Radiological assessment of NORM Industries in Ireland – Radiation doses to workers and members of the public
Radioactivity is measured in units called becquerels (Bq). One becquerel corresponds to one radioactive disintegration per second.

When measuring radioactive discharges to the environment or referring to the content of radioactive sources used in medicine, industry and education, it is more usual to talk in terms of kilobecquerels (kBq), megabecquerels (MBq), gigabecquerels (GBq) or terabecquerels (TBq)

\[
\begin{align*}
1 \text{ kBq} &= 1000 \text{ Bq} \\
1 \text{ MBq} &= 1,000,000 \text{ Bq} \\
1 \text{ GBq} &= 1,000,000,000 \text{ Bq} \\
1 \text{ TBq} &= 1,000,000,000,000 \text{ Bq}
\end{align*}
\]

Much lower concentrations of radioactivity are normally found in the environment and so the measurement is often reported in units of millibecquerels (mBq). There are one thousand millibecquerels in a becquerel.

\[
1 \text{ Bq} = 1000 \text{ mBq}
\]

Radiation Dose

When radiation interacts with body tissues and organs, the radiation dose received is a function of factors such as the type of radiation, the part of the body affected, the exposure pathway, etc. This means that one becquerel of radioactivity will not always deliver the same radiation dose. A unit called ‘effective dose’ has been developed to take account of the differences between different types of radiation so that their biological impact can be compared directly. Effective dose is measured in units called sieverts (Sv).

The sievert is a large unit, and in practice it is more usual to measure radiation doses received by individuals in terms of fractions of a sievert.

\[
\begin{align*}
1 \text{ sievert} &= 1000 \text{ millisievert (mSv)} \\
&= 1,000,000 \text{ microsievert (µSv)} \\
&= 1,000,000,000 \text{ nanosievert (nSv)}
\end{align*}
\]

In RPII reports the term ‘effective dose’ is often referred to as ‘radiation dose’ or simply ‘dose’.

Collective dose is the sum of the radiation doses received by each individual in the population. This allows comparison of the total radiation dose received from different sources. Collective dose is reported in units of man sieverts (man Sv) or man millisieverts (man mSv).

Per caput dose is the collective dose divided by the total population. Per caput dose is reported in units of sieverts, or fractions of a sievert.
Radiological assessment of NORM Industries in Ireland – Radiation doses to workers and members of the public

Catherine Organo and David Fenton

December 2008
Contents

List of Figures................................................................................................................................. 2
List of Tables................................................................................................................................. 2
List of Illustrations......................................................................................................................... 3

1 Executive Summary ................................................................................................................. 4
2 Introduction ............................................................................................................................. 6
3 European and Irish Legislative Frameworks ........................................................................... 7
4 European and International Guidance on NORM ................................................................. 9
  4.1 Identifying industries with potential NORM radiological issues ........................................... 9
  4.2 Regulating: when and what? ............................................................................................... 9
  4.3 Industries with potential NORM issues ............................................................................. 11
5 Radiological Issues in NORM Industries .............................................................................. 12
  5.1 Radionuclides of interest .................................................................................................... 12
  5.2 Exposure pathways ............................................................................................................ 12
  5.3 Assessment Methodology ................................................................................................. 13
6 Industry-Specific Radiological Assessments .......................................................................... 15
  6.1 Peat-fired electricity production ......................................................................................... 15
  6.2 Coal-fired electricity production ......................................................................................... 19
  6.3 Natural gas extraction ........................................................................................................ 26
  6.4 Bauxite refining ................................................................................................................ 30
7 Conclusions ............................................................................................................................. 36
8 Acknowledgements ................................................................................................................. 38
9 References ............................................................................................................................... 39
10 Glossary of Terms ................................................................................................................. 45
Appendix A................................................................................................................................... 46
List of Figures

Figure 1  Uranium 238 decay series. .................................................................59
Figure 2  Thorium 232 decay series.................................................................59
Figure 3  Diagram of the studied peat-fired power plant with schematic
locations of the measurements and samples. ..............................................60
Figure 4  Coal combustion cycle at the studied coal-fired power plant........61
Figure 5  Radon levels measured in the Irish natural gas. ..............................62

List of Tables

Table 1  Comparison of exclusion / exemption levels (Bq/kg) recommended
by the EC and the IAEA for use in NORM industries..............................48
Table 2  Specific activity concentrations of radionuclides from the U-238 and
Th-232 series, K-40 and Cs-137 measured in peat, peat ash and
ash pond effluent samples by gamma spectrometry...............................49
Table 3  Activity concentrations (Bq/kg) of radionuclides in other NORM
materials and in Irish soils. ........................................................................50
Table 4  Maximum (with no respiratory protective equipment) effective dose
from inhalation of airborne peat dust (total fraction) in the bunker
area..............................................................................................................51
Table 5  Summary of the occupational radiation doses calculated at the
studied peat-fired power plant.................................................................52
Table 6  Activity concentrations (Bq/kg dry weight) of radionuclides measured
in samples collected at the studied coal-fired power plant.......................53
Table 7  Activity concentrations (Bq/kg) of radionuclides in coal and PFA as
found in the literature................................................................................54
Table 8  Annual effective dose from inhalation of radionuclides emitted by
the stack of the studied power plant........................................................55
Table 9  Radon concentrations in the Irish natural gas extracted from the
studied gas field - Grab sampling technique. ...........................................55
Table 10  Radon concentrations in the Irish natural gas extracted from the
studied gas field – 3-month continuous measurements...........................56
Table 11  Radon concentrations in the Irish natural gas extracted from the studied gas field – 8-month continuous measurements. ...............................56
Table 12  Radionuclide activity concentrations (Bq/kg dry weight, unless specified) in the two sludge samples collected on the offshore platform (gas extraction industry). .................................................................56
Table 13  Radionuclide activity concentrations (Bq/kg dry weight) in samples collected in the bauxite refinery and comparison with other published data. ..................................................................................57
Table 14  Range of doses to workers and members of the public from each of the four industries reviewed in this report. ..............................................................................58

List of Illustrations

Photo 1.  Coal yard where the coal is stacked prior to being burnt ................19
Photo 2.  Coal ash landfill and plant in the background ................................20
Photo 3.  One of the 16 burners inside one of the furnace where boiler residues were collected .................................................................22
Photo 4.  Discharge point of the effluent .....................................................22
Photo 5.  Setup used to monitor the radon concentrations in the gas stream. ....28
Photo 6.  One of the 2 separators where the sludge sample was collected ........29
Photo 7.  Sludge sample .............................................................................29
Photo 8.  A digester with a skip in front of it containing residues removed after maintenance .................................................................32
Photo 9.  Overview of the bauxite residue disposal area (BRDA) with plant in the background ........................................................................33
1 Executive Summary

Natural resources that are extracted from the ground such as coal, oil, natural gas and other mineral ores contain various amounts of natural radioactivity. When these resources are extracted and processed, their natural state can be modified which may result in the enhancement of the natural radioactivity content originally present. Such enhancements may be observed in the residues or the waste created and/or in the products or by-products and are sometimes high enough to pose a risk to both humans and the environment if they are not controlled properly. Materials of this kind are commonly referred to as Naturally Occurring Radioactive Materials or NORM.

Up to 1996, international regulatory attention dealing with exposure to natural sources of radiation focused mostly on exposures arising from the mining and processing of uranium ores because such activities need to be controlled as part of the nuclear fuel cycle. More recently, the attention of the international radiation protection community has been broadened to include industries dealing with NORM. The most recent revision of the European Basic Safety Standards (BSS) Directive took place in 1996 and includes special provisions concerning exposure to natural sources of ionising radiation.

The implementation of the 1996 European Directive resulted in significant legal changes in Ireland. Previously the national radiation protection regulations did not cover work activities involving exposure to natural sources. This changed on 13th May 2000 and according to current Irish regulations, work activities involving exposure to natural sources of radiation such as NORM are amenable to control if they are liable to give rise to an effective dose to workers or members of the public in excess of 1 mSv above background in any 12-month period.

