monitoring exposures, defining controlled and supervised areas and dose limits.

Where radon concentrations remain above the Action Level after attempts at remedying then monitoring should be undertaken. Monitoring may be of individuals or of the areas in which they work. In most circumstances, workers should be categorised in the same way as they are for other work with radiation. If radon levels are just above the Action Level then area monitoring may be adequate. If exposures might approach the dose limit, personnel monitoring will normally be preferred (see ICRP Publication 65 paragraph 99). In cases where radon levels are high in areas which are normally unoccupied, area monitoring together with individual control of occupation periods may be appropriate. Records of monitoring radon exposures of workers shall be kept. Such records may be in terms of Bq/m^3 h or in mJh/m^3 . Nevertheless, despite the use of special units for radon exposures, there will be a need to calculate and record effective doses.

The conversion convention recommended by ICRP in Publication 65 should be used for this purpose on a provisional basis. In the case of workers, paragraph C of Annex III of the BSS shows that 1 mJh/m^3 of radon decay products is equivalent to 1.4 mSv; with equilibrium factor 0,4, 3,2 x 10^5 Bq h/m^3 radon gas is equivalent to 1 mSv. The historical unit of a Working Level Month (WLM) is still encountered though its use is deprecated. For workers, 1 WLM is equivalent to 5 mSv. Under standard assumptions 1 WLM would be incurred by working for a year in a time averaged radon concentration of about 750 Bq/m^3. (1 WL = 3700 Bq/m^3 EEC; divide by F = 0,4 and 12 months yields 771 Bq/m^3, rounded downwards.) For members of the public, 1 mJh/m^3 is equivalent to 1,1 mSv and 4 x 10^5 Bq m^{-3} h radon gas is equivalent to 1 mSv. The conversion convention is based on the epidemiological data discussed in ICRP Publication 65. Nevertheless, it is recognised that there is, at present, a discrepancy of a factor of about two to three between risk estimates from dosimetry and from epidemiology, and conversion conventions may change.

It is emphasised that estimates of doses from radon should be made only if these exposures are important in their own right. There is no requirement to assess radon doses purely because other radiation doses are being assessed and recorded.

If radon and other exposures are combined, personal dose records should contain separate estimates of dose from radon as well as the sum of doses from radon and from other occupational exposures. Time integrated gas exposures (Bqh/m^3, mJh m^3 or WLM) should be retained for personal monitoring. If area monitoring is used to control exposures, then similar information should also be kept as specified in Title VI.

7.4 Controlled and Supervised Areas

Making decisions on the boundaries of supervised and controlled areas should not be purely based on whether individual doses can be reliably predicted to be below 3/10 of the dose limit (ICRP 60, paragraph 252). Rather the distinction should be a matter of judgement involving not just the level of dose but also its variability and the potential for unpredictable exposures. A key point will be whether or not special operating procedures are required.

The primary dose limits are defined in Article 9 of the Directive. These are 100 mSv in a consecutive five year period with a maximum of 50 mSv in any one year. In practice a number of quantities and units have been used for controlling radon exposures – in particular the Working Level Month the use of which is not recommended any more. There are uncertainties in the conversion of time integrated radon exposure data to mSv and there may be advantage in working in terms of the former when controlling radon exposures. Under standard assumptions including an equilibrium factor of 0,4 and 2000 hours occupational exposure to an annual dose of 20 mSv is equivalent to about 6 x 10^6 Bqh/m^3 radon gas and this level of exposure would be reached by working continuously in a radon concentration of about 3.000 Bq/m^3.

Although not explicitly mentioned in Title VII, it would be sensible to consider preventing high radon levels arising in new workplaces rather than taking remedial measures after they had been built. It is simple and cheap to incorporate measures to reduce radon levels at the time that the building is being constructed. It should be noted that radon preventative measures which prevent the entry of soil gas into dwellings have incidental advantages, e.g. in inhibiting the entry of damp and moulds. National Authorities should delimit localities within radon prone areas or elsewhere within which appropriate radon preventative measures should be included in the construction of new workplaces. These should ensure that radon levels in new workplaces are as low as reasonably achievable and that further remedial measures can easily be introduced if necessary.

Building materials are not usually a dominant source of radon. Nevertheless, it may be found that high levels of Ra-226 or other natural radionuclides in some materials should be avoided. Certain kinds of lightweight alum shale concrete, tuff or granites may provide examples. It should be noted that other factors, for example γ radiation, may need to be considered in the choice of building materials with high levels of natural radioactivity. High gamma doses from the ground or from building materials will only arise if there are high levels of U-238, Th-232 or their decay products. Surveys will show where these circumstances may arise. It should be noted that in many circumstances the same concentration of natural radionuclides which results in elevated levels of gamma radiation may lead to doses from radon or thoron (the radon nuclide Rn-220 from the Th-232 decay chain) which are of greater radiological significance.

Article 41 – Protection against exposure from terrestrial natural radiation sources

For each work activity declared by them to be of concern, the Member States shall require the setting-up of appropriate means for monitoring exposure and as necessary:

c) the implementation of corrective measures to reduce exposures pursuant to all or part of Title IX;

d) the application of radiation protection measures pursuant to all or part of Titles III, IV, V, VI and VIII.

Surveys may show that there are circumstances in which the use and storage of materials not generally regarded as radioactive nevertheless give rise to significant doses because the materials contain elevated levels of natural radionuclides. Examples might include monazite sands, rare earth ores and also the scale which can build up in pipes and valves of parts of mineral processing or similar plant. In these circumstances the appropriate national authority might declare that exposures due to work activities with these materials should be regarded as falling within the definition of occupational and/or public exposure to radiation (see ICRP 60).

Several industrial processes which may result in significant exposures from natural radionuclides to workers and/or members of the public are discussed among radiation protection experts. Whenever materials contain uranium and thorium consideration should be given to the extent to which their decay products are also present. It should be noted that the degree of exposure depends not only on the activity concentration of the material involved but also on any chemical or physical processing which may increase the availability of the material. For example, grinding up raw materials may generate respirable dusts and may also make it easier for radon to escape into the air of the workplace. Processing materials rich in uranium or thorium families at high temperatures (e.g. coal combustion) could enrich airborne dust in some radionuclides of the uranium and thorium series, e.g. Po-210 and Pb-210. Attention must be paid to the possibility that waste streams may be responsible for a more significant hazard than the main process leading to the product.

The important routes of radiation exposure of workers from these processes for are normally external gamma irradiation and inhalation of contaminated dust aerosols in the room atmosphere. The appropriate control measures may include limitation of exposure time, attention to the arrangements for storage of bulk material and dust control. In some cases radon or thoron (the radon nuclide Rn-220 from the Th-232 decay chain) may present a problem and surface contamination may also need to be considered. It is not necessarily the case that the highest doses arise when the plant is operating normally. In some circumstances, the maximum doses will be incurred during maintenance.

Normal common sense precautions should be taken to avoid all unnecessary exposures to radiation. Beyond this, assessments should be made to estimate the doses to workers from such natural radionuclides. If the doses are less than 1 mSv per year then no special precautions are required. If annual doses exceed 1 mSv then the normal scheme for controlling exposures can usually be applied. The Directive requires that, as necessary, Titles III, IV, V, and VI would apply in whole or in part. If doses exceed 6 mSv then it may, in rare cases, be appropriate to define a controlled area. If doses exceed 1 mSv, but are less than 6 mSv it would be appropriate to consider , for example , whether doses could effectively be reduced and whether there is a possibility that doses increase either over time or as the result of an accident. If doses are low and cannot effectively be reduced and if there is no realistic potential for accidents then few radiation protection measures are likely to be required beyond whatever is necessary to ensure that doses do not increase.

Exposures of the public may arise from the product of a process (e.g. , building materials) or from atmospheric or liquid discharges, from re-use of by-product material or from disposal of solid waste. The important routes of radiation exposure of the public are external gamma irradiation, inhalation and ingestion. The practical protection of members of the public is dealt with in Title VIII. Article 43 lays down a general duty on Member States to create the conditions for the best possible protection of the public. Article 47 stipulates that the undertaking responsible for a practice shall be responsible for achieving and maintaining an optimal level of protection for the environment and the population. The same general principles should apply to work involving natural radiation even if it falls outside the definition of a practice [5].

7.5 The United Kingdom (UK) approach

In joining the European Union the UK became subject to the provisions of the Euratom treaty and was obliged to implement the 1980 Basic Safety Standards Directive (BSS80 / 84) [3]. The use of radioactive materials is regulated by the Health & Safety Executive (HSE), as part of its wide ranging activity under the Health & Safety at Work etc. Act, 1974 (HSWA) to ensure that risks to the health and safety of employees and other persons who may be affected by work activities are reduced so far as is reasonably practicable. In other words the emphasis in the HSWA is on workplace health and safety, and the potential impact on members of the public arising from these workplace activities. Regulations made under the HSWA address the control of specific risks, such as ionising radiation. The ownership of radioactive material is regulated by the Environment Agency being mainly concerned with protecting the environment against discharges of radioactivity. Its power is granted under the Radioactive Substances Act (RSA). In this way, the UK regulatory approach makes a distinction between ownership and use of radioactive materials. The HSE and Environment Agency work closely together on issues of mutual interest, such as the development of legislation, practical advice, inspection and enforcement of legislation in the workplace [20]. UK regulatory approach required the introduction of specific legislation under HSWA to cover the use of radioactive materials (Ionising Radiation Regulations 1985, IRR85), alongside the existing legislation covering the ownership of radioactive materials (RSA60), to satisfy the 1984 amended BSS80 Directive.

With respect to the specific, major change for the explicit arrangements for treatment of natural radiation sources (NRS´s), the existing IRR85 was extensively reviewed in order to decide what will be required for the UK to demonstrate compliance with the Euratom Directive by May 2000. The HSE has published a draft set of revised regulations (IRRrev), and is engaged in extensive consultation with user groups on issues including controls for NORM in the workplace. As NORM in the workplace was not specifically addressed by IRR85 it included in its definitions as work with ionising radiation nevertheless „any work involving the production, processing, handling, use, storage, moving, transport or disposal of any radioactive substance". The wording „radioactive substance" thereby means namely „any substance having an activity concentration of more than 100 Bq/g and any other substance which contains more radionuclides whose activity cannot be disregarded for the purposes of radiation protection,.."[20]

The IRR85 is supported by an Approved Code of Practice (ACOP) giving extensive guidance on the Regulations, more specific advice on compliance with ALARA for particular processes, but without addressing work with NORM. There is a separate part to ACOP covering exposure to radon, mainly in below ground workplaces. Substances as zircon, baddeleyite and monazite sands and similar rare earth ores are said to present a radiological hazard even having activity concentrations of less than 100 Bq/g. This is a result of being involved in dusty processes and may create an internal radiation hazard from inhalation. Moreover, there may be an external radiation hazard from bulk storage of such materials. Research modelling these pathways using parameters appropriate to typical industrial exposures to dusts and bulk storage situations resulted in statements of lower specific radionuclide concentrations of 1 and 9 Bq/g for U-238 progeny, respectively. With the aim of devoting the IRR to NRS including specific reference to NORM the main duty on member states is to establish a national picture, through surveys or other means. The UK has retained its definition of what constitutes a radioactive substance for regulatory purposes, but it now qualifies the phrase „..whose activity cannot be disregarded for the purposes of radiation protection" in specific guidance. This indicates that if a dose of ionising radiation to employees or other persons in excess of 1 mSv in a year is likely to arise as a result of use of NORM, then it will be considered that activity of the NORM cannot be disregarded for the purposes of radiation protection and this will be sufficient to trigger the application of the IRRrev.

Regulation 6 of IRR85 implies that the employer needs to assess the risk to employees working with NORM to see whether it would be regarded as a "radioactive substance" as described. The experience of HSE has been that few employers have access to the required radiation protection advice within their immediate organisation. Hence, in most cases, the employer must seek advice from a qualified expert (QE). Where the use of NORM in the workplace will trigger the IRRrev, the employer will be required to carry out a risk assessment before commencing work with ionising radiation. In the case of potential exposure to NORM dust, the provision and use of local ventilation systems to extract airborne dusts from the workplace may be justified. Additionally, protection of the individual employee may be enhanced by the provision and use of suitable respiratory protective equipment. Systems of work designed to minimise exposure to airborne dusts may also be required. In the case of work with ionising radiation solely involving the handling or use of NORM, there is currently no requirement for the employer to formally appoint a QE.

