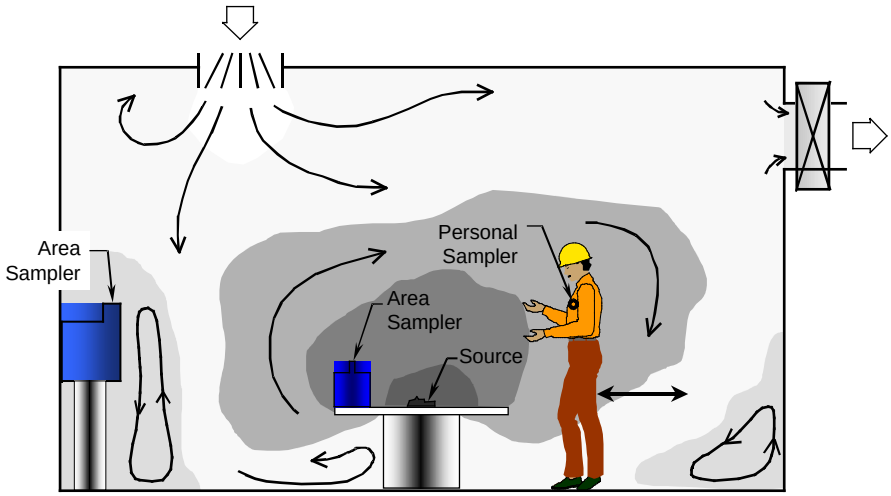
Strategies and Methods for Optimisation of Protection against Internal Exposures of Workers from Industrial Natural Sources (SMOPIE)

FINAL REPORT of the SMOPIE Project carried out under contract N° FIGM-CT2001-00176 by order of the European Commission



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1 Introduction

Occupational exposure from natural radiation is, in the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2000 Report, estimated to contribute more than 80 percent of the world-wide annual collective dose from occupational exposure, uranium mining excluded. Also individual doses to workers exposed to naturally occurring radioactive materials (NORM) in industry can be significant. The relevant routes of exposure of workers to NORM are external radiation, and internal exposure, either by inhalation of radon in workplaces or by inhalation of aerosols in dusty working conditions. When the employer is not aware of the problems associated with enhanced levels of NORM in raw materials, products or residues and when no protective actions are taken, the doses may even exceed the occupational dose limit.

Three main points are relevant to the overall management of occupational exposure to NORM, namely awareness, regulations and guidance. In many countries, NORM industries traditionally have not been subject to radiological protection measures. Consequently there is a general lack of awareness and knowledge of radiological hazards and exposure levels by legislators, regulators and operators (particularly operators of small businesses). This persists in many cases, despite the number of studies and international meetings dedicated to the radiological consequences of NORM in the last 10 to 15 years. As a result of this lack of knowledge, producers and subsequent users of these materials are often fearful of the implications of regulation.

Within the European Union, Council Directive 96/29/Euratom paid specific attention to natural sources of radiation. EU Member States are obliged to identify the work activities that cannot be ignored from a radiological protection point of view and declare parts of the Directive applicable in their national regulations with respect to natural sources. This has helped increase awareness of NORM issues substantially, as have EC guidance documents such as Radiation Protection 88 (1997), Radiation Protection 95 (1999) and Radiation Protection 122, Part II (2001). Despite this, there is still a need for more practical guidance, both for the operator and for the regulator, on appropriate control measures and the extent to which these can be achieved. Due to the large quantities of NORM-containing materials in industry, and the potential for dusty work conditions, internal exposure is in many cases the dominant exposure pathway for NORM. Exposure conditions in these industries can differ considerably with respect to type of industry, work place conditions and radionuclides involved. There is a need for guidance on appropriate radiological protection measures for workplaces in NORM industries, specifically for recommended monitoring strategies and methods for optimisation of internal exposures. This guidance needs to be practical and specific for the type of industry, and be directed at assisting regulatory bodies and operators in identifying effective ways of meeting the radiological requirements.

The above-mentioned need for guidance on internal exposure control has also been expressed in recommendations from the second and third Workshop of the European ALARA Network (EAN), on “Good practices in radiation protection in the non nuclear industry and research” (23-25 November 1998, Chilton, UK) and “Managing internal exposures” (15-18 November 1999, Neuherberg, Germany). The SMOPIE project may therefore be considered as a response of the European Commission to the EAN recommendations.

2 Objectives

The main objective of the project was to recommend monitoring strategies and methods, for optimising internal exposure in a range of NORM workplaces and work activities. The project therefore considered a broad variety of exposure parameters, including the generation of (and exposure to) dust, whether the exposure is continuous or discontinuous, whether it is worker induced or process induced and the variability of doses between workers. The characterisation of these parameters has been carried out in a number of case studies of real NORM exposure situations.

There are various monitoring techniques available to assess internal doses, such as static air samplers (SAS), personal air samplers (PAS), whole body or lung counting, and analysis of excreta. Efforts have been made to show how the characteristics of these techniques fit with the specific needs of the optimisation of radiation protection. The project therefore led to recommendations on the use of appropriate monitoring methods and tools to help implement the optimisation principle.

The detailed objectives of the project were:

(1) To provide information on the numbers of workers in NORM industries exposed to internal contamination, and on the associated levels of dose.

(2) To obtain a set of case studies on the monitoring strategies for internal exposure applied in real NORM workplaces, which provide valuable experience in the development of monitoring strategies and methods.

(3) To define the main characteristics of different exposure situations and work activities identified in the case studies.

(4) To critically review potentially useful monitoring methods and tools relevant to optimisation of predictable occupational internal exposure under different work place conditions.

(5) To develop recommendations for strategies and methods for optimisation of internal exposures covering the main exposure categories derived from the case studies.

The work carried out in the project has been subdivided in Work Packages that address each of the above-mentioned objectives. The results of the Work Packages are presented in the next section of this report.

3 Progress and Results

3.1 Summary of Work Package 1: EU NORM industries – Review of number of exposed workers and magnitude of internal exposures

3.1.1 Approach

The objectives of Work Package 1 of the SMOPIE project were to provide information on the numbers of industrial workers exposed to naturally occurring radioactive materials (NORM) and the magnitude of the internal radiation exposures received. In collecting such information, the initial intention was to draw upon the national dose registration/record systems in the countries of the principle contractors. In addition to this, other potential sources of information have been identified, such as:

- European studies and projects relating (in some way) to internal radiation exposures; ESOREX, ESOREX-EAST, EURADOS, OMINEX, BIODOS and EULEP; and
- work done in relation to the implementation of Title VII, Article 40 of Council Directive 96/29/EURATOM (Basic Safety Standards). This includes:
  - EC guidance on identifying NORM industries with the potential for significant occupational exposures;
  - national studies carried out in response to Title VII and the above guidance; and
  - the draft EC report on the evaluation of the implementation of Title VII.

Other information was specifically sought and provided for the SMOPIE project by the principal contractors. Of these information sources, the SMOPIE industrial partners and other NORM industry representatives were especially valuable.

A full description of the work performed in Work Package 1 and the results are presented in an accompanying report as Annex 1.

From the information presently available, it is concluded that national dose registration systems do not provide useful information on either the number of workers exposed to NORM or the internal exposures received. Organisations (including the EC) that rely on the national dose registration systems for this type of information will have no indication of either the scale or the magnitude of NORM exposures.

Several EC sponsored studies, i.e. EURADOS, OMINEX, BIODOS and EULEP, have been identified and reviewed to determine whether information relevant to SMOPIE is available, or is likely to become available in the near future. Although some of these may have some relevance to the general scope of SMOPIE, none provide the information (numbers of exposed NORM workers, and doses received) required for SMOPIE Work Package 1.

A number of national studies have been carried out in response to Title VII of the European Council Directive 96/29EURATOM (Basic Safety Standards) [3]. This title requires that Member States identify NORM work activities that may lead to significant radiation exposures of workers and/or members of the public. The national studies contain information on industrial processes involving NORM and on potential occupational radiation exposures in these industries. In addition, EC projects on the implementation of Title VII by Member States and by applicant countries also provide some information of relevance to the SMOPIE project. Specifically these are the German and Dutch national studies, the EC publications RP 95 and RP 107, the Title VII project and the TENORMHARM project. The above studies and reports associated with the implementation of Title VII identify an extensive list of NORM materials, industries and work activities that could give rise to significant occupational radiation exposures. It should however be noted that:

- occupational exposures derived from generic exposure scenarios such as in RP95 and RP107 are deliberately conservative, and should not be taken to represent actual exposures. The use of more site-specific parameters in the RP107 methodology should, however, enable more realistic (and representative) doses to be estimated, as in the Dutch study;
- NORM exposure data based on actual workplace monitoring is very scarce; and
- information on the number of exposed workers is also very scarce: only the German study provides an estimate of the number of exposed workers in each industry.

It became clear during the project that additional information was needed to meet the objectives of Work Package 1. Therefore, the principal contractors collated additional information from UK, Ireland and France specifically for the SMOPIE project. All the information was used to derive dose ranges and number of exposed workers on a European level.

As might be expected, these other sources of information commissioned specifically for the SMOPIE project have provided data that are more relevant to Work Package 1. Even then, however, for many of the NORM work activities previously identified there is no site-specific data on the doses received. It is suspected that, in many cases, this is simply due to not recognising the potential radiological hazard in the industries concerned.

It is important to distinguish between the total number of employees and the number of exposed workers. The latter is almost certainly a very small percentage of the total (and may even be 0% in some cases). For example, the French data includes estimates of all workers involved in the fertiliser industry. However, the fertiliser industry covers many production facilities not involving NORM, such as the production of nitrogenous fertilisers. The relevant NORM industries are those producing phosphoric acid or complex phosphate fertilisers from phosphate ore. No data on the numbers of workers involved in those sectors of the fertiliser industry could be made available. Moreover, there are further difficulties in estimating the fraction of that workforce potentially exposed to significant doses by internal contamination. The number of workers involved in the trade and application of complex phosphate fertiliser produced directly from phosphate rock is even more difficult to estimate.

Due to the reasons given above, and the general lack of data on doses received, it is impossible to accurately determine the number of exposed workers. The most reliable information is considered that supplied directly from the industries concerned, but even then it is only possible to derive “order of magnitude” estimates of the number of exposed persons. Although not ideal, these are considered to represent the best currently available data.

3.1.2 Conclusions

3.1.2.1 Range of doses from work with NORM

This information is **not** available from national dose registries or from other current European Research projects. There are, however some data from work done in response to Title VII of the Euratom BSS, and from sources specifically commissioned for the SMOPIE project.

From all the information considered so far, potential annual exposures by inhalation in NORM industries span a range from below 1 mSv to above 20 mSv. In many cases, doses have been modelled rather than being based on actual workplace measurements. Such estimated doses would appear to be grossly pessimistic in many cases.

In some cases, there are more realistic estimates of dose: in fact, these occupy the same dose range, i.e. from below 1 to greater than 20 mSv. Overall, there is insufficient data to provide any more than a broad indication of the doses involved, as shown in Table 1.

Table 1: Summary of data on dose ranges associated with NORM work activities

Potential annual dose from inhalation (mSv)	Type of NORM industry
Above 20 mSv	Rare earth processing (a few workers)
From 6 to 20 mSv	Grinding of thoriated electrodes Zircon milling (a few workers)
Below 6 mSv	All other NORM industries

3.1.2.2 Estimates of number of exposed workers

The information is **not** available from national dose registries, current European Research projects, or work done in response to Title VII of the Euratom BSS. The exceptions to this are the German study and, to a lesser extent, the on-going work in the Republic of Ireland, which do contain estimates of the number of exposed workers.

The information that has been gathered from other sources specifically for the SMOPIE project does provide a better indication of the number of exposed workers. Even then, only approximate, order-of-magnitude, estimates are considered possible. These estimates are shown in Table 2, and have been compiled using all the relevant data identified in Work Package 1. The estimates do not cover all industrial processes that may involve significant exposures to NORM by internal contamination. Also, there are work activities listed for which no reasonable estimate of the number of exposed workers can be given.

3.1.3 Comments and recommendations

It has been surprisingly difficult to obtain estimates of the number of exposed workers and the doses received. Even obtaining data on the *total number* of employees has been difficult in some cases. Consequently, some comments and recommendations have arisen from undertaking Work Package 1. These are listed below.

- There is a lack of published data on the *actual* numbers of exposed workers and the doses received. Much more data based on industry surveys and workplace measurements is required to provide an accurate picture of the situation in EU NORM industries.
- The implementation of Title VII of the European Directive 96/29/Euratom [10] has so far provided very little published data of the kind referred to above. It is recommended that any studies made in response to Title VII aim to include the number of workers and the *actual doses* received, preferably as a dose distribution.
- Very much the largest NORM work activity, in terms of number of workers, appears to be the use of thoriated welding rods. Furthermore, there is evidence that inhalation doses can be significant from both welding and grinding activities. Despite this very little is known about the precise scale of the problem and it is recommended that this work activity warrants further specific study at a European level.

Table 2: SMOPIE Work Package 1 estimates of the number of potentially exposed workers in EU NORM industries.

NORM industry and work activity	Number of exposed workers (rounded)	Basis for estimate
Thoriated electrodes, production, grinding and use	70 000	Extrapolation of Dutch and German data
Phosphate fertiliser trade and use	10 000	German data multiplied by 4
Oil and gas production, exposure to scale dust at maintenance	2 000	Based on 1000 production installations and two workers potentially exposed annually per installation
Zircon sands, milling and processing	500	UK and German estimate multiplied by 5 for European Union
Rare earth extraction industry, (Y, Ce, Eu, La, etc.)	400	Based on French data, multiplied conservatively by 3 for other producers
Cement production, maintenance of clinker ovens	300	Based on 60 cement production plants and 5 exposed workers per plant
Coal-fired power plants, Maintenance of boilers	100	Based on 70 plants and 2 exposed workers per plant annually
Phosphoric acid production, scale removal	100	Ten plants producing phosphoric acid from phosphate rock. Ten exposed workers per plant.
Primary iron production, exposure to sinter dust	100	Based on 7.4 million tonnes total annual EU blast furnace primary iron production in 20 plants. Five exposed workers per plant
TiO_2 pigment, solid waste and Ra-scale	80	Based on 16 production plants, sulphuric acid and chloride process. Five exposed workers per plant.
Rare earth catalyst production, maintenance, scales	20	Largely replaced by much cleaner “concentrates” as raw material. Assumed number of plants 10, and two exposed workers per plant
Thermal phosphorus production	20	Based on Thermphos input into SMOPIE, one plant
Lead/zinc smelters	20	Number of plants 20 and 1 exposed worker per plant
Tantalum, niobium extraction from ores or slags	Not known	Number of plants at least 1.
Ground water treatment, scales and sludges	Not known	
Residues from past industrial activities	Not known	
Total (rounded)	**85 000**	

3.2 Summary of Work Package 2: Case studies with industrial partners

3.2.1 Introduction

A total of five case studies in different workplaces were undertaken in close co-operation with industrial partners, as follows:

Case Study Number	Industrial Partner
UK1	UK Heavy Mineral Sands Association
UK2	UK Heavy Mineral Sands Association
F1	Comhurex, France
N1	Thermphos, Netherlands
N2	Kerr McGee, Netherlands

The complete case study reports are presented in the accompanying report as Annex 2, and these may be of interest to persons responsible for radiation protection arrangements in similar workplaces. A summary of the main findings relevant to the SMOPIE project is given in this section.

3.2.2 Processes and radioactivity

Descriptions of the industrial processes and plant in each case study are presented in the accompanying report as Annex 2. All the workplaces studied are involved in the handling and processing of substantial quantities of materials containing radionuclides of natural origin. In four of these cases, the materials in question are minerals and derivatives with NORM radionuclide concentrations up to a few becquerels per gram. In the other case (F1), the material is concentrated uranium ore and its derivatives. A summary of the quantity of material processed and its radioactive content is given in Table 3.

Table 3: Summary of Process Materials in case study workplaces

Case Study	**Main process materials**	**Annual production (tonnes)**	**Typical radionuclide concentrations (Bq/g)**	
			U-238 decay series	**Th-232 decay series**
UK1	Zircon sand	100 000	3	0.7
UK2	Titanium dioxide (waste)	90 000	0.2 ^{226}Ra+ up to 1.5	0.2 – 0.7 ^{228}Ra+ up to 3
F1	Uranium concentrates	14 000	^{238}U+ up to 12,000	n.a.
N1	Phosphate ores (waste)	600 000 1 000	0.25 – 1.5 ^{210}Pb+ up to 1000	0.05
N2	Titanium dioxide (ore)	80 000	0.1 - 1	0.02 – 1.8

3.2.3 Internal dose assessment: Monitoring programmes and results

In all case studies, air sampling is used to assess the internal radiation exposures received by workers. A summary of the different air sampling programmes is shown in Table 4.

Table 4: Summary of air sampling programmes in the case studies

Case Study	Type of sampling	Sampling programme	Quantity assessed
UK1	PAS	4 different worker shifts monitored each month. 8 hr sampling.	Gravimetric (mg/m^{-3}) - total inhalable dust and respirable dust.
	SAS	To check plant operation 2-4 times per month. 4 hour sampling using PAS in fixed locations.	As above.
	RTDM	Special surveys for SMOPIE project – see Annex 2 case 1	Gravimetric (mg/m^{-3}) by light scattering. Total inhalable dust, plus some measurements of respirable and thoracic dust.
UK2	PAS	At least 4 key worker shifts monitored each month. Typically 6-8 hour sampling.	Gravimetric (mg/m^3) total inhalable dust and respirable dust.
	RTDM	Special surveys for SMOPIE project – see Annex 2 case 2	Gravimetric (mg/m^3) by light scattering. Total inhalable dust.
F1	SAS	26 SAS in workplace, operated continuously during the work.	Radiometric (Bq/m^3) by gross alpha counting.
	PAS	Non-routine monitoring and special surveys for the SMOPIE project – see Annex 2 case 3.	Radiometric (Bq/m^3) by gross alpha counting.
N1	PAS	6 worker shifts monitored each month. 8 hour sampling.	Radiometric (Bq/m^3) - total beta and total alpha. Total inhalable dust.
	SAS (cascade impactor)	Special (single) measurements in static locations.	Gravimetric (mg/m^{-3}) particle size distribution 0 - >21 _m.
N2	SAS	Continuous sampling (1 month/sample) in two locations where airborne dust is expected.	Gravimetric (mg/m^{-3}) total inhalable dust and respirable dust.

Notes:
PAS refers to Personal Air Sampling, i.e. with the samplers worn by workers. SAS refers to Static Air Sampling at fixed positions in the workplace. RTDM refers to Real Time Dust Monitoring – see Annex 2 for details.

Not all the sampling undertaken has been used to assess internal doses. For example, some monitoring campaigns have been undertaken to check the effectiveness of engineering controls. Furthermore, in

case study F1, urine sampling and lung monitoring have been used in addition to air sampling to assess internal doses (see the accompanying report, Annex 2 case 3). A summary of the occupational internal dose information derived from the different monitoring techniques is given in Table 5.

Table 5: Summary of information on inhalation exposure from different monitoring programmes.