To assist Member States in the implementation of the 1996 European Directive with regards to the provisions dealing with natural sources of radiation, recommendations on how to target only those industries with potential NORM issues were first published by the European Commission in 1997 and were followed by more specific guidance documents covering particular aspects to NORM: building materials, remediation of contaminated sites, NORM effluents and discharges, waste types produced by industries dealing with special metal and ceramics and NORM waste management and treatment options. Countries located outside Europe may follow and/or implement the International Atomic Energy Agency (IAEA) Safety Standards requirements. As far as the identification of work activities involving NORM is concerned, the IAEA has equally produced a number of important and very helpful documents in the recent years, complementary to those published by the EC which capture the essential aspects of the approach advocated by the IAEA to identify NORM industries.

Four large industries operating in Ireland and dealing with NORM were prioritised and investigated to determine the level of radiation to which workers and members of the public were exposed as a result of their work practices: the peat-fired power production, the coal-fired power production, the extraction of natural gas and the bauxite refining for the production of alumina.

In each case, a thorough examination of the industrial process has been carried out to identify the potential radiation exposure situations arising from the occurrence of NORM
at different stages of the respective process. At the core of our assessment methodology, the following aspects were targeted:

- the potential for enhancement of radionuclide concentrations above their natural levels in products, by-products, residues and waste;
- their availability to be released into the biosphere, due to physicochemical changes during processing or due to the method used to manage the residues and the waste produced.

Occupational radiation doses were estimated based on field measurements and analysis of samples collected onsite. For particular scenarios, exposure of members of the public were also considered: exposure to building materials containing peat and coal ash used by the construction industry, exposure to effluents discharged in the atmosphere (coal) and in rivers (peat, coal, bauxite) as well as exposure to radon for domestic gas users. Results were compared to national and international radiation protection standards to determine if any of these four industries needed to be controlled from a radiological point of view.

None of the four industries reviewed was found liable to give rise to an effective dose to workers or members of the public in excess of 1 mSv above background in any 12-month period. As such they do not come under the scope of the Irish regulations, as far as ionising radiation is concerned. Compared to the situation in other countries, this is a very positive outcome which will need to be reviewed in the future and particular areas have already been identified for this purpose.
2 Introduction

Radioactivity of natural origin is present everywhere, in the ground we walk on, in the air we breathe and in the water we drink. As a result, exposure to natural sources of radiation is responsible for about 90 per cent of the total radiation dose received by Irish people every year [Colgan et al., 2008]. Although the level of activity varies considerably with the type of environment and the location, exposures to natural sources of radiation are, with the exception of radon, normally not amenable to control.

Natural resources extracted from the ground such as coal, oil, natural gas and other mineral ores also contain various amounts of natural radioactivity. When these resources are extracted and processed, their natural state can be modified which may result in the enhancement of the natural radioactivity content originally present in the material. Such enhancements may be observed in the residues or in the waste created by the process, in the products or in the by-products and can sometimes be high enough to pose a risk to both humans and the environment if they are not controlled properly. Materials of this kind are commonly referred to as Naturally Occurring Radioactive Materials or NORM.

The International Atomic Energy Agency (IAEA) defines NORM as a “radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides” and includes “materials in which the activity concentrations of the naturally occurring radionuclides have been changed by a process” [IAEA, 2007]. Additionally, a NORM residue is defined as a “material that remains from a process and comprises or is contaminated by NORM”. A NORM residue may or may not be considered as a waste depending if it is reused and/or recycled.

Investigations of four large industries operating in Ireland have been carried out to assess the extent of exposures of workers directly involved in dealing with NORM as well as members of the public. In each case, the objective was to determine if any of these work activities needed to be regulated as specified in Irish law [Ireland, 2000] as explained in the third chapter of this report. The identification process of those NORM industries where radiological issues might be present is dealt with in chapters four and five and chapter six contains industry-specific assessments. In each case, a review of the industrial process and potential radiation exposures arising from the occurrence of NORM at different stages of the process is given. Dose calculations were carried out based on field measurements and analysis of samples collected onsite. For particular scenarios, exposures of members of the public were also assessed. The doses received as a result of the work activities carried out by each industry were compared with the national and international standards of radiation protection for workers and members of the public and are summarised in the final chapter.
3 European and Irish Legislative Frameworks

In Europe, radiation protection standards to control exposures to all sources of radiation are revised approximately every ten to fifteen years. Up to 1996, international regulatory attention dealing with exposure to natural sources of radiation has been focused mostly on exposures arising from the mining and processing of uranium ores because such activities need to be controlled as part of the nuclear fuel cycle. More recently, the attention of the international radiation protection community has been broadened to include industries dealing with NORM, in recognition of their potential to also give rise to significant exposures to workers and members of the public, thereby implying that they could also be regarded as amenable to control. Some examples of specific situations requiring such attention might include [IAEA, 2003]:

- Cases where industries are producing such a large amount of waste that it becomes unsustainable over time;
- Cases where hazards from natural radionuclides having a long life are increased by their high radiotoxicity;
- Cases where there is a higher likelihood for members of the public to be exposed to NORM wastes and products.

The most recent revision of the European Basic Safety Standards (BSS) Directive took place in 1996 [European Commission, 1996] and includes special provisions concerning exposure to natural sources of ionising radiation. It sets down a framework for controlling work activities where the presence of natural radiation sources could lead to a significant increase in exposure to workers or members of the public which cannot be disregarded from the radiation protection point of view.

The implementation of the 1996 Council Directive resulted in significant legal changes in Ireland. Previously the national radiation protection regulations did not cover work activities involving exposure to natural sources. This changed on 13\textsuperscript{th} May 2000 with the enactment of S.I. 125 of 2000 [Ireland, 2000] which sets out national radiation protection regulations of both practices and other work activities\(^1\) where the presence of natural radioactivity leads to the risk of a significant increase in exposure to workers or members of the public.

From a practical point of view, Article 32 (1) of S.I. 125 of 2000 provides for the regulation of work activities where the presence of natural sources of radiation is liable to give rise to an effective dose to workers or members of the public in excess of 1 mSv above background in any 12-month period. This dose limit is exclusive of radon gas

\(^1\) A practice is defined as a human activity that can increase the exposure of individuals to radiation from an artificial source or from a natural radiation source where natural radionuclides are processed for their radioactive, fissile or fertile properties, except in the case of an emergency exposure [European Commission, 1996; IAEA, 1996a (para. 2.1); Ireland, 2000]. A corollary of this is that a work activity can be defined as a human activity that can increase the exposure of individuals to radiation from a natural radiation source but where natural radionuclides are not processed for their radioactive, fissile or fertile properties.
which is treated separately and for which S.I. 125 of 2000 sets a national Reference Level of 400 Bq/m$^3$ in the working environment.

The responsibility for identifying activities and working conditions where it is appropriate to regard doses from natural sources of radiation as amenable to control lies with the regulatory authority responsible for the implementation of the 1996 Council Directive in each Member State. As the national regulatory authority, the Radiological Protection Institute of Ireland (RPII) is the competent authority for S.I. 125 of 2000 and for identifying those work activities which, according to European and international guidance, are liable to result in an increased exposure to natural radiation sources and for investigating the extent of this exposure.
4 European and International Guidance on NORM

4.1 Identifying industries with potential NORM radiological issues

To assist Member States in the implementation of the 1996 Council Directive with regards to the provisions dealing with natural sources of radiation, recommendations on how to target only those industries with potential NORM issues were first published by the European Commission in 1997 [European Commission, 1997]. National inventory of NORM activities through site surveys are advocated to identify the circumstances in which the use and storage of materials, not generally regarded as radioactive, could nevertheless give rise to significant doses depending on the activity concentration of the material involved but also on any chemical or physical processing which may increase the availability of the material.

Other documents have been published by the European Commission (EC) covering some more specific aspects to NORM such as building materials [European Commission, 1999a], remediation of sites contaminated by past or old practices or work activities [European Commission, 1999b and 2001b], NORM effluents and discharges [European Commission, 2003], waste types produced by industries dealing with special metal and ceramics [Harvey et al., 1994] and NORM waste management and treatment options [Scholten, 1996 and Wiegers et al., 2000].

Countries located outside Europe may follow and/or implement the IAEA Safety Standards requirements. As far as the identification of work activities involving NORM is concerned, the IAEA has produced a number of important and helpful documents in the recent years, complementary to those published by the EC. The most recent of these, Safety Reports Series No. 49 [IAEA, 2006] captures the essential aspects of the approach advocated by the IAEA to identify NORM industries.