The assessment of risks associated with the work with NORM will have identified likely doses to employees (and others) in various workplace activities. If such doses are likely to exceed 15 mSv, then the employer will need to designate a “controlled area“. If doses are likely to exceed 5 mSv, then a “supervised area“ must be designated. Entry into controlled areas is limited to authorised radiation workers or persons operating under a written system of work directives. Due account must be given to access for maintenance purposes, e.g. servicing of dust or smoke extraction equipment. Experience has shown that this can have considerable potential for exposure. IRRrev, while being less prescriptive about the criteria for designating such areas will in most practical situations reduce these trigger points to 6 mSv and 1mSv, respectively. If the employer has designated controlled areas that persons enter, then actual doses will need to be assessed when persons enter such areas. The employer will probably need to discuss such a programme of assessments with a QE.

Suppliers of NORM whose products may, in the course of reasonably foreseeable circumstances, be considered radioactive substances for regulatory purposes, need to provide adequate information about radiological and other hazards to the user. This is a requirement of the HSWA. In order to comply with the HSWA, the supplier must carry out an analysis of the material in order to determine the potential risk to users. This analysis and associated information to users must periodically be reviewed regarding changing circumstances, e.g. changes in the supply of raw materials). In the 13 year period of application of the IRR85 in the UK, the HSE has found that users are not always aware of the potential for risk of radiation exposure as a result of exposure to NORM. Therefore it is almost always the case that the user needs to assistance by a QE in order to manage the risk associated with NORM.

7.6 The German approach

A statement of the Radiation Protection Commission (Strahlenschutz-Kommission, SSK) concerning radiation exposure at workplaces due to naturally occurring radionuclides was published in 1997. A working group was established in order to identify possible exposures, the associated risks and the number of people concerned. With respect to the chemical industry the following workplaces were identified as related to the use of NORM:

- the phosphate and fertilizer industry
- certain metal production industries, like Al and Cu production
- processing of zirconium sands
- processing of rare earths
- processing of Pyrochlore to produce niobium / ferro-niobium

The résumé of the commission was to give special regard to exposures above 6 mSv per year. This is based upon the observation that exposures to natural radionuclides, cosmic radiation and radon are of about that order of 1 to 6 mSv for the Federal Republique of Germany. Thus, none of the above mentioned industries is subject to NORM associated regulation [7]. If doses of more than 6 mSv are expected despite the installed actions taken for conventional working protection measurements the employer must inform the responsible authorities about the doses estimated for the exposure scenario. The individual body doses have to be assessed either by monitoring for the local dose rate or by estimating the doses from the contamination of the working place. The employees have to be informed about possible radiation risks and measures for protection. If doses between 1 and 6 mSv are expected, the working conditions must be improved by rendering proper protection measures operational, such as enhanced ventilation or reduced quantities of radioactive material at the workplace.

This proposal of the SSK was made part of the draft amendment of the Radiation Protection Regulations (Novellierung der **S**trahlen **S**chutz-**V**er**or**dnung, SSVO). This amendment has been circulated during the last months to concerned groups that will be invited to a hearing of the German Federal Ministry for the Environment, Nature Preservation, and Nuclear Safety.

With respect to radon concentrations at workplaces the SSK recommended the values formerly proposed by IRCP and IAEA. The annual average of 1.000 Bq/m³ is the limit above which regulatory radiation protection measures must be made effective. This will lead to radon concentration limits of 2*10E+6 Bqh/m³ if 2000 hours per year are taken for presence at the workplace [13].

7.7 The Dutch approach

The Dutch Ministry of Social Affairs and Employment has ordered a study on the occupational exposures to natural radiation sources in Dutch industries from KEMA/ECN. The methodology used was taken from the UK-NRPB report [42]. Therefore, the classification of work activities within the concerned industries follows a similar procedure establishing exposure scenarios for both normal and unlikely conditions. Most forms of exposure to sources of natural radiation within the chemical industry are related to the processing of ores, products and residues of the following list:

- the phosphate and fertilizer industry
- the metal production industry
- the production of rare earths
- the ceramic industry
- the pigment industry.

The doses estimated in the frame of exposure scenarios for selected work activities which can lead to increased exposure to natural radiation are taken to classify defined work activities according to the following dose categories:

A. doses under normal conditions less than 0,1 mSv per year and for unlikely conditions less than 1 mSv per year;

B. doses under normal conditions between 0,1 and 1 mSv per year and for unlikely conditions between 1 and 6 mSv per year;

C. doses under normal conditions between 1 and 6 mSv per year and for unlikely conditions between 6 and 20 mSv per year;

D. doses under normal conditions between 6 and 20 mSv per year and for unlikely conditions between 20 and 50 mSv per year;

E. doses under normal conditions above 20 mSv per year and for unlikely conditions above 50 mSv per year.

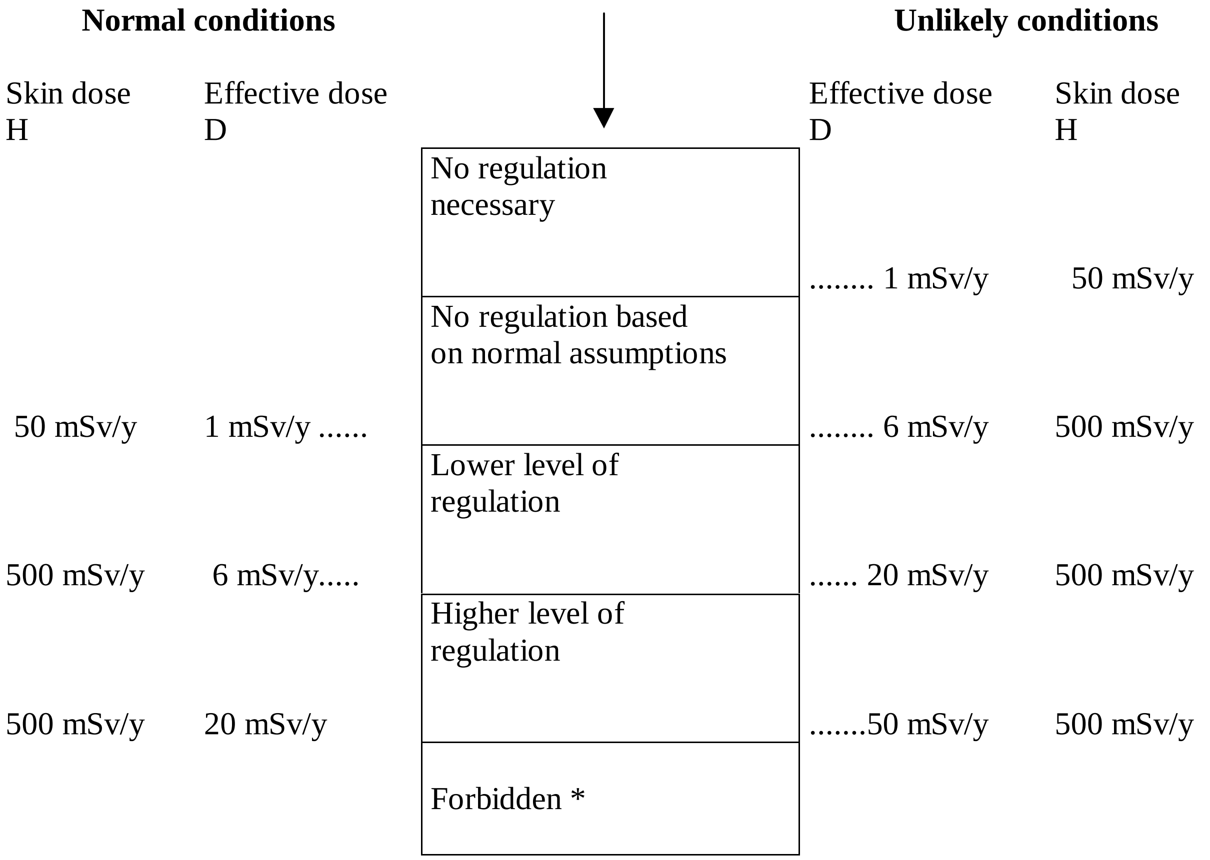
Category B., equivalent to small exposure, was identified for sintering and phosphor production of the thermal phosphor process as well as for the milling of fertilizer production and for the storage of raw and milled products of the mineral sands industry. In addition, the storage and application of Baddeleyite for the ceramic industry was identified as falling under category B.. Category C., equivalent to significant exposure, was identified for maintenance and cleaning of contaminated production installations of both thermic phosphor and wet phosphoric acid production. Furthermore the grinding of mineral sands was identified as category C.. Category D., high exposure, and category E., extreme exposure, were both not found to apply at all [21, 22]. This classification system, including skin and effective doses, is graphically represented in Figure 12 using the following logic.

- If the activity concentration is less than that corresponding to the first reference point, then there is no need to consider regulation.
- If the activity concentration is less than that corresponding to the second reference point, then there is no regulation needed on the basis of normal assumptions.
- If the activity concentration is between the values corresponding to the second and third reference points, then the lower level of regulation should be applied.
- If the activity concentration is between the values corresponding to the third and fourth reference points, then the higher level of regulation should be applied.
- If the activity concentration is higher than that corresponding to the fourth reference point, then the practice is interdicted.

Besides these aspects of work activities, radiation protection for the members of the public are to be dealt with. To avoid confusion the proposed system is also based on dose criteria. A source not exceeding the ambient dose of 1 mSv per year is exempted from regulation when this dose is due to the materials containing naturally occurring radionuclides. The requirement of reporting must apply if exemption or clearance levels are exceeded. Prior authorisation will be required if levels are exceeded by more than a factor of 10. Both levels, either for exemption or clearance, respectively, should have the same values. As NORM stands for different types of materials, these can be divided into three groups:

1. raw material, stored on sites and used in processes, residues and as waste.
2. discharges in water and emissions to air,
3. contaminated objects.

In practice no distinction can be made between residues and raw material. For reasons of consistency the values for the third group should correspond to the already mentioned materials. Only NORM discharges into water and air should be handled separately because different scenarios are involved [23].



*Note: Detailed analysis of the working practices is necessary to obtain sound dose assessments. If these doses are above the worker dose limits, the practice must be abandoned/changed.

Figure 12: Graphical representation of the classification system [42]

EU-guidelines for the formulation of rules concerning water politics (KOM(97) 49, final

Concerning water supply stategies, changed guidelines for the formulation of rules were proposed by the European Parliament and the Council of Ministers in 1999 (KOM(1999) 271, final). Several points are of interest for practices in use at industries dealing with NORM. The dumping of wastes containing dangerous materials that results in contamination of rivers and finally the open sea has to be strictly supervised. In consent with the declaration of the fourth Conference for the Protection of the North Sea in Esbjerg, the EU Parliament appealed for the continuous decrease and final termination of dumping dangerous materials. The declaration of the Esbjerg Conference intends to finish the dumping completely and stop deliberate and accidental emissions within one generation's time. This declaration was signed by seven EU members and the Commission in 1995 and integrated into the OSPAR-Convention 1998. The claims are declared as political intentions without legal obligation. According to the judiciary kind of this aim and according to its social and economic implications, the European Commission refused to take the complete termination of such emissions as binding into the water guidelines. Hence, the Commission accepted the basic ideas of the Parliament's proposals by modifying the aims of the guidelines and adding therein the intention to restrict the concentrations of the naturally occurring materials close to their basic level and to result in zero emissions for anthropogenic synthetic substances.

The condition of negligible anthropogenic pollution was added as aim in order to ensure that tendencies in the direction of considerable and long-term concentration increases of pollutants are turned round into a progressive decrease of pollution.

The use of surface water for the delivery of tap water was decided to be more strictly subjected to the application of quality specifications. The guideline 75/440/EWG representing the present legal situation demands without any exception the treatment of surface water which is meant for consumption as tap water.

8 Discussion of Reduction of Limits

As consequence of 2 million Mg of gypsum waste annually from the Dutch fertilizer industry the Health Council of The Netherlands was advised by a Special Committee on searching an acceptable destination for this waste. The Committee advised the Dutch government in the following way:

- Primary emphasis is to be laid on furthering the development of process alternatives that would free the bulk of the gypsum waste from deleterious components, like cadmium and U-progeny. Discharge of sufficiently cleaned phosphogypsum into Rhine delta could be tolerated.
- The fact that the main part of the objectionable components exit the plants via the manufactured fertilizer should be attended to. Po-210 might require attention in terms of on-site and peripheral health physics.
- Land-surface storage of the gypsum waste can be considered an environmentally acceptable alternative only if the complete shielding of the ground water from leachate can be guaranteed indefinitely [27].