Case study	Type of monitoring[1]	Internal dose information provided[2]
UK1	PAS	· Calculation of *annual dose to average worker* = 0.5 mSv/y · Identification of dusty tasks and areas.
	SAS	· No dose estimates. · Some information on long-term (monthly and yearly) variations in dust at fixed locations.
	RTDM	· No dose estimates. · Information on variation in instantaneous dust levels throughout the workplace. · Information on short-term dust variations, e.g. from discrete activities. · Checking the effectiveness of engineering controls.
UK2	PAS	· Calculation of *average annual dose to groups of workers* in different work areas = <0.1 to 0.2 mSv/y.
	RTDM	· No dose estimates · Information on dust levels - as for UK1
F1	SAS only	· Calculation of *annual dose to individual workers* · Average = 0.6 mSv/y · Most exposed workers = 1.5 to 6mSv/y · Dose variation between workers.
	PAS only	· Calculation of *annual dose to individual workers* · Up to 16 mSv/y · Calculation of *individual doses from specific tasks* · Identification of dusty tasks and areas
	SAS+PAS	· Difference between SAS and PAS results · PAS estimates 30-100 times higher than SAS estimates. · Due to localised (worker induced) dust · Due to inappropriate use of average shift dust levels (from SAS) to estimate individual doses to operators working in multiple locations – see case study for details.
	Urine	· Assessment of *annual individual dose to most exposed workers* = 10 to 40 mSv/y
	Lung	· Screening for *high individual doses* = all below 50 mSv/y
NL1	PAS	· Calculation of *annual dose to individual workers* · Average = 1.2 mSv/y · Most exposed worker = 2.8 mSv/y · Shows dose variation between workers undertaking different tasks.
	SAS (cascade)	· To determine appropriate internal dose coefficients.
NL2	SAS	· Calculation of *average annual dose to groups of* workers in different work areas = <0.1 to 1.2 mSv/y depending on occupancy. · Information on monthly variation in dust/doses.

Notes:

1. PAS refers to Personal Air Sampling, i.e. with the samplers worn by workers. SAS refers to Static Air Sampling at fixed positions in the workplace. RTDM refers to Real Time Dust Monitoring – see Annex 2 for details.
2. Doses are in terms of committed effective dose.

3.2.4 Categorisation of workplaces

One of the principle aims of undertaking the case studies was to help determine a categorisation system for different workplaces. This would consider issues such as the levels of dose, the variation in

dust exposures between tasks and workers, and the spatial and temporal variation in dust levels in the workplace.
Descriptions of the workplace exposure characteristics are given in the individual case studies. From these, it is concluded that real workplaces do not fall easily into a categorisation system. Instead, a number of common exposure characteristics emerge, which are evident from all the case studies to a greater or lesser extent. These characteristics are summarised below.

3.2.4.1 Types of workplace and sources of airborne dust

All the case studies relate to relatively large-scale processes with multi-stage operations. These operations often take place simultaneously within the same workspace.

The level of containment (i.e. to prevent airborne contamination entering the general work area) varies. The workplace studied in F1 has the highest level of containment of all the case studies. Even then, however, containment is only partial, as demonstrated by the monitoring results.

In the other case studies, traditional systems of control have been based on (non-radioactive) industrial hygiene considerations. These have focused on keeping dust levels below prescribed limits, rather than optimising individual exposures. Dust control measures, such as containment, local extraction and general ventilation, are used (though not throughout the process), and these continue to be improved and expanded. Typically, total containment is impractical, even where substantial investment in such controls has been made. All the workplaces studied have dust within the working environment. Often, this is clearly visible on the floor and other surfaces and represents a further source of dust from resuspension.

In summary, all the workplaces studied are considered to have multiple sources of airborne dust present at any one time. Some of these sources are continuous, e.g. due to routine plant operation (conveyors, mills, etc); some are intermittent, e.g. due to batch operations such as sand tipping, maintenance, etc.

The actions of workers are another source of airborne dust, due to resuspension. In practice, this produces a similar pattern, i.e. multiple and simultaneous sources that collectively produce a continuously varying airborne contamination/dust levels.

3.2.4.2 Variation in airborne dust levels with time

All the case studies show that dust levels vary over time, even where workplace and monitoring conditions remain constant. As would be expected, the variation in measured dust levels shows an inverse relationship to the air sampling time. This ranges from a factor of 2 to 3 between individual samples, each taken over a one-month sample period (NL2), to a variation of up to 100 between individual readings obtained by real-time sampling with measurement periods of less than one minute (UK1). The latter variation occurred during a very dusty operation (sand tipping), and was, therefore, mostly expected. The reading-to-reading variation at other times (i.e. when there were no obvious changes in conditions) was typically up to a factor of 10.

The most common sampling time is over a working day/shift. In many cases, repeated sampling has been carried out under the same workplace conditions (i.e. same location or work pattern, same plant operations, etc). In case study F1, individual results (i.e. in terms of the day-to-day dust concentration produced by essentially the same workplace conditions) varied greatly. In theory, SAS results might be expected to be less variable than PAS results. In fact, the reverse was true. In other case studies, smaller variations are seen, especially where dust levels appear to be persistently high. Even then, individual daily PAS results often vary by a factor of 2-3.

The variations described above are significant and must be borne in mind when attempting to analyse monitoring results for trends or patterns. For example, it is common for workplaces to compare year-

on-year dust survey results, often on the basis of a small number of samples taken in any one location. In such cases, even significant changes in the measurement results could be due to the inherent uncertainties due to the small number of measurements ("sampling error")[1], rather than a true change in dust/contamination levels.

3.2.4.3 Variation in dust levels within the work area (spatial variation)

A significant spatial variation of airborne dust levels within workplaces is evident (apart from NL2 where this was not assessed). There are clearly "dusty areas", many of which are consistently indicated by routine monitoring programmes.

Proximity to dust sources is obviously a factor. In UK1, airborne dust levels just one metre further away from a source were about a factor of 10 lower. However, the situation is often complicated by the many competing dust sources present, including those produced by the workers themselves. The local pattern of air movement is also a significant factor.

3.2.4.4 Work patterns

In all cases, workers undertake a continuously changing range of tasks in different work areas.
Some tasks do involve static work operations, such as drum disbanding (F1) and bag packing (UK1). Typically, however, the nature of these operations is such that they are very close to dust sources. As such, the level of airborne dust can vary significantly even within this small area.

3.2.5 Monitoring strategies: Comparison and conclusions

A significant number of specific conclusions are given in the individual case studies (see Annex 2), and these should be of interest to persons responsible for monitoring and/or radiation protection at similar workplaces. More wide-ranging observations and conclusions are given in this section.

Table 5 indicates that the different types of monitoring programme provide different information. Some of these programmes do not even attempt to assess individual radiation doses, but may still provide information that can be used to restrict exposures in practice. To illustrate this, a summary of the information available from the different types of monitoring strategy is shown in Table 6.

Table 6 provides a basis for selecting an appropriate monitoring technique, provided the caveats in the footnotes are observed. There are, however, other factors to take into account when devising a monitoring strategy, as indicated in the text below.

3.2.5.1 Sampling statistics

As indicated earlier, monitoring results can vary significantly, even where working conditions remain constant. All monitoring techniques aim at sampling the quantity of interest: for air sampling this quantity is the constantly changing airborne dust level as inhaled by workers. Therefore, air sampling has inherent uncertainties. In practice, limited sampling is undertaken, and this has been shown to produce wildly varying individual results. Longer sampling times **do** provide a better indication of the average air concentration. However, even with sampling times of a week or more, a single result can differ from the average dust level by a factor of 2 or more. In practice, shorter sampling times, over a working day/shift, are the norm. A single sample result cannot be expected to be a reliable indicator of annual worker exposure, and the case studies confirm this with individual air sample results varying by factors of 10, even where the working conditions are constant. Therefore, several sample results should be obtained before attempting to estimate likely occupational exposures. In the case studies, for example, annual dose estimates are typically based on a minimum of 50 daily personal air samples.

[1] The measurement technique (air sampling and sample assessment) will also produce uncertainties in the reported result – this is considered in more detail in Work Package 4.

The evidence from the case studies is that these inherent sampling statistics and the resulting uncertainties are often overlooked. In comparison, great care is usually taken to obtain an accurate assessment of the sample obtained, even though any assessment errors are likely to be relatively small. The issue of sampling statistics is considered further in Work Package 4.

Table 6: Type of information provided by the case studies

Type of information	**Type of monitoring and suitability[1,2]**			
	SAS	**PAS**	**RTDM**	**Urine /Lung**
Internal dose assessment				
· Average annual doses				
- Average for all workers	*	**		*
- for groups of workers (e.g. in same location)	*	**		*
· Individual annual doses		**		*
· Variation between different workers		**	*	
· Dose from specific tasks	*	**	*	
Other useful information				
· **Sources of airborne contamination**				
- Identify specific sources	*		**	
- Identify key locations	*	**	**	
- Identify key tasks	*	*	**	
- Monitor effectiveness of engineering controls	*		**	
· **Airborne contamination levels: variation with time**				
- Long-term (months/years)	**	*		
- Medium-term (days/weeks)	**	*		
- Short-term (minutes/hours)	*	*	**	
· **Airborne contamination levels: variation with location**				
- In separate work areas			*	
- Different locations within same area	**	**	*	
- Variations within a single workstation	**	*	**	

Notes:

1. PAS refers to Personal Air Sampling, i.e. with the samplers worn by workers. SAS refers to Static Air Sampling at fixed positions in the workplace. RTDM refers to Real Time Dust Monitoring – see Annex 2 for details.
2. "**" indicates that the technique is suitable for providing the information listed. "*" indicates that the technique may be suitable, but a carefully designed monitoring programme will typically be required to yield the required results. These rankings are approximate and are provided for general guidance. They may not be appropriate in all cases.

3.2.5.2 Monitoring information: Dose assessments and ALARA

Table 6 indicates that only certain monitoring techniques may be suitable for reliably assessing worker doses. However, the information provided by other types of measurement is often more valuable when deciding how to reduce doses (ALARA) in practice. In the case studies, a combination of monitoring techniques was found to be the most useful approach.

A good example is real-time dust monitoring. Due to sampling errors, this should not be used for estimating worker doses, unless extended sampling (long times or large numbers of shorter samples) is

undertaken. However, it is capable of quickly identifying dust sources – something that other techniques used for dose assessment cannot do.

3.2.5.3 Air samplers and determination of airborne activity

Prior to the SMOPIE project, only case study N1 had tried to determine which type of air sampler (in terms of the collection efficiency/particle size range) might be most suitable. In all the other cases, sampler heads were either chosen by default, or according to those recommended for industrial hygiene purposes.

The case studies utilise either a gravimetric (mg/m^3) or radiometric (Bq/m^3) determination method. Gravimetric determinations are often required anyway (e.g. to monitor chemical hazards) and it is clearly an advantage if the results can also be used for radiation protection purposes. As well as using existing monitoring resources, workers are already familiar with wearing personal air samplers. Gravimetric determinations are also not constrained by long counting times, nor is self-absorption (especially for alpha emitting materials) an issue.

To assess radiation doses from gravimetric results, the activity concentration of airborne dust must be reliably known. In some workplaces (e.g. UK1) this can accurately be inferred from the process materials. In others, representative analysis of airborne dust may be possible. If not, radiometric analysis is likely to be the best option.

All these issues are considered in more detail in Work Package 4.

3.2.6 Summary of Work Package 2

The case studies are a fundamental part of the SMOPIE project, and have drawn heavily on the co-operation of industrial partners and their input. Each case study is different and provides practical information that may be of value to persons responsible for radiation protection at similar workplaces. Because of this, the case studies are reproduced in full in Annex 2.

In terms of the subsequent sections of this report, the case studies provide the following information:

3.2.6.1 Categorisation of workplaces

Based on the workplaces studied, a strict categorisation of exposure conditions is not considered helpful. Instead, it is more useful to focus on the common characteristics, as summarised below.

- All the workplaces studied have multiple sources of dust; these arise from the process, processing machinery and the actions of workers.
- Total containment is not practicable, and airborne dust is almost always present in the workplace.
- The level of airborne dust (and hence inhalation doses) over time is always changing. Sometimes this is predictable (e.g. due to known dusty operations), but often it is not.
- Dust levels are not uniform within the workplace. Variations should be expected and can be substantial, especially at fixed workstations such as product bagging.
- Working patterns are rarely constant. Most workers have several tasks and frequently move around the workplace during the working day.

3*.2.6.2 Monitoring strategies*

- To implement ALARA in practice requires an assessment of internal dose, **and** information on how this dose arises. Different monitoring techniques provide different information: a combination of monitoring methods is required to provide all the necessary information.
- Air sampling, rather than biological sampling (or whole body counting) is the best way of assessing doses and providing ALARA information.

- Sampling errors are generally overlooked. From the case studies, a single air sample may vary significantly from the true annual average air concentration, as follows:
  Sampling over 1 or more working days: -a factor of 3 or more
  Sampling over 1 hour or less: -a factor of 10 or more
  The above factors are based only on the data presented by the case studies, and are considered further later in this report.
- Personal air sampling provides the best estimate of individual (or group) worker doses.
- Static air sampling can sometimes be used to check that doses are low, but any results should be assumed to be underestimates, and a comparison using personal air samplers should always be considered.
- Real-time dust monitoring should generally not be used as a means of determining dose. It is also only suitable for airborne dust with a predictable activity concentration (Bq/g). However, in suitable workplaces, it is capable of providing more ALARA information than any other technique.

3.3 Work Package 3: Categorisation of exposure situations

As described in the previous section, the case studies provide little basis for a strict system of categorisation for different workplace exposure situations. Nevertheless, establishing a categorisation system was one of the original SMOPIE objectives. As such, the objective of this Work Package was still pursued, i.e. to try to categorise exposure situations described in the case studies in terms of a limited number of exposure parameters relevant to the implementation of ALARA. The characterisation criteria considered are those that are important for the monitoring strategy of choice, i.e. either to verify compliance with a dose criterion (for instance 1 mSv/y), or for optimisation purposes. These cover the following items:

(1) the choice of air sampling method (Personal Air Sampling, Static Air Sampling) for exposure assessment;

(2) the scope and scale of the monitoring programme for exposure assessment (choice of workers, sampling duration, number of air samples taken, …);

(3) the choice of air sample analysis method (gravimetric or radiometric, or light scattering/particle counting in the case of real time monitoring);

(4) the method of obtaining task-specific information; and

(5) the identification of protective actions (airborne sources confinement, cleaning of deposited activity available for resuspension, modification of the process and/or working procedures).

As a first step, categorisation on the basis of the following exposure characteristics was considered:

- Spatial variation of airborne activity concentrations
  - Uniform (U) throughout the workplace / non uniform (N)
- Local variation of airborne activity concentrations
  - Locally uniform (U) around the workstations / non uniform (N)
- Time variation of airborne activity concentrations
  - Continuous (C)
  - Discontinuous, process-related (DP)
  - Discontinuous, worker’s activity-related (DW)
  - Discontinuous, due to discreet incidents (I)
- Type of jobs performed
  - Continuous presence at a single workstation (C)
  - Routine but discontinuous presence at a set of given workstations (R)
  - Non-routine discontinuous presence at a set of given workstations (N)

- Discontinuous presence at unpredictable locations (cleaning operations, maintenance,…) (D)

· Number of airborne contamination sources
  - Single sources (S) / multiple sources (M)

· Type of airborne contamination sources
  - Airborne releases (A) / Resuspension (R)

The results of applying this to the case studies in Work Package 2 are presented in table 7.

Table 7: Results of applying preliminary categorisation system to case studies

	Activity air concentration			**Jobs Performed**	**Airborne Contamination sources**	
	Space variation		**Time Variation**			
Case studies	**Global**	**Local**			**Number**	**Type**
NL1 Phosphate ores	N*	U, N	DP, DW, I	N, D	M	A, R
NL2 Titanium ores	N*	U, N	DP, DW, I	N, D	M	R**
UK1 Zircon sand	N*	U, N	DP, DW, I	N, D	M	A, R
UK2 Titanium ores	N*	U, N	DP, DW, I	N, D	M	A, R
F1 Uranium concentrates	N*	U, N	DP, DW, I	N, D	M	A

(*) For workplaces where workers may receive significant exposures
(**) The airborne dust originates in material deposited in a wet form and resuspended after drying

It can be concluded from table 7 that, for every case study:

· for workplaces where workers may receive significant exposures, the airborne activity concentrations are never uniform throughout the workplace;

· the local space variation of airborne activity concentrations depends, in each industry, on the characteristics of the considered workstation;

· the airborne activity concentrations are never constant with time and may be due, depending on the particular situations considered in each industry, to the process, to the worker's activity or to small incidents;

· the jobs performed never involve a simple continuous presence at a single workstation or a predictable discontinuous presence at a set of given workstations, but rather more complex situations; and

· the sources of airborne contamination are always multiple.

These confirm the conclusions from Work Package 2, i.e. that the characterisation criteria considered in this table do not lead to a useful categorisation of the different exposure situations in the industrial cases. This does, however, produce a practical conclusion, namely that the preferred choice of the air sampling method (i.e. to implement ALARA) will be the same in all the industries considered.

In evaluating the case studies, other criteria for categorising exposure situations emerged, namely:

- constancy of the airborne dust specific activity (Bq/g), i.e. that will determine whether accurate exposure assessment from gravimetric analysis is possible;
- constancy of the airborne dust radionuclides activity ratios (with aerodynamic diameter and/or with time), i.e. that will determine whether accurate exposure assessment from either gravimetric or gross activity radiometric analysis is possible; and
- the dose coefficient (Sv/Bq) and airborne dust specific activity (Bq/g), i.e. that will influence the choice of the analysis method due to measurement sensitivity considerations.

These criteria are considered in detail in Work Package 4.

3.4 Work Package 4: Review and evaluation of monitoring strategies and methods

3.4.1 Introduction

The types of monitoring strategy currently applied in practice, and the categorisation of different workplaces, have been described in work packages 2 and 3, respectively. The purpose of this work package is to review the technical capabilities and limitations of different forms of internal radiation monitoring. This includes a consideration of monitoring strategies, methods and equipment, as appropriate. The aim of the review is to determine which types of monitoring (if any) are the most effective in terms of contributing to the optimisation of internal exposures (from inhalation). The review also considers whether further developments are needed, especially in relation to existing monitoring equipment. The following Appendices to WP4 are provided in Annex 3 to this Final Report:

Appendix 1: Sampling for particulate airborne contaminants, Review and analysis of techniques (Witschger 2002).

Appendix 2: Dose coefficients.

Appendix 3: Aerosol sampling and the bias produced between the true and estimated effective dose for the radionuclides of the ^{238}U and ^{232}Th natural decay chains.

Appendix 4: Sensitivity of air sampling methods.

A more detailed discussion on the sensitivity of air sampling methods is provided in JP Degrange 04.

3.4.2 Evaluation criteria

The aim is to judge different monitoring methods in terms of their ability to help the optimisation of internal doses (ALARA). This judgement is based on the following four criteria:

1. **Sensitivity** – it is clear that the monitoring technique should have sufficient sensitivity to assess doses well below dose limits. For NORM industries, an annual occupational dose of 1 mSv/y is often the trigger level for the application of regulatory controls. Consequently, the monitoring undertaken should be sensitive enough to assess doses of this magnitude. In most cases, this application level relates to the dose from all exposure pathways: internal doses much lower than 1 mSv/y may, therefore need to be assessed.

   Note: Adequate sensitivity is a fundamental requirement - any monitoring technique that fails to meet this criterion (no matter how good in other respects) is, therefore, excluded from further consideration.

2. **Accuracy** – reliable estimates of doses are fundamental to the ALARA process. The monitoring method should, therefore, be capable of provide a reasonably accurate estimate of internal dose, avoiding (or correcting for) any bias, and minimising any uncertainties[2].
3. **ALARA information** – sensitivity and accuracy provide a sound base for optimisation. However, to implement ALARA in practice, the monitoring results must also provide more detailed information on the pattern of exposures. This might include doses from specific tasks (Coates 93), or information on how airborne contamination levels vary in the workplace. Such information can then be analysed, for example to identify the main sources of exposure, and to help in the selection of protection options (Lefaure 99).
4. **Equipment suitability** – for certain types of monitoring, there is little or no choice in the type of equipment that can be used. For air sampling, however, a variety of devices are available with different sampling characteristics. In such cases, the aim is to identify which types of equipment are most suitable, in terms of the above three criteria, and also in terms of their practical use in the workplace. As stated earlier, the review also aims to identify whether any further developments or improvements to monitoring equipment are needed.

There are two basic forms of monitoring internal radiation exposures, i.e.:

- **bioassay monitoring techniques**: either in-vivo (e.g. activity retained in the lung and the whole-body), or in-vitro (e.g. urine or faeces sampling); or
- **air sampling** (personal or static).