4.2 Regulating: when and what?

Once the NORM industries to be investigated have been identified, the next step is to determine if there is a need to regulate or not. This requires an investigation to determine if any worker or member of the public is liable to receive an annual effective dose from natural sources of radiation arising from the operation of this industry in excess of the statutory dose limit of 1 mSv [Ireland, 2000].

Undertaking a complete dose assessment which takes into account all the exposure pathways and scenarios requires some form of modelling based on reasonable assumptions. As far as possible these assumptions need to represent the real situation to avoid false estimations of the dose received and more importantly to avoid taking the wrong decision with regards to regulating or not [Wymer, 2007].

To simplify the dose assessment process, the EC has produced a simple set of reference values which can specifically be used to determine the extent of the dose received by workers dealing with NORM [European Commission, 1999c and d]. Based on generic scenarios and very conservative assumptions, these documents offer a simple technique...
for screening and categorising the relevant NORM industries by relating radiation dose
criteria to measurable reference levels in terms of activity concentrations of the feed
material or of enhanced activity concentrations in materials at different stages of the
industrial process. Additionally, together with Hofmann et al. [2000] and Martin et al.
[1997] these publications identify relevant pathways, typical exposure situations and
include a comprehensive review of NORM industries within the European Union, taking
into account their potential radiological hazards, their scale and their economic
significance.

Generic exemption levels for practices are included in Schedule 5 of S.I. 125 of 2000
and are based on the concept of triviality of risk of exposure, as defined in the Basic
Safety Standards of the IAEA [IAEA, 1996a], which is associated with a dose of 10 µSv in
a year and a collective dose criterion of approximately 1 manSv/y. While they are
applicable for practices dealing with artificial radionuclides or with natural radionuclides
when these are processed in view of their radioactive fissile or fertile properties, they are
not applicable to work activities dealing with bulk or large quantities of natural
radionuclides as it is the case for NORM industries. Indeed, if one excludes radon gas,
the range of doses resulting from terrestrial natural radiation lies between a few hundred
µSv/y to a few mSv/y. Therefore, applying dose criteria of 10 µSv/y and 1 manSv/y for
exposure to natural sources of radiation could bring large areas of the world under
regulatory control and it would not be practicable to implement a control scheme for
such a small increment to the natural radiation background, which is, in fact, below the
natural variability.

An attempt was made by the EC to provide for exemption/clearance levels (Table 1)
calculated in terms of activity concentrations specifically applicable to natural sources of
radiation [European Commission, 2001a]. Contrary to the exemption levels for practices,
scenarios involving large quantities of materials were used and for each scenario one or
more pathways were included.

The IAEA advocates applying the same radiation protection standards for artificial and
natural radionuclides but with the view that they should relate to the optimisation
principle [ICRP, 1991] rather than to the concept of trivial dose used for regulating
practices [Wymer, 2007 and IAEA, 1996a, para. 2.8]. As a starting point for exemption, it
suggests using the activity concentration specified in the Standards [IAEA, 2004] below
which it is usually unnecessary to regulate irrespective of the quantity of material and
whether it is in its natural state or has been subject to some form of processing (Table 1).
For those industries dealing with materials that are exceeding the suggested exemption
values, the same procedure as outlined in Radiation Protection 107 [European
Commission, 1999d] is then used by the IAEA [IAEA, 2006] to calculate the doses arising
from exposure to various types of material with different activity concentrations (mSv/y
per Bq/g). These calculations are based on the same range of exposure situations as
Radiation Protection 107 but more realistic assumptions are made. For example, radon
exposure is excluded from the dose calculations on the basis that radon concentrations
in large scale industries such as NORM industries are usually below the legal
action/reference level due to the existence of good ventilation standards [Wymer, 2007].
4.3 Industries with potential NORM issues

Lists of specific industries where NORM may be a problem have been published by the EC and the IAEA. Classified roughly in descending order of priority, the following industrial sectors would require attention [IAEA, 2006]:

- Extraction of rare earth elements
- Production and use of thorium and its compounds
- Production of niobium and ferro-niobium
- Mining of ores other than uranium ore
- Production of oil and gas
- Manufacture of titanium dioxide pigments
- Phosphate industry
- Zircon and zirconia (zirconium oxide) industries
- Production of tin, copper, aluminium, zinc, lead, and iron and steel (smelters)
- Combustion of coal
- Water treatment

In terms of industrial processes, these industries usually fall in one of the following categories [IAEA, 2006]:

- Mining and comminution\(^2\) of ore
- Physical mineral separation processes
- Wet chemical extraction processes
- Thermal processes for extraction, processing and combustion of minerals
- Residue management

Additionally and based on information gathered in the literature, the types of materials handled and/or produced by NORM industries which might have to be considered from a radiological point of view are:

- Feedstocks (raw material)
- Bulk residues
- Slags
- Scales, sludges and sediments
- Precipitator dust
- Intermediate products
- Products

Only some of the above mentioned industries are currently operating in Ireland and taking into account their size as well as their economical significance, it was decided to prioritise our investigations on the following industries:

- Peat-fired power production
- Coal-fired power production
- Natural gas extraction
- Bauxite refining (first step in aluminium production)

---

\(^2\) Comminution is the breaking or grinding up of a material to form smaller particles.
5 Radiological Issues in NORM Industries

5.1 Radionuclides of interest

The naturally occurring radioactive elements of interest as far as NORM are concerned belong to the two natural decay series of U-238 and Th-232 (Figure 1 and 2). The third natural decay series led by U-235 is usually not considered in radiological assessments for NORM because it is less abundant than U-238.

When they are left undisturbed for a sufficient amount of time, the daughter radionuclides in each of the chains reach an equilibrium state with the parent such that the activity concentration of each member of the decay series is the same. This state is called secular equilibrium. Disturbances to this equilibrium can arise naturally but also through human activities such as those taking place in NORM industrial processes and they are due to the different physical and chemical properties of the element to which individual decay products are related to. It is these disturbances that are responsible for the radioactivity enhancement or depletion observed in NORM industrial processes. For example, Ra-226 in the U-238 decay series is soluble in water and chemically very different from uranium. By emitting alpha particles, it produces radon (Rn-222), an inert gas that does not react chemically but can escape via gaseous pathways. Lead (Pb) and polonium (Po) which are produced further down the U-238 chain are highly volatile and this is the reason why Pb-210 and Po-210 activity concentrations can be enhanced in compounds which are volatile at high temperatures, making it possible for them to escape by airborne routes. They can also subsequently be adsorbed onto respirable aerosols, thus depositing and contaminating local surfaces as well as lungs.

5.2 Exposure pathways

Individuals are exposed to radiation in different ways and these are commonly referred to as exposure pathways. Relevant exposure pathways to be taken into account in NORM studies are the following:

- External exposure to gamma radiation
- Internal exposure through dust inhalation
- Internal exposure through ingestion
- Skin contamination (from material deposited directly on the skin).

Occupational exposures occur when workers come into close and prolonged contact with NORM materials or inhale dust generated during the process. This can occur when the industrial process itself takes place but also during maintenance operations. Based on studies carried out in a range of industries, the most common routes of exposure from the processes involving naturally occurring radionuclides tend to be external gamma radiation, for example from large quantities or piles of stored material or from residues deposited inside process equipment, and inhalation of dust [IAEA, 2005].
Inhalation of re-suspended radioactivity can occur when someone breathes dust-loaded air with NORM-containing particles that have been re-suspended into the air, for example when the material is transported, broken up or dumped at a landfill. Inhalation doses are estimated on the basis of dust concentrations, breathing rates and radionuclides’ concentrations in the fine dust fraction. Dose calculations related to inhalation of furnace fume and precipitator dust usually only take into account Pb-210 and Po-210 because of their volatile properties [Döring et al., 2005, European Commission, 2003].

It is unlikely for NORM residues and waste to be ingested in a direct way, although dust deposited on the skin can always be inadvertently ingested by workers or members of the public. However, general health and safety legislation and good practice requires that when an industrial process has the potential to produce airborne dust, workers are required to wear personal protective equipment (overcoat, gloves and sometimes masks) to prevent or reduce the risk of contamination through this pathway.