It does not make much sense to reduce the allowable concentrations at which radionuclides naturally may occur. The limits currently in use and recommended by international expert organisations are doses of radiation exposure or hazard to health originating from radiation. Whether or not these limits have any impact on the use of materials depends on a variety of technical parameters and process details. These are the items which can be adapted. The other concern is beyond this study and refers to long term enrichment processes in the environment caused by the use of such natural materials like zirconium sands and others, and by the consequences which can be expected from such processes. Is it advantageous to let the material where mother nature put it, or make intelligent beneficial use of it.

Concerning means and ways of harmonisation, it is our recommendation to use the approaches already applied in a few member states in a manner which adapts the reasoning behind these decisions to the situation in the respective other member states.

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10 Appendix

10.1 Exposure Calculations

10.1.1 Dose Uptake by direct Gamma-Radiation

Material: Phosphate Ore

density: 3 Mg/m^3
volume: 10 m^3

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	2.000	6,00E+07			
U-234	*2.000*	6,00E+07			
Th-230	*2.000*	6,00E+07	1,16E-12	6,96E-05	1,39E-01
Ra-226	*2.000*	6,00E+07	6,38E-11	3,83E-03	7,66E+00
Rn-222	*2.000*	6,00E+07	6,41E-12	3,85E-04	7,69E-01
Pb-210	*2.000*	6,00E+07			
Po-210	*2.000*	6,00E+07	1,07E-13	6,42E-06	1,28E-02
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	50	1,50E+06	6,09E-13	9,14E-07	1,83E-03
Ra-228	*50*	1,50E+06			
Th-228	*50*	1,50E+06	9,65E-12	1,45E-05	2,90E-02
Total				**4,30E-03**	**8,61E+00**

Material: Zircon Sands

density: 5 Mg/m^3
volume: 10 m^3

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	4.000	2,00E+08			
U-234	*4.000*	2,00E+08			
Th-230	*4.000*	2,00E+08	1,16E-12	2,32E-04	4,64E-01
Ra-226	*4.000*	2,00E+08	6,38E-11	1,28E-02	2,55E+01
Rn-222	*4.000*	2,00E+08	6,41E-12	1,28E-03	2,56E+00
Pb-210	*4.000*	2,00E+08			
Po-210	*4.000*	2,00E+08	1,07E-13	2,14E-05	4,28E-02
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	700	3,50E+07	6,09E-13	2,13E-05	4,26E-02
Ra-228	*700*	3,50E+07			
Th-228	*700*	3,50E+07	9,65E-12	3,38E-04	6,76E-01
Total				**1,47E-02**	**2,93E+01**

Table 10.1: Dose uptake by direct gamma-radiation

Material: Aluminium Ore

density: 3 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	300	9,00E+06			
U-234	*300*	9,00E+06			
Th-230	*300*	9,00E+06	1,16E-12	1,04E-05	2,09E-02
Ra-226	*300*	9,00E+06	6,38E-11	5,74E-04	1,15E+00
Rn-222	*300*	9,00E+06	6,41E-12	5,77E-05	1,15E-01
Pb-210	*300*	9,00E+06			
Po-210	*300*	9,00E+06	1,07E-13	9,63E-07	1,93E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	100	3,00E+06	6,09E-13	1,83E-06	3,65E-03
Ra-228	*100*	3,00E+06			
Th-228	*100*	3,00E+06	9,65E-12	2,90E-05	5,79E-02
Total				**6,74E-04**	**1,35E+00**

Material: Copper Ore

density: 4,6 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	40	1,84E+06			
U-234	*40*	1,84E+06			
Th-230	*40*	1,84E+06	1,16E-12	2,13E-06	4,27E-03
Ra-226	*40*	1,84E+06	6,38E-11	1,17E-04	2,35E-01
Rn-222	*40*	1,84E+06	6,41E-12	1,18E-05	2,36E-02
Pb-210	*40*	1,84E+06			
Po-210	*40*	1,84E+06	1,07E-13	1,97E-07	3,94E-04
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	30	1,38E+06	6,09E-13	8,40E-07	1,68E-03
Ra-228	*30*	1,38E+06			
Th-228	*30*	1,38E+06	9,65E-12	1,33E-05	2,66E-02
Total				**1,46E-04**	**2,91E-01**

Table 10.1: Dose uptake by direct gamma-radiation (continued)

Material: Pyrochlore

density: 5,3 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	17.000	9,01E+08			
U-234	*17.000*	9,01E+08			
Th-230	*17.000*	9,01E+08	1,16E-12	1,05E-03	2,09E+00
Ra-226	*17.000*	9,01E+08	6,38E-11	5,75E-02	1,15E+02
Rn-222	*17.000*	9,01E+08	6,41E-12	5,78E-03	1,16E+01
Pb-210	*17.000*	9,01E+08			
Po-210	*17.000*	9,01E+08	1,07E-13	9,64E-05	1,93E-01
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232		0,00E+00	6,09E-13	0,00E+00	0,00E+00
Ra-228		0,00E+00			
Th-228		0,00E+00	9,65E-12	0,00E+00	0,00E+00
Total				**6,44E-02**	**1,29E+02**

Material: Fertilizer SSP

density: 2,4 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	500	1,20E+07			
U-234	*500*	1,20E+07			
Th-230	670	1,61E+07	1,16E-12	1,87E-05	3,73E-02
Ra-226	300	7,20E+06	6,38E-11	4,59E-04	9,19E-01
Rn-222	*300*	7,20E+06	6,41E-12	4,62E-05	9,23E-02
Pb-210	300	7,20E+06			
Po-210	*300*	7,20E+06	1,07E-13	7,70E-07	1,54E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	20	4,80E+05	6,09E-13	2,92E-07	5,85E-04
Ra-228	10	2,40E+05			
Th-228	10	2,40E+05	9,65E-12	2,32E-06	4,63E-03
Total				**5,28E-04**	**1,06E+00**

Table 10.1: Dose uptake by direct gamma-radiation (continued)

Material: Fertilizer TSP

density: **2,4 Mg/m³**
volume: **10 m³**

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m³]	[μSv/Bq/h]	[μSv/h]	[μSv]
U-238	800	1,92E+07			
U-234	*800*	1,92E+07			
Th-230	500	1,20E+07	1,16E-12	1,39E-05	2,78E-02
Ra-226	200	4,80E+06	6,38E-11	3,06E-04	6,12E-01
Rn-222	*200*	4,80E+06	6,41E-12	3,08E-05	6,15E-02
Pb-210	*200*	4,80E+06			
Po-210	*200*	4,80E+06	1,07E-13	5,14E-07	1,03E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	45	1,08E+06	6,09E-13	6,58E-07	1,32E-03
Ra-228	*45*	1,08E+06			
Th-228	*45*	1,08E+06	9,65E-12	1,04E-05	2,08E-02
Total				**3,63E-04**	**7,25E-01**

Material: Fertilizer PK

density: **2,4 Mg/m³**
volume: **10 m³**

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m³]	[μSv/Bq/h]	[μSv/h]	[μSv]
U-238		0,00E+00			
U-234		0,00E+00			
Th-230		0,00E+00	1,16E-12	0,00E+00	0,00E+00
Ra-226	200	4,80E+06	6,38E-11	3,06E-04	6,12E-01
Rn-222	*200*	4,80E+06	6,41E-12	3,08E-05	6,15E-02
Pb-210	*200*	4,80E+06			
Po-210	*200*	4,80E+06	1,07E-13	5,14E-07	1,03E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	10	2,40E+05	6,09E-13	1,46E-07	2,92E-04
Ra-228	10	2,40E+05			
Th-228	8	1,92E+05	9,65E-12	1,85E-06	3,71E-03
Total				**3,40E-04**	**6,79E-01**

Table 10.1: Dose uptake by direct gamma-radiation (continued)

Material: Phosphogypsum

density: **2 Mg/m³**
volume: **10 m³**

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	200	4,00E+06			
U-234	*200*	4,00E+06			
Th-230	*200*	4,00E+06	1,16E-12	4,64E-06	9,28E-03
Ra-226	600	1,20E+07	6,38E-11	7,66E-04	1,53E+00
Rn-222	*600*	1,20E+07	6,41E-12	7,69E-05	1,54E-01
Pb-210	*600*	1,20E+07			
Po-210	*600*	1,20E+07	1,07E-13	1,28E-06	2,57E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	20	4,00E+05	6,09E-13	2,44E-07	4,87E-04
Ra-228	70	1,40E+06			
Th-228	20	4,00E+05	9,65E-12	3,86E-06	7,72E-03
Total				**8,53E-04**	**1,71E+00**

Material: Calcium Silicate Slag

density: **2,5 Mg/m³**
volume: **10 m³**

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	2.000	5,00E+07			
U-234	*2.000*	5,00E+07			
Th-230	*2.000*	5,00E+07	1,16E-12	5,80E-05	1,16E-01
Ra-226	*2.000*	5,00E+07	6,38E-11	3,19E-03	6,38E+00
Rn-222	*2.000*	5,00E+07	6,41E-12	3,21E-04	6,41E-01
Pb-210	200	5,00E+06			
Po-210	*200*	5,00E+06	1,07E-13	5,35E-07	1,07E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	400	1,00E+07	6,09E-13	6,09E-06	1,22E-02
Ra-228	*400*	1,00E+07			
Th-228	*400*	1,00E+07	9,65E-12	9,65E-05	1,93E-01
Total				**3,67E-03**	**7,34E+00**

Table 10.1: Dose uptake by direct gamma-radiation (continued)

Material: Red Sludge

density: 1,5 Mg/m^3
volume: 10 m^3

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	250	3,75E+06			
U-234	*250*	3,75E+06			
Th-230	*250*	3,75E+06	1,16E-12	4,35E-06	8,70E-03
Ra-226	*250*	3,75E+06	6,38E-11	2,39E-04	4,79E-01
Rn-222	*250*	3,75E+06	6,41E-12	2,40E-05	4,81E-02
Pb-210	*250*	3,75E+06			
Po-210	*250*	3,75E+06	1,07E-13	4,01E-07	8,03E-04
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	300	4,50E+06	6,09E-13	2,74E-06	5,48E-03
Ra-228	*300*	4,50E+06			
Th-228	*300*	4,50E+06	9,65E-12	4,34E-05	8,69E-02
Total				**3,14E-04**	**6,28E-01**

Material: Copper Slag

density: 3,5 Mg/m^3
volume: 10 m^3

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	800	2,80E+07			
U-234	*800*	2,80E+07			
Th-230	*800*	2,80E+07	1,16E-12	3,25E-05	6,50E-02
Ra-226	*800*	2,80E+07	6,38E-11	1,79E-03	3,57E+00
Rn-222	*800*	2,80E+07	6,41E-12	1,79E-04	3,59E-01
Pb-210	*800*	2,80E+07			
Po-210	*800*	2,80E+07	1,07E-13	3,00E-06	5,99E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	80	2,80E+06	6,09E-13	1,71E-06	3,41E-03
Ra-228	*80*	2,80E+06			
Th-228	*80*	2,80E+06	9,65E-12	2,70E-05	5,40E-02
Total				**2,03E-03**	**4,06E+00**

Table 10.1: Dose uptake by direct gamma-radiation (continued)

Material: **Tin Slag**

density: **3,5 Mg/m³**
volume: **10 m³**

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	500	1,75E+07			
U-234	*500*	1,75E+07			
Th-230	*500*	1,75E+07	1,16E-12	2,03E-05	4,06E-02
Ra-226	*500*	1,75E+07	6,38E-11	1,12E-03	2,23E+00
Rn-222	*500*	1,75E+07	6,41E-12	1,12E-04	2,24E-01
Pb-210	*500*	1,75E+07			
Po-210	*500*	1,75E+07	1,07E-13	1,87E-06	3,75E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	250	8,75E+06	6,09E-13	5,33E-06	1,07E-02
Ra-228	*250*	8,75E+06			
Th-228	*250*	8,75E+06	9,65E-12	8,44E-05	1,69E-01
Total				**1,34E-03**	**2,68E+00**

Table 10.1: Dose uptake by direct gamma-radiation (continued)

10.1.2 Dose Uptake by Dust Inhalation

Material: Phosphate Ore

Dust concentration: 0,1 mg/m³

Nuclide	mean specific activity	air activity concen-tration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[mSv/Bq/m³/h]	[mSv/h]	[mSv]
U-238	2.000	2,00E-01	6,70E-03	1,34E-03	2,68E+00
U-234	*2.000*	2,00E-01	7,87E-03	1,57E-03	3,15E+00
Th-230	*2.000*	2,00E-01	7,87E-02	1,57E-02	3,15E+01
Ra-226	*2.000*	2,00E-01	1,52E-02	3,04E-03	6,08E+00
Rn-222	*2.000*	2,00E-01	1,37E-05	2,74E-06	5,48E-03
Pb-210	*2.000*	2,00E-01	4,68E-03	9,36E-04	1,87E+00
Po-210	*2.000*	2,00E-01	3,60E-03	7,20E-04	1,44E+00
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	50	5,00E-03	8,35E-02	4,18E-04	8,35E-01
Ra-228	*50*	5,00E-03	1,34E-02	6,70E-05	1,34E-01
Th-228	*50*	5,00E-03	3,35E-02	1,68E-04	3,35E-01
Total					**4,80E+01**