As long as in radiation protection, limits of internal and external exposure are not directly expressed in terms of average air concentration (like in industrial hygiene) but in terms of effective dose, bioassays (especially the in vivo activity measurements) have often been considered as the primary means of exposure evaluation (Boecker 94).

However, workplace air measurements have been considered essential to permit a correct interpretation of bioassays by providing information on the time or the time course of the intake (Selby 94, Birchall et al. 98). Moreover, the minimum detectable doses (MDD) associated with in-vivo bioassays of some nuclides (actinides) may be so high that air sampling has to be considered for workers exposure evaluation (Henrichs 98).

The suitability of these two different techniques, in terms of the above criteria, is considered below.

3.4.3 Sensitivity of different monitoring techniques

In this case, sensitivity is defined in terms of the minimum detectable annual dose achieved by a typical routine monitoring frequency. Calculations have been made for the different bioassay techniques (lung and whole-body counting, urine sampling and faeces collection), and for personal and static air sampling. For bioassay techniques, calculated sensitivities are based on established measurement methods. For air sampling, both radiometric (alpha or beta counting) and gravimetric analysis[3] have been considered.

For the radiometric analyses, the measurement sensitivity will depend on the counting time used – a typical value of 1 hour has been assumed in the calculations. For gravimetric analysis, counting time is not an issue[4]: the detectable dose will, however, depend (inversely) on the activity concentration of the sampled dust and a typical value of 10 $Bq.g^{-1}$ has been considered.

[2] Accuracy and sensitivity are related by the fact that, in order to assess with reasonable uncertainty 1 mSv/y, the monitoring technique should be associated with a Minimum Detectable Dose (MDD) well below this level.
[3] The case studies indicate that this technique is commonly used in practice for materials of low specific activity.
[4] It is usually necessary to "condition" the filters for up to two days, to eliminate any bias due to moisture. After this step has been completed (and many filters can be conditioned simultaneously), the actual measurement (i.e. weighing the filter) takes only a few seconds.

The results of these calculations for the U-238 and Th-232 chains in equilibrium are shown in Tables 8 to 11.

Table 8: Typical sensitivity achieved by different bioassay techniques (U-238 chain in equilibrium) *)

Measurement parameters	Measurement technique (and radionuclide)			
	Lung Counting (U-238)	**Whole body counting (Ra-226)**	**Urine sampling (U-238)**	**Faeces sampling**
	Measurement frequency and detectable annual doses			
Number of measurements per year	2	2	4-12	4
Fast absorption	-	>20 mSv	0.04 - 7 mSv 12 samples/y	0.01 – 0.8 mSv (Po-210)
Moderate absorption	>20 mSv	>20 mSv	0.02 - 5 mSv 4 samples/y	0.03 – 0.6 mSv (Po-210)
Slow absorption	>20 mSv	>20 mSv	0.5 - 100 mSv 4 samples/y	24-4 800 µSv (U-238)

*) The values for detectable doses in each cell correspond to the range of detection limits reviewed in the literature, applied to the mean value of Sv/Bq measured for the considered monitoring frequency . The considered monitoring frequency is the minimum value that ensures that the uncertainty on the time of intake will not lead to a relative error on the dose estimate significantly greater than a factor of 3.

Table 9: Typical sensitivity achieved by different air sampling techniques (U-238 chain in equilibrium)

Measurement parameters: absorption Type and sampling duration	Measurement technique					
	Personal air sampling (2 l/min)			**Static air sampling (20 l/min)**		
	Detectable doses in µSv per year for typical sampling duration [1])					
Fast	Alpha	Beta	Gravimetry	Alpha	Beta	Gravimetry
Week	58	1300	49	5.8	130	4.9
Day	290	6300	240	29	630	24
Hour	1500	32.000	1200	150	3.200	120
Moderate	Alpha	Beta	Gravimetry	Alpha	Beta	Gravimetry
Week	18	380	15	1.8	38	1.5
Day	88	1900	73	8.8	190	7.3
Hour	440	9.500	370	44	950	37
Slow	Alpha	Beta	Gravimetry	Alpha	Beta	Gravimetry
Week	16	350	13	1.6	35	1.3
Day	81	1800	67	8.1	180	6.7
Hour	400	8.800	340	40	880	34

[1]) The sensitivities provided for alpha (low background) and beta counting (high background) are based on a background count rate of 0.01 and 0.1 counts per second respectively and on one hour counting time. The sensitivities for gravimetric analysis are based on an assumed specific activity of U-238 of 10 Bq/g. More details on the sensitivity of air sampling methods are provided in detail in Annex 3, Appendix 4.

Table 10: Typical sensitivity achieved by different bioassay techniques (Th-232 chain in equilibrium)

Measurement parameters	Measurement technique (and radionuclide)			
	Lung Counting (Th-232)	Whole body counting (Ra-228)	Urine sampling (Th-232)	Faeces sampling (Th-232)
	Measurement frequency and detectable annual doses			
Number of measurements per year	2	2	2-12	4
Fast absorption	-	>20 mSv	0.2 – 57 mSv 12 samples/y	3 – 30 mSv
Moderate absorption	>20 mSv	>20 mSv	0.2 – 63 mSv, 4 samples/y	0.1 - 12 mSv,
Slow absorption	19-27 mSv	>20 mSv	6 – 1500 mSv, 2 samples/y	0.05 - 7 mSv

Table 11: Typical sensitivity achieved by different air sampling techniques (Th-232 chain in equilibrium)

Measurement parameters: absorption Type and sampling duration	Measurement technique					
	Personal air sampling (2 l/min)			Static air sampling (20 l/min)		
	Detectable doses in µSv per year for typical sampling duration [1])					
Fast	Alpha	Beta	Gravimetry	Alpha	Beta	Gravimetry
Week	100	2600	65	10	260	6.5
Day	520	13000	330	52	1300	33
Hour	2600	64000	1600	260	6400	160
Moderate	Alpha	Beta	Gravimetry	Alpha	Beta	Gravimetry
Week	34	830	21	3.4	83	2.1
Day	170	41000	110	17	4100	11
Hour	850	21000	530	85	2100	53
Slow	Alpha	Beta	Gravimetry	Alpha	Beta	Gravimetry
Week	31	760	19	3.1	76	1.9
Day	160	38000	97	16	3800	9.7
Hour	780	19000	490	78	1900	49

[1]) The sensitivities provided for alpha (low background) and beta counting (high background) are based on a background count rate of 0.01 and 0.1 counts per second respectively and on one hour counting time. The sensitivities for gravimetric analysis are based on an assumed specific activity of Th-232 of 10 Bq/g. More details on the sensitivity of air sampling methods are provided in detail in Annex 3, Appendix 4.

The following conclusions are drawn from the results of the sensitivity calculations:

Bioassay techniques (tables 8 and 10)

- Lung and whole-body counting are far too insensitive to be of any practical use in optimisation.
- Faeces sampling offers better sensitivity, although this is still only adequate (for optimisation purposes) in the case of the U-238 series. However, it would typically require an exclusion period of 6 to 9 days (unrealistic for quarterly measurements) to reduce the uncertainty associated with the time of intake to less than factor of 3. This is not a popular technique in practice and is unlikely to be undertaken where other, less intrusive, techniques are available. Consequently, faeces sampling is not considered further in this report.
- Urine sampling potentially has an adequate sensitivity (to assess 1 mSv/year with a 10% relative uncertainty) for Fast and Moderate compounds of the U-238 chain and, to a lesser extent, the Th-232 chain. For Slow compounds of either chain, it is not possible to assess doses less than a

few mSv/year with a 10% relative uncertainty. Given that many NORM materials fall into this category, the potential for using urine sampling in optimization is extremely limited.

Air sampling (tables 3 and 11)

- Static air sampling is capable of achieving a satisfactory sensitivity in all cases when alpha counting is an available option.
- The same is mostly true for personal air sampling, despite the lower pump flow rate. For materials with a Moderate and Slow absorption rate, personal air sampling has sufficient sensitivity (with either alpha counting or gravimetric analysis) to assess doses of 1 mSv/year with a 10% relative uncertainty, even for short duration (1 hour) sampling. For materials with a fast absorption rate, PAS offers adequate sensitivity for 1 week and 1 day measurements, but not for 1 hour measurements with radiometric assessment. To achieve this, an increase in the flow rate from 2 l/min to 10 l/min would be required. An adequate increase in sensitivity at a flow rate of 2 l/min can also be achieved by using counting times considerably longer than 1 hour, but long counting times could lead to problems of throughput of the samples analysis process in case of routine air sampling.
- Self absorption may significantly reduce the alpha counting efficiency of filters with rather low-specific activity material. In such cases beta counting is generally preferred because it is much less affected by self-absorption. However, it will require low-background (typical 0.02 s^{-1}) beta counting for considerably longer than 1 hour to achieve the same sensitivity as with 1 hour normal low-background alpha counting.
- The sensitivity achievable with gravimetric analysis (for a specific activity of 10 Bq/g or less) is superior to that obtained from radiometric analyses utilizing a 1-hour counting time.

The overall conclusion is that none of the bioassay or body/lung counting techniques considered are suitable[5] for ALARA purposes. **The remaining part of this Work Package will be thus entirely devoted to a more detailed evaluation of different types of air sampling.**

3.4.4 Accuracy of air sampling

As stated earlier, the implementation of ALARA requires a reasonably accurate assessment of occupational doses. For air sampling, there are a number of factors to consider, for example:

- is the sampled air representative of that in the breathing zone of workers?;
- does the sampler have an appropriate collection efficiency (for radiation protection purposes) for different size particles?;
- does the uncertainty on particle size distribution produce a bias when sampling results are converted into committed effective doses (i.e. using dose coefficients) and can this be corrected for? and;
- what are the statistical uncertainties, for example where worker exposures are based on a small number of air samples?

These questions are discussed in sections 3.4.4.1 to 3.4.4.3 below. In addition, the accuracy of the sampling may also be affected by various physical factors encountered in the workplace. These effects are influenced by the particular design of the sampling equipment, and are considered in section 6.

[5] Not only from the sensitivity point of view (as demonstrated above) but also from the accuracy point of view: it should be noted that, contrary to air sampling techniques, all bioassay techniques can be affected by significant uncertainties where intakes of decay series are involved (ICRP 98). These uncertainties arise when the radionuclide used for the analysis is both directly incorporated (after inhalation, or ingestion with diet) and also produced in the body by the radioactive decay of its incorporated parents.

3.4.4.1 Representative sampling of the inhaled air

Although static air sampling (SAS, also called general air sampling, workplace air sampling or area sampling) has sometimes been used to estimate workers exposure (and continues to be used in some cases), it is increasingly recognised that air samples should be representative of the air breathed by the worker (NRC 92, Henrichs 98, ICRP 97) and that SAS does generally not meet that criterion (DOE 00).

The same conclusions have been reached from an industrial hygiene perspective[6], in which sampling air representative of that in the breathing zone is also a priority (WHO99). For example, international and national guidance has recommended:

- As long as there are spatial and temporal variations of the concentrations in any work environment, a sampling strategy must be designed so that the data obtained are representative of the worker's exposure, accounting for all factors that may lead to a variation in the results (WHO 99); and
- It is not appropriate to compare general air samples with the exposure limit because the distribution of dust in the workplace is not uniform (HSE 00).

These issues are considered in more detail in the following section.

3.4.4.1.1 Spatial variation of air concentrations

When considering the spatial variation of airborne contaminants, two scales of variation may be distinguished: from one workstation to another (larger scale), and locally within a single workstation (smaller scale).

a) Between workstations

As shown in the case studies, air concentrations are never uniform throughout a workplace. Airborne particles are produced by discreet sources and localised activities (Kenny03) and it should be expected that the concentration of airborne contaminants will differ between locations. Consequently, the air concentration at a workstation can only be determined by sampling at that location. To assess individual exposures, the sampling results need to be combined with worker occupancy data. For example, one study (Price89) involved the acquisition of detailed occupancy data (to the nearest hour) at 80 locations within a workplace. However, other studies have recognised that, although reliable exposure estimates could sometimes be obtained, this approach is too cumbersome for routine application (Breslin 75, in EGG 88). At some sites, the wide range of work carried out by different people within the same facility prevents the application of reliable occupancy factors to static air sampling results (Boecker 94). This has been recognised in some studies (Denvir 95) as one of the causes of the poor correlation observed between SAS and PAS results, as very few workers remained in one position throughout the day.

b) Within the workstation

It has been recognised that on a smaller scale, large variations of activity air concentration can be expected in the vicinity of a workstation (by an order of magnitude within 1 m (WHO 99, and also see the case studies)). Air monitoring results, depending on where the sampler is located, could significantly underestimate intakes (by up to three orders of magnitude(NRC 98)) due to the fact that air is generally more contaminated near a worker than at some distance (Jonhson 89). This applies particularly when the worker is generating the aerosol (DOE 99 b). It has been also recognised that intakes estimated from SAS have limited correlation with those derived from bioassay results (DOE 99 b, West 95). Unrepresentative air sampling was identified as a significant contributor to this poor correlation

Several studies (see Witschger 00) have shown differences of up to several orders of magnitude between air concentrations measured by PASs worn by the workers and SASs (Dias da Cunha et al.

[6] The term "industrial hygiene" is used in a general way to describe the control of non-radiological hazards, i.e. from airborne contaminants in the workplace.

98, Gibert 98). Workers activities caused increased airborne concentrations of radioactive materials, for example through localised releases or resuspension of the surface contamination induced by the work in progress (NRC 93, EGG 88, ICRP 97). It has been shown (Linkov 2001) that the ratio of PAS:SAS results for Nuclear Power Plant workers can be high (median 37) and also significantly variable (GSD 2.1).

It has been recognised that when material with relatively low intrinsic hazard is moved around the work place and directly manipulated at a number of locations (as is the case in the NORM industry), fixed breathing-zone samplers usually would be unsatisfactory and PAS would be required for estimating an individual worker's exposure (DOE 00).

Even when exposure estimates are obtained using PAS, the non-uniformity of the dust cloud surrounding the worker may still be a problem, especially where sources of dust are close to the breathing zone (HSE 00). The concentration gradient between the lapel and the nose (in case of a chest-mounted sampling head) can be significant, and sometimes is due to the resuspension of dust from the fabric when the sampling head was mounted on work clothing. This can result in a serious bias in the exposure estimate. More reliable results may be obtained by placing the sampling head closer to the nose or mouth, by mounting it on a work helmet, or by using an extension device (Beverly et al. 84).

c) The radiological approach to air sampling

While it is now widely recognised in the field of industrial hygiene that PAS is the preferred mode of aerosol measurements for occupational exposure assessments (Corn 85,Witschger 2000) in nearly all circumstances (HSE 89), the situation for radiation protection in the nuclear industry is more complex. Even when it has been concluded that PAS are the only means of making a reliable estimate of exposure (Marshall and Stevens 80), a graded approach (NRC 92) is still often proposed. In this approach, PAS and static breathing zone samples[7] are considered to be equally representative of the air breathed by the worker. Other samples not taken in the breathing zone must be shown to be representative by either comparison with PAS results bioassay results, or with the results from multiple static samplers. The following options are recommended when samples are not representative: relocation of air samplers; application of correction factors to sampling results; use of personal air sampling; or use of bioassay techniques to determine intakes.

The latest recommendations of ICRP regarding the general principles for the radiation protection of workers (ICRP 97) state that if representative air samples can be used to determine worker exposure (see also IAEA 99), the most common form of representative sampling is by using fixed samplers at a number of locations intended to be reasonably representative of the workers breathing zone, this being particularly relevant where there are fixed high occupancy work stations and the sample air intake can be conveniently situated close to the breathing zone. This approach is not consistent with the conclusions of this report. Neither does it match the practices found in NORM workplaces, i.e. which are more closely aligned with industrial hygiene practices.

The choice of such an approach may have originated in the fact that in most nuclear sites, where highly radioactive materials were processed, the monitoring strategy has been designed to detect air contamination incidents as soon as possible, i.e. in order to timely initiate bioassay monitoring and to limit the further exposure of workers. Consequently, a network of SAS was used most often, either to detect contamination incidents[8] or a slow degradation of containment. As long as numerous SAS were already present at the site, it was convenient to use them as well (Marshall and Stevens 80) for the assessment of workers' normal exposure (by correcting their results with breathing zone ratios[9] or moving them towards the workers breathing zone), especially when the use of actinides implied the assessment of workers exposure by air sampling. In such situations, the use of PAS for the routine assessment of workers exposure was regarded as an additional expense and often restricted to validate

[7] Samples taken by static air samplers in the worker's breathing zone
[8] Alarming static air samplers (Continuous Air Monitors) were also used for this purpose
[9] Ratio of the PAS and SAS concentrations

a breathing zone sampling strategy, based on a well-placed network of breathing zone samplers, and to conduct special investigations (DOE 00) [10].

A progressive move towards PAS has, however, been seen in a number of situations:

- At the nuclear waste reprocessing site of Sellafield, extensive investigations with PAS of the spatial and temporal distribution of airborne contamination showed that exposures measured by PAS were almost invariably greater than those calculated from SAS and that the ratio of PAS/SAS exposure estimates varied with the operation carried out and between operators carrying the same task; as a consequence, it was decided in 1984 that PAS should be the preferred method of exposure assessment (Tagg and Smith 91).
- At the BNFL uranium fuel manufacture site, the workers exposure assessment relied essentially on SAS combined with occupancy, supplemented by PAS campaigns for validation of the breathing zone ratios The routine use of PAS was progressively introduced after 1992 in zones with the highest potential for exposure (Fishwick 94).
- A recent survey of internal dose monitoring programmes for radiation workers, within the framework of the EC project OMINEX (Rahola et al. 03), has found that for uranium monitoring (among seven reporting organisations), PAS were used in most of the cases, almost always together with other direct (whole-body and lung counting) and indirect methods (urine and faecal monitoring) and that for thorium monitoring (among four reporting organisations), PAS was used for routine monitoring while urine analysis was used for incident monitoring.

Finally, it has been recognised that the routine use of PAS, whose results are delivered regularly to the workforce, fosters the communication between the workers and engineering, and increases worker knowledge and ownership of how the controls are implemented and utilised (Funke 03).

It has been progressively recognised that agreement between SAS and PAS measurements can only be obtained when the complex system of the workplace air movement (exchange rates, air flow and room mixing patterns), effectiveness of engineering controls and the workers' actions are clearly understood (Munyon and Lee 02). Assessments of individual exposure based on SAS data should therefore be viewed with caution (EGG 88). The air samples should be collected in the worker's breathing zone[11] (EGG 88, NRC 93, WHO 99) and that, in many situations, only PAS could give a reasonably reliable estimate of activity intake (Marshall and Stevens 80).

3.4.4.1.2 Temporal variation of air concentrations

Knowledge of temporal distribution of radionuclides has also been found to be also essential to determine appropriate sampling strategies (Tagg and Smith 91, Boecker 94, WHO 99). However, it is important to distinguish the temporal variation of the activity airborne concentration from one day to the other (medium-term) and within a single day or shift (short-term):

a) Day-to-day temporal variation

Plant and process conditions and general ventilation characteristics may vary from shift to shift, day to day or display a seasonal pattern (Corn 85, HSE 89, WHO 99). This medium-term temporal variation impacts the general sampling strategy, for example in terms of total number and temporal distribution of the samples[12] (rather than the type of sampler used), which should be chosen to get the best estimate of the long-term average exposure and to get an indication of the exposure's temporal variability.

[10] It must be recognised that the situation is significantly different in the NORMs industry where PAS are often already used for Industrial Hygiene purposes and where no significantly extended network of SAS exist or is necessary.

[11] Defined as a memisphere centered on the mouth and nose, having a radius of about 30 cm

[12] Medium-term temporal variation may be taken into account by a random sampling stratified along the characteristics (season, process conditions, production, shift,…) that have been shown (or suspected) to impact the airborne activity concentration.

b) Short term temporal variation

Shorter-term changes of airborne concentration pattern can be produced in many ways (opening a door, or by a person changing position close to the source, see Marshall and Stevens 80), and airborne contamination is often localised and transient (ICRP 97). Moreover, it has been stated that in contaminated areas subject to significant temporal and spatial variations in the activity concentrations, only PAS or virtually continuous grab samples collected from within the breathing zone of workers could provide reliable breathing zone samples (EGG 88).