Skin contamination is usually not considered to be relevant in dose assessments related to NORM because they are low specific activity materials.

Exposures of the public may arise from the product(s) of a process, from the atmospheric or liquid discharges, from the re-use of by-product material(s) such as fly ash incorporated into cement and concrete, or from the disposal of solid waste(s). The most important routes of radiation exposure of the public are usually external gamma radiation, inhalation and ingestion [European Commission, 2001a].

The regulation of radon gas in the occupational environment is a separate issue to NORM even though it is also a natural source of radiation. Radon is dealt with in S.I. 125 of 2000 [Ireland, 2000] in a specific manner and accordingly is not included in the estimation of the total effective dose to be compared with the legal dose limit of 1 mSv/y. For this reason, doses from exposure to radon in air are not presented in this report.

5.3 Assessment Methodology

The two important aspects of the potential impact of NORM on human health and the environment are:

- The enhancement of the radionuclides’ concentrations above their natural levels in the products, by-products or residues produced
- The enhancement of their availability for release into the biosphere through physicochemical changes or due to the method by which the wastes or residues are managed

Generally, radionuclide activity concentrations observed in natural mineral and raw materials are moderately or non-elevated compared to background levels encountered in all types of rocks or soils. Therefore, the need for regulatory attention is likely to arise more from the mobilisation of radionuclides during the extraction or processing of the raw material, especially if concentrations are increased or if exposure pathways to humans are modified [IAEA, 2006]. Industries affected by the presence of NORM differ
considerably with respect to the type of process, the type of material which is processed, the workplace conditions and the radionuclides involved. These aspects need to be taken into account when evaluating the potential degree of exposure as they can all influence the availability of the material.

When carrying out dose assessments, it is necessary to cover all the exposure situations for all those individuals potentially exposed. Exposure scenarios are designed to link the radioactivity contents in various types of materials with the potential dose(s) received. The scenarios should take account of the various receptors (workers and members of the public) and habits, of the characteristics and types of materials, how they are handled, stored and disposed of. All the various pathways through which a dose can be delivered should also be included.

When the objective is to determine the likelihood of the annual effective dose limit of 1 mSv being exceeded, carrying out an in-depth and fully comprehensive dose assessment is neither justified nor necessary. For each NORM investigation the following steps were completed:

- Review of the available literature dealing with the specific industry to get a general overview of the potential issues;
- Contact the operator and organise meeting(s);
- Agree on a methodology describing the objective(s) of the study and how this will be achieved;
- Collect more accurate and technical information on the process, number of workers involved in specific activities, characteristics of these activities (occupancy, duration, use of personal protective equipment PPE etc.);
- Whenever it is possible, organise the collection of representative samples and carry out onsite measurements;
- Analyse the collected samples in the laboratory;
- Carry out the dose calculations and analyse the results i.e. compare with the legal requirements (1 mSv/y dose limit and/or international recommended exemption values);
- Conclusions and recommendations.
6 Industry-Specific Radiological Assessments

6.1 Peat-fired electricity production

Since 2000, peat-fired electricity production in Ireland has changed dramatically due to changes in the regulation of Irish electricity production. As a result, all the existing peat-fired power stations (up to 9 plants) built between 1950 and the early 1980s have been decommissioned and replaced with two new plants which have commenced production between the end of 2004 and the beginning of 2005. Between 2001 and 2003, a collaborative study between the RPII and Trinity College Dublin (TCD) was undertaken to investigate NORM issues at a peat-fired power plant which had produced electricity for some forty years, from 1965 until early 2005. The results of this study have been published elsewhere [Organo et al., 2005] and while they describe a process that has since ceased, they are still relevant from a radiological point of view.

6.1.1 The industrial process

With a capacity of 125 MW the studied plant was, at the time the investigation started, the largest peat-fired power station in operation in Ireland, consuming approximately 1.1 to 1.2×10⁶ tonnes of raw peat and producing on average 20 to 25×10³ tonnes of ash every year (i.e. 1/3 of the total amount of ash produced by all the combined peat-fired plants). Over the years, the raw peat had been supplied to the plant from a local bog where it was mechanically harvested, coarsely milled and solar dried. From there it was transported to the plant in light rail convoys made of 15 wagons carrying a total of 75 tonnes of peat. On arrival at the plant two tipplers unloaded each wagon sequentially into a hopper and the peat was transferred by conveyor belts to the three ‘bunkers’ situated inside the plant. The bunkers acted as an intermediate storage area for the peat before it was sent to the mills. They were each capable of holding a 4-hour supply of peat at any one time and were, without a doubt, the dustiest places in the plant. From the bunkers the peat was transferred to the mills where it was pulverised into a fine dust, blown into the boilers (or furnaces) and burnt in suspension at about 1,000-1,100 °C.

Two main types of ash are produced in the process: 5 to 10% of the total ash falls below the furnace to form the ‘bottom ash’ while the remaining 90 to 95% passes into the flue gas stream as ‘fly ash’. This gaseous-particulate mixture is drawn through a series of grit arrestors designed to remove the majority of the fly ash (in the case of the studied power

---

3 This plant was decommissioned and replaced by a more efficient 150 MW plant which currently produces approximately 3.5% of the total Irish demand for electricity.

4 The two new peat-fired power plants use the latest efficient and environmentally friendly technologies and both comply with the recent EC Large Combustion Plant Directive [European Commission, 2001c]. As a way of comparison, the studied power plant consisted of three boiler/turbine units as opposed to one in each of the new plants. Current emissions can therefore be expected to be much smaller and occupational health and safety control measures are also likely to be more efficient as they would have been planned at the design stage.
plant, 90%) as well as any unburned carbon. Only a small fraction of the flue gases which passes through the grit arrestors will contain radionuclides in gaseous form and this is discharged through the stack into the atmosphere.

At the studied power plant, 2/3 of the produced bottom ash was transported in a trailer to a ‘dry ash’ pile situated a short distance away from the plant. The remaining 1/3 and the totality of the fly ash trapped in the grit arrestors were hydraulically piped out by flexible tubing to two nearby ‘wet ash’ ponds where the ash was kept in a 50% minimum aqueous environment to minimize the production of airborne particles. A total of approximately five million tonnes of ash have been landfilled on site over the years.

6.1.2 Scenarios and pathways

The primary objective of this investigation was to estimate the total annual effective dose received by workers involved in peat processing and peat ash management activities. Public exposure to radionuclides emitted with the gaseous emissions from the stack was not included in the overall assessment. After an exhaustive review of the industrial process followed by site visits, the number of exposure pathways of relevance from the point of view of an occupational dose assessment were narrowed down to the following two:

- inhalation of peat dust in the bunker area assuming no respiratory protection;
- external gamma radiation at different locations in and around the plant.

Following the first site visit, it was decided not to include the inhalation of peat ash dust on landfill sites arising from the generation of windborne ash because the vast majority of the total ash produced is transferred into a pond which makes it very unlikely to be wind blown. Maintenance duties such as cleaning of the hoppers and freeing blockages in the grit arrestors were also deliberately omitted despite the fact that during these activities workers are in close contact with the fly ash. This was decided on the basis that these activities do not occur very frequently (3 times per year), they are usually completed within a few hours/days to avoid long outage and, more importantly, they are undertaken in wet conditions with extensive personal protective equipment (total overall and full respiratory protection).

To cover all the possible exposure situations, it was assumed that in the future peat fly ash could be recycled and used as an additive in the manufacture of construction materials as is already the case for the coal fly ash [Lyons, 2001]. If the natural radioactivity content of the ash was found to be significant, there could be a potential for an increased radiation exposure to persons occupying buildings constructed with such materials and to workers handling and working with the ash.

6.1.3 Materials and methods

Samples of milled peat, fly ash, bottom ash and liquid effluents from the ash ponds were collected and analysed for their radioactive content and onsite measurements of ambient gamma dose rates at various locations in and around the plant were carried out (Figure 3). Details of the analytical techniques and field equipments used in this
investigation can be found in Organo et al. [2005]. To assess the radiological health significance of the potential use of peat ash in building materials, the methodology recommended in Radiation Protection 112 [European Commission, 1999a] was followed, as explained in Organo et al. [2005].