Material: Zircon Sands

Dust concentration: 0,1 mg/m³

Nuclide	mean specific activity	air activity concen-tration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[mSv/Bq/m³/h]	[mSv/h]	[mSv]
U-238	4.000	4,00E-01	6,70E-03	2,68E-03	5,36E+00
U-234	*4.000*	4,00E-01	7,87E-03	3,15E-03	6,30E+00
Th-230	*4.000*	4,00E-01	7,87E-02	3,15E-02	6,30E+01
Ra-226	*4.000*	4,00E-01	1,52E-02	6,08E-03	1,22E+01
Rn-222	*4.000*	4,00E-01	1,37E-05	5,48E-06	1,10E-02
Pb-210	*4.000*	4,00E-01	4,68E-03	1,87E-03	3,74E+00
Po-210	*4.000*	4,00E-01	3,60E-03	1,44E-03	2,88E+00
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	700	7,00E-02	8,35E-02	5,85E-03	1,17E+01
Ra-228	*700*	7,00E-02	1,34E-02	9,38E-04	1,88E+00
Th-228	*700*	7,00E-02	3,35E-02	2,35E-03	4,69E+00
Total					**1,12E+02**

Table 10.2: Dose uptake by dust inhalation

Material: Aluminium Ore

Dust concentration: 0,1 mg/m^3

Nuclide	mean specific activity	air activity concentration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m^3]	[mSv/Bq/m^3/h]	[mSv/h]	[mSv]
U-238	300	3,00E-02	6,70E-03	2,01E-04	4,02E-01
U-234	*300*	3,00E-02	7,87E-03	2,36E-04	4,72E-01
Th-230	*300*	3,00E-02	7,87E-02	2,36E-03	4,72E+00
Ra-226	*300*	3,00E-02	1,52E-02	4,56E-04	9,12E-01
Rn-222	*300*	3,00E-02	1,37E-05	4,11E-07	8,22E-04
Pb-210	*300*	3,00E-02	4,68E-03	1,40E-04	2,81E-01
Po-210	*300*	3,00E-02	3,60E-03	1,08E-04	2,16E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	100	1,00E-02	8,35E-02	8,35E-04	1,67E+00
Ra-228	*100*	1,00E-02	1,34E-02	1,34E-04	2,68E-01
Th-228	*100*	1,00E-02	3,35E-02	3,35E-04	6,70E-01
Total					**9,61E+00**

Material: Copper Ore

Dust concentration: 0,1 mg/m^3

Nuclide	mean specific activity	air activity concentration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m^3]	[mSv/Bq/m^3/h]	[mSv/h]	[mSv]
U-238	40	4,00E-03	6,70E-03	2,68E-05	5,36E-02
U-234	*40*	4,00E-03	7,87E-03	3,15E-05	6,30E-02
Th-230	*40*	4,00E-03	7,87E-02	3,15E-04	6,30E-01
Ra-226	*40*	4,00E-03	1,52E-02	6,08E-05	1,22E-01
Rn-222	*40*	4,00E-03	1,37E-05	5,48E-08	1,10E-04
Pb-210	*40*	4,00E-03	4,68E-03	1,87E-05	3,74E-02
Po-210	*40*	4,00E-03	3,60E-03	1,44E-05	2,88E-02
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	30	3,00E-03	8,35E-02	2,51E-04	5,01E-01
Ra-228	*30*	3,00E-03	1,34E-02	4,02E-05	8,04E-02
Th-228	*30*	3,00E-03	3,35E-02	1,01E-04	2,01E-01
Total					**1,72E+00**

Table 10.2: Dose uptake by dust inhalation (continued)

Material: Pyrochlore

Dust concentration: 0,1 mg/m^3

Nuclide	mean specific activity	air activity concen-tration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m^3]	[mSv/Bq/m^3/h]	[mSv/h]	[mSv]
U-238	17.000	1,70E+00	6,70E-03	1,14E-02	2,28E+01
U-234	*17.000*	1,70E+00	7,87E-03	1,34E-02	2,68E+01
Th-230	*17.000*	1,70E+00	7,87E-02	1,34E-01	2,68E+02
Ra-226	*17.000*	1,70E+00	1,52E-02	2,58E-02	5,17E+01
Rn-222	*17.000*	1,70E+00	1,37E-05	2,33E-05	4,66E-02
Pb-210	*17.000*	1,70E+00	4,68E-03	7,96E-03	1,59E+01
Po-210	*17.000*	1,70E+00	3,60E-03	6,12E-03	1,22E+01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232		0,00E+00	8,35E-02	0,00E+00	0,00E+00
Ra-228		0,00E+00	1,34E-02	0,00E+00	0,00E+00
Th-228		0,00E+00	3,35E-02	0,00E+00	0,00E+00
Total					**3,97E+02**

Material: Fertilizer SSP

Dust concentration: 0,1 mg/m^3

Nuclide	mean specific activity	air activity concen-tration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m^3]	[mSv/Bq/m^3/h]	[mSv/h]	[mSv]
U-238	500	5,00E-02	6,70E-03	3,35E-04	6,70E-01
U-234	*500*	5,00E-02	7,87E-03	3,94E-04	7,87E-01
Th-230	670	6,70E-02	7,87E-02	5,27E-03	1,05E+01
Ra-226	300	3,00E-02	1,52E-02	4,56E-04	9,12E-01
Rn-222	*300*	3,00E-02	1,37E-05	4,11E-07	8,22E-04
Pb-210	300	3,00E-02	4,68E-03	1,40E-04	2,81E-01
Po-210	*300*	3,00E-02	3,60E-03	1,08E-04	2,16E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	20	2,00E-03	8,35E-02	1,67E-04	3,34E-01
Ra-228	10	1,00E-03	1,34E-02	1,34E-05	2,68E-02
Th-228	10	1,00E-03	3,35E-02	3,35E-05	6,70E-02
Total					**1,38E+01**

Table 10.2: Dose uptake by dust inhalation (continued)

Material: Fertilizer TSP

Dust concentration: 0,1 mg/m³

Nuclide	mean specific activity	air activity concen-tration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[mSv/Bq/m³/h]	[mSv/h]	[mSv]
U-238	800	8,00E-02	6,70E-03	5,36E-04	1,07E+00
U-234	*800*	8,00E-02	7,87E-03	6,30E-04	1,26E+00
Th-230	500	5,00E-02	7,87E-02	3,94E-03	7,87E+00
Ra-226	200	2,00E-02	1,52E-02	3,04E-04	6,08E-01
Rn-222	*200*	2,00E-02	1,37E-05	2,74E-07	5,48E-04
Pb-210	*200*	2,00E-02	4,68E-03	9,36E-05	1,87E-01
Po-210	*200*	2,00E-02	3,60E-03	7,20E-05	1,44E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	45	4,50E-03	8,35E-02	3,76E-04	7,52E-01
Ra-228	*45*	4,50E-03	1,34E-02	6,03E-05	1,21E-01
Th-228	*45*	4,50E-03	3,35E-02	1,51E-04	3,02E-01
Total					**1,23E+01**

Material: Fertilizer PK

Dust concentration: 0,1 mg/m³

Nuclide	mean specific activity	air activity concen-tration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[mSv/Bq/m³/h]	[mSv/h]	[mSv]
U-238		0,00E+00	6,70E-03	0,00E+00	0,00E+00
U-234		0,00E+00	7,87E-03	0,00E+00	0,00E+00
Th-230		0,00E+00	7,87E-02	0,00E+00	0,00E+00
Ra-226	200	2,00E-02	1,52E-02	3,04E-04	6,08E-01
Rn-222	*200*	2,00E-02	1,37E-05	2,74E-07	5,48E-04
Pb-210	*200*	2,00E-02	4,68E-03	9,36E-05	1,87E-01
Po-210	*200*	2,00E-02	3,60E-03	7,20E-05	1,44E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	10	1,00E-03	8,35E-02	8,35E-05	1,67E-01
Ra-228	10	1,00E-03	1,34E-02	1,34E-05	2,68E-02
Th-228	8	8,00E-04	3,35E-02	2,68E-05	5,36E-02
Total					**1,19E+00**

Table 10.2: Dose uptake by dust inhalation (continued)

Material: Phosphogypsum

Dust concentration: 0,1 mg/m³

Nuclide	**mean specific activity**	**air activity concen-tration**	**normalized effective dose**	**effective Dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m³]	[mSv/Bq/m³/h]	[mSv/h]	[mSv]
U-238	200	2,00E-02	6,70E-03	1,34E-04	2,68E-01
U-234	*200*	2,00E-02	7,87E-03	1,57E-04	3,15E-01
Th-230	*200*	2,00E-02	7,87E-02	1,57E-03	3,15E+00
Ra-226	600	6,00E-02	1,52E-02	9,12E-04	1,82E+00
Rn-222	*600*	6,00E-02	1,37E-05	8,22E-07	1,64E-03
Pb-210	*600*	6,00E-02	4,68E-03	2,81E-04	5,62E-01
Po-210	*600*	6,00E-02	3,60E-03	2,16E-04	4,32E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	20	2,00E-03	8,35E-02	1,67E-04	3,34E-01
Ra-228	70	7,00E-03	1,34E-02	9,38E-05	1,88E-01
Th-228	20	2,00E-03	3,35E-02	6,70E-05	1,34E-01
Total					**7,21E+00**

Material: Calcium Silicate Slag

Dust concentration: 0,1 mg/m³

Nuclide	**mean specific activity**	**air activity concen-tration**	**normalized effective dose**	**effective Dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m³]	[mSv/Bq/m³/h]	[mSv/h]	[mSv]
U-238	2.000	2,00E-01	6,70E-03	1,34E-03	2,68E+00
U-234	*2.000*	2,00E-01	7,87E-03	1,57E-03	3,15E+00
Th-230	*2.000*	2,00E-01	7,87E-02	1,57E-02	3,15E+01
Ra-226	*2.000*	2,00E-01	1,52E-02	3,04E-03	6,08E+00
Rn-222	*2.000*	2,00E-01	1,37E-05	2,74E-06	5,48E-03
Pb-210	200	2,00E-02	4,68E-03	9,36E-05	1,87E-01
Po-210	*200*	2,00E-02	3,60E-03	7,20E-05	1,44E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	400	4,00E-02	8,35E-02	3,34E-03	6,68E+00
Ra-228	*400*	4,00E-02	1,34E-02	5,36E-04	1,07E+00
Th-228	*400*	4,00E-02	3,35E-02	1,34E-03	2,68E+00
Total					**5,42E+01**

Table 10.2: Dose uptake by dust inhalation (continued)

Material: Red Sludge

Dust concentration: 0,1 mg/m^3

Nuclide	**mean specific activity**	**air activity concen-tration**	**normalized effective dose**	**effective Dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m^3]	[mSv/Bq/m^3/h]	[mSv/h]	[mSv]
U-238	250	2,50E-02	6,70E-03	1,68E-04	3,35E-01
U-234	*250*	2,50E-02	7,87E-03	1,97E-04	3,94E-01
Th-230	*250*	2,50E-02	7,87E-02	1,97E-03	3,94E+00
Ra-226	*250*	2,50E-02	1,52E-02	3,80E-04	7,60E-01
Rn-222	*250*	2,50E-02	1,37E-05	3,43E-07	6,85E-04
Pb-210	*250*	2,50E-02	4,68E-03	1,17E-04	2,34E-01
Po-210	*250*	2,50E-02	3,60E-03	9,00E-05	1,80E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	300	3,00E-02	8,35E-02	2,51E-03	5,01E+00
Ra-228	*300*	3,00E-02	1,34E-02	4,02E-04	8,04E-01
Th-228	*300*	3,00E-02	3,35E-02	1,01E-03	2,01E+00
Total					**1,37E+01**