The short-term (intra-day or intra-shift) temporal variability of the airborne activity concentration at a given workstation has different implications in terms of worker's exposure assessment, depending on the mobility of the workers. For example:

- PAS – should be as good as, or preferable to, SAS in all cases, as the method of determining individual exposures. In the absence of any other information, it should be assumed that short-term temporal variations are significant. In such cases, PAS should always be the first choice.
- SAS – provides an average measurement (over the sampling period) in the same way that PAS does. However, short-term temporal variations (within the sampling period) are problematic for SAS, especially where workers move about the workplace. The obvious solution is to compile worker occupancy data and calculate exposures accordingly. If the temporal variations are significant (and this is suggested by the case studies), precise occupancy data will be required. As well as being cumbersome in practice, this approach is not guaranteed to give reliable results. Case study F1 indicated that the temporal variation is a function of the workers' presence (i.e. because the workers produce airborne particles). Consequently, simple occupancy calculations will tend to underestimate exposures. These problems can be overcome by ensuring that SAS are switched on only when workers are present. However, the use of PAS is likely to be a more straightforward solution.

3.4.4.1.3 Inter-worker exposure variation

Significant worker-to-worker variability may be expected when the worker has direct influence over the process or the number or nature of the sources of contaminant release, particularly where manual handling operations are concerned (HSE 89). This additional source of variability must be taken into account in the sampling strategy (see NIOSH 77, BOHS 93 and Rappaport 93, Rappaport et al. 95), recognising that different workers implementing the same tasks could receive significantly different exposures, due to different working routines (Lyles 97).

3.4.4.1.4 Conclusion

Under workplace conditions such as those usually encountered in the NORM industries, the sources of exposure are often multiple, extended, not totally contained, and/or closely associated with the worker's activity. Large spatial and temporal variability of the airborne activity concentration may be expected and the workers mobility is often important. Therefore, it is recommended that assessments of dose should be based, where practicable, on PAS rather than SAS[13].

Historically, the use of PAS has been regarded as labour-intensive, and too dependent on worker co-operation. However, it is now widely accepted that health-related sampling in the workplace should be conducted by PAS located in the "breathing zone" of workers.

3.4.4.2 Aerosol sampling and bias correction

As part of the SMOPIE project, IRSN were subcontracted to undertake a review of air sampling tools (equipment and techniques) in terms of their applicability to radiation protection. The full report of this work is reproduced in Annex 3, Appendix 1, as is an extension to this work (to extend the range of radionuclides considered) undertaken by CEPN. The main findings are summarised below.

[13] SAS may still provide ALARA information – see section 5.

3.4.4.2.1 Air sampling - industrial hygiene versus radiation protection.

The IRSN report explains the differences between industrial hygiene and radiation protection. In summary, the results are that:

- radiation protection focuses on the assessment of (committed) effective dose via the application of respiratory tract and other biokinetic models (IRCP, etc)`, through the use of dose coefficients that depend on the particle's rate of clearance from the lungs and on the particle size distribution. This approach starts with a consideration of the *true ambient aerosol*, e.g. in the workplace; **however**
- air sampling equipment has mostly been designed within an industrial hygiene context, where the focus is on sampling specific *inhaled* particle size distributions (e.g. inhalable, thoracic and respirable fractions). Samplers do not (and cannot) sample the *true ambient aerosol* required for radiation protection purposes.

There are two notable consequences from the above; firstly in terms of assessing the **air concentration** (e.g. in Bq/m^3), and therefore also the **intake** (e.g. in Bq); and secondly in terms of assessing **effective dose** (e.g. in mSv). These consequences are summarised below.

3.4.4.2.2 Assessment of air activity concentration and intake

Air samplers are designed to follow a specific particle size sampling convention (i.e. based on industrial hygiene sampling criteria) and so will typically underestimate the true ambient aerosol. Therefore, the result in terms of the estimated air concentration will contain a bias, the magnitude of which will depend on the sampler collection efficiency and the particle size distribution of the ambient aerosol. This bias can be corrected for, but this will only be possible in cases where all the relevant parameters are known. More likely, it will be necessary to select a technique in which the degree of bias can be minimised. For the assessment of air activity concentration, the characteristics most relevant to making this choice are:

- whether the sampling efficiency is known (and corrected for); and
- whether the particle size distribution (AMAD and GSD) of the aerosol are known.

The air sampler's sampling efficiency will generally vary with the aerosol particle size dispersion characteristics (AMAD and GSD) and air samplers will generally underestimate the true ambient air activity concentration[14], and therefore the activity inhaled. The degree of underestimation will depend on the particle size distribution and on the type of sampler. The results of this are shown in Figures 2 and 3 of the IRSN report. These indicate, for example, that in extreme cases (e.g. respirable sampling of an aerosol with a AMAD above 15 _m), less than 10% of the true ambient aerosol is actually collected by the sampler. For information, the correction factors for different AMADs (GSD = 2.5) are listed in Table 12.

[14] As described in the IRSN report, care is always needed to avoid the problem of oversampling (compared to the sampling of a reference person), due to factors such as inappropriate air sampling rates or the direct impaction of particles on the filtrating medium due to the presence of a very close dust source.

Table 12: Correction factors to be applied to the measured activity concentration for the estimation of the true ambient aerosol activity concentration (GSD = 2.5)

AMAD (_m)	Correction factor		
	Inhalable Sampler	Thoracic Sampler	Respirable Sampler
1	1.04	1.05	1.11
2	1.08	1.12	1.36
3	1.12	1.20	1.67
4	1.15	1.30	2.1
5	1.18	1.41	2.5
6	1.21	1.54	3.0
8	1.27	1.80	4.1
10	1.31	2.1	5.6
12	1.36	2.4	7.3
14	1.40	2.8	9.4
16	1.43	3.2	11.8
18	1.46	3.6	14.5
20	1.49	4.0	17.7
25	1.55	5.3	27

The sampling efficiency (or at least the sampling convention it approximates to) should be known. Therefore, **for assessing ambient air activity concentrations and intakes** for radiation protection purposes, the correction factors in Table 12 appropriate to both aerosol particle size distribution characteristics (AMAD and GSD) and type of sampling should always be applied.

To apply the correction factors, it is necessary to know the particle size distribution. In many cases, this is not expected to be well known[15] and, in such cases, a range of possible values of remaining bias exists may exist depending on the actual particle size distribution. Consequently, the best that can be done is to choose a sampling method that minimises this range. This is considered in detail in the IRSN report. Consequently, it is recommended that, **for assessing ambient air activity concentrations and intakes (but not effective doses**) for radiation protection purposes:

- **inhalable** sampling should generally be preferred because it minimises the bias in assessing the concentration of the ambient aerosols where the particle size distribution is not well known[16];
- respirable sampling should not be used. It has a much greater potential for bias where the aerosol particle size distribution is not perfectly known, and it also has a lower measurement sensitivity than either thoracic or respirable sampling[17]; and
- where the AMAD is not known, a default AMAD of 5 μm (and GSD of 2.5) should be used[18], as well as correction factors appropriate to both default aerosol particle size distribution characteristics and type of sampling.

It is important to note, however, that the above relates only to the assessment of air activity concentrations or the total activity inhaled. **Different conclusions apply to the assessment of**

[15] This uncertainty is generally due to the lack of adequate measurement of the AMAD (and GSD) of the ambient aerosol, due to their intrinsic variability with location and circumstances of dust production. (Johnston 91, Dorrian 95) and significant daily variation (Jonhson 89).

[16] This uncertainty is generally due to the lack of adequate measurement of the AMAD (and GSD) of the ambient aerosol, due to their intrinsic variability with location and circumstances of dust production. (Johnston 91, Dorrian 95) and significant daily variation (Jonhson 89).

[17] Calculations indicate that, for a 5 μm AMAD, the sensitivity is 1.2 times greater than thoracic sampling, and 2.1 times greater than respirable sampling.

[18] The 5 μm AMAD value has been found to minimise the bias in assessing the activity concentration of the aerosol, whatever the true value of AMAD and the sampling type. The 2.5 GSD value is recommended by ICRP (ICRP 94) for aerosols with an AMAD above 1 μm.

effective dose (which is usually the main quantity of interest) or indeed where the air concentrations/total activity inhaled is used as a direct surrogate of effective dose, as discussed below.

3.4.4.2.3 Assessment of effective dose

3.4.4.2.3.1 Dose coefficients

ICRP Publication 68 provides inhalation dose coefficients (DC) for intakes of radionuclides by workers for 1 μm and 5 μm AMAD particles respectively. For some of the NORM nuclides the DC is provided for all three absorption types (Fast (F), Moderate (M) and Slow (S)) of the inhaled particles. For others the DCs have only been calculated by ICRP for one or two default absorption types. For instance, the DC for Pb-210 is only provided for Type F, and for Ra-226 only for Type M. Consequently, as part of SMOPIE, NRPB has calculated the inhalation DC for all NORM nuclides and absorption types for an AMAD range from 1 to 20 μm (GSD 1.5 and 2.5) In addition, DCs have been calculated for Ra-226 contained in compounds with very low Rn-emanation rate. The results are presented in Appendix 2 in Annex 3. They show that the DC's of the NORM nuclides are strongly dependent on absorption type of the particles. The ratio between the DC's for S and F particles can be as high as about 90 for Ra-226 with a low radon emanation rate, and as low as 0.06 for Th-230. From the data provided in Appendix 2 it is also clear that the DC for Type F particles is much less AMAD dependent than for Type S particles.

3.4.4.2.3.2 Bias in assessing dose

The bias in assessing effective dose is due to a combination of two effects - the bias in assessing the *true* air activity concentration, as described in 3.4.4.2.2, and the variation of the dose coefficients with the aerosol particle size distribution. In general, dose coefficients reduce with increasing AMAD (e.g. See figure 5 of the IRSN report), and this partially corrects for the bias due to collection efficiency. In fact, an ideal sampler would have a collection efficiency curve identical to the dose coefficient curve.

For the assessment of effective dose, the characteristics most relevant to select a technique in which the degree of bias can be minimised (see Figure 4 of the IRSN report), are:

- whether the sampling efficiency is known (and corrected for);
- whether the particle size distribution (AMAD and GSD) of the aerosol are (perfectly) known: and
- whether the dose coefficient is (significantly) AMAD-dependent.

Regarding the first characteristic (sampling efficiency), the same considerations apply as described in 3.4.4.2.2. Therefore, correction factors should be applied in the same way (see Table 12). The situation in respect of any residual bias due to an imperfectly known particle size distribution is, however, different. This is because the AMAD dependency of the DC is also a factor.

Whether dose coefficients are significantly AMAD-dependent, depends on the lung absorption Type of the compound .The dose coefficients for NORM radionuclides in soluble (Type F) materials change only slightly with particle size. In practice, however, the dose coefficients for the radionuclides of interest to SMOPIE can usually expected to be strongly AMAD-dependent because they are mostly contained in an insoluble matrix (Type S).

To minimise the possible variation in bias, the sampling efficiency should thus follow, as closely as possible, the AMAD-dependency of the relevant dose coefficients. The report by IRSN considered only uranium-234, types S and F – see figure 9 in the IRSN report. This indicated that both inhalable and respirable sampling could either significantly underestimate or overestimate the effective dose, depending upon the true AMAD (i.e. as compared to the default value assumed). Subsequent to the IRSN report, CEPN have expanded this work to cover all the main radionuclides of interest in the U-238 and Th-232 decay chains, and all three lung absorption types (F, M and S). The main calculations were using PLEIADES [PL03] and IMBA [IM02, IM03] software. The results of these additional

calculations, in terms of the bias in estimating effective dose, are also presented in Appendix 3 in Annex 3.

From this work, it is recommended that, **for assessing effective doses**:

- the lung absorption Type of the compound should be identified;
- **thoracic** sampling should be preferred for compounds with **lung absorption Types S and M**. This would be the case, for example, for insoluble mineral sands and sulphate scales;
- **inhalable** sampling should be preferred for compounds with **lung absorption Type F**, i.e. for soluble materials.; and
- where the AMAD is not known, default AMAD of 5 _m (and GSD of 2.5) should be used to asses the sampling efficiency correction factors and the dose coefficients[19],

3.4.4.2.4 Air sample analysis methods

Different techniques exist for the analysis of air samples. In all cases, however, the objective is to obtain a reliable estimate of the airborne contamination level (in Bq/m^3) for each radionuclide of interest. The identification of the radionuclides spectrum is often done on the basis of a preliminary air sampling campaign (using often high flow-rate samplers for sensitivity reasons, see Johnston 91). These samples are analysed using gamma spectrometry, or more sophisticated radiochemical analyses, that generally involve successive steps of preparation and pre-concentration of the sample, (radionuclide separation), and preparation of the source for alpha/beta counting (or spectrometry).

Subsequently, if the composition of the airborne aerosol may be considered as reasonably constant with time (as is often the case for a given workplace, processed material and process conditions), the analysis of air samples may rely on simpler radiometric techniques of (alpha or beta) gross counting of the sampling medium, after an up to 3-4 days waiting period, allowing for radon daughters to decay away (Johnston 91).

If the specific activity ($Bq.g^{-1}$) of the airborne aerosol may be considered as reasonably constant with time and with particle-size[20], still simpler gravimetric methods may be used as surrogates of gross counting radiometric methods. Gravimetric analysis does not, however, distinguish between radioactive and non-radioactive particles, and should not be used when the specific activity of the airborne aerosol may be highly variable as is the case where the airborne aerosol consists of a mix (in variable proportions) between relatively high specific activity radioactive particles released by the process and inert dust (as in the F1 case study).

3.4.4.3 Sampling statistics

Any measurement is subject to statistical uncertainties, as is the process of sampling. With regard to SMOPIE, an important question is to know how confident you can be that the annual expected dose of a worker will not exceed a certain level. This is of particular relevance to NORM workplaces where the application of regulatory control depends on whether doses exceed 1 mSv/y. Another question is what is the uncertainty associated with estimated annual doses to workers as they are usually derived from a limited set of monitoring results.

In practice, these questions translate into the following:

- which workers should be sampled and when should they be sampled in order to minimise the bias in the estimate of the mean exposure?; and

[19] The 5 µm AMAD value has been found to reasonably minimise the bias in assessing the effective dose, whatever the true value of AMAD, the sampling type, the radionuclide and the lung class. The 2.5 GSD value is recommended by ICRP for aerosols with an AMAD above 1 µm.

[20] This latter condition is essential for using a constant specific activity value, independently of the aerosol particle size distribution. Caution should be thus exercised when dealing with materials that have been subject to thermal processes. In such conditions, some natural radionuclides with low vaporisation temperature (Pb, Po) may have condensed on the surface of the airborne particles, and the specific activity will then depend on the ratio of the particles surface and volume.

- how many workers should be sampled and how many times should they be sampled in order to obtain a reasonable uncertainty in the estimate of the mean exposure?

To fully answer these questions requires a detailed statistical analysis of the actual measurement results obtained, the description of which is considered beyond the scope of this report. However, these questions have been – at least partially – addressed elsewhere (see BOHS 93, HSE 89, NIOSH 77, AIHA 91). A preliminary review of the literature and statistical analyses have been undertaken, and these suggest that:

- in any one workplace, there is often a wide distribution of monitoring results (Marshall and Stevens 80), most often showing a log-normal distribution (Corn 85, Tagg and Smith 91, HSE 89, Waters 91, Rappaport 91, 93,). Plant and process conditions and general ventilation characteristics may vary from shift to shift, day to day or display a seasonal pattern (Corn 85, HSE 89). Moreover, significant worker-to-worker variability may be expected when the worker has direct influence over the process or the number or nature of the sources of contaminant release, particularly where manual handling operations are concerned (HSE 89). As a consequence, it is not advisable to make assumptions about long-term exposure patterns on the basis of a single estimate/survey of contamination concentrations at one point of time (HSE 89, Peretz et al. 97). In such conditions, the mean value of several results has usually a large uncertainty, and may be of little practical use. Consequently, monitoring programmes should aim to define reasonably homogenous groups of workers[21], and take representative samples within each group, in order to determine both the average value and the degree of variability[22] and;
- within each group, if possible, at least five workers (chosen at random) should be monitored, in order to get an indication of the distribution of exposures between workers (worker to worker variability). In addition, a set of at least five representative measurements per worker (on days chosen at random) should be taken in order to get an indication of the within-workers distribution of exposures (day to day variability).

Therefore, a minimum of 25 samples from each group of workers is recommended. Even then, the statistical uncertainties are likely to be significant. Even where the results follow a typical log-normal distribution, the uncertainties associated with determining annual exposures are typically a factor of 2 to 3. Where the results show a wide variation, further sampling (and possibly a larger number of worker groups) should be considered.

These preliminary findings suggest that the inherent variability of exposures is potentially one of the greatest sources of uncertainty in the estimate of annual exposures, and that sampling statistics should be thus a major consideration when designing monitoring programmes. If anything, the case studies suggest that the reverse is true in practice. Consequently, it is recommended that further guidance is needed for users on the statistical nature and analysis of monitoring results.

3.4.5 Alara information

The first step of any ALARA procedure should involve an assessment of the doses being received. For work with NORM, the results of this assessment are often used to determine whether regulatory controls (including ALARA) should be applied at all. Therefore, it is expected that the **first aim** of any monitoring strategy will be to determine the doses arising using personal air sampling. In particular, the aim should be to determine the maximum annual doses being received. If doses are shown to be low (i.e. well below 1mSv/y), then no further action may be necessary.

[21] For example, workers may be assigned to groups according to the types of job undertaken, workplace location, etc

[22] while not forgetting that if, in certain situations, it seems too costly and difficult to demonstrate compliance (or non compliance) with a standard, it may be better just to reduce the exposure (WHO 99)

If doses are significant (but below dose limits), then the focus should switch to optimisation, i.e. what can reasonably be done to further restrict exposures? In practice, this requires more detailed information on the exposures being received. For example:

- is the dose at work received uniformly, or is it mainly from certain tasks?
- do certain workers receive higher exposures than others while fulfilling the same task, due to specific working routines producing higher doses?
- what are the specific sources of airborne contamination/dust?

Finally, when optimisation has been achieved, monitoring is still required in order to verify that the engineering and administrative controls are operating properly and that workers exposures are kept ALARA.

The purpose of this section is to consider whether any of the available monitoring techniques can provide some or all of the required information. It is not, for example, necessary that the same technique is also capable of accurately assessing individual doses.

Bioassay monitoring techniques have already been discounted due to inadequate sensitivity. Even if that were not the case, these techniques are not generally able to provide the type of detailed dose information required. In contrast, the case studies have shown that air sampling can provide various types of ALARA information, as summarised in table 6.in section 3.2.5. Three types of sampling (static, personal, and real-time) are available, and the ALARA capabilities of each of these are summarised below.

3.4.5.1 Personal Air Sampling (PAS)

This has been shown to be the best technique for the assessment of individual doses, i.e. as required for the first part of the monitoring strategy. Such sampling should normally provide a range of results obtained from monitoring individuals over a complete working shift (e.g. 8 hours). The results obtained from this can begin to provide information that is useful for ALARA purposes, in particular in terms of the **distribution** of results, e.g.:

- which PAS results give the highest estimated doses?; and
- of these results, are the highest doses associated with particular workers (e.g. due to differences in working procedures), or with particular tasks (e.g. due to proximity to dust sources, etc)?