6.1.4 Results

The activity concentrations measured in the different samples collected at the studied peat-fired power station were found to be moderately variable in the raw peat but extremely variable in both the fly ash and bottom ash samples (Table 2). Peat is an organic deposit and this is reflected in the low activity concentrations in Th-232 and K-40, two radionuclides characteristic of a detritic influence. The clear disequilibrium observed in the peat samples between U-238 and Ra-226 on the one hand and Pb-210 on the other hand is not surprising as re-distribution of soluble and redox-sensitive elements like radium and uranium are a likely occurrence in soil profiles or deposits undergoing intense weathering such as peat. Atmospheric fallout of Pb-210 could also be a contributor to the observed excess Pb-210.

The elevated Pb-210 activity concentrations measured in the ash samples (Table 2) compared with other radionuclides are linked to the volatile properties of Pb at furnace temperatures. Between the furnace and the grit arrestors the mixture of gas and fly ash passes over banks of tubes containing water or air to give a more efficient removal of the heat prior to discharge into the atmosphere. As the flue gases cool down to about 200°C, the volatilised elements condense onto fly ash particles resulting in the observed enrichment. Except for Pb-210 in the peat fly ash, the analysed peat and peat ash samples contain lower levels of naturally occurring radionuclides than other NORM materials or even Irish soils (Table 3).

The activity concentrations measured in the effluents were found to be extremely low. Under Irish regulations, there are no specific exemption levels applicable to liquid discharges from NORM industries as is the case for most of the European countries [European Commission, 2003]. However, if the peat-fired power generation was considered to be a practice, the analysed effluents would be exempted under Schedule 5 of S.I. 125 of 2000 [Ireland, 2000].

A single air sampling experiment over an entire working shift was carried out in one of the three bunkers to assess the annual effective dose arising from the inhalation of peat dust which may be received by an employee carrying out dry sweeping duties of spilled peat dust. Bunkers are temporary storage areas which are located indoor and constantly filled with a 4-h supply of milled peat. The airborne dust concentration (total fraction) measured during our experiment at this location was found to be as high as 25.6 mg/m³ which is significant in terms of occupational dust exposure as the Irish occupational exposure limit (OEL) for nuisance dust is set at 10 mg/m³ [HSA, 2007].

---

5 A sediment (or deposit) has a detritic origin if at least 50% of its constituents derive from the erosion of previously deposited rocks. Examples of detritic sediments or rocks are sandstone, mudstone, sand and loess.
Based on the activity concentrations measured in the peat dust sampled in the bunker (Table 2) and on the airborne dust concentration, the maximum annual effective dose arising from inhalation received by an employee working in the bunker for 100 hours per year, assuming this employee is not wearing any respiratory protection, is about 0.5 µSv/y (Table 4). These conditions are representative of a worse-case scenario as work in the bunkers is only carried out for short periods of time and personal protective equipment (PPE) including protective clothing and face dust mask (EN 149 PP3) is mandatory.

Ambient gamma dose rate measurements were carried out at various locations around the plant, including disposal areas (Figure 3). The measured values, uncorrected for ambient background ranged from 60 to 70 nGy/h (control measurement outside the perimeter of the plant 70 nGy/h). By subtracting a cosmic contribution of 33 nGy/h [Colgan, 1980 and McAulay and Colgan, 1980], a terrestrial background in the local area of 8 nGy/h [Marsh, 1991] and using a conversion factor of 1 Sv/Gy [UNSCEAR, 2000] estimated annual effective doses from exposure to external gamma radiation were all found to be below 20 µSv/y. While no measurement of external gamma dose rate of terrestrial origin was carried out at locations where peat is harvested, dose rates were calculated on the basis of activity concentrations measured in the raw peat (Table 2) and were found to be lower than the natural ambient background [Organo et al., 2005]. Peat harvesting occurs outdoor in the open air by machinery (shielding effect) and both facial mask and protective clothing are mandatory to protect employees from the windborne peat dust thereby minimising the inhalation pathway.

To assess the radiological health significance of the potential use of peat ash in building materials, an Activity Concentration Index (I) was calculated to convert the specific activity of a building material (Bq/kg) into a measure of radiation dose (mSv) that may be received by an individual occupying a ‘model room’ constructed from a building material with a specific radioactivity, based on its activity concentrations in Ra-226, Th-232 and K-40 [European Commission, 1999a]. The index I was calculated for all the peat ash samples and a maximum value of 0.15 was found in two cases, one fly ash sample and one bottom ash sample. According to the EC [1999a] an index of 0.5 or less ensures a dose of less than 0.3 mSv per annum and materials falling into this category can be used in bulk in building works without restrictions.

6.1.5 Conclusions

Table 5 summarises all the doses calculated in the course of this study. The total effective dose received by a worker carrying out a combination of work duties involving peat processing and peat ash management is approximately 50 µSv per annum, i.e. twenty times less than the maximum allowable radiation dose from practices for members of the public. Therefore this NORM industry does not come under the scope of the Irish regulations. The activity concentrations measured in the peat ash indicate that this material could be recycled as an additive in the manufacture of building materials such as cement and/or concrete without concern for workers involved in the manufacture process itself or for members of the public living in buildings constructed with it.
6.2 Coal-fired electricity production

Coal combustion appears in various lists of NORM industries involving minerals and raw materials that may lead to a significant increase in exposure to natural sources which cannot be disregarded from the radiation protection point of view. With this regard, the lack of a comprehensive review of the coal-fired power generating industry in the Republic of Ireland prompted the setting up of a collaborative study between TCD, the RPII and the Electricity Supply Board (ESB) which started in 2002.

6.2.1 The industrial process

Ireland has only one coal-fired power plant but with a 915 MW total capacity (three units of 305 MW\(^6\)), it is the second largest power plant in the country. It was commissioned in 1979 and it currently supplies approximately 20% of the country’s daily electricity requirements. To reach this demand, bituminous coal is imported, mainly from Australia, Indonesia, the USA and Columbia and approximately \(2 \times 10^6\) tonnes are burnt annually (Photo 1).

![Photo 1. Coal yard where the coal is stacked prior to being burnt](image)

The imported coal is first milled and pulverised down to less than 100 \(\mu\)m particle size [Meij, 2003] and is then fed into the furnaces where the combustion temperature is approximately 1,100°C (Figure 4). During combustion most of the mineral matter contained in the coal is fused into a vitrified ash. The lighter particles are commonly referred to as pulverised fly ash (PFA) and represent 85% of the total amount of ash produced. The PFA is carried out of the furnaces by the hot exhaust gases and is

---

\(^6\) Each of the three 305 MW units consists of one low NO\(_x\) boiler (Foster Wheeler Drum type, natural circulation) four coal bunkers (600 tonnes of capacity each), four mills, two electrostatic precipitators (ESPs) and one turbine.
subsequently extracted at 99.5% (in quantity) by electrostatic precipitators (or ESPs). The plant produces $17 \times 10^4$ tonnes of PFA each year. Volatilised mineral compounds and the fly ash which are not trapped in the ESPs (0.5%) are released to the atmosphere and constitute what is commonly known as escaping fly ash. The remaining 15% of the total amount of ash produced (heavier particles and unburned organic matter) condense onto the boiler tubes and fall at the bottom of each furnace where it sinters to form the furnace bottom ash. Approximately $3 \times 10^4$ tonnes are produced annually.

The PFA collected by the ESPs is pneumatically transferred into silos where it is temporarily stored in dry form. Each year, $1 \times 10^5$ tonnes of the produced PFA is sold to a cement company which uses it as a shale substitute in cement products. As a result, almost half of all the Normal Portland cement produced in Ireland contains coal PFA. In the cement mix, the fly ash amounts to approximately 5% in mass while concrete only contains between 0.25 and 1% because cement represents only 5 to 20% of the concrete mix in mass. The fly ash which is sold is transported in sealed tankers. The remaining PFA which is not sold ($7 \times 10^4$ tonnes each year) as well as the totality of the bottom ash produced are conditioned with water (to reduce the dust emissions) and transported separately in open trucks to a dedicated landfill site situated nearby (Photo 2). The maximum disposal capacity of the coal ash landfill currently in use is $3 \times 10^6$ m$^3$. This represents an accumulation of ash of approximately 10 m high in places.