Material: Copper Slag

Dust concentration: 0,1 mg/m^3

Nuclide	**mean specific activity**	**air activity concen-tration**	**normalized effective dose**	**effective Dose rate**	**annual dose 2000 h/a**
	[Bq/kg]	[Bq/m^3]	[mSv/Bq/m^3/h]	[mSv/h]	[mSv]
U-238	800	8,00E-02	6,70E-03	5,36E-04	1,07E+00
U-234	*800*	8,00E-02	7,87E-03	6,30E-04	1,26E+00
Th-230	*800*	8,00E-02	7,87E-02	6,30E-03	1,26E+01
Ra-226	*800*	8,00E-02	1,52E-02	1,22E-03	2,43E+00
Rn-222	*800*	8,00E-02	1,37E-05	1,10E-06	2,19E-03
Pb-210	*800*	8,00E-02	4,68E-03	3,74E-04	7,49E-01
Po-210	*800*	8,00E-02	3,60E-03	2,88E-04	5,76E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	80	8,00E-03	8,35E-02	6,68E-04	1,34E+00
Ra-228	*80*	8,00E-03	1,34E-02	1,07E-04	2,14E-01
Th-228	*80*	8,00E-03	3,35E-02	2,68E-04	5,36E-01
Total					**2,08E+01**

Table 10.2: Dose uptake by dust inhalation (continued)

Material: Tin Slag

Dust concentration: 0,1 mg/m^3

Nuclide	mean specific activity	air activity concentration	normalized effective dose	effective Dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m^3]	[mSv/Bq/m^3/h]	[mSv/h]	[mSv]
U-238	500	5,00E-02	6,70E-03	3,35E-04	6,70E-01
U-234	*500*	5,00E-02	7,87E-03	3,94E-04	7,87E-01
Th-230	*500*	5,00E-02	7,87E-02	3,94E-03	7,87E+00
Ra-226	*500*	5,00E-02	1,52E-02	7,60E-04	1,52E+00
Rn-222	*500*	5,00E-02	1,37E-05	6,85E-07	1,37E-03
Pb-210	*500*	5,00E-02	4,68E-03	2,34E-04	4,68E-01
Po-210	*500*	5,00E-02	3,60E-03	1,80E-04	3,60E-01
U-235			7,66E-03	0,00E+00	0,00E+00
Pa-231			1,01E-01	0,00E+00	0,00E+00
Ac-227			4,43E-01	0,00E+00	0,00E+00
Th-232	250	2,50E-02	8,35E-02	2,09E-03	4,18E+00
Ra-228	*250*	2,50E-02	1,34E-02	3,35E-04	6,70E-01
Th-228	*250*	2,50E-02	3,35E-02	8,38E-04	1,68E+00
Total					**1,82E+01**

Table 10.2: Dose uptake by dust inhalation (continued)

10.1.3 Dose Uptake by Truck Driver

Material: Phosphate Ore

density: 3 Mg/m^3
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	2.000	4,00E+07			
U-234	*2.000*	4,00E+07			
Th-230	*2.000*	4,00E+07	1,16E-12	4,64E-05	2,78E-02
Ra-226	*2.000*	4,00E+07	6,38E-11	2,55E-03	1,53E+00
Rn-222	*2.000*	4,00E+07	6,41E-12	2,56E-04	1,54E-01
Pb-210	*2.000*	4,00E+07			
Po-210	*2.000*	4,00E+07	1,07E-13	4,28E-06	2,57E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	50	1,00E+06	6,09E-13	6,09E-07	3,65E-04
Ra-228	*50*	1,00E+06			
Th-228	*50*	1,00E+06	9,65E-12	9,65E-06	5,79E-03
Total				**2,87E-03**	**1,72E+00**

Material: Zircon Sands

density: 5 Mg/m^3
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	4.000	8,00E+07			
U-234	*4.000*	8,00E+07			
Th-230	*4.000*	8,00E+07	1,16E-12	9,28E-05	5,57E-02
Ra-226	*4.000*	8,00E+07	6,38E-11	5,10E-03	3,06E+00
Rn-222	*4.000*	8,00E+07	6,41E-12	5,13E-04	3,08E-01
Pb-210	*4.000*	8,00E+07			
Po-210	*4.000*	8,00E+07	1,07E-13	8,56E-06	5,14E-03
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	700	1,40E+07	6,09E-13	8,53E-06	5,12E-03
Ra-228	*700*	1,40E+07			
Th-228	*700*	1,40E+07	9,65E-12	1,35E-04	8,11E-02
Total				**5,86E-03**	**3,52E+00**

Table 10.3: Dose uptake by truck driver (direct gamma-radiation)

Material: **Aluminium Ore**

density: **3 Mg/m³**
mass: **20 Mg**

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 600 h/a**
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	300	6,00E+06			
U-234	*300*	6,00E+06			
Th-230	*300*	6,00E+06	1,16E-12	6,96E-06	4,18E-03
Ra-226	*300*	6,00E+06	6,38E-11	3,83E-04	2,30E-01
Rn-222	*300*	6,00E+06	6,41E-12	3,85E-05	2,31E-02
Pb-210	*300*	6,00E+06			0,00E+00
Po-210	*300*	6,00E+06	1,07E-13	6,42E-07	3,85E-04
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	100	2,00E+06	6,09E-13	1,22E-06	7,31E-04
Ra-228	*100*	2,00E+06			
Th-228	*100*	2,00E+06	9,65E-12	1,93E-05	1,16E-02
Total				**4,49E-04**	**2,70E-01**

Material: **Copper Ore**

density: **4,6 Mg/m³**
volume: **20 Mg**

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 600 h/a**
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	40	8,00E+05			
U-234	*40*	8,00E+05			
Th-230	*40*	8,00E+05	1,16E-12	9,28E-07	5,57E-04
Ra-226	*40*	8,00E+05	6,38E-11	5,10E-05	3,06E-02
Rn-222	*40*	8,00E+05	6,41E-12	5,13E-06	3,08E-03
Pb-210	*40*	8,00E+05			
Po-210	*40*	8,00E+05	1,07E-13	8,56E-08	5,14E-05
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	30	6,00E+05	6,09E-13	3,65E-07	2,19E-04
Ra-228	*30*	6,00E+05			
Th-228	*30*	6,00E+05	9,65E-12	5,79E-06	3,47E-03
Total				**6,33E-05**	**3,80E-02**

Table 10.3: Dose uptake by truck driver (direct gamma-radiation) (continued)

Material: Pyrochlore

density: 5,3 Mg/m³
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	17.000	3,40E+08			
U-234	*17.000*	3,40E+08			
Th-230	*17.000*	3,40E+08	1,16E-12	3,94E-04	2,37E-01
Ra-226	*17.000*	3,40E+08	6,38E-11	2,17E-02	1,30E+01
Rn-222	*17.000*	3,40E+08	6,41E-12	2,18E-03	1,31E+00
Pb-210	*17.000*	3,40E+08			
Po-210	*17.000*	3,40E+08	1,07E-13	3,64E-05	2,18E-02
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232		0,00E+00	6,09E-13	0,00E+00	0,00E+00
Ra-228		0,00E+00			
Th-228		0,00E+00	9,65E-12	0,00E+00	0,00E+00
Total				**2,43E-02**	**1,46E+01**

Material: Fertilizer SSP

density: 2,4 Mg/m³
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	500	1,00E+07			
U-234	*500*	1,00E+07			
Th-230	670	1,34E+07	1,16E-12	1,55E-05	9,33E-03
Ra-226	300	6,00E+06	6,38E-11	3,83E-04	2,30E-01
Rn-222	*300*	6,00E+06	6,41E-12	3,85E-05	2,31E-02
Pb-210	300	6,00E+06			
Po-210	*300*	6,00E+06	1,07E-13	6,42E-07	3,85E-04
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	20	4,00E+05	6,09E-13	2,44E-07	1,46E-04
Ra-228	10	2,00E+05			
Th-228	10	2,00E+05	9,65E-12	1,93E-06	1,16E-03
Total				**4,40E-04**	**2,64E-01**

Table 10.3: Dose uptake by truck driver (direct gamma-radiation) (continued)

Material: Fertilizer TSP

density: 2,4 Mg/m³
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	800	1,60E+07			
U-234	*800*	1,60E+07			
Th-230	500	1,00E+07	1,16E-12	1,16E-05	6,96E-03
Ra-226	200	4,00E+06	6,38E-11	2,55E-04	1,53E-01
Rn-222	*200*	4,00E+06	6,41E-12	2,56E-05	1,54E-02
Pb-210	*200*	4,00E+06			
Po-210	*200*	4,00E+06	1,07E-13	4,28E-07	2,57E-04
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	45	9,00E+05	6,09E-13	5,48E-07	3,29E-04
Ra-228	*45*	9,00E+05			
Th-228	*45*	9,00E+05	9,65E-12	8,69E-06	5,21E-03
Total				**3,02E-04**	**1,81E-01**

Material: Fertilizer PK

density: 2,4 Mg/m³
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 2000 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238					
U-234					
Th-230			1,16E-12	0,00E+00	
Ra-226	200	4,00E+06	6,38E-11	2,55E-04	1,53E-01
Rn-222	*200*	4,00E+06	6,41E-12	2,56E-05	1,54E-02
Pb-210	*200*	4,00E+06			
Po-210	*200*	4,00E+06	1,07E-13	4,28E-07	2,57E-04
U-235			1,49E-09		
Pa-231					
Ac-227					
Th-232	10	2,00E+05	6,09E-13	1,22E-07	7,31E-05
Ra-228	10	2,00E+05			
Th-228	8	1,60E+05	9,65E-12	1,54E-06	9,26E-04
Total				**2,83E-04**	**1,70E-01**

Table 10.3: Dose uptake by truck driver (direct gamma-radiation) (continued)

Material: Phosphogypsum

density: 2 Mg/m^3
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	200	4,00E+06			
U-234	*200*	4,00E+06			
Th-230	*200*	4,00E+06	1,16E-12	4,64E-06	2,78E-03
Ra-226	600	1,20E+07	6,38E-11	7,66E-04	4,59E-01
Rn-222	*600*	1,20E+07	6,41E-12	7,69E-05	4,62E-02
Pb-210	*600*	1,20E+07			
Po-210	*600*	1,20E+07	1,07E-13	1,28E-06	7,70E-04
U-235			1,49E-09		
Pa-231					
Ac-227					
Th-232	20	4,00E+05	6,09E-13	2,44E-07	1,46E-04
Ra-228	70	1,40E+06			
Th-228	20	4,00E+05	9,65E-12	3,86E-06	2,32E-03
Total				**8,53E-04**	**5,12E-01**

Material: Calcium Silicate Slag

density: 2,5 Mg/m^3
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m^3]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	2.000	4,00E+07			
U-234	*2.000*	4,00E+07			
Th-230	*2.000*	4,00E+07	1,16E-12	4,64E-05	2,78E-02
Ra-226	*2.000*	4,00E+07	6,38E-11	2,55E-03	1,53E+00
Rn-222	*2.000*	4,00E+07	6,41E-12	2,56E-04	1,54E-01
Pb-210	200	4,00E+06			
Po-210	*200*	4,00E+06	1,07E-13	4,28E-07	2,57E-04
U-235			1,49E-09	0,00E+00	0,00E+00
Pa-231					
Ac-227					
Th-232	400	8,00E+06	6,09E-13	4,87E-06	2,92E-03
Ra-228	*400*	8,00E+06			
Th-228	*400*	8,00E+06	9,65E-12	7,72E-05	4,63E-02
Total				**2,94E-03**	**1,76E+00**

Table 10.3: Dose uptake by truck driver (direct gamma-radiation) (continued)

Material: Red Sludge

density: 1,5 Mg/m³
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	250	5,00E+06			
U-234	*250*	5,00E+06			
Th-230	*250*	5,00E+06	1,16E-12	5,80E-06	3,48E-03
Ra-226	*250*	5,00E+06	6,38E-11	3,19E-04	1,91E-01
Rn-222	*250*	5,00E+06	6,41E-12	3,21E-05	1,92E-02
Pb-210	*250*	5,00E+06			0,00E+00
Po-210	*250*	5,00E+06	1,07E-13	5,35E-07	3,21E-04
U-235			1,49E-09		
Pa-231					
Ac-227					
Th-232	300	6,00E+06	6,09E-13	3,65E-06	2,19E-03
Ra-228	*300*	6,00E+06			
Th-228	*300*	6,00E+06	9,65E-12	5,79E-05	3,47E-02
Total				**4,19E-04**	**2,51E-01**

Material: Copper Slag

density: 3,5 Mg/m³
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	800	1,60E+07			
U-234	*800*	1,60E+07			
Th-230	*800*	1,60E+07	1,16E-12	1,86E-05	1,11E-02
Ra-226	*800*	1,60E+07	6,38E-11	1,02E-03	6,12E-01
Rn-222	*800*	1,60E+07	6,41E-12	1,03E-04	6,15E-02
Pb-210	*800*	1,60E+07			
Po-210	*800*	1,60E+07	1,07E-13	1,71E-06	1,03E-03
U-235			1,49E-09		
Pa-231					
Ac-227					
Th-232	80	1,60E+06	6,09E-13	9,74E-07	5,85E-04
Ra-228	*80*	1,60E+06			
Th-228	*80*	1,60E+06	9,65E-12	1,54E-05	9,26E-03
Total				**1,16E-03**	**6,96E-01**