In addition, the results can be used to determine the future PAS monitoring strategy, e.g.:

- PAS campaigns can be planned to focus on specific groups of tasks, associated with the highest exposures (Tagg and Smith 91). This should, in the first instance, involve obtaining a larger number of measurements from these tasks (workstation exposure values should be logged for at least a week, see Jonhson 89), i.e. to explore the variability in results. For example, if statistically significant differences are found between the exposure of workers implementing the same tasks, working procedures should be investigated and modified as necessary (Lyles et al. 97).
- In addition, as PAS may be particularly useful for assessing potential intakes involving short-term exposures (DOE 2000), or task-specific information, especially when the releases are of local extent and rather infrequent (Boecker 94), several shorter-duration samples can be taken to help identify the pattern of exposures during the group of tasks (OSHA 03) and reveal short-term, high exposures that would be missed during full-shift sampling (Reames 01). Therefore, PAS may be used to provide task-specific information (Reames 91) and, in particular, highlight any air contamination created by the workers' presence.

- This can be done either by:
  - allocating PAS to a worker on a task per task (or workstation per workstation) basis (see F1 case study part 1) in order to obtain information on the contribution of each task to the exposure associated with the group of tasks: the worker may wear several task (or workstation)-specific PAS and switch each one on only during his presence at the given workstation[23] or by
  - asking the workers to switch on and off static breathing zone samplers (see F1 case study part 2) during their presence at the key workstations. The switched static samplers should be preferably PAS (used in a static way) if one wants to obtain information on the contribution of each workstation to the exposure, by comparing the results with the results of the breathing zone samplers with those of the PAS worn by the workers[24]. The switched samplers could be SAS if one only wants to identify short-term contamination associated with the worker's presence by comparing their results (in terms of time-averaged airborne activity concentration) with those of similar SAS placed at the same location but operated continuously.
- Finally, PAS will need to be used for the re-assessment of doses to check the effectiveness of any protection measures implemented.

The tracking of PAS data can be used to monitor and refine the effectiveness of existing engineered controls or for training workers in better decontamination techniques. It fosters the communication between the workers and engineering, and increases worker knowledge and ownership of how the controls are implemented and utilised (Funke 03). It gives workers feedback about their work practices and may allow them to develop better radiological control habits (DOE 99b).

3.4.5.2 Static Air Sampling (SAS)

In most cases, it is concluded that the best role of SAS is to complement the workers individual exposure measurements obtained by PAS, i.e. rather than replacing such measurements. Consequently, the recommended strategy is to consider the possible role of SAS after the aforementioned PAS monitoring has been undertaken.

- SAS can be used to provide a series of reference readings at key locations in the workplace. This can help determine daily variations in airborne activity, and allow analysis of trends of air concentrations with time (West 95, NRC 92, HSE 89, WHO 99) or comparison with administrative action levels (same references and COMURHEX F1 case study (see Gibert 98)) in order to determine whether airborne concentrations are within the normal range, detect a gradual loss of containment at early stages (HSE 89, DOE 2000), identify areas/processes that would require changes in containment or ventilation characteristics (Boecker 94) and verify that administrative and engineering controls are operating properly to maintain occupational doses ALARA (NRC 92) ; and
- multiple SAS can be arranged around a single workstation to show localised variations in airborne activity/dust levels. This can help identify possible dust sources and/or determine the optimum worker position.

3.4.5.3 Real-time dust monitoring (RTDM)

The only real-time monitoring devices considered here are those that determine total count or mass and particle size distribution based on non-radiometric (most often optical) techniques. The Continuous Air Monitoring (CAM) devices based on real-time radiometric counting, while routinely

[23] The total working duration spent by a worker at each workstation will be easily derived from the total volume sampled by the corresponding sampler.
[24] One should note however that, because of aerodynamic effects, static PAS will not exhibit the same characteristics as when mounted on the body, and will usually underestimate the inhalable dust concentration (MDHS 00).

used in the nuclear industry[25], have proven (see F1 case study) to be much too insensitive to be of any interest for the optimisation of exposures in the NORM industry. An important disadvantage of such devices is that radioactive particles cannot be distinguished from non-radioactive particles (Hoover and Newton 01, ILO 98). As a consequence, the use of such equipment is thus only appropriate in certain cases, i.e. where the specific activity of airborne dust is low (i.e. to ensure adequate measurement sensitivity) and the composition of airborne dust can be reliably inferred from the NORM material being processed (see chapter 4.2.4). In such cases it can be a powerful ALARA tool, as demonstrated in two of the case studies, although it is not recommended as a means of directly estimating doses.

RTDM may be used during a general walk-through survey (ILO 98) or more detailed ALARA studies, to rapidly determine how variable the air concentration is with time and place where, alternatively, it would be necessary to take large numbers of SAS to determine the variability(WHO 99). In particular, RTDM is considered to be the best technique for identifying specific sources of airborne activity/dust (WHO 99). This information has been shown to be of prime importance in identifying possible protection options. In addition, sometimes dust enters the air at a particular point in a work cycle and a direct reading instrument placed beside the worker can identify it (WHO 99). Finally, some RTDM are small enough to be worn by the worker and may be even connected in line with a PAS.

Overall, RTDM is recommended for use (in addition to PAS) wherever appropriate, to get a better knowledge on when and where dust arises (WHO 99). Possible monitoring strategies (supported by the case studies) include:

- taking a detailed "snapshot" of the dust levels throughout the workplace (UK1 case study). Although any single measurement may be subject to significant uncertainties (i.e. because of the variability in dust levels) , a large number of measurements can be easily made. This helps to build up a detailed map of airborne dust levels throughout the works*;*
- more detailed surveys can be undertaken at specific workstations, i.e. to determine the localised variation in dust levels, and pinpoint dust sources. Also, this can indicate whether specific worker actions or movements are contributing significantly to airborne dust levels;
- the variations in dust levels over the working day (or shorter periods) can be explored (F1 and UK1 case studies). This can help determine whether the operating mode of the plant is a significant factor. It can also show whether exposures are received continuously or due to a series of discreet events. Such information may be used to optimise the wearing of Personal Protective Equipment; and
- RTDM can be used to check the effectiveness of engineering controls, for example by checking whether leaks in containment are being prevented.

More sophisticated techniques combine direct-reading instruments and video imaging and can record for later analysis which parts of a process or work practice generates the dust (Martin et al. 99, NIOSH 92, Rosen 93). Such video exposure monitoring techniques may be particularly effective in comparing the relative efficiencies of different control measures in combination with work practices such as worker position, researching best work practices for a particular task and training for better work practices and use of control (WHO 99).

3.4.5.4 Visual inspection

It is also noted, that in many NORM plants, airborne dust is actually visible, or else it can easily be made visible by using a simple beam of light (or "Dust lamp", see HSE 97 and HSE 89) for illuminating dust by forward scattering of light (Tyndall effect). These dust-lamp techniques are not quantitative like direct reading instruments but usually cost less (WHO 99). A variety of ALARA information may, therefore, be obtainable with a simple visual survey, for example:

- obvious dust sources and faults in containment;

[25] Internal exposures in the nuclear industry often come from significant releases due to incidental confinement failure of otherwise well-contained sources.

- evidence of dust resuspension from surfaces;
- effectiveness of dust dissemination controls during their development or after their installation; and
- dust dispersion conditions

3.4.5.5 Air-flow studies

The direction of airflow is useful information when considering improvements to workplace ventilation, and cannot be determined by any of the other monitoring techniques (SAS, PAS, RTDM) considered above. In cases where the flow of airborne dust cannot be made visible, such information may be provided by using qualitative methods such as smoke candles and smoke tubes (NRC 93, WHO 99) or quantitative methods such as tracer aerosols (HSE 89, NRC 92, NRC 93), that can be used to estimate the effectiveness of containment systems, and also help to select the best local ventilation (Boulaud 94).

3.4.6 Equipment suitability (current air sampling devices)

In terms of the overall performance of currently available sampling equipment, the conclusions of the study, originating from the IRSN report, the literature review and the case studies are as follows:

3.4.6.1 All personal air samplers

There is clearly a continuing need for simple, cheap and reliable personal samplers, (Peretz et al. 97). More modern designs of the pumps usually are smaller and lighter than their predecessors, and it is considered that this trend needs to continue further, if possible.

During the study, the following areas of improvement of PAS characteristics (sometimes partly contradictory) were identified:

3.4.6.1.1 PAS pumps

- development of lighter pumps and well-adapted belts / harnesses to which they can be conveniently fixed (HSE 00 , case studies);
- higher flow rates (up to 10-15 $l.min^{-1}$, as opposed to the current 2- 4 $l.min^{-1}$ values, see sensitivity analysis and F1 case study), in order to meet the minimum sensitivity requirement with reasonably low sampling and counting times (DOE 99, NRC 93, case studies), but to be balanced against the weight of pump plus batteries (Marshall and Stevens 80, case studies). Although current flow rates have been shown to be sufficient for one day sampling times, higher flow rates would have practical benefit in terms of shorter sampling (or radiometric counting) times that would allow a better sensitivity for task-specific sampling;
- producing a device that would enable a single personal pump to be switched among several sampling heads and to account separately for the sampled volume among each of them, for an easier collection of task-related exposure data (F1 case study). This added function must not conflict with the necessary malfunction indicator or automatic cut-out if the air-flow is reduced or completely stopped (HSE 00);
- producing a personal air sampler integrating both a pump and a sampling head for an easier and faster exchange, for an easier collection of task-related exposure data (F1 case study);
- a more robust self-adjusting flow-rate function, to diminish the need of frequent and time-consuming flow-rate calibration (Denvir 95, case studies); and
- use of more appropriate material for the construction of the pumps in order to make them more resistant in an industrial environment (Denvir 95, case studies).

3.4.6.1.2 PAS sampling head

- Developing PAS sampling heads that follow either the thoracic or the inhalable curve not only for standard (2-4 $l.min^{-1}$) but also for increased (up to 10-15 $l.min^{-1}$) flow-rates, and with good sampling performances;
- producing PAS sampling heads with a well-known and robust sampling efficiency, insensitive to wind speed and direction and to impaction of big particles projected by close sources of dust;
- development of PAS sampling heads that could be readily adapted, as needed, to both thoracic and inhalable sampling fractions and
- PAS sampling heads specifically adapted to radiometric counting (i.e. with negligible deposition outside the filter).

3.4.6.2 Inhalable personal air samplers

- At this time, the Button (inhalable) 4 l/min sampler, is considered the most reliable aerosol sampler in the present market. Sampling performance is good, with reduced oversampling due to large particles and a low sensitivity to direction and velocity of the incoming moving air. In addition, the absence of transmission losses and a very uniform deposit of the collected particles on the filter area make them very appropriate for radiometric analysis of the samples.
- The closed-face filter 2 l/min cassette (37mm cassette), either closed or open, is no longer considered a reliable personal aerosol sampler, showing poor sampling performances and large dispersion of results. Traditionally, this sampler has been used widely in the workplaces (see F1 case study), but it should no longer be used to assess exposures.
- In addition to showing a large dispersion of results and a propensity for oversampling, the IOM 2 l/min sampler is not really appropriate where radiometric analysis of the aerosol collected on filters is required, due to internal deposition of the collected particles on the cartridge internal walls.
- The GSP/CIS 3.5 l/min sampler, despite having a good precision compared to the IOM or the filter cassette, is not really appropriate for radiometric analysis, due to internal deposition of the collected particles. The PAS6 2 l/min sampler has been found to be more precise than the IOM and 37 mm filter cassette but less than the GSP. However, the GSP/CIS and PAS6 samplers need more investigations, particularly in very slowly moving air.
- Finally, the CIP-10 I 10 l/min sampler can be used for measuring the inhalable[26], (as well as thoracic and respirable) fraction, by changing the particle-size selectors.

3.4.6.3 Thoracic personal samplers

- The GK 2.69 cyclone at the working flow rate of 1.6 l/min has been shown to be in close agreement with the thoracic convention.
- The CIP-10T 7 l/min sampler (see above) can be used for measuring the thoracic (as well as inhalable and respirable) fraction, by changing the particle-size selectors, identical to those of the CATHIA SAS sampler (Fabries et al.98). It's higher than average flow-rate together with its compact sampling head and pump integrated design, make it especially suitable for task-specific sampling. However, its foam filter does not allow a direct radiometric counting of the samples and it presents significant under-retention by the foam filter of sampled particles with an aerodynamic diameter below 2 μm.
- Another possible approach to size-selective sampling is the use of porous foam pre-separators that allow existing samplers to be modified for different applications. Foam plugs to convert the IOM

[26] A new inhalable particle-size selector is currently under development at the French INRS laboratories, to diminish the deposition of particles on the top part of the selector

inhalable sampler have been investigated (Maynard and Jensen 01). However, the use of foam filters precludes any radiometric counting without chemical preparation of the sample.

3.4.6.4 Real-time dust monitors

These devices provide more rapid measurements with less effort than the traditional approach using the filter collection. These factors, and the ability to provide short-term, task-specific (or even "instantaneous") readings (Maynard and Jensen 01) make them potentially very attractive in terms of providing information on the spatial and temporal distribution of airborne dust concentrations for ALARA analysis. One must however not forget that the non-radiometric technique used in these devices make them suitable only for situations (often met in the NORM industry) where the specific activity of the airborne dust is low (for sensitivity), and is reasonably constant with time and particle size (for accuracy).

The technical characteristics of specific types of instrument have not been considered in details in the IRSN report. However, as a general comment, care should be taken with the calibration of optical based instruments (like photometers) to avoid erroneous dust measurements[27], especially if large particles[28] (above 10 μm) are involved (Maynard and Jensen 01). There is considered to be a general need for further development of such instruments to extend their application to larger particles (Maynard and Jensen 01).

Finally, the recent development of individual RTDM devices should allow easier individual task-specific sampling and one may hope that the coupling of such devices with modern camcorders will allow the development of new video exposure monitoring techniques.

3.4.7 Conclusions

The technical capabilities and general suitability of different internal monitoring techniques, in relation to implementing ALARA, have been considered in this section. The main conclusions are:

1. bioassay techniques (in-vitro or in-vivo) are not suitable for ALARA purposes due mainly to insufficient sensitivity. Even if this were not the case, such techniques are not considered capable of providing the type of dose information required to implement ALARA;
2. personal air sampling (PAS) is the best method of assessing occupational doses from internal radiation. The first step in any monitoring strategy should be an assessment of worker doses using this technique;
3. PAS follow the inhalable, thoracic or respirable dust sampling conventions. None of these is a perfect match for radiation protection purposes, and all produce a bias in the results when the particle size dispersion characteristics (AMAD and GSD) of the airborne aerosol are not perfectly known. Respirable sampling efficiency is highly AMAD-dependent and is not generally recommended;
4. for the assessment of **effective dose**, either Inhalable or Thoracic sampling conventions may be used, provided that the AMAD is reasonably well known. In such cases, an appropriate correction factor (see main text) for sampling efficiency should be applied. The use of the relevant dose coefficients will then ensure that any bias in the dose calculation is eliminated;
5. where the AMAD is not perfectly known, the possibility of an associated bias in the calculated **effective dose** cannot be eliminated. However, the possible range of this bias can be minimised by:
   - using the AMAD value (and assuming a default AMAD of 5 μm if the AMAD is not known), to select both the sampler efficiency correction factor **and** the dose coefficients; and

[27] Light scattering generally provides an estimate of the physical size distribution of the observed particles rather than an estimate of the aerodynamic size distribution that is needed for the exposure calculation (Hoover and Newton 01)

[28] As large particles are undersampled by such devices, even with such a calibration, the application to determine the inhalable mass concentration is possible only when the fine particles detected form a constant fraction of the inhalable aerosol.

- using an inhalable sampler in the case of soluble materials (lung class F), or using a Thoracic sampler for all other materials (lung class S and M). NB: most mineral sands are expected to fall into this second category;

6. from the above, thoracic sampling would seem to be the preferred option for many NORM industries. In practice, however, this would appear to be the least used sampling convention. Further development and use of this type of sampler should be encouraged;
7. more generally, the development of PAS sampling heads following either the inhalable or the thoracic sampling convention, with good, robust and established sampling performances, and adapted to radiometric counting, should be encouraged;
8. the sampling rate of currently available PAS is generally adequate for ALARA purposes. However, in some cases (for sampling periods of up to a few hours) a higher flow rate would be an advantage, and the possibility of this should be explored;
9. analysis of air samples by gravimetric techniques may be preferred in practice to radiometric analysis, provided radionuclide activity concentrations ($Bq.g^{-1}$) in the airborne aerosol are reasonably constant with time and particle size (for accuracy) and of the order of 10 Bq/g or less (for sensitivity);
10. real-time dust monitoring (RTDM) is not suitable for assessing doses directly, but has the greatest potential in terms of providing rapid and easy to collect information on the spatial and temporal variation of airborne dust concentrations for ALARA purposes. Specifically, it is capable of providing comprehensive and detailed results, especially for the identification of dust sources during walk-through surveys, and for identifying short-term variations in the airborne dust concentration;
11. the further development of low-cost and easy to use individual devices integrating direct-reading instruments and video imaging should be encouraged;
12. static air sampling should not be used to assess workers individual exposure but can be used to complement PAS, to provide additional information for ALARA purposes, mainly by the analysis of trends with time of the daily variations in airborne activity; and
13. in addition to spatial and temporal variability of airborne activity concentrations, inter and within (day to day) workers variability of exposures is potentially one of the greatest source of uncertainty in the estimate of annual exposures, and should be a major consideration when establishing a monitoring strategy. These have only been briefly explored in SMOPIE, and further work to develop guidance for users is recommended.

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3.5 Work Package 5: Recommended strategies, methods and tools

3.5.1. Introduction

This Work Package aims to recommend strategies, methods and tools for optimisation of internal exposures in industrial work activities involving natural radionuclides. It is based on the case studies as described in Work Package 2 and the analysis of these studies in Work Package 3. It also takes account of the assessment of monitoring strategies, methods and tools described in Work Package 4.

The main conclusions and recommendations from Work Package 4 directly relevant for Work Package 5 are listed below.

- Static Air Samplers (SAS) may be suitable for a preliminary indication of the presence of airborne contamination but they do not allow a realistic exposure assessment and identification of the most exposed workers.
- In all situations in which air sampling is carried out for the purpose of dose assessment, PAS is the preferred sampling tool.
- Radiometric methods of analysis of PAS filters are in most cases sensitive enough for the assessment of annual effective doses well below 1 mSv/a resulting from exposure to intermediate and high specific activity aerosols even for short (1 hour) sampling durations. Gravimetric analysis also provides a more than adequate sensitivity for monitoring low-specific activity materials (at least up to up to 10 Bq/g).
- Direct reading devices or Real Time Dust Monitoring (RTDM) devices, although not really useful for quantitative assessment of exposure to dust, are of particular value in terms of the rapid assessment of dust levels, the identification and characterisation of dust sources, and for assessing the effectiveness of dust control measures.
- The sampling efficiency of the chosen sampling tool should be corrected for to represent true ambient aerosol. When the particle size distribution is perfectly known, the application the application of the appropriate correction factors allows the elimination of any bias in the estimate of the true ambient aerosol concentration. When the particle size distribution is not well known the inhalable and thoracic sampling conventions, compared to respirable sampling, will provide the least bias in the estimate of the true ambient aerosol concentration. Recommended default sampling efficiency correction factors based on a default AMAD of 5 µm and GSD 2.5 are 1.2 for inhalable and 1.4 for thoracic sampling.
- Dose coefficients for the natural radionuclides of interest are often highly dependant on lung absorption Types. This dependence is strong for most individual radionuclides of the U-238 and Th-232 decay series and less so for the series as a whole in secular equilibrium, as they occur in many natural raw materials such as heavy mineral sands. Dose coefficients are also AMAD and GSD dependant for the natural radionuclides of interest.
- To reduce bias in estimating effective dose when particle size distribution is not known, it is recommended that:
    - thoracic sampling is used for compounds with lung classes S(low) and M(oderate);
    - inhalable sampling is used for absorption Type F(ast), i.e. for soluble compounds; and
    - the relevant sampling efficiency correction factors should be applied based on a default AMAD of 5 µm in both cases. The effective dose is then derived on the basis of the assessed intake, a default AMAD of 5µm (GSD 2.5) and the appropriate dose coefficient for the lung absorption Type assumed or known.
- When the particle size distribution is known the sampling efficiency can be corrected for each of the sampling conventions and dose coefficients can be chosen for each combination of AMAD and lung absorption Type. It should be noted that in many cases the non-radioactive

matrix determines the lung absorption Type. As a consequence the lung absorption classes of the different radionuclides within the same matrix must be considered as identical.