Photo 2. Coal ash landfill and plant in the background

### 6.2.2 Radiological issues investigated

In a report published in 2001 [Smith et al., 2001], the then National Radiological Protection Board (NRPB)\(^7\) concluded that the radiological impact of the UK coal-fired electricity generation on the UK population was low and did not warrant the application of radiological controls except in two cases:

- The use of flyash in building materials for which the NRPB calculated an excess dose (i.e. a dose above that received outdoors) arising from the ash component in

\(^7\) The NRPB was merged with the Health Protection Agency (HPA) in April 2005.
building materials containing 30% ash of approximately 600 $\mu$Sv/y after subtraction of the external background$^8$. This dose is within the range of 0.3 to 1 mSv/y within which the EC recommends that controls on the use of such building materials should be considered [European Commission, 1999a].

- The possible occurrence of Pb-210 enriched scales inside boilers (low NO$_x$ type) as reported in Dutch coal-fired power stations [Huijbregts et al., 2000]. In their report, the NRPB conservatively estimated that doses in the region of 100 $\mu$Sv/y could be received by workers involved in boiler maintenance if a scale with a Pb-210 concentration of 100 Bq/g was present.

The activity concentrations measured in coal and coal ash samples collected at the Irish power plant in 1986, 1988 and 1993 (Table 6) are relatively constant and, most importantly, similar to those published in the UK report (Table 7)$^9$. On this basis and assuming similar characteristics between the coal power generation industry in the UK and in Ireland, we have assumed that the NRPB report’s conclusions were applicable to the Irish situation and decided to focus our investigation on the use of fly ash in Irish building materials and on the possible occurrence of Pb-210 enriched scales. For completeness, it was also decided to include the unpublished results of a study carried out between 1986 and 1990 by the ESB looking at the offsite radiological impact of the plant’s atmospheric emissions.

6.2.3 Materials and methods

Coal and coal ash samples collected at the studied power plant were analysed by gamma spectrometry in TCD. Some of the results from earlier studies (1986, 1988) are included in Table 6 for completeness alongside results of more recent measurements specifically carried out for the purpose of this assessment. Details of the gamma spectrometry analysis technique used by TCD can be found in Organo et al. [2005]. The radiological health significance of the inclusion of coal fly ash in Irish building materials was investigated according to the methodology recommended in Radiation Protection 112 [European Commission, 1999a] and is described in more details in Lee et al. [2004] and Lee [2006]. Samples of residues collected inside one of the boilers of the studied plant (Photo 3) were analysed by the RPII using a p-type GEM gamma ray detector with a relative efficiency of 38.9% and 1.75 keV resolution at 1.33 MeV and a n-type HPGe GMX gamma detector with a relative efficiency of 40.5% and 1.89 keV resolution at 1.33 MeV. Liquid effluents from the ash landfill site collected at the discharge point (Photo 4) were also analysed using a n-type HPGe GMX gamma ray detector of 29% relative efficiency and 1.88 keV resolution at 1.33 MeV.

$^8$ 218 $\mu$Sv/y due to radon and 382 $\mu$Sv/y due to external gamma radiation.

$^9$ Activity concentrations in coal fly ash can vary considerably depending on the origin of the coal. The doses reported here are specific to the coal presently being burnt in Ireland. If in the future coal is sourced from other international markets, then its radioactive content may differ and the estimated doses to workers and the public will need to be revised.
Between 1986 and 1990, an assessment of the offsite radiological impact of the studied power plant in terms of radionuclides dispersion in the plume released from the stack was carried out by the ESB at the request of the Nuclear Energy Board (NEB), the predecessor of the RPII. The model chosen by the ESB at the time was used to model SO$_2$ emissions and was validated by An Foras Forbartha (which later became the Environmental Protection Agency or EPA).

6.2.4 Results

The activity concentrations measured in the various types of coal supplied at the power plant under investigation (Table 6) are very similar to those encountered in other countries (Table 7). As far as fly ash is concerned (Table 6), results are significantly higher than indicated in the UK (Table 7), particularly for the U-238 decay series. The reason for this has not been identified but it is clear that even when the origin of coal

Photo 3. One of the 16 burners inside one of the furnace where boiler residues (white patches around the opening) were collected

Photo 4. Discharge point of the effluent
supplies remains unchanged throughout the years (as it is the case for this plant), the activity concentrations in the coal itself can vary by an order of magnitude.

Coal fly ash contains increased levels of radioactivity compared with those measured in the original coal, typically by an order of magnitude, because combustion of coal results in a 80-95% mass reduction, thus yielding 5-20\%\(^{10}\) ash which contains most of the original radioactive material but now at an enhanced concentration. Radionuclide concentrations in the fly ash can be “predicted” by dividing those measured in the coal by the ash fraction\(^{11}\) and then compared with activity concentrations measured in the PFA samples. In our case, there is good agreement between the two.

Volatile elements such as Pb-210 and Po-210 usually display higher and highly variable enrichment factors on the smallest particles of escaping fly ash and/or the fly ash trapped in the ESPs [Coles et al., 1979]. Enrichments are radionuclide-specific and depend also largely upon various factors such as the original radioactivity content of the coal, its chlorine and sulphur content, the characteristics of the pulverised fuel (particle size), the type of furnace and the efficiency of the ESPs. Lead-210 and Po-210 were not measured in the Irish coal but an indication that they are not particularly enhanced in the trapped fly ash lies with the apparent absence of radioactive disequilibrium between Ra-226 and Pb-210 in the analysed fly ash (Table 6). Escaping fly ash was not collected for this study because high radioactivity content was not expected. Hence a temporary outage of the plant was not warranted. The potential enrichment of volatile radionuclides onto emitted particles which would indicate a process of volatilisation and preferential condensation onto particles of smaller size was therefore not verified.

Lead-210 was measured in two samples of boiler residues collected inside one of the boilers (Table 6) and an average concentration of 0.4 Bq/g was found. This is well below the activity concentrations which were measured in Dutch boilers and exceeding 100 Bq/g [Huijbregts et al., 2000] and well below both EU and IAEA recommended exemption/exclusion values for Pb-210 in NORM material (Table 1). It means that the radiation dose received by a worker or a member of the public dealing with this type of material would not exceed 0.3 mSv/y.

There are three reasons to explain why the condensation of Pb-210 does not occur in the studied power plant compared to the situation described in the Netherlands [McCarthy, F., personal communication]:

- The lower chlorine content of the coal burnt in the Irish plant; high chlorine contents favour reducing conditions in the boiler which in turn lower the condensation temperature of the lead;
- The boilers used in the Irish plant belong to the first generation of low NO\(_x\) boilers; they operate in “naturally reducing” conditions while the Dutch boilers operate in “forced reducing” conditions. In oxidising conditions (Irish boilers), lead is in

\(^{10}\) The average ash content of the coal burned in the plant investigated here is 10%.

\(^{11}\) In our case, it means that the radionuclide activity concentrations in the fly ash compared with those in the raw coal can be expected to be multiplied by a factor of 10.
PbSO₄ form which has a high condensation point. In the Dutch boilers, lead is present as PbS or PbCl₂, both in gaseous form with low condensation points.

- The Irish boilers are smaller than the Dutch ones; therefore the time allotted to particles to react between each other is smaller and, more importantly, the combustion temperature is higher and exceeds the temperature of condensation of lead (880 °C).

New low NOx boilers similar to those used in the Netherlands are due to be installed by 2008 to meet the new environmental requirements set by the EU with the possibility that Pb-210 scales could develop over time. Additionally, improved emission control systems (dry desulphurisation system or FGD) to reduce the SO₂ emissions to the atmosphere will also be installed and are likely to result in the production of up to 12x10⁴ tonnes of CaSO₃ per year which will have to be landfilled. It is therefore recommended for the future that the radiological consequences of these new operations be investigated.

Two duplicate samples of the liquid effluent collected at the point of discharge originating from the coal ash disposal area were analysed (Table 6) and apart from K-40 which was measured in negligible concentrations, no other radionuclide could be detected by gamma spectrometry.