Table 10.3: Dose uptake by truck driver (direct gamma-radiation) (continued)

Material: Tin Slag

density: 3,5 Mg/m³
mass: 20 Mg

Nuclide	mean specific activity	mean total activity	normalized effective dose	external dose rate	annual dose 600 h/a
	[Bq/kg]	[Bq/m³]	[µSv/Bq/h]	[µSv/h]	[µSv]
U-238	500	1,00E+07			
U-234	*500*	1,00E+07			
Th-230	*500*	1,00E+07	1,16E-12	1,16E-05	6,96E-03
Ra-226	*500*	1,00E+07	6,38E-11	6,38E-04	3,83E-01
Rn-222	*500*	1,00E+07	6,41E-12	6,41E-05	3,85E-02
Pb-210	*500*	1,00E+07			
Po-210	*500*	1,00E+07	1,07E-13	1,07E-06	6,42E-04
U-235			1,49E-09		
Pa-231					
Ac-227					
Th-232	250	5,00E+06	6,09E-13	3,05E-06	1,83E-03
Ra-228	*250*	5,00E+06			
Th-228	*250*	5,00E+06	9,65E-12	4,83E-05	2,90E-02
Total				**7,66E-04**	**4,60E-01**

Table 10.3: Dose uptake by truck driver (direct gamma-radiation) (continued)

10.1.4 Dose Uptake resulting from Material Dumping

Dispersion conditions (worst case)

wind velocity	0,1 m/s
precipitation	0,5 mm/h rain
diffusion category	D respectively F
emission altitude	3 m
emission period	0,5 h

release factor:	1,00E-04	
volume	10	m^3

Material: Phosphate Ore

density: 3 Mg/m^3
volume: 10 m^3

				normalized effective dose			**effective dose per unloading**		
Nuclide	**mean specific activity**	**mean total activity**	**released aerosols**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	2.000	6,00E+07	6,00E+03	1,26E-07	2,28E-08	6,24E-08	7,56E-04	1,37E-04	3,74E-04
U-234	*2.000*	6,00E+07	6,00E+03	1,48E-07	2,65E-08	6,90E-08	8,88E-04	1,59E-04	4,14E-04
Th-230	*2.000*	6,00E+07	6,00E+03	1,48E-06	2,07E-07	3,02E-07	8,88E-03	1,24E-03	1,81E-03
Ra-226	*2.000*	6,00E+07	6,00E+03	2,85E-07	8,72E-08	9,05E-07	1,71E-03	5,23E-04	5,43E-03
Rn-222	*2.000*	6,00E+07	6,00E+03	2,57E-10	3,42E-11	6,84E-10	1,54E-06	2,05E-07	4,10E-06
Pb-210	*2.000*	6,00E+07	6,00E+03	8,80E-08	2,00E-07	2,30E-06	5,28E-04	1,20E-03	1,38E-02
Po-210	*2.000*	6,00E+07	6,00E+03	6,76E-08	8,16E-08	1,58E-06	4,06E-04	4,90E-04	9,48E-03
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	50	1,50E+06	1,50E+02	1,57E-06	2,20E-07	3,30E-07	2,36E-04	3,30E-05	4,95E-05
Ra-228	*50*	1,50E+06	1,50E+02	2,51E-07	1,59E-07	5,47E-06	3,77E-05	2,39E-05	8,21E-04
Th-228	*50*	1,50E+06	1,50E+02	6,29E-07	8,74E-08	3,02E-07	9,44E-05	1,31E-05	4,53E-05
Total							**1,35E-02**	**3,82E-03**	**3,22E-02**

Table 10.4: Dose uptake resulting from material dumping

Material: Zircon Sands

density: 5 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	released aerosols	normalized effective dose			effective dose per unloading		
				worker (10 m)	adults * (100 m)	infants * (100 m)	worker (10 m)	adults * (100 m)	infants * (100 m)
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	4.000	2,00E+08	2,00E+04	1,26E-07	2,28E-08	6,24E-08	2,52E-03	4,56E-04	1,25E-03
U-234	*4.000*	2,00E+08	2,00E+04	1,48E-07	2,65E-08	6,90E-08	2,96E-03	5,30E-04	1,38E-03
Th-230	*4.000*	2,00E+08	2,00E+04	1,48E-06	2,07E-07	3,02E-07	2,96E-02	4,14E-03	6,04E-03
Ra-226	*4.000*	2,00E+08	2,00E+04	2,85E-07	8,72E-08	9,05E-07	5,70E-03	1,74E-03	1,81E-02
Rn-222	*4.000*	2,00E+08	2,00E+04	2,57E-10	3,42E-11	6,84E-10	5,14E-06	6,84E-07	1,37E-05
Pb-210	*4.000*	2,00E+08	2,00E+04	8,80E-08	2,00E-07	2,30E-06	1,76E-03	4,00E-03	4,60E-02
Po-210	*4.000*	2,00E+08	2,00E+04	6,76E-08	8,16E-08	1,58E-06	1,35E-03	1,63E-03	3,16E-02
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	700	3,50E+07	3,50E+03	1,57E-06	2,20E-07	3,30E-07	5,50E-03	7,70E-04	1,16E-03
Ra-228	*700*	3,50E+07	3,50E+03	2,51E-07	1,59E-07	5,47E-06	8,79E-04	5,57E-04	1,91E-02
Th-228	*700*	3,50E+07	3,50E+03	6,29E-07	8,74E-08	3,02E-07	2,20E-03	3,06E-04	1,06E-03
Total							**5,25E-02**	**1,41E-02**	**1,26E-01**

Material: Aluminium Ore

density: 3 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	released aerosols	normalized effective dose			effective dose per unloading		
				worker (10 m)	adults * (100 m)	infants * (100 m)	worker (10 m)	adults * (100 m)	infants * (100 m)
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	300	9,00E+06	9,00E+02	1,26E-07	2,28E-08	6,24E-08	1,13E-04	2,05E-05	5,62E-05
U-234	*300*	9,00E+06	9,00E+02	1,48E-07	2,65E-08	6,90E-08	1,33E-04	2,39E-05	6,21E-05
Th-230	*300*	9,00E+06	9,00E+02	1,48E-06	2,07E-07	3,02E-07	1,33E-03	1,86E-04	2,72E-04
Ra-226	*300*	9,00E+06	9,00E+02	2,85E-07	8,72E-08	9,05E-07	2,57E-04	7,85E-05	8,15E-04
Rn-222	*300*	9,00E+06	9,00E+02	2,57E-10	3,42E-11	6,84E-10	2,31E-07	3,08E-08	6,16E-07
Pb-210	*300*	9,00E+06	9,00E+02	8,80E-08	2,00E-07	2,30E-06	7,92E-05	1,80E-04	2,07E-03
Po-210	*300*	9,00E+06	9,00E+02	6,76E-08	8,16E-08	1,58E-06	6,08E-05	7,34E-05	1,42E-03
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	100	3,00E+06	3,00E+02	1,57E-06	2,20E-07	3,30E-07	4,71E-04	6,60E-05	9,90E-05
Ra-228	*100*	3,00E+06	3,00E+02	2,51E-07	1,59E-07	5,47E-06	7,53E-05	4,77E-05	1,64E-03
Th-228	*100*	3,00E+06	3,00E+02	6,29E-07	8,74E-08	3,02E-07	1,89E-04	2,62E-05	9,06E-05
Total							**2,71E-03**	**7,03E-04**	**6,53E-03**

Table 10.4: Dose uptake resulting from material dumping (continued)

Material: Copper Ore

density: 4,6 Mg/m³
volume: 10 m³

				normalized effective dose			**effective dose per unloading**		
Nuclide	**mean specific activity**	**mean total activity**	**released aerosols**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	40	1,84E+06	1,84E+02	1,26E-07	2,28E-08	6,24E-08	2,32E-05	4,20E-06	1,15E-05
U-234	*40*	1,84E+06	1,84E+02	1,48E-07	2,65E-08	6,90E-08	2,72E-05	4,88E-06	1,27E-05
Th-230	*40*	1,84E+06	1,84E+02	1,48E-06	2,07E-07	3,02E-07	2,72E-04	3,81E-05	5,56E-05
Ra-226	*40*	1,84E+06	1,84E+02	2,85E-07	8,72E-08	9,05E-07	5,24E-05	1,60E-05	1,67E-04
Rn-222	*40*	1,84E+06	1,84E+02	2,57E-10	3,42E-11	6,84E-10	4,73E-08	6,29E-09	1,26E-07
Pb-210	*40*	1,84E+06	1,84E+02	8,80E-08	2,00E-07	2,30E-06	1,62E-05	3,68E-05	4,23E-04
Po-210	*40*	1,84E+06	1,84E+02	6,76E-08	8,16E-08	1,58E-06	1,24E-05	1,50E-05	2,91E-04
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	30	1,38E+06	1,38E+02	1,57E-06	2,20E-07	3,30E-07	2,17E-04	3,04E-05	4,55E-05
Ra-228	*30*	1,38E+06	1,38E+02	2,51E-07	1,59E-07	5,47E-06	3,46E-05	2,19E-05	7,55E-04
Th-228	*30*	1,38E+06	1,38E+02	6,29E-07	8,74E-08	3,02E-07	8,68E-05	1,21E-05	4,17E-05
Total							**7,42E-04**	**1,79E-04**	**1,80E-03**

Material: Pyrochlore

density: 5,3 Mg/m³
volume: 10 m³

				normalized effective dose			**effective dose per unloading**		
Nuclide	**mean specific activity**	**mean total activity**	**released aerosols**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	17.000	9,01E+08	9,01E+04	1,26E-07	2,28E-08	6,24E-08	1,14E-02	2,05E-03	5,62E-03
U-234	*17.000*	9,01E+08	9,01E+04	1,48E-07	2,65E-08	6,90E-08	1,33E-02	2,39E-03	6,22E-03
Th-230	*17.000*	9,01E+08	9,01E+04	1,48E-06	2,07E-07	3,02E-07	1,33E-01	1,87E-02	2,72E-02
Ra-226	*17.000*	9,01E+08	9,01E+04	2,85E-07	8,72E-08	9,05E-07	2,57E-02	7,86E-03	8,15E-02
Rn-222	*17.000*	9,01E+08	9,01E+04	2,57E-10	3,42E-11	6,84E-10	2,32E-05	3,08E-06	6,16E-05
Pb-210	*17.000*	9,01E+08	9,01E+04	8,80E-08	2,00E-07	2,30E-06	7,93E-03	1,80E-02	2,07E-01
Po-210	*17.000*	9,01E+08	9,01E+04	6,76E-08	8,16E-08	1,58E-06	6,09E-03	7,35E-03	1,42E-01
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232		0,00E+00	0,00E+00	1,57E-06	2,20E-07	3,30E-07	0,00E+00	0,00E+00	0,00E+00
Ra-228		0,00E+00	0,00E+00	2,51E-07	1,59E-07	5,47E-06	0,00E+00	0,00E+00	0,00E+00
Th-228		0,00E+00	0,00E+00	6,29E-07	8,74E-08	3,02E-07	0,00E+00	0,00E+00	0,00E+00
Total							**1,98E-01**	**5,63E-02**	**4,70E-01**

Table 10.4: Dose uptake resulting from material dumping (continued)

Material: Fertilizer SSP

density: 2,4 Mg/m³
volume: 10 m³

				normalized effective dose			**effective dose per unloading**		
Nuclide	**mean specific activity**	**mean total activity**	**released aerosols**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	500	1,20E+07	1,20E+03	1,26E-07	2,28E-08	6,24E-08	1,51E-04	2,74E-05	7,49E-05
U-234	*500*	1,20E+07	1,20E+03	1,48E-07	2,65E-08	6,90E-08	1,78E-04	3,18E-05	8,28E-05
Th-230	670	1,61E+07	1,61E+03	1,48E-06	2,07E-07	3,02E-07	2,38E-03	3,33E-04	4,86E-04
Ra-226	300	7,20E+06	7,20E+02	2,85E-07	8,72E-08	9,05E-07	2,05E-04	6,28E-05	6,52E-04
Rn-222	*300*	7,20E+06	7,20E+02	2,57E-10	3,42E-11	6,84E-10	1,85E-07	2,46E-08	4,92E-07
Pb-210	300	7,20E+06	7,20E+02	8,80E-08	2,00E-07	2,30E-06	6,34E-05	1,44E-04	1,66E-03
Po-210	*300*	7,20E+06	7,20E+02	6,76E-08	8,16E-08	1,58E-06	4,87E-05	5,88E-05	1,14E-03
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	20	4,80E+05	4,80E+01	1,57E-06	2,20E-07	3,30E-07	7,54E-05	1,06E-05	1,58E-05
Ra-228	10	2,40E+05	2,40E+01	2,51E-07	1,59E-07	5,47E-06	6,02E-06	3,82E-06	1,31E-04
Th-228	10	2,40E+05	2,40E+01	6,29E-07	8,74E-08	3,02E-07	1,51E-05	2,10E-06	7,25E-06
Total							**3,12E-03**	**6,74E-04**	**4,24E-03**