- Dose assessments by bioassay techniques, including whole body and lung counting, have a very limited value in the optimisation of internal exposures by inhalation because:
  - they generally lack sufficient sensitivity in terms of the the dose range of interest; and
  - they do not provide the analytical information needed for guidance in the process of optimisation of exposures.

3.5.2 Recommended strategy for a first screening of workers exposure

3.5.2.1. Introduction

These recommendations pertain to situations in which it is already recognised that the nature of the processes as well as the characteristics of the raw materials, products and residues can potentially give rise to significant exposure of workers by inhalation. In such cases the first step is to visually identify sources of dust. Measurement campaigns to assess the exposure of workers should in the first place be directed to these visible sources. However, visible proof of sources of dust such as apparent deposition on surfaces does not, by itself, indicate potentially significant exposure. The dust may have accumulated over long time periods, and may also have characteristics quite different from the inhalable dust that remained airborne. Extensive dust abatement measures cannot be justified on the basis of visible traces of dust sources alone, without any indication of the significance of these sources with respect to the exposure of the workers. Therefore the evaluation of the exposure situation of workers should start with a first screening of their exposures.

3.5.2.2. First screening of workers exposure

3.5.2.2.1. Dust characteristics

Radionuclide composition

Even for the first screening of worker exposures, information is needed about the dust to which the workers are exposed. The likely radionuclide composition of the dust may be derived directly from the nature of the process. For instance industries processing heavy mineral sands can be expected to know what radionuclides occur in what concentrations in the raw materials. These characteristics are likely to be retained if the processing only involves mechanical methods like milling and sieving.

At other workplaces the radionuclide composition of airborne aerosols may not be so easily derived, and this information, therefore, must be part of the output of the first screening by sampling and sample analysis. This is an important issue because the dose coefficients to be used in the dose calculations are strongly radionuclide dependent and cannot reasonably be replaced by default values because of the absence of the radionuclide composition of the sampled aerosol.

Absorption Type

At this stage it is assumed that the likely lung absorption Type of the ambient aerosol is chosen on the basis of knowledge of the chemical characteristics of the raw materials, products and residues in the process. In the absence of convincing evidence about the true absorption Type of the ambient aerosols a default Type should conservatively be chosen on the basis of the data on inhalation dose coefficients provided in Appendix 2 of WP4. The same absorption Type should be assumed for the different radionuclides in a common matrix.

Particle size distribution

In this phase of the process an inherent lack of knowledge is assumed with respect to particle size distribution of the ambient aerosols.

3.5.2.2.2. Monitoring strategy

Aim and constraints

In the case of external exposure, it is possible to (conservatively) estimate likely annual worker doses from workplace measurements (e.g. dose rates) and assumptions about working patterns. This type of approach is not normally appropriate for estimating internal exposures, due to the large variations in airborne activity/dust present in workplaces, i.e. as shown in Work Package 2. Instead, it is concluded that there is no reliable alternative to a measurement campaign based on personal air sampling (see Work Package 4). At this stage, the aim of such a campaign is to obtain a conservative first estimate of the range of exposures of workers performing different tasks at different workstations under the normal variation of working conditions. It is acknowledged that the costs associated with such measurements can be very significant. Moreover, in practice most workplaces have a limited number of PAS at their disposal.

Consequently, the aim is to obtain the minimum number of measurements necessary to estimate exposures with a reasonable statistical confidence.

Number of workers to be monitored

From par. 5.3 of WP4 it appears that the variability of individual measurement results is potentially one of the greatest source of uncertainty in the estimate of annual exposures, and that sampling statistics should be thus a major consideration when designing monitoring programmes. With a small workforce (e.g.10 workers or less), it should be practicable to sample all the exposed workers within the period of the measurement campaign. Where larger workforces are involved, this may well be impractical. However, even then a large number of samples may still be required to determine the mean exposure with any degree of precision, due to the significant variation in individual PAS results that is typically seen. Moreover, the usefulness of the mean exposure of the whole exposed population, comprising workers achieving different tasks and/or working at different workstations, may be questionable. Consequently, to adequately estimate average exposures, and to concentrate sampling resources on groups at the higher risk, it is recommended that the exposed population is divided into reasonably homogeneous worker groups based on the similarity of functions: e.g. similar tasks performed in the same areas[29]. Typical group sizes between 10 and 50 workers are recommended although smaller group sizes may be appropriate to ensure reasonable homogeneity within groups. There even may be certain tasks that are essentially unique; this implies a group size of one. Ideally, at least five workers in each group should be sampled, and for large group sizes it is recommended that at least one worker in 10 in a group should be sampled. Furthermore, at least five representative samples per worker should be obtained.

If workers frequently change tasks from one shift to another the monitoring should better be aimed at obtaining sufficient information on the exposures resulting from these tasks rather than on individual workers. Workers exposures can be derived from the annual exposure times of the workers performing these tasks.

Sampling duration

The minimum sampling time should normally cover one full working shift (6 to 8 hours). Longer samples (e.g. one week) could significantly reduce the dispersion of the results from one sample to the other for a given worker and thus reduce (for a given total number of samples) the width of confidence interval of the group's mean exposure. However, shift-long sampling is usually easier to arrange and manage in practice, and it is easier to identify reasons why some samples might give significantly different results. Therefore, the collection of shift-long samples is generally recommended. However, shorter sampling durations will be appropriate to assess exposures resulting from short-term tasks performed at a low frequency but that are nevertheless identified as a potential source of exposure to high dust concentrations.

[29] It is recommended to not allocate too much resources to the groups selection for the initial grouping will be refined, if necessary, on the basis of the first exposure assessment results.

Total number of samples

In order to give some indication of the variability of exposures from one shift to the other, at least five samples should be taken for each sampled worker. In addition, to simplify the statistics calculation, it is preferable to take the same number of samples from each worker. In most cases, it should be expected that the shift-to-shift variability of the exposures will be significant. Consequently, the aim should be to collect a sufficient number of samples to cover the expected variation of the working conditions over the year. If some tasks of short duration could significantly contribute to the total exposure, it should be ensured that exposures during these tasks are representatively included in the sampling.

In summary, even where the exposed workforce is small, a significant number of samples is required, even for an initial evaluation of the likely exposures. For example, in a workforce of just 10 potentially exposed persons, the number of samples required is likely to be in the range 20 to 40.

3.5.2.2.3. Choice of sampling device

At this stage, the preferred sampling device is a PAS that samples inhalable particles, because of the slightly higher amount of material (activity) collected, as compared to thoracic samplers, and also because it is more widely available in practice. Presently the Button sampler (see Appendix 1 in Annex 3) is recommended, although other samplers may be proven satisfactory in the near future.

For aerosols of lung absorption Type Moderate and Slow the results obtained with thoracic samplers would provide the least bias in the exposure assessment when AMAD and GSD are not perfectly known. However, presently, thoracic samplers are not as widely available as inhalable samplers and the bias introduced by using inhalable samplers must be addressed in the dose assessment.

3.5.2.3. Analysis of filters

The analysis of the PAS filters must provide the identification of radionuclides and their activities on the filters, if such information cannot be obtained otherwise. Repeated radionuclide identification is not necessary if there is only one well-known source of airborne material. This is likely to be the case for instance in the processing of heavy mineral sands by milling and sieving. The reader is referred to Appendix -4- in Annex 3 for a discussion on radiometric analysis methods and their attainable sensitivities.

It is noted here that:

- low-background alpha and beta counting have low limits of detection but do not provide radionuclide identification;
- gamma spectrometry is useful to identify and quantify radionuclides on the filters but will not detect pure alpha emitters such as Th-232 and Po-210). Minimum detectable activities (MDA) for U-238 (Th-234), Ra-226, Pb-210, Ra-228 and Th-228 are of the order of 0.2 Bq, which may exceed that collected on a PAS filter. If so, it may be necessary to obtain a higher volume sample (e.g. by high volume SAS, or long duration PAS) purely for the purpose of radionuclide characterisation. This technique will normally only be available at specialised laboratories;
- radiochemical analysis of Pb-210 and Po-210 is very sensitive (MDA a few mBq) but requires specific laboratory skills and alpha spectrometers. Radiochemical analyses of Pb-210 takes a few months of waiting for ingrowth of Po-210;
- Radiochemical analysis of pure alpha emitters (Th-232, Th-230) is very costly and time consuming and requires very special skills and equipment. It is unlikely to be a practical option for NORM workplaces, except as a special monitoring tool;
- neutron activation analysis has been applied as an analytical tool for measurement of very small amounts of Th-232 on PAS filters from monitoring TIG welders using thoriated welding

rods(ref Ludwig et al., 1999 in Appendix TIG welding of Annex1). It is evident that this analytical tool requires very specific skills and equipment; and

- all radiometric analyses methods require considerable operational skills. Even for gross alpha and beta counting, the correct calibration of the counting system for the specific radionuclide composition of the material to be analysed is not straightforward.

Gravimetric analysis may be used in cases where the mass of material of low specific activity on the filter can be directly related to the radionuclides and their activities. This may be the case in sampling of heavy mineral sand dust (i.e. where this is the predominant source of dust) or other comparable cases.
The activities obtained from the analysis of the filters must be corrected for the estimate of the true ambient aerosol concentration according to the guidance provided in par. 3.4.4.2.2. Default correction factors for an assumed AMAD of 5µm (GSD 2.5) are 1.2 for inhalable samplers, and 1.4 for thoracic samplers.

3.5.2.4. Dose estimate

The aim of the first screening is to obtain a conservative but realistic assessment of workers exposures. Firstly, annual intakes must be estimated on the basis of the duration of the sampling relative to maximum annual exposures. After annual intakes having been assessed for each of the radionuclides from the ambient aerosol the main factor affecting the outcome is the choice of the dose coefficients. As has been explained in Appendix 2 of WP4 these depend strongly on the lung absorption Type of the aerosol particles. With thorium isotopes Th-230 and Th-232 as clear exceptions, the dose coefficients for the other nuclides of interest are the highest for lung absorption Type S(low). In the absence of information on the absorption of the particles in lung fluid the default absorption Type therefore should be assumed to be S for all other radionuclides. This is likely the correct and conservative choice for Ra bearing scales from the oil and gas industry, TiO_2 pigment production and phosphoric acid production. However, for materials with the decay chains of U-238 and Th-232 in secular equilibrium, such as heavy mineral sands, the choice of absorption class S appears not be conservative. The dose coefficients for Type F, AMAD 5 µm and GSD 2.5 for these materials are a factor of 2 to 3 higher than for Type S (see Table 15 of Appendix 2 of Annex 3). Having said that, it is clear that Type S is an appropriate assumption for materials such as insoluble mineral sands.

The use of inhalable samplers for aerosols of lung absorption Type Slow or Moderate, corrected for sampling efficiency assuming a default AMAD of 5 µm (GSD 2.5), will introduce a negative bias (underestimate) of up to about -40% in the resulting dose estimate (for a true AMAD of 1 µm, GSD 2.5) and a positive bias (overestimate) of up to 170% in the resulting dose estimate (for a true AMAD of 20 µm, GSD 2.5. For aerosols of Type Fast the inhalable sampling, corrected for sampling efficiency assuming a default AMAD of 5 µm (GSD 2.5), does not introduce a significant bias (less than 30%) in the dose estimate, irrespective of the true AMAD and GSD of the sampled aerosol.
Four examples of dose assessment, highlighting a number of the issues discussed above, are provided below.

Example 1: Workplace with Pb-210 aerosols from thermal processing of NORM materials

The Button inhalable sampler has a working flow rate of 4 l/min. After 6 hours of operation a volume of 1.44 m^3 of air has been sampled. The sampling efficiency correction factor is 1.2. Therefore if 1.7 Bq Pb-210 and 0.4 Bq Po-210 is collected on the filter the true ambient aerosol concentration (AMAD 5µm, GSD 2.5) is calculated at (1.7 * 1.2)/1.44 = 1.42 Bq/m^3 for Pb-210 and 0.33 Bq/m^3 for Po-210.

Conservatively it is assumed that the aerosol is of lung absorption S for both radionuclides (DC 4.3 10^{-6} and 2.7 10^{-6} Sv/Bq respectively). The annual intake of a worker 1600 hrs/a, breathing rate 1.2 m^3/h, is estimated 2.7 10^3 Bq Pb-210 and 6.4 10^2 Bq Po-210. The committed effective dose is calculated at 11.7 mSv from Pb-210 and 1.7 mSv from Po-210 (total 13.4 mSv). The positive bias (overestimate) possibly introduced by using an inhalable sampler for absorption Type Slow Pb-210/Po-210 aerosol is up to about a factor of two if the true AMAD is 20 µm rather thaa 5 µm, while the negative bias (underestimate) is below 30% if the true AMAD is 1 µm rather than 5 µm. If the aerosol particles may eventually be characterised by lung absorption class F the calculated dose decreases by a factor of about 3 because of the smaller DC and no positive bias is introduced

From this example it follows that the beta counting equipment must be capable of measuring an activity of about 50 mBq Pb-210 with acceptable uncertainty if annual exposures of the order of 300 µSv have to be assessed on the basis of 6 hours sampling durations.

The assumed activity on the filter of 1.7 Bq Pb-210 corresponds to 17 mg and 1.7 mg for Pb-210 dust with specific activities of 100 and 1000 Bq/g respectively. Gravimetric analysis of the dust load on the filters can easily be done but conversion to activity intake is unreliable if the specific activity of the dust may vary widely. If this is the case (NLCase1) and Po-210 may also be present in varying ratio's to Pb-210 there is no alternative to radiometric analysis. Both radionuclides can be measured with proportional counters set to discriminate between the beta particles from the Pb-210 daughter Bi-210 and the alpha particles from Po-210. A low-background counter will satisfy the requirement to measure the 50 mBq Pb-210 mentioned above with a coefficient of variation of less than 10% within 16 hours counting time.

Example 2: Exposure to dust from processing of heavy mineral sand

The Button inhalable sampler has a working flow rate of 4 l/min. After 6 hours of operation a volume of 1.44 m^3 of air has been sampled. The amount of dust on the filter is determined gravimetrically. The sampling efficiency correction factor is 1.2. Therefore if 1.2 mg zircon sand dust is collected on the filter the true ambient aerosol concentration (AMAD 5µm, GSD 2.5) is calculated at (1.2 * 1.2)/1.44 = 1.0 mg/m^3. The total intake during 1600 hrs/a is 1.9 g. At concentrations of 3.0 and 0.7 Bq/g of U-238sec and Th-232sec respectively in the zircon sand (UKCase1), this intake corresponds to 5.8 Bq U-238sec and 1.3 Bq Th-232sec. The committed effective dose from this annual intake can be calculated at 0.43 mSv for U-238sec and 0.081 mSv for Th-232sec and 0.44 mSv total on the basis of DC's of 6,5 10^{-5} and 4,9 10^{-5} Sv/Bq for U-238sec and Th-232sec respectively (class Slow assumed). The dose coefficient for U-238sec contains a contribution of Ra-226 based on a very low radon emanation rate of the aerosol particles. The positive bias (overestimate) possibly introduced by using an inhalable sampler for absorption Type Slow aerosol is up to a factor of 2.3 (e.g. if the true AMAD is 20 µm, rather than 5 µm) while the negative bias (underestimate) is below 30% if the true AMAD is 1 µm rather than 5 µm.

The amount of 1.2 mg zircon sand dust on the filter corresponds to about 4 mBq U-238sec and 0.8 mBq Th-232sec. These activities are too low in view of the attainable sensitivity of low-background gross alpha or beta counting (i.e. within a practicable counting time). Gravimetric analysis is the preferred method. The exposures will be significantly overestimated when the dust load on the filters is only partly related to zircon sand.

Example 3: Processing of natural uranium
Radiometric analysis of a PAS filter at a facility for processing natural uranium during a 7 hour shift of a worker provides a result of 0.1 Bq U-238 on the filter. A Button inhalable sampler with a working flow rate of 4 l/min was used. The total volume of air sampled is 1.7 m^3. The sampling efficiency correction factor is 1.2. Therefore, if 0.1 Bq U-238 was collected on the filter, the true U-238 ambient aerosol concentration (AMAD 5µm, GSD 2.5) is calculated at (0.1 * 1.2)/1.7 = 0.07 Bq/m^3. The same applies to U-234. The total annual intake during 46 weeks (46 * 35 hours, breathing rate 1.2 m^3/h) is estimated at 1.4 10^2 Bq for both U-238 and U-234. The dose coefficients for conservatively assumed solubility class Slow are 5.6 10^{-6} and 6.8 10^{-6} Sv/Bq for U-238 and U-234 respectively (total 1.2 10^{-5} Sv/Bq). The annual dose is estimated at 1.7 mSv. The positive bias (overestimate)possibly introduced by using an inhalable sampler for Type Slow U-aerosol is up to a factor of 2.3, while the negative bias is below 30% if the true AMAD is 1 µm rather than 5 µm.
At a specific activity of about 10 kBq/g U-238 of the uranium compound the activity of 0.1 Bq U-238 (100 mBq) on the filter corresponds to an amount as small as 10^{-5} gram. Gravimetric analysis is not an option. Radiometric analysis based on low-background proportional alpha counting can provide acceptable counting statistics for 10 mBq U-238 at counting times not exceeding 24 hours.

Example 4: Exposure to Th at TIG welding
By inhalable sampling with a Button sampler, a TIG welder using AC on WT20 electrodes was monitored during a shift of 8 hours. By neutron activation 1 mBq Th-232 was measured on the filter. Alpha spectrometry on the welding rod material revealed the presence of Th-230 at 20% of the Th-232 activity concentration and Th-228 at 50%. The total volume of air sampled was 1.92 m^3 and the true ambient concentration of Th-232 (AMAD 5µm, GSD 2.5) is (1*1.2)/1.92 = 0.63 mBq/m^3 for Th-232, 0.13 mBq/m^3 for Th-230 and 0.31 mBq/m^3 for Th-228. Annual intake on the basis of 800 hrs TIG welding can then be estimated at 0.60 Bq Th-232, 0.12 Bq Th-230 and 0.30 Bq Th-228. The solubility Type of the aerosol is conservatively assumed to be Fast. The dose coefficients for Th-232, Th-230 and Th-228 are 1.3 10^{-4}, 1.2 10^{-4} and 3.4 10^{-5} respectively. The annual dose is estimated at 0.10 mSv.
If Slow would be the correct absorption Type of the aerosol the estimated annual dose would decrease by a factor of about 7 to 0.016 mSv and the use of an inhalable sampler would possibly introduce a positive bias (overestimate) in the estimated dose of about a factor of 2.5 if the true AMAD is 20 µm rather than 5 µm, or a negative bias (underestimate) below 30% if the true AMAD is 1 µm rather than 5 µm. If the aerosol would be characterised by absorption Slow as well as a true AMAD of 1 µm (GSD 2.5) the calculated annual dose increases by a factor of about two to 0.027 mSv.
At an assumed specific activity of 60 Bq/g of Th-232 in the welding rods the activity of 1 mBq on the PAS filter corresponds to 0.02 mg and would not allow gravimetric analysis. Low-background gross alpha counting would not provide acceptable counting statistics even at counting times exceeding 24 hrs and would not reveal from what long-lived or short-lived radionuclides the alpha particles originate.

3.5.3. Recommended strategy for elimination from further consideration of workplaces that give rise to worker doses well below 1 mSv/yr

3.5.3.1. Choice of dose level of no further concern for internal exposure

Based on the first screening, a decision should be made about whether workers' exposures can be ignored for further radiological considerations. This will depend on individual national regulatory requirements. In many countries, exposed NORM workers are defined as potentially receiving an annual dose of more than 1 mSv from both internal and external exposure. It is proposed that exposures (i.e. as determined from the initial screening) whose upper confidence limits are above a few hundred µSv/a would require further evaluation and exposures below that level can be eliminated from further consideration. A dose level of 300 µSv/a has been chosen as appropriate in the application of the concept of exemption to natural sources (RP 122 Part II). This level of dose may also be used as an exemption level or ALARA threshold when evaluating the dose to workers arising from internal exposure in NORM industries.