Cement and concrete containing some amount of the coal fly ash produced by the studied power plant were analysed by TCD and apart from Pb-210, all the other radionuclides had lower activity concentrations than in the raw fly ash (Table 6). Activity concentrations in cement containing fly ash were found to be higher than in concrete containing fly ash. This was expected as greater quantities of fly ash are incorporated into cement compared to concrete.¹²

The radiological health significance of the potential use of coal fly ash in Irish building materials was assessed following the methodology recommended by the EU [European Commission, 1999a]. An Activity Concentration Index (I) was calculated for each of the coal fly ash, cement and concrete sample collected for this study and they were all found to be well below the limits of 6 and 2 for superficial materials, implying doses of less than 0.3 mSv/y. Only three fly ash samples had an index greater than the limits of 1 and 0.5 for building materials used in bulk amounts. Although coal fly ash may have higher radioactivity content than other constituents such as sand or aggregates, it is not a building material in itself and it can be considered a “superficial material”. It only constitutes up to 5% of a cement mix so its radioactivity does not impact significantly on the Activity Concentration Index of the final product. The overall increase in the radioactivity levels of cement and concrete containing fly ash is therefore very limited and for this reason coal fly ash can be considered of no radiological health significance if incorporated into Irish building materials. More details on this issue can be found in Lee et al. [2004] and Lee [2006].

Using a model, the ESB calculated the amount of radioactivity discharged by the stack of the studied power plant (source terms) as 2,920 Bq/kg of ash emitted in total alpha and

¹² Concrete only contains fly ash as a result of the inclusion in the concrete mix of cement made with fly ash.
2,409 Bq/kg of ash emitted in total beta (see Appendix A). The ESPs keep the specific emissions of particulate matter well below 50 µg/m³ which is equivalent to an emission of 13.66 g/s of ash per 305 MW unit. Therefore the total activity emitted was calculated for each 305 MW unit as 2920 x 13.66 = 40 Bq/s total alpha and 2409 x 13.66 = 33 Bq/s total beta. Radon emissions were also calculated using a normal coal throughput for each 305 MW unit of 29.3 kg/s, an average Ra-226 activity concentration in the coal of 30 Bq/kg (Table 6) and assuming 100% volatilisation (gas). The result was calculated as 30 x 29.3 = 879 Bq/s per 305 MW unit.

Ground level concentrations, effectively air concentration at approximately head height were modelled by the ESB using a matrix spatially distributed in a 31 x 41 km grid around the power station and the maximum annual average concentration were 223 nBq/m³ for the total alpha activity concentration, 184 nBq/m³ for the total beta activity concentration and 5 µBq/m³ for the radon activity concentration. Contour maps showing the spatial distributions (or isopleths) of ground level activities were obtained and indicate three areas of maximum concentrations at ground level directly to the North-East, South-East and South-West at a distance of approximately 8.5 to 9 km from the power station.

The maximum annual average radon concentration at ground level calculated by the ESB model (5 µBq/m³) corresponds to an annual effective dose of 0.05 nSv/y and 0.04 nSv/y for workers and members of the public, respectively. The total alpha and beta activity concentrations at ground level as calculated by the ESB model cannot be transformed directly into inhalation dose as this would require knowing the individual radionuclide activity concentrations at ground level. To estimate these, we used the methodology described in Smith et al. [2001] and the results of the calculations in terms of dose to adult members of the public as shown in Table 8 reach a total of 0.02 µSv/y (or 20 nSv/y). As internal exposure to K-40 is excluded from the international regulations [IAEA, 1996a] it was also ignored in this scenario and we used the activity concentrations of the fly ash as measured for this study (Table 6) as opposed to those used by the ESB in their model (see Appendix A). According to Smith et al. [2001], the plume inhalation pathway represents approximately 70% of the total dose received by a typical individual from the stack releases. Based on the above calculated inhalation dose, it can be concluded that the overall radiological impact of atmospheric emissions from the studied power station is negligible.

6.2.5 Conclusions

The results reported and discussed in the previous section indicate that, in the context of the Irish regulations, the work activities carried out at the studied coal-fired power station do not give rise to doses liable to exceed 1 mSv to any individual in any 12-month period. Moreover, the recycling of coal fly ash as an additive used in the manufacture of Irish building materials was found to be of no radiological health significance as were the

---

13 Using an F factor of 0.6 for outdoor exposure [UNSCEAR, 2000] and an exposure duration of 2000 h/y for workers and 1800 h/y for members of the public.
atmospheric releases resulting from the coal combustion or the liquid discharges from the ash disposal area.

6.3 Natural gas extraction

The only hydrocarbon resource or fossil fuel which is readily and commercially available in Ireland is natural gas. One reservoir is currently in production, since 1978, and it is located offshore in the South West of the country, approximately 15 km off the coast. It produces a dry gas made at 94% of pure methane (density 0.95 g/m$^3$) and as such it does not need to be treated or heavily processed apart from dehydration which takes place offshore before the gas is sold for distribution to Irish consumers.

6.3.1 The radiological issues linked to the industrial process

Oil and gas reservoirs are rock formations that contain elements such as calcium, strontium, barium and radium. It is not uncommon for these elements to be preferentially dissolved relative to the uranium and thorium which will tend to stay in the reservoirs. When oil and natural gas are extracted, temperature and pressure variations occur that disrupt the chemical balance in the extracted fluids as they are brought to the surface. This eventually may lead to the deposition of residues such as scale or sludge throughout the production equipment. Some of these may show increased radionuclide concentrations, the most common being radium isotopes from both U-238 and Th-232 decay series and their respective decay-products, mostly Pb-210 and Th-228.

One radionuclide of major importance in the gas extracting industry from a radiological point of view is the radon which is released from the reservoir (by diffusion from radium deposits) and is transported with the natural gas to the gas processing plant. During routine operations, as the gas flows continuously through the system and radon gas decays, its short-lived decay-products (Figure 1) tend to plate out on the surfaces that come into contact with the gas stream to form thin dark grey/black films on the internal side of the production equipment [Bjornstad and Ramsoy, 1999]. As these short-lived daughters decay, they emit penetrative gamma radiation which can result in high occupational external gamma radiation doses when working close to the contaminated equipment.

During shut downs for repair, maintenance or cleaning operations, the gas flow stops. Within several hours after the shut down and without a continuous flow bringing new radon gas into the gas stream, radon gas and its short-lived decay-products have decayed and penetrative gamma radiations are no longer emitted. However, the long-lived decay-products of radon (Figure 1) remain in the thin film-like deposits emitting weak gamma radiation and mainly beta and alpha radiation. The energetic alpha emissions of Po-210 and Pb-210, in particular, represent a potential hazard if they become airborne and are ingested or inhaled.

Residues such as sludge are a common occurrence in gas extracting equipment and they usually accumulate in separator vessels, storage tanks, gas lines and other filter assemblies. They mainly contain radium isotopes as well as Pb-210, Bi-210 and Po-210. Scales on the other hand are a rare occurrence in gas production equipment.
6.3.2 Scenarios and pathways investigated

The main pathways by which workers involved in the extraction of natural gas could be exposed to NORM are the following:

- The external gamma radiation from films/coatings of radon short-lived daughters when the equipment is opened for maintenance and during routine operations
- The inhalation of long-lived airborne radionuclides at vessel entries during maintenance or decontamination operations and while handling NORM contaminated parts of equipment
- The inhalation of radon and radon decay-products at vessel entries

During routine operations, significant radiation exposures are unlikely to occur as NORM are mostly contained within pipes and vessels. It is possible however that gamma radiation emitted from radionuclides deposited on the inside of this equipment could pass through the steel walls leading to a potential dose rate at their surface. Personnel carrying out duties on a regular basis in close proximity to such equipment could be unacceptably exposed. These issues were investigated by carrying out radiation surveys of production equipment offshore and onshore (disused equipment) to check for the presence of above background gamma radiation and Pb-210 plating. Radionuclide analysis of NORM residues sampled offshore during maintenance operation was also completed.

The end users of the natural gas extracted in Ireland are members of the public and it is important to investigate the extent of their exposure to the radon which is contained in the gas commercially distributed in the country. The RPII asked the company responsible for the extraction of the gas to carry out a routine monitoring of the radon concentrations in the gas stream for a period of two years. The Physics Department from University College Dublin (UCD) was contracted to carry out the work and radiation doses were calculated by the RPII according to Dixon [2001].

6.3.3 Materials and methods

UCD monitored the radon gas concentrations in the onshore gas stream for a 2-year period (September 2003 to October 2005) using two different techniques of which both detected and recorded alpha particle emissions from radon and its short-lived decay products (Po-218 and Po-214):

- The grab sampling technique: samples of the gas were taken from a suitable pipeline location into previously evacuated 400 cm³ Lucas cells (Photo 5). The inside of the cell is coated with an alpha particle scintillator (ZnS (Ag)) and at its bottom there is a transparent window. Once a sample is taken and the cell is closed the radon and its short-lived alpha emitting decay products cause scintillations to occur in the ZnS (Ag) scintillation coating. After a period of about 4 hours, in which a state of approximate radioactive equilibrium is reached, the rate of scintillation within the cell reaches its maximum value. The Lucas cell is then placed on top of the photomultiplier in a scintillation counter and the alpha particle scintillation count rate is recorded. The gas filled Lucas cells were
counted in UCD on the day after taking each gas grab sample and the
corrections for the effect of radioactive decay back to the time of
sampling.

Photo 5. Setup used to monitor the radon concentrations in the gas stream.
In this unique experiment, the equipment was setup in the onshore metering station,
next to calorimeter. Photo courtesy of Dr. J. McLaughlin (UCD)

- The continuous monitoring technique: the radon concentrations are integrated
  over long periods of time (3 and 8 months in our case) using passive SSNTDs
  (solid state nuclear track detectors), here CR-39. In this experiment, three
detectors were placed within a specially fabricated cylindrical aluminium chamber
which was attached to the gas line as shown in the photograph above. At the end
of the exposure period, the detectors were removed and processed by chemical
etching to reveal the alpha tracks caused by radon and its progeny. The tracks
were counted by optical microscopy and from the track density data, the mean
radon concentration during the exposure period was determined.

Two site visits were conducted, the first one on the offshore platform where the gas is
treated directly after extraction and the second one at the warehouse (on the mainland)
where the offshore disused equipment is stored. The purpose of these visits was to
establish if and where there was a NORM contamination problem at these locations by
carrying out ambient gamma dose rates measurements and checking for alpha/beta
contamination (Pb-210 plating or invisible scale) inside and outside the equipment to
evitably quantify and assess the occupational risk.

Two samples of sludge were collected in two separators on the offshore platform (Photos
6 and 7) and analysed by alpha and gamma spectrometry. This equipment is usually
opened, inspected and cleaned once every four years by specialised contractors, using
pressurised water jets. From a waste management point of view, the sludge that is left at
the bottom of the tanks after cleaning is collected and stored in drums that are sent
ashore where the water is drained and the concentrated residue sent to landfill.
6.3.4 Results

Table 9 (grab sampling technique), Table 10 (continuous 3-month) and Table 11 (continuous 8-month) as well as Figure 5 summarise the results of the radon gas monitoring as described in the previous section. It is interesting to note that the average radon concentration obtained by the grab sampling technique (638 Bq/m$^3$) is about 2.5 times greater than the average radon concentration determined by the continuous monitoring method (288 and 265 Bq/m$^3$ for the 3-month and 8-month measurements, respectively). The reason for this difference is not known but large fluctuations of radon levels over time in natural gas supplies have been recorded for other gas fields [Gesell, 1974].

A study looking at the radon gas concentrations in the commercially distributed gas in the UK showed that for typical rates of gas usage and an average radon concentration of about 200 Bq/m$^3$, the estimated dose for domestic users of natural gas was only 4 $\mu$Sv
and for a critical group representing commercial users a few tens of $\mu$Sv [Dixon, 2001]. Using this relationship, the radiation dose to members of the public in Ireland resulting from exposure at the average radon concentrations measured in the studied natural gas stream (397 Bq/m$^3$) is about 8 $\mu$Sv, well below the general 1 mSv/y dose limit for members of the public. To reach this dose limit, a radon concentration of 50,000 Bq/m$^3$ would be needed. Equally, radon in the gas stream will not be an issue for employees working on the offshore platform or at the onshore terminal because they are never in direct contact with the gas itself as it is always confined and enclosed in production equipment at any point in time.

External gamma radiation fields and contamination signals measured on the offshore platform and at the onshore warehouse were all indistinguishable from the natural background and therefore not considered to be a cause for concern.

The analysis of the two sludge samples (Table 12) show that the activity concentrations are all below the indicative recommended exclusion/exemption values for NORM materials published separately by the EC and the IAEA (Table 1). While these recommendations are not mandatory they both provide guidance for the implementation of the EU and IAEA Basic Safety Standards with regard to natural radiation sources. Estimates were made to assess the annual effective dose received by workers handling the sludge during the cleaning of production equipment. The results of these calculations all indicate that in very conservative conditions (maximum activity concentrations measured, exposure duration of 2000 h/y) the annual effective dose received will be at most around 100 $\mu$Sv and as such this work activity does not need to be regulated from a radiological point of view.

6.3.5 Conclusions

Radon gas concentrations in the gas stream brought ashore were monitored continuously during a 2-year period. The annual radiation dose to the domestic gas end users resulting from exposure at the measured average radon concentrations was estimated to be about 8 $\mu$Sv. The radiation dose received by workers involved in the maintenance and cleaning of the offshore equipment was estimated to be at most around 100 $\mu$Sv per year and the radiation surveys carried out offshore and onshore both indicated that the external gamma radiation fields and contamination signals were indistinguishable from natural background values. From a radiological point of view, it can be concluded that the work activities associated with natural gas extraction in Ireland give rise to doses that are well below the 1 mSv/y statutory limit and as such do not need to be regulated.

6.4 Bauxite refining

Aluminium is the third most abundant element in the Earth’s crust but it does not exist in nature in its pure form. Instead, it is chemically bonded with other elements and found in its most concentrated form in bauxite ore, a repository which contains sufficiently high levels of Al$_2$O$_3$ and suitably low levels of Fe$_2$O$_3$ and silica to be economically exploited. Named after the French district of Les Baux where it was first discovered in 1821,
Bauxite is a red deposit produced by tropical or semitropical weathering of alumina-bearing rocks. Bauxite deposits are generally very extensive and found on just about all the continents in the world but the largest known economic resources of bauxite are located in Australia (40%), Guinea, followed by Brazil, Jamaica and India. The US, Japan and Germany are the world’s largest consumers of aluminium but they possess little or no bauxite deposits of their own.

The production of aluminium metal takes place in three main stages: the mining of the ore, its refining to recover alumina, and finally the smelting of the alumina (anhydrous aluminium oxide) to produce aluminium. This report deals only with the second stage of this process.

There are approximately thirty bauxite refineries worldwide and six of these are located within the EU. Europe’s largest\textsuperscript{14} and most recently-built alumina refinery is situated in Ireland. Its construction took place between 1978 and 1983 and was, at the time, the largest construction project in Europe. It was commissioned in 1983 and currently employs approximately 450-500 permanent employees as well as 200 contractors. Ireland does not have a smelting industry and the $1.5 \times 10^6$ tonnes of alumina produced each year is shipped to aluminium smelters and other manufacturers mostly in the UK, Scandinavia and elsewhere in Europe.

6.4.1 The industrial process

The site of the Irish bauxite refinery spreads over a total area of 440-hectares of which 150 ha are dedicated to the refining process only. Sixty percent of the $3.5 \times 10^6$ tonnes of bauxite ore that are processed annually are imported from Boké in the Republic of Guinea (West Africa) with the remaining 40% being imported from Brazil. The bauxite is shipped in bulk ore carriers, $5 \times 10^3$ tonnes at a time, and delivered to the plant’s own marine terminal which is located 800 m away from the site. One tanker per week is unloaded on average. From there, the bauxite is transported by conveyor belts and stored in four bulk storage warehouses. The maximum capacity of each warehouse is $15 \times 10^4$ tonnes.

In nearly all commercial operations, alumina is produced by the Bayer process\textsuperscript{15}. It is a very energy-intensive and large-scale process involving high temperatures and high pressures which consists of four steps:

- Digestion: the finely ground bauxite is digested at a temperature in excess of $250 \, ^\circ C