Material: Fertilizer TSP

density: 2,4 Mg/m³
volume: 10 m³

				normalized effective dose			**effective dose per unloading**		
Nuclide	**mean specific activity**	**mean total activity**	**released aerosols**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	800	1,92E+07	1,92E+03	1,26E-07	2,28E-08	6,24E-08	2,42E-04	4,38E-05	1,20E-04
U-234	*800*	1,92E+07	1,92E+03	1,48E-07	2,65E-08	6,90E-08	2,84E-04	5,09E-05	1,32E-04
Th-230	500	1,20E+07	1,20E+03	1,48E-06	2,07E-07	3,02E-07	1,78E-03	2,48E-04	3,62E-04
Ra-226	200	4,80E+06	4,80E+02	2,85E-07	8,72E-08	9,05E-07	1,37E-04	4,19E-05	4,34E-04
Rn-222	*200*	4,80E+06	4,80E+02	2,57E-10	3,42E-11	6,84E-10	1,23E-07	1,64E-08	3,28E-07
Pb-210	*200*	4,80E+06	4,80E+02	8,80E-08	2,00E-07	2,30E-06	4,22E-05	9,60E-05	1,10E-03
Po-210	*200*	4,80E+06	4,80E+02	6,76E-08	8,16E-08	1,58E-06	3,24E-05	3,92E-05	7,58E-04
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	45	1,08E+06	1,08E+02	1,57E-06	2,20E-07	3,30E-07	1,70E-04	2,38E-05	3,56E-05
Ra-228	*45*	1,08E+06	1,08E+02	2,51E-07	1,59E-07	5,47E-06	2,71E-05	1,72E-05	5,91E-04
Th-228	*45*	1,08E+06	1,08E+02	6,29E-07	8,74E-08	3,02E-07	6,79E-05	9,44E-06	3,26E-05
Total							**2,78E-03**	**5,70E-04**	**3,57E-03**

Table 10.4: Dose uptake resulting from material dumping (continued)

Material: Fertilizer PK

density: 2,4 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	released aerosols	normalized effective dose			effective dose per unloading		
				worker (10 m)	adults * (100 m)	infants * (100 m)	worker (10 m)	adults * (100 m)	infants * (100 m)
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238		0,00E+00	0,00E+00	1,26E-07	2,28E-08	6,24E-08	0,00E+00	0,00E+00	0,00E+00
U-234		0,00E+00	0,00E+00	1,48E-07	2,65E-08	6,90E-08	0,00E+00	0,00E+00	0,00E+00
Th-230		0,00E+00	0,00E+00	1,48E-06	2,07E-07	3,02E-07	0,00E+00	0,00E+00	0,00E+00
Ra-226	200	4,80E+06	4,80E+02	2,85E-07	8,72E-08	9,05E-07	1,37E-04	4,19E-05	4,34E-04
Rn-222	*200*	4,80E+06	4,80E+02	2,57E-10	3,42E-11	6,84E-10	1,23E-07	1,64E-08	3,28E-07
Pb-210	*200*	4,80E+06	4,80E+02	8,80E-08	2,00E-07	2,30E-06	4,22E-05	9,60E-05	1,10E-03
Po-210	*200*	4,80E+06	4,80E+02	6,76E-08	8,16E-08	1,58E-06	3,24E-05	3,92E-05	7,58E-04
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	10	2,40E+05	2,40E+01	1,57E-06	2,20E-07	3,30E-07	3,77E-05	5,28E-06	7,92E-06
Ra-228	10	2,40E+05	2,40E+01	2,51E-07	1,59E-07	5,47E-06	6,02E-06	3,82E-06	1,31E-04
Th-228	8	1,92E+05	1,92E+01	6,29E-07	8,74E-08	3,02E-07	1,21E-05	1,68E-06	5,80E-06
Total							**2,67E-04**	**1,88E-04**	**2,44E-03**

Material: Phosphogypsum

density: 2 Mg/m³
volume: 10 m³

Nuclide	mean specific activity	mean total activity	released aerosols	normalized effective dose			effective dose per unloading		
				worker (10 m)	adults * (100 m)	infants * (100 m)	worker (10 m)	adults * (100 m)	infants * (100 m)
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	200	4,00E+06	4,00E+02	1,26E-07	2,28E-08	6,24E-08	5,04E-05	9,12E-06	2,50E-05
U-234	*200*	4,00E+06	4,00E+02	1,48E-07	2,65E-08	6,90E-08	5,92E-05	1,06E-05	2,76E-05
Th-230	*200*	4,00E+06	4,00E+02	1,48E-06	2,07E-07	3,02E-07	5,92E-04	8,28E-05	1,21E-04
Ra-226	600	1,20E+07	1,20E+03	2,85E-07	8,72E-08	9,05E-07	3,42E-04	1,05E-04	1,09E-03
Rn-222	*600*	1,20E+07	1,20E+03	2,57E-10	3,42E-11	6,84E-10	3,08E-07	4,10E-08	8,21E-07
Pb-210	*600*	1,20E+07	1,20E+03	8,80E-08	2,00E-07	2,30E-06	1,06E-04	2,40E-04	2,76E-03
Po-210	*600*	1,20E+07	1,20E+03	6,76E-08	8,16E-08	1,58E-06	8,11E-05	9,79E-05	1,90E-03
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	20	4,00E+05	4,00E+01	1,57E-06	2,20E-07	3,30E-07	6,28E-05	8,80E-06	1,32E-05
Ra-228	70	1,40E+06	1,40E+02	2,51E-07	1,59E-07	5,47E-06	3,51E-05	2,23E-05	7,66E-04
Th-228	20	4,00E+05	4,00E+01	6,29E-07	8,74E-08	3,02E-07	2,52E-05	3,50E-06	1,21E-05
Total							**1,35E-03**	**5,80E-04**	**6,71E-03**

Table 10.4: Dose uptake resulting from material dumping (continued)

Material: Calcium Silicate Slag

density: 2,5 Mg/m³
volume: 10 m³

				normalized effective dose			effective dose per unloading		
Nuclide	**mean specific activity**	**mean total activity**	**released aerosols**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	2.000	5,00E+07	5,00E+03	1,26E-07	2,28E-08	6,24E-08	6,30E-04	1,14E-04	3,12E-04
U-234	*2.000*	5,00E+07	5,00E+03	1,48E-07	2,65E-08	6,90E-08	7,40E-04	1,33E-04	3,45E-04
Th-230	*2.000*	5,00E+07	5,00E+03	1,48E-06	2,07E-07	3,02E-07	7,40E-03	1,04E-03	1,51E-03
Ra-226	*2.000*	5,00E+07	5,00E+03	2,85E-07	8,72E-08	9,05E-07	1,43E-03	4,36E-04	4,53E-03
Rn-222	*2.000*	5,00E+07	5,00E+03	2,57E-10	3,42E-11	6,84E-10	1,29E-06	1,71E-07	3,42E-06
Pb-210	200	5,00E+06	5,00E+02	8,80E-08	2,00E-07	2,30E-06	4,40E-05	1,00E-04	1,15E-03
Po-210	*200*	5,00E+06	5,00E+02	6,76E-08	8,16E-08	1,58E-06	3,38E-05	4,08E-05	7,90E-04
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	400	1,00E+07	1,00E+03	1,57E-06	2,20E-07	3,30E-07	1,57E-03	2,20E-04	3,30E-04
Ra-228	*400*	1,00E+07	1,00E+03	2,51E-07	1,59E-07	5,47E-06	2,51E-04	1,59E-04	5,47E-03
Th-228	*400*	1,00E+07	1,00E+03	6,29E-07	8,74E-08	3,02E-07	6,29E-04	8,74E-05	3,02E-04
Total							**1,27E-02**	**2,32E-03**	**1,47E-02**

Material: Red Sludge

density: 1,5 Mg/m³
volume: 10 m³

				normalized effective dose			effective dose per unloading		
Nuclide	**mean specific activity**	**mean total activity**	**released aerosols**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**	**worker (10 m)**	**adults * (100 m)**	**infants * (100 m)**
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	250	3,75E+06	3,75E+02	1,26E-07	2,28E-08	6,24E-08	4,73E-05	8,55E-06	2,34E-05
U-234	*250*	3,75E+06	3,75E+02	1,48E-07	2,65E-08	6,90E-08	5,55E-05	9,94E-06	2,59E-05
Th-230	*250*	3,75E+06	3,75E+02	1,48E-06	2,07E-07	3,02E-07	5,55E-04	7,76E-05	1,13E-04
Ra-226	*250*	3,75E+06	3,75E+02	2,85E-07	8,72E-08	9,05E-07	1,07E-04	3,27E-05	3,39E-04
Rn-222	*250*	3,75E+06	3,75E+02	2,57E-10	3,42E-11	6,84E-10	9,64E-08	1,28E-08	2,57E-07
Pb-210	*250*	3,75E+06	3,75E+02	8,80E-08	2,00E-07	2,30E-06	3,30E-05	7,50E-05	8,63E-04
Po-210	*250*	3,75E+06	3,75E+02	6,76E-08	8,16E-08	1,58E-06	2,54E-05	3,06E-05	5,93E-04
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	300	4,50E+06	4,50E+02	1,57E-06	2,20E-07	3,30E-07	7,07E-04	9,90E-05	1,49E-04
Ra-228	*300*	4,50E+06	4,50E+02	2,51E-07	1,59E-07	5,47E-06	1,13E-04	7,16E-05	2,46E-03
Th-228	*300*	4,50E+06	4,50E+02	6,29E-07	8,74E-08	3,02E-07	2,83E-04	3,93E-05	1,36E-04
Total							**1,93E-03**	**4,44E-04**	**4,70E-03**

Table 10.4: Dose uptake resulting from material dumping (continued)

Material: Copper Slag

density: 3,5 Mg/m^3
volume: 10 m^3

Nuclide	mean specific activity	mean total activity	released aerosols	normalized effective dose			effective dose per unloading		
				worker (10 m)	adults * (100 m)	infants * (100 m)	worker (10 m)	adults * (100 m)	infants * (100 m)
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	800	2,80E+07	2,80E+03	1,26E-07	2,28E-08	6,24E-08	3,53E-04	6,38E-05	1,75E-04
U-234	*800*	2,80E+07	2,80E+03	1,48E-07	2,65E-08	6,90E-08	4,14E-04	7,42E-05	1,93E-04
Th-230	*800*	2,80E+07	2,80E+03	1,48E-06	2,07E-07	3,02E-07	4,14E-03	5,80E-04	8,46E-04
Ra-226	*800*	2,80E+07	2,80E+03	2,85E-07	8,72E-08	9,05E-07	7,98E-04	2,44E-04	2,53E-03
Rn-222	*800*	2,80E+07	2,80E+03	2,57E-10	3,42E-11	6,84E-10	7,20E-07	9,58E-08	1,92E-06
Pb-210	*800*	2,80E+07	2,80E+03	8,80E-08	2,00E-07	2,30E-06	2,46E-04	5,60E-04	6,44E-03
Po-210	*800*	2,80E+07	2,80E+03	6,76E-08	8,16E-08	1,58E-06	1,89E-04	2,28E-04	4,42E-03
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	80	2,80E+06	2,80E+02	1,57E-06	2,20E-07	3,30E-07	4,40E-04	6,16E-05	9,24E-05
Ra-228	*80*	2,80E+06	2,80E+02	2,51E-07	1,59E-07	5,47E-06	7,03E-05	4,45E-05	1,53E-03
Th-228	*80*	2,80E+06	2,80E+02	6,29E-07	8,74E-08	3,02E-07	1,76E-04	2,45E-05	8,46E-05
Total							**6,83E-03**	**1,88E-03**	**1,63E-02**