3.5.3.2. Analysis of exposure data

A description of the detailed statistical analysis of the calculated exposures is considered beyond the scope of this report. A minimum of 25 samples from each group of workers is recommended. Even then, the statistical uncertainties are likely to be significant and where the results follow a typical log-normal distribution, the uncertainties associated with determining annual exposures are typically a factor of 2 to 3. Where the results show a wide variation, further sampling (and possibly a larger number of worker groups) should be considered.

The inherent variability of exposures is potentially one of the greatest source of uncertainty in the estimate of annual exposures. ***S***ampling statistics should be thus a major consideration when designing monitoring programmes. If anything, the case studies suggest that the reverse is true in practice. Consequently, it is recommended that further guidance is needed for users on the statistical nature and analysis of monitoring results.

3.5.4 Recommended strategy for optimisation of the exposure assessment

The first screening is based on assumptions regarding the choice of the absorption Type of the airborne dust, and the default AMAD and GSD chosen. A more detailed exposure assessment for those exposed to dose levels that are of radiological concern should remove any uncertainties from these assumptions as far as possible. The detailed exposure assessment may partly be based on recalculations of the dose estimates from the screening stage and partly on repeated monitoring of workers with exposure estimates exceeding the exemption level of dose.

3.5.4.1. Identification of airborne radioactive dust absorption Type

Table 13, based on the data provided in Appendix 2 in Annex 3, illustrates the varying dependence of the inhalation dose coefficients on lung absorption Type of the aerosol. It provides a strong case for assessing the true absorption Type of the ambient aerosol. Material-specific rates of absorption into blood should be used in the respiratory tract model for compounds for which reliable human or experimental data exist. For other compounds, like most if not all NORM materials, ICRP recommends default parameters according to "whether the absorption from the lungs to the blood is **considered** to be fast (Type F), moderate (M) or slow (S)". A correct assessment of the absorption Type of the ambient aerosol is therefore an important issue for all individual radionuclides and chain segments with strongly absorption Type dependent dose coefficients. Ideally one would like to experimentally determine the lung absorption Type of the actual ambient aerosol. This can, however, be a very time consuming and costly exercise requiring sensitive and sophisticated analytical techniques only available at a few specialised laboratories. Therefore it is recommended firstly that as much information on the likely absorption Type of the ambient aerosol should be drawn from the characteristics of the raw materials, products and residues known by the operator of the installations. In most NORM industries the materials involved are of low specific activity. This means that the bulk mass of these materials and their aerosol particles comprises non-radioactive elements and their compounds. These matrices determine the solubility of the particles. Consequently, the absorption Type chosen for the particles should be identical for all radionuclides contained in them. The latter situation applies to many raw materials in NORM industries as well as to raw materials and products in the heavy mineral sand industry. Non-radiometric analytical methods such as X-ray crystallography may help to characterise the matrix and to derive its likely solubility.

Heavy mineral sands and ores like rutiles are resistant to almost all forms of chemical attack and their dust particles are obviously of Type S. The same applies to the Ra bearing sulphate scales encountered in oil and gas production facilities, in the wet processing of phosphate rock, in both the sulphuric acid and chloride process of TiO_2 pigment production and in other chemical processes. The most likely absorption Types of uranium compounds encountered in processing natural uranium are Moderate for uranates and Slow for oxides(Case Study F1).

Table 13: Workers' inhalation dose coefficients for AMAD 5 µm and GSD 2.5 (Sv/Bq)

Nuclide, chain or chain segment	Fast	Moderate	Slow	Ratio S/F	Ratio S/M
U-238	5.9E-07	1.7E-06	5.7E-06	**9.8**	3.5
U-234	6.5E-07	2.1E-06	6.8E-06	**10**	3.2
	1.2E-04	2.8E-05	7.2E-06	**0.06**	0.26
Ra-226	4.4E-07	2.2E-06	6.9E-06	**16**	3.2
Ra-226 *)	4.4E-07	1.4E-05	3.8E-05	**87**	2.8
Pb-210	1.1E-06	7.4E-07	4.3E-06	**3.8**	5.7
Po-210	7.3E-07	2.2E-06	2.7E-06	**3.7**	1.25
U-238sec	1.2E-04	3.7E-05	3.4E-05	**0.28**	0.92
U-238sec *)	1.2E-04	4.8E-05	6.5E-05	**0.53**	1.36
Ra-226+	2.3E-06	5.1E-06	1.4E-05	**6.1**	2.7
Ra-226+ *)	2.3E-06	1.6E-05	4.5E-05	**20**	2.8
*) Low Rn emanation rate					
	Fast	Moderate	Slow	**Ratio S/F**	Ratio S/M
Th-232	1.3E-04	2.9E-05	1.2E-05	**0.09**	0.41
Ra-228	1.1E-06	1.7E-06	1.1E-05	**10**	6.7
Th-228	3.4E-05	2.2E-05	2.5E-05	**0.74**	1.14
Th-232sec*)	1.6E-04	5.3E-05	4.9E-05	**0.30**	0.92

*) Exclusive a contribution of $\leq$ 10% from Ra-224 in secular equilibrium with Th-228

In all other cases, experimental verification of the lung absorption Type of the ambient aerosol in terms of absorption Types F, M and S should be seriously considered in this stage if it cannot be derived otherwise. This can relatively easily be done for particles with a true absorption F within a one day experiment. This Type of absorption is characterised by a 100% absorption with a half-time of 10 minutes. Virtually complete dissolution in simulated body fluid can be expected in 24 hours. The analytical aspects of the experimental verification of Type F may still be complicated as individual radionuclides from a chain segment may, at least theoretically, have different solubility characteristics. Their rate of dissolution from their common matrix has to be confirmed by the analyses of all relevant radionuclides in the simulated lung fluid. It should also be born in mind that the analyses may take much more time than the 24 hours for the experiment. For example, if Pb-210 has to be measured by the sensitive radiochemical method, based on the ingrowth of Po-210, it will take several months before the results become available. These analytical aspect significantly add to the associated costs of even a rather simple experiment of short duration. However, proof or exclusion of Type F as the true absorption Type of the ambient aerosol can remove considerable uncertainty from the exposure assessment.

Type M absorption is characterised by 10% absorption with a half-time of 10 minutes and 90% with a half-time of 140 days and that of Type S by 0.1% absorption with a half-time of 10 minutes and 99.9% with a half-time of 700 days. Experimental discrimination between these two absorption Types requires the maintenance of the experimental conditions over periods of many months, repeated sampling from the simulated lung fluid and much higher sensitivity of the radionuclide analysis methods.

3.5.4.2. Particle size distribution

A detailed assessment of exposures should require in principle the determination of the actual particle size distribution of the ambient aerosol. However, as explained in par. 3.4.4.2.3 (WP4) the choice of an appropriate sampling convention and sampling efficiency correction factor is actually more important The use of these, together with a assumed default AMAD of 5 µm (GSD 2.5) will avoid excessive bias in the exposure assessment.

3.5.4.3. Choice of PAS

As explained in detail in WP4, PAS is the preferred sampling tool for evaluation of workers' exposures. To reduce potential bias in the exposure estimates, for aerosols of absorption Type Slow and Moderate the preferred sampling convention is thoracic, and for Type Fast it is inhalable. This again stresses the importance of the assessment of the true absorption Type of the ambient aerosol. The degree of bias in dose estimates caused by sampling with the "incorrect" sampling convention can be derived from the data provided in Appendix 3 in Annex 3. It should be noted that sampling according to the thoracic convention collects only a part of the inhalable aerosol. Consequently, the detection limit of the analytical method to be applied must still allow the somewhat smaller amount of material on the filter to be measured compared with inhalable sampling.
It is acknowledged that thoracic sampling equipment is less widely used, and that such samplers often rely on "sponges", rather than flat filters, which are not suitable, for example, for alpha counting. Therefore, in practice it may be necessary to use inhalable sampling for Types S and M but the remaining bias, when particle size distribution is not well known, will be higher than if a thoracic sampler would have been chosen. It should be stressed that not correcting for using an inhalable sampler for Type Slow aerosol may have a much smaller effect on the resulting estimated dose than the assumption of an incorrect absorption Type. For instance the bias in the dose estimate from intake of Ra-226 aerosol of Type Slow sampled with an inhalable sampler is about +130%. However, using the dose coefficient for Type Fast would underestimate the dose by a factor of 90 if the true absorption Type was Slow and the emanation rate of radon from the particles was also slow.

3.5.4.4. Sampling duration

Although prolonged sampling duration may be necessary in exceptional cases, shift sampling is to be preferred in for the same reasons as provided for the screening campaign (par. 3.5.2.2).

3.5.4.5. Optimised exposure assessment

The optimised exposure assessment in principle comprises four steps:

- recalculation of the exposure data obtained from the first screening on the basis of the additional information obtained on absorption Type, bias from sampling convention and, possibly, particle size distribution;
- identification of in homogeneity of worker group(s) with respect to exposure and regrouping of workers if needed;
- repeated shift monitoring of workers with PAS and appropriate sampling convention; and
- reassessing workers exposures.

3.5.5. Recommended strategy for optimisation of exposure control

3.5.5.1. No workers exposure exceeds exemption level

In this case one would conclude that there is no need for optimisation, although there is still a need for some monitoring to verify that exposure conditions and exposures are not changing significantly.
Notwithstanding the above conclusion, it should be expected that reasonable standards of industrial hygiene should be maintained in the workplace. These should continue to provide a degree of control on exposures, even though optimisation is not formally a requirement.

3.5.5.2. Workers exposure exceeds exemption level

In this case the next step is the identification of those workstations and tasks that contribute most to the dose (see section 3.5.6.). This level of exposure may pertain to only a small number of workers at a particular workplace.

3.5.6. Recommended strategy for identifying the most exposing workstations and tasks

3.5.6.1. Aim and strategy

At this stage the information obtained on workers exposure is based on results from PAS during shifts that may involve one or several tasks. In the latter case information is still lacking on what task contributes most to the exposure, and in both cases it is still unknown what worker's actions or workstation conditions dominate the exposure. Their identification is the aim of this part of the exposure assessment. As is explained in Chapter 5 of WP4 the recommended strategy is to go from exposure assessments of shifts down to workstations and workers actions at workstations. The aim is to determine the spatial and temporal distribution. For further details of this approach than given below the reader is referred to the Case Study F1.

3.5.6.2. PAS and SAS

Workstations within shifts

In principle, multiple PAS's each switched on by the worker only at a particular workstation will reveal what workstations dominate the exposure of the worker. Alternatively, the exposure at each particular workstation may be monitored with one PAS device during successive shifts. Either approach should provide sufficient observations to assess the variability of the exposure at the workstations per unit occupancy time. The ambient aerosol concentration at different workstations can also be monitored by employing static air samplers at each workstation. However, the air sampled by the SAS must be representative of the air from the breathing zone of the worker. When this is difficult, time consuming and/or expensive to prove, there is really no benefit in using SAS for this purpose.

Worker-induced exposure

Airborne activity may or may not be due to the worker's activity (tasks, actions) at the workstation. This question can be addressed by same approach using PAS's switched on only during the performance of these specific tasks at the workstation. As this is likely to imply rather short sampling durations the number of samples on the same PAS filter may need to be adapted to achieve the required measurement sensitivity.

3.5.6.3. PAS and RTDM

PAS may reveal high contributions to workers exposure from occupancy at specific workstations that appear not to be related to high dust levels generated at that workstation, whether or not by workers actions (Case Studies UK1 and UK2). In that case the dust source is apparently not related to the workstation and will not be revealed by additional PAS of workers at that workstation. Such conditions can easily and quickly be confirmed by RTDM during execution of specific tasks at the workstation. RTDM has also been proven to be valuable tool in identifying dust sources and patterns in particular for airborne dust of relatively low and intermediate specific activity. It allows large numbers of measurements within a period of a few days only and can be very effective in pinpointing yet unknown individual dust sources not likely to be detected even with an extensive PAS programme. However, RTDM does not replace PAS as the preferred basis for workstation or task- related dose assessments.

3.5.6.4. Input to exposure assessment

The results from workstation and task monitoring can provide a useful additional input to the assessment of the workers exposure. Annual exposures can be derived on the basis of known annual occupancies at workstations and annual frequencies of the performance of specific tasks. They help to validate the outcome of exposure assessments based on monitoring of shifts.

3.5.7. Countermeasures and their efficiency

3.5.7.1. Identification of sources of air borne dust

The monitoring at workstations and of tasks may have already provided some clues with respect to the sources of dust that give rise the exposure of the workers. When the process involves several steps taking place in the same large structure, it can be difficult to identify discreet sources of dust from monitoring using PAS. A dedicated search for these sources would involve the following approaches:

- visual surveys, including with a light source, may help in a simple way to identify sources of air borne dust of low-specific activity material. They will also reveal dust deposited on floors, ledges and other surfaces that may become air borne again;
- wipe tests will easily detect dust on surfaces, even invisible deposited dust of high specific activity;
- surveys with RTDM can quickly reveal whether specific process steps or specific equipment are a significant source of air borne dust; and
- multiple SAS can be used to look for spatial variation of the air borne dust concentration and can help to pinpoint the source. However, RTDM is a more effective tool for this purpose if the air borne dust is of low specific activity as is the case in most NORM industries.

3.5.7.2. Countermeasures

The countermeasures to be considered depend on the type of source of the airborne dust. Some examples given below are derived from the experience from the case studies.

- Drying of a wet filter cake on a belt dryer appeared unexpectedly to generate an uncontrollable source of fine dust and the operation of the dryer was abandoned (Case NL2).
- Resuspension of material spilled on floors and dried up can be prevented by frequent removal of spills with water (Case NL2).
- A “roadsweeper” used to clean floors appeared an efficient resuspender of dust into the air (Case UK1) and it was replaced with a more effective machine.
- Dust removal with vacuum cleaners may unintentionally be the cause of resuspension because of the cleaner being faulty. Repair or replacement was the appropriate countermeasure (Case UK1).
- Dust removal with vacuum cleaners may unintentionally be the cause of resuspension because of the air turbulence caused by the exhaust. The use of plug-in connections to a central exhaust system removes this source of resupension (Case NL1).
- Open conveyor-belts are recognised sources of spills (CaseNL1, CaseNL2), countermeasures far from easily being implemented, dust removal remained the only remedy.
- Material transport/transfer pipes may turn out to be leaky and need repair (Case UK1).
- Cooling and exhaust air from electric motors may bring dust in the air unless fitted with an air filter system (CaseUK1).
- At the sampling workstation, the task of “rebanding” was identified as being responsible for over 50% of the total exposure at that workstation. Results of measurements with PAS and SAS supported the decision to modify and confine the filling station (Case F1).
- Options to reduce exposures of workers in TIG welding with thoriated welding rods are the use of closed machinery for grinding the welding rods and replacement of thoriated welding rods by welding rods dopes with non-radioactive substitutes (Appendix TIG of Annex 1).
- In a number of situations described in the Case Studies the only practicable way to protect workers against exposure to high levels of air borne dust appears to be the use of respiratory protective equipment. Typical situations are maintenance work on inner surfaces of furnaces and vessels, localised and temporarily high dust levels due to loading, unloading, transfer and bagging of dry and fine-grained material.

3.5.7.3. Validation of effectiveness of countermeasures

The first step in the validation of the effectiveness of countermeasures uses the same methods as those that identified the sources of the exposure of the workers. RTDM can be used close to the source to

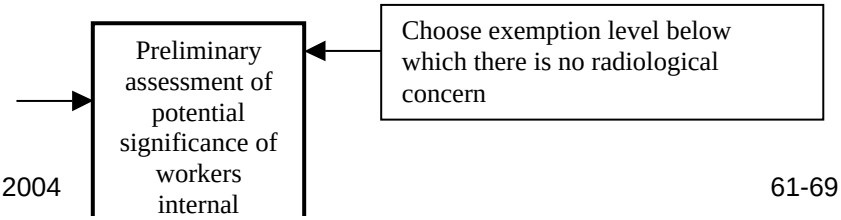
Information from non-radiological industrial hygiene (IH): dust levels from industrial processing of raw materials, products and residues

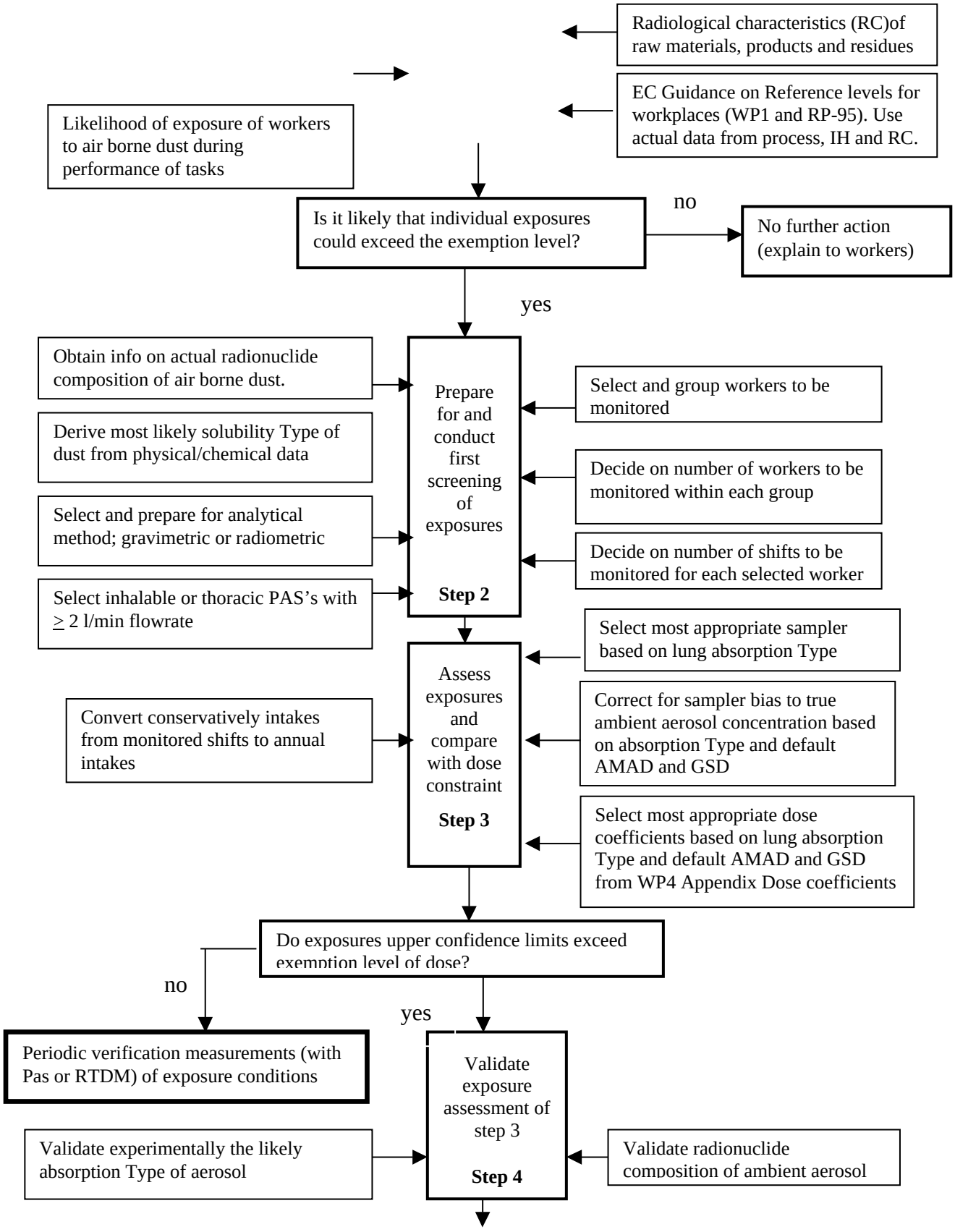
res have indeed resulted in reduction of air borne dust concentrations.
s processing material of low specific activity. If long-term average
available from a number of static air samplers throughout the
is can be repeated after the implementation of the countermeasures.
This may be the preferred first step for workplaces processing material with relatively high specific activity.
The second step would comprise a monitoring campaign of the workers using PAS and compare the results with the exposure data obtained prior to the implementation of countermeasures.

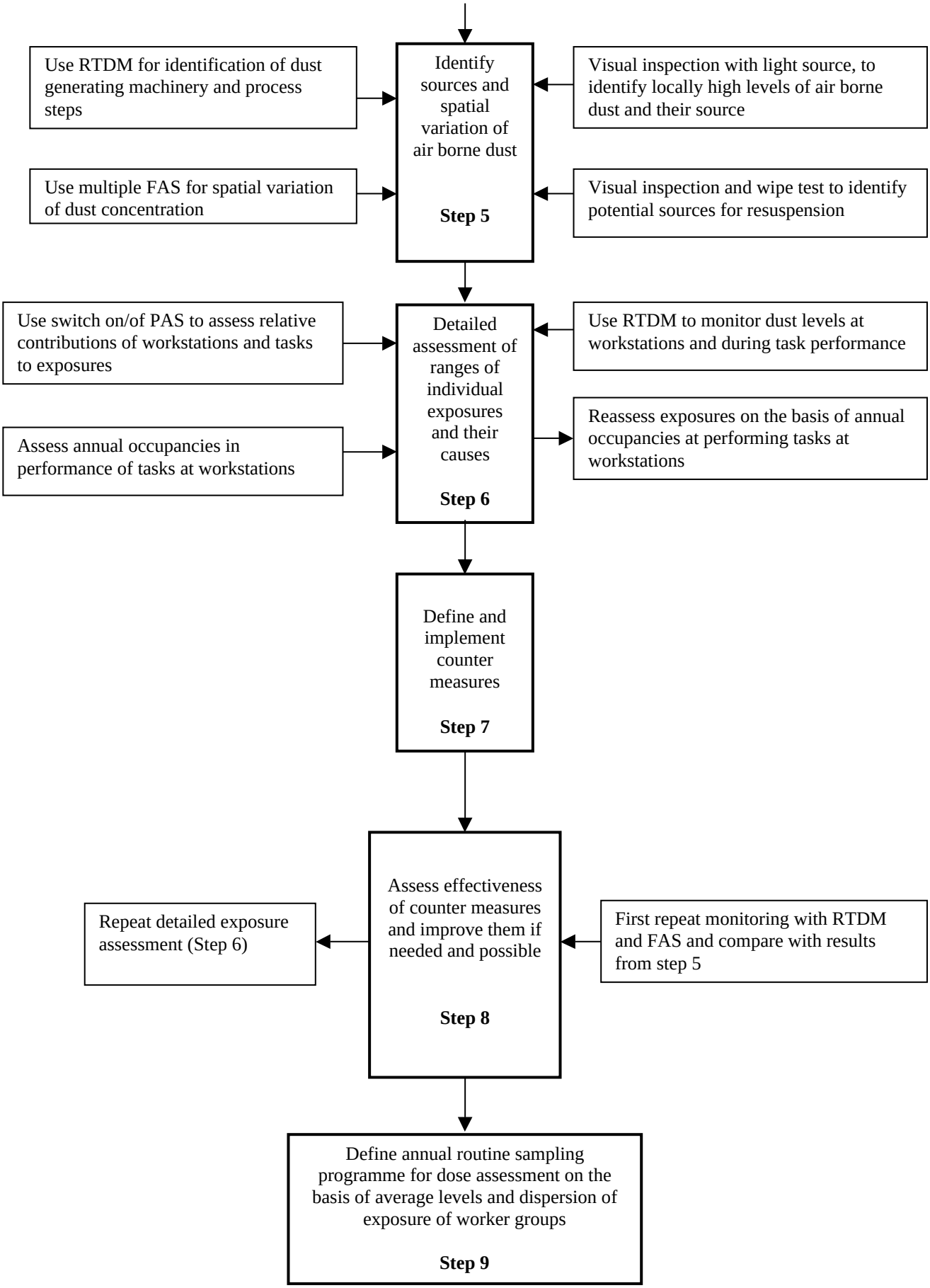
3.5.8 Conclusions and schematic summary

- The assessment of internal exposure of workers to industrial natural sources should be based on personal air sampling (PAS).
- Static air sampling (SAS) and Real Time Dust Monitoring (RTDM) can be useful to identify specific workstations and tasks likely to contribute most to the exposures, to identify specific sources of airborne dust and to assess the effectiveness of countermeasures against such sources. SAS and RTDM cannot replace PAS for dose assessment purposes.
- Usually there is no (detailed) information available on the particle size distribution of ambient aerosols from industrial natural sources.
- The dose coefficients for the natural radionuclides are AMAD-dependent when their absorption Type is Slow or Moderate.
- The preferred sampling convention for PAS is thoracic for aerosols with absorption Type S and M and inhalable for Type Fast.
- The exposure assessment should take care of the following:
  - Correction of the sampled activity to true ambient aerosol concentration with 5µm default AMAD (GSD 2.5) depending on the sampling convention.
  - Correction of the bias in the assessed dose if the preferred sampling convention (i.e. in relation to absorption Type) is not available.
  - Application of a dose coefficient based on the actual or most likely absorption Type of the aerosol.
- A large bias (positive or negative) can result when the DC applied is based on an assumed absorption Type that is different from the true absorption Type of the aerosol.
- The strategy for assessment of internal exposures of workers from industrial natural sources should comprise a graded (stepwise) approach that is schematically represented in the figure below.
- Further guidance for users is needed on the statistical nature and analysis of monitoring results.

Schematic presentation of the stepwise approach in the assessment and optimisation of internal exposures of workers from industrial natural sources




Radiological characteristics (RC)of raw materials, products and residues
EC Guidance on Reference levels for workplaces (WP1 and RP-95). Use actual data from process, IH and RC.
Likelihood of exposure of workers to air borne dust during performance of tasks
Is it likely that individual exposures could exceed the exemption level?
no
No further action (explain to workers)
yes
Obtain info on actual radionuclide composition of air borne dust.
Derive most likely solubility Type of dust from physical/chemical data
Select and prepare for analytical method; gravimetric or radiometric
Select inhalable or thoracic PAS's with ≥ 2 l/min flowrate
Prepare for and conduct first screening of exposures
Step 2
Select and group workers to be monitored
Decide on number of workers to be monitored within each group
Decide on number of shifts to be monitored for each selected worker
Select most appropriate sampler based on lung absorption Type
Convert conservatively intakes from monitored shifts to annual intakes
Assess exposures and compare with dose constraint
Step 3
Correct for sampler bias to true ambient aerosol concentration based on absorption Type and default AMAD and GSD
Select most appropriate dose coefficients based on lung absorption Type and default AMAD and GSD from WP4 Appendix Dose coefficients
Do exposures upper confidence limits exceed exemption level of dose?
no
yes
Periodic verification measurements (with Pas or RTDM) of exposure conditions
Validate exposure assessment of step 3
Step 4
Validate experimentally the likely absorption Type of aerosol
Validate radionuclide composition of ambient aerosol


Use RTDM for identification of dust generating machinery and process steps
Identify sources and spatial variation of air borne dust
Step 5
Visual inspection with light source, to identify locally high levels of air borne dust and their source
Use multiple FAS for spatial variation of dust concentration
Visual inspection and wipe test to identify potential sources for resuspension
Use switch on/of PAS to assess relative contributions of workstations and tasks to exposures
Detailed assessment of ranges of individual exposures and their causes
Step 6
Use RTDM to monitor dust levels at workstations and during task performance
Assess annual occupancies in performance of tasks at workstations
Reassess exposures on the basis of annual occupancies at performing tasks at workstations
Define and implement counter measures
Step 7
Assess effectiveness of counter measures and improve them if needed and possible
Step 8
Repeat detailed exposure assessment (Step 6)
First repeat monitoring with RTDM and FAS and compare with results from step 5
Define annual routine sampling programme for dose assessment on the basis of average levels and dispersion of exposure of worker groups
Step 9

4 Main Achievements

4.1. Achievements of Work Package 1

The review of the number of exposed workers in EU NORM industries and the magnitude of the associated internal doses has proven to be much more difficult than expected. Although some EU countries have identified NORM industries with the potential for significant occupational exposures, to comply with Title VII, Article 40, of Council Directive 96/29/EURATOM, information on the actual number of exposed workers and dose ranges is very scarce. Originally, when writing the Description of Work for the project (Annex 1 of the contract), the total number of workers potentially exposed to internal radiation doses in NORM industries in the EU was roughly estimated as 5,000 to 10,000 persons. Based on mainly German data, a rounded number of 85,000 persons has been estimated now, of which 70,000 are working with thoriated welding electrodes, either in their production, grinding or use. The second main industry, in terms of the number of exposed workers, seems to be the phosphate fertiliser trade with some 10,000 persons.

With regard to occupational doses, the data indicate a dose range of 6 - 20 mSv/y for persons grinding thoriated electrodes. This suggests that it is important to look in more detail at this group of workers, throughout the EU, in order to get a more reliable estimate of their real exposures. The small number of exposed workers in other industries seems to be reassuring, but one should keep in mind that the estimate is based on assumptions of the number of exposed workers per plant and multiplied by the number of plants in the EU, as far as knowledge is available. However, the availability of scientifically sound data is scarce. The detailed information of the deliverable for Work Package 1 is contained in Annex 1 of the accompanying report.

Ultimately, it has not been possible to reliably estimate the number of exposed workers in EU NORM industries, nor the magnitude of the associated internal doses, from currently available data. Only a rough indication could be given, but this concerns a group of workers with significant potential doses. In conclusion, the objectives of Work Package 1 could not be fully achieved, and it is considered that this will remain the case unless deliberate efforts are made to assess the relevant data. Much more data based on industry surveys and workplace measurements is required to provide an accurate position of the situation in EU NORM industries. It is recommended that any studies made in response to the implementation of Title VII of the Euratom Directive, both in the existing Member States and in the Accessing and Applicant Countries, should aim to include the number of workers and the *actual doses* received.

4.2. Achievements of the other Work Packages

The results of the other Work Packages can be considered as satisfying the objectives of the project. In particular, the co-operation with the industrial partners has been very successful. For all the case studies, the participating industries provided a large amount of specific information on radiation protection programs, the monitoring equipment used, and the monitoring data obtained. Although agreement was reached at the first progress meeting on the format of the required data, it took much more time to gather these data than expected. This is mainly due to the fact that the industries are very different with respect to the industrial processes, the working conditions, the exposure situations and the monitoring strategy. On one hand this was an advantage because it helped ensure that a broad range of exposure situations was considered. On the other hand, it took quite some time to develop the questionnaires for the industrial partners such that the responses could be used for a meaningful description of exposure situations. The detailed information of all the case studies (Work Package 2) is presented in Annex 2 of this report.

The information from Work Package 2 was used to make a categorisation of working conditions that give rise to internal exposure of workers (Work Package 3). It was shown in every case study that the

airborne activity concentrations are never uniform throughout the workplace. The local spatial variation of airborne activity concentrations depends very much on the characteristics of the considered workstation. Also, the airborne activity concentrations are never constant with time. The reasons for this variability are due, depending on the particular situations considered in each industry, to the process, to the worker's activity or to small incidents. Moreover, the jobs performed never involve a simple continuous presence at a single workstation and the sources of airborne contamination are always multiple.

The original characterisation criteria did not lead to a useful categorisation of the different exposure situations in the industrial cases. This, in itself is a conclusion worth noting, since the same monitoring strategy should be broadly applicable to different NORM industries and workplaces. In evaluating the case studies, other criteria for categorising exposure situations emerged, namely constancy of the airborne dust specific activity, constancy of the airborne dust radionuclides activity ratios (with aerodynamic diameter and/or with time), dose coefficients for the specific radionuclide compounds and airborne dust specific activity. The details of Work Package 3 are described in this report (section 3.3).

The aforementioned criteria have been used in an extensive evaluation of monitoring strategies, methods and tools (Work Package 4, section 3.4 in this report). One of the main achievements is that a scientific basis has been developed for applying air-sampling devices for radiation protection purposes, even though they have been designed originally for industrial hygiene purposes. The differences between industrial hygiene and radiation protection are that radiation protection focuses on the assessment of (committed) effective dose via application of respiratory tract and other biokinetic models, while monitoring in an industrial hygiene context focuses on sampling specific *inhaled* particle size distributions (e.g. inhalable, thoracic and respirable fractions). Samplers do not, and cannot, sample the *true ambient aerosol* required for radiation protection purposes. The objective of this Work Package was to provide a method for choosing the most appropriate type of currently available commercial air sampling equipment and minimising the bias between the true and estimated exposure in the results obtained from using this equipment. Work Package 4 also contains other intermediate deliverables of the project. They are provided as four Appendices brought together as Annex 3 to this report. Appendix 1 provides a review of air sampling tools (equipment and techniques) in terms of their applicability to radiation protection. Appendix 2 provides the calculated dose coefficients for natural radionuclides in the three lung absorption Types and different AMADs. For a number of radionuclide/absorption Type combinations such information was not available from ICRP Publications. The data provided show that the dose coefficients for NORM nuclides in a low-solubility matrix are clearly AMAD dependent. In addition, the results show (for a number of key NORM nuclides) a very strong dependence of the inhalation dose coefficient on lung absorption Type. This information is very pertinent to those involved in assessing internal exposures from industrial natural sources. Appendix 3 deals with the potential bias in dose estimates based on air sampling. This bias, positive or negative appears to depend on the chosen sampling convention and the true AMAD and lung absorption Type of the ambient aerosol. Finally, Appendix 4 deals with a review of the sensitivity of air sampling methods and shows that moderately sophisticated analytical tools are sufficient to attain the required analytical sensitivity for assessment of exposures well below 1 mSv/a.

In Work Package 5 a synthesis has been made of the results of the Work Packages 2, 3 and 4 by recommending strategies, methods and tools for monitoring internal exposures in various types of NORM industries. It provides practical information on how to perform a preliminary screening to assess the order of magnitude of occupational doses due to internal exposures. With this, one can discriminate between work situations that are of no concern and other situations that warrant a more detailed analysis. It also provides information on what is necessary for this detailed analysis and how to optimise the radiation protection of workers by countermeasures. Finally, it provides recommendations on how to assure the optimal radiation protection level by a periodical monitoring program. The details of Work Package 5 are described in this report (section 3.5).
In conclusion, one can consider the results of the project as satisfying the initial objectives with, in some cases, additional beneficial outputs being realised.

5. Discussion

5.1. Review of the number of exposed workers and magnitude of internal doses in EU NORM industries

The results of Work Package 1 have revealed that there still is a severe lack of information on the number of exposed workers in NORM industries and the associated occupational doses. The studies carried out so far, on a national level in response of the implementation of Title VII of the European BSS or ordered by the European Commission, do not provide the information for a scientifically sound evaluation of the problem. The number of 85,000 exposed workers, as derived in this report, warrants more research in this area.

There are some observations to be made with respect to this assessment.

- The available data were very scarce and originating from only a few of the EU Member States. This necessarily led to a very rough estimation of the total number of exposed workers in the EU.
- The greatest group of exposed workers (70,000) seems to be welders using thoriated welding electrodes. The data that do exist suggest that grinding of welding rods may give rise to doses between 6 and 20 mSv per year. Although there are tens of thousands of such workers in this area, dose assessment data is surprisingly scarce. Furthermore, there is some evidence that alternative (non-radioactive) welding rods are increasingly being used. This means that the number of exposed workers should decrease in the future. Again, however, precise details on this trend were not available
- The second largest group of exposed workers (10,000) are those trading or using phosphate fertilisers. Here also, the data are originating only from one country, i.e. Germany.
- The results indicate that, apart from grinding of thoriated welding rods, zircon milling may also give rise to doses between 6 and 20 mSv per year, in workplaces where protection measures are poor or non-existent. Rare earth processing may even give rise to doses above 20 mSv per year. In both industries, the number of exposed workers is small.
- Most of the industries give rise to doses below 6 mSv per year. With the exception of the industrial areas mentioned above, the number of exposed workers per type of industry is moderate to small. Given the rough and conservative dose assessments this is, to some extent, reassuring. However, from a radiation protection point of view these dose levels are still significant and justify a closer and more specific evaluation, certainly when one compares this with the attention paid to decrease the collective and individual doses due to exposure to artificial radionuclides.
- The information gathered from the Accessing and Applicant Countries is even less than that from the EU Member States. In fact, the only project where some information may become available from some of those countries is TENORMHARM. It should be noted that some of these countries have important mining industries, several of which have considerable problems with NORM. There is no information included in Work Package 1 about this type of industries.

In most cases, exposure of workers to natural radionuclides can be reduced considerably when operators and authorities are aware of the problems. The findings of this project show that there still is a basic lack of data. The guidance of the European Commission to the EU Member States about the implementation of Title VII of the Euratom BSS has not led to specific information, necessary to accurately assess the magnitude of the problems. It is recommended that the European Commission should promote and direct future research in this area.

5.2 Monitoring strategies, methods and tools

The co-operation with the industrial partners has contributed, to a large extent, to the success of the project. The companies were selected on the basis of the work that they have carried out in the past to

understand the radiological consequences of the presence of natural radionuclides in the processes, products, residues and wastes. They all belong to the major industries in their sector and, in fact, they were the only sources of information on numbers of exposed workers and doses associated with certain types of jobs. All the companies have a long record of radiation protection research. They provided a wealth of information and data, which has been used in the project in order to formulate practical and useful recommendations for monitoring strategies, both for themselves, for other operators and for authorities.

The results of the project provide a scientific and practical basis for monitoring programs, both for individual workers and for the workplace. The details of the work are presented in a separate accompanying report. The importance for radiation protection is illustrated by the fact that it describes the way to use sampling equipment that has intrinsically been designed for industrial hygiene instead of radiation protection purposes. This is by no means self-evident, since samplers cannot sample the true ambient aerosol required for radiation protection purposes. This has two notable effects, firstly in terms of assessing the activity concentration in air, and therefore the intake in Becquerels, and secondly in terms of assessing the effective dose. The results show that for specific situations a preferred sampling protocol should be used. It also provides correction factors, to be used to minimise the bias in the dose assessment, either because of unknown parameters or because of a non-ideal sampling procedure. Without such correction factors, significant errors can be made in the assessment of internal exposures.

In conclusion, the project has generated important information about practical radiation protection monitoring programs in NORM industries. It provides practical information how to assess the radiological consequences for the workforce in a first screening campaign, and how to get more information when the first screening warrants further research. By this approach, the most efficient use can be made of resources, without spending unnecessary time and money where this is not justified and by advising on the use of the right instrumentation for the job, in a way that produces the quality of results required to implement radiation protection controls.

The scientific basis for monitoring can also be relevant to manufacturers, for further development of sampling equipment, in order to make them more suitable for use in radiation protection in NORM industries.

6 Acknowledgements

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In particular, we wish to acknowledge the hospitality of Thermphos International, Johnson Matthey Zircon and COMURHEX for hosting the first three progress meetings at their facilities, in Flushing (11-12 March 2002), Newcastle (9-10 September 2002) and Narbonne (27-28 February 2003) respectively. This gave all the scientific partners a clear picture of the wide range of radiological problems and solutions associated with NORM in industry.

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Subsequent to the IRSN report, CEPN has expanded this work to cover all the main radionuclides of interest in the ^{238}U (i.e. ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po) and ^{232}Th (i.e. ^{232}Th, ^{228}Ra, ^{228}Th) decay chains, and all three lung absorption Types (F, M and S). The main calculations were performed by Alan Birchall and colleagues from the NRPB Inhalation Studies Group, using PLEIADES and IMBA software. Their assistance is kindly acknowledged.