Material: Tin Slag

density: 3,5 Mg/m^3
volume: 10 m^3

Nuclide	mean specific activity	mean total activity	released aerosols	normalized effective dose			effective dose per unloading		
				worker (10 m)	adults * (100 m)	infants * (100 m)	worker (10 m)	adults * (100 m)	infants * (100 m)
	[Bq/kg]	[Bq]	[Bq]	[mSv/Bq]	[mSv/Bq]	[mSv/Bq]	[mSv]	[mSv]	[mSv]
U-238	500	1,75E+07	1,75E+03	1,26E-07	2,28E-08	6,24E-08	2,21E-04	3,99E-05	1,09E-04
U-234	*500*	1,75E+07	1,75E+03	1,48E-07	2,65E-08	6,90E-08	2,59E-04	4,64E-05	1,21E-04
Th-230	*500*	1,75E+07	1,75E+03	1,48E-06	2,07E-07	3,02E-07	2,59E-03	3,62E-04	5,29E-04
Ra-226	*500*	1,75E+07	1,75E+03	2,85E-07	8,72E-08	9,05E-07	4,99E-04	1,53E-04	1,58E-03
Rn-222	*500*	1,75E+07	1,75E+03	2,57E-10	3,42E-11	6,84E-10	4,50E-07	5,99E-08	1,20E-06
Pb-210	*500*	1,75E+07	1,75E+03	8,80E-08	2,00E-07	2,30E-06	1,54E-04	3,50E-04	4,03E-03
Po-210	*500*	1,75E+07	1,75E+03	6,76E-08	8,16E-08	1,58E-06	1,18E-04	1,43E-04	2,77E-03
U-235				1,44E-07	2,55E-08	6,67E-08	0,00E+00	0,00E+00	0,00E+00
Pa-231				1,89E-06	2,82E-07	5,30E-07	0,00E+00	0,00E+00	0,00E+00
Ac-227				8,33E-06	1,16E-06	2,49E-06	0,00E+00	0,00E+00	0,00E+00
Th-232	250	8,75E+06	8,75E+02	1,57E-06	2,20E-07	3,30E-07	1,37E-03	1,93E-04	2,89E-04
Ra-228	*250*	8,75E+06	8,75E+02	2,51E-07	1,59E-07	5,47E-06	2,20E-04	1,39E-04	4,79E-03
Th-228	*250*	8,75E+06	8,75E+02	6,29E-07	8,74E-08	3,02E-07	5,50E-04	7,65E-05	2,64E-04
Total							**5,98E-03**	**1,50E-03**	**1,45E-02**

Table 10.4: Dose uptake resulting from material dumping (continued)

10.1.5 Radiological consequences of fertilizer use

Material: **Fertilizer SSP**

Thickness of fertilizer layer: 0,02 [kg/m^2]

Nuclide	**mean specific activity**	**concentration on land**	**norm. effective dose**		**effective dose (50 y)**	
			adults	infants	adults	infants
	[Bq/kg]	[Bq/m^2]	mSv/Bq/m^2	mSv/Bq/m^2	[mSv]	[mSv]
U-238	500	10,00	4,56E-04	3,47E-03	4,56E-03	3,47E-02
U-234	*500*	10,00	5,09E-04	3,79E-03	5,09E-03	3,79E-02
Th-230	670	13,40	8,44E-04	1,52E-02	1,13E-02	2,04E-01
Ra-226	300	6,00	5,00E-03	6,58E-02	3,00E-02	3,95E-01
Rn-222	*300*	6,00			0,00E+00	0,00E+00
Pb-210	300	6,00	1,40E-02	1,70E-01	8,40E-02	1,02E+00
Po-210	*300*	6,00	5,39E-03	1,17E-01	3,23E-02	7,02E-01
U-235		0,00	5,71E-04	3,72E-03	0,00E+00	0,00E+00
Pa-231		0,00	2,35E-03	3,33E-02	0,00E+00	0,00E+00
Ac-227		0,00	4,15E-03	1,21E-01	0,00E+00	0,00E+00
Th-232	20	0,40	8,86E-04	1,64E-02	3,54E-04	6,56E-03
Ra-228	10	0,20	9,29E-03	4,04E-01	1,86E-03	8,08E-02
Th-228	10	0,20	2,96E-04	1,52E-02	5,92E-05	3,04E-03
Total					**1,70E-01**	**2,48E+00**

Table 10.5: Radiological consequences of fertilizer use

Material: **Fertilizer TSP**

Thickness of fertilizer layer: 0,02 [kg/m^2]

Nuclide	**mean specific activity**	**concentration on land**	**norm. effective dose**		**effective dose (50 y)**	
			adults	infants	adults	infants
	[Bq/kg]	[Bq/m^2]	mSv/Bq/m^2	mSv/Bq/m^2	[mSv]	[mSv]
U-238	800	16,00	4,56E-04	3,47E-03	7,30E-03	5,55E-02
U-234	*800*	16,00	5,09E-04	3,79E-03	8,14E-03	6,06E-02
Th-230	500	10,00	8,44E-04	1,52E-02	8,44E-03	1,52E-01
Ra-226	200	4,00	5,00E-03	6,58E-02	2,00E-02	2,63E-01
Rn-222	*200*	4,00			0,00E+00	0,00E+00
Pb-210	*200*	4,00	1,40E-02	1,70E-01	5,60E-02	6,80E-01
Po-210	*200*	4,00	5,39E-03	1,17E-01	2,16E-02	4,68E-01
U-235		0,00	5,71E-04	3,72E-03	0,00E+00	0,00E+00
Pa-231		0,00	2,35E-03	3,33E-02	0,00E+00	0,00E+00
Ac-227		0,00	4,15E-03	1,21E-01	0,00E+00	0,00E+00
Th-232	45	0,90	8,86E-04	1,64E-02	7,97E-04	1,48E-02
Ra-228	*45*	0,90	9,29E-03	4,04E-01	8,36E-03	3,64E-01
Th-228	*45*	0,90	2,96E-04	1,52E-02	2,66E-04	1,37E-02
Total					**1,31E-01**	**2,07E+00**

Material: **Fertilizer PK**

Thickness of fertilizer layer: 0,02 [kg/m^2]

Nuclide	**mean specific activity**	**concentration on land**	**norm. effective dose**		**effective dose (50 y)**	
			adults	infants	adults	infants
	[Bq/kg]	[Bq/m^2]	mSv/Bq/m^2	mSv/Bq/m^2	[mSv]	[mSv]
U-238		0,00	4,56E-04	3,47E-03	0,00E+00	0,00E+00
U-234		0,00	5,09E-04	3,79E-03	0,00E+00	0,00E+00
Th-230		0,00	8,44E-04	1,52E-02	0,00E+00	0,00E+00
Ra-226	200	4,00	5,00E-03	6,58E-02	2,00E-02	2,63E-01
Rn-222	*200*	4,00			0,00E+00	0,00E+00
Pb-210	*200*	4,00	1,40E-02	1,70E-01	5,60E-02	6,80E-01
Po-210	*200*	4,00	5,39E-03	1,17E-01	2,16E-02	4,68E-01
U-235		0,00	5,71E-04	3,72E-03	0,00E+00	0,00E+00
Pa-231		0,00	2,35E-03	3,33E-02	0,00E+00	0,00E+00
Ac-227		0,00	4,15E-03	1,21E-01	0,00E+00	0,00E+00
Th-232	10	0,20	8,86E-04	1,64E-02	1,77E-04	3,28E-03
Ra-228	10	0,20	9,29E-03	4,04E-01	1,86E-03	8,08E-02
Th-228	8	0,16	2,96E-04	1,52E-02	4,74E-05	2,43E-03
Total					**9,96E-02**	**1,50E+00**

Table 10.5: Radiological consequences of fertilizer use (continued)

10.1.6 Radiological consequences of Phosphogypsum use

Material: **Phosphogypsum**

density: **2 Mg/m^3**
mass: **1,3 Mg**

Nuclide	**mean specific activity**	**mean total activity**	**normalized effective dose**	**external dose rate**	**annual dose 8760 h/a**
	[Bq/kg]	[Bq/m^3]	[μSv/Bq/h]	[μSv/h]	[μSv]
U-238	200	2,60E+05			
U-234	*200*	2,60E+05			
Th-230	*200*	2,60E+05	1,16E-12	3,02E-07	2,64E-03
Ra-226	600	7,80E+05	6,38E-11	4,98E-05	4,36E-01
Rn-222	*600*	7,80E+05	6,41E-12	5,00E-06	4,38E-02
Pb-210	*600*	7,80E+05			0,00E+00
Po-210	*600*	7,80E+05	1,07E-13	8,35E-08	7,31E-04
U-235			1,49E-09		
Pa-231					
Ac-227					
Th-232	20	2,60E+04	6,09E-13	1,58E-08	1,39E-04
Ra-228	70	9,10E+04			
Th-228	20	2,60E+04	9,65E-12	2,51E-07	2,20E-03
Total				**5,54E-05**	**4,85E-01**

Table 10.6: Radiological consequences of Phosphogypsum use

10.2 Dispersion and Exposure Calculation Models

The evaluation of dispersion and exposure is based on a Gaussian dispersion model and includes calculation algorithms defined by the German “Allgemeine Verwaltungsvorschrift (AVV) zu §45 StrlSchV” which complies with international standards and recommendations.

The dose factors used for the particular radionuclides are taken from “Bekanntmachung des BMU vom 5. Sept. 1989 (Bundesanzeiger G 1990A, Nr. 185a vom 30.09.1989) and from ICRP Publications No. 68 (1995) and 72 (1996).

10.2.1 Exposure paths

The exposure paths considered are:

External exposure:

- β-submersion (skin)
- γ-submersion (skin, bones, lung, marrow, effective dose)
- γ-ground radiation (skin, bones, lung, marrow, effective dose)

Internal exposure:

- inhalation (skin, bones, lung, marrow, effective dose)
- ingestion (skin, bones, lung, marrow, effective dose)

Particularities of the inhalation path

The radiological effect of radionuclides, in particular via the inhalation exposure path, depends on their chemical form which is considered by so-called retention classes. The dose factors for one radionuclide therefore can differ up to a factor of 10. Since the chemical form is not known in detail in most cases, the most unfavourable dose factors are taken for the calculation, resulting in conservative values of the inhalation exposure.

Particularities of the ingestion path

According to the AVV model used, the radiation exposure is evaluated for a person with standardised nutrition behaviour. This persons is supposed to nourish exclusively from vegetable and animal products generated under the conditions of the calculated surface contamination for 50 years. The contamination is modified with time only by the biological and physical half lives of the corresponding radionuclide.

The ingestion exposure values derived using this procedure are therefore to be considered extremely conservative.

10.2.2 Exposure groups

The person considered for the evaluation of radiation exposure are:

- adults: These are workers of the disposal site and persons of the public in the immediate neighbourhood of the disposal site.
- Infants: children up to 1 year old

10.2.3 Discussion of dispersion results

Assuming different weather conditions, the activity concentration and surface contamination was evaluated as a function of distance for the main wind direction. The release conditions and the weather conditions are assumed to be constant during the release period of appr. 0,5 h. The following findings are discussed:

(1) Influence of wind velocity

The absolute values of activity concentration and surface contamination depend on the wind velocity while their relations as a function of distance remain almost constant. The maximum values are reached in 20 m distance from the point of release but differ only slightly (<2%) from the values in 10 m distance.

(2) The average wind velocity is very much depending on the site. In the present case 4 m/s have been used as an average value for mid Europe. Unfavourable wind conditions depend on the ratio emission altitude and distance. In the case of the given low emission altitude (3 m) a small wind velocity is to be considered as most unfavourable. The value of 0,1 m/s used has a probability of 4% in mid Europe. Using the average instead of the most unfavourable wind velocity would lead to a reduction of the activity concentration and surface contamination by 40%.

(3) Up to a distance of 60 m the highest concentration and contamination occur for diffusion category D which together with diffusion category C is applicable for average whether conditions. There is only <4% difference between these diffusion categories up to a distance of 20 m.

The following is a distribution of diffusion categories which is typical for middle European weather conditions. Local situations, however, can differ considerably from these values.

Diffusion category	probability
A	10%
B	15%
C	35%
D	25%
E	10%
F	5%

(4) Above a distance of 80 m the diffusion category F is the most unfavourable, giving 22% higher values in 100 m distance as category C.

(5) The surface contamination is almost completely caused by fallout. Washout only contributes insignificantly.

The calculation of the dispersion and nuclide specific radiation exposure has been performed for the following conditions:

distance	Diffusion category	Wind velocity	persons	Ingestion path
10 m	D	0,1 m/s	adults	without
20 m	D	0,1 m/s	adults	without
50 m	D	0,1 m/s	adults, infants	included
100 m	F	0,1 m/s	adults, infants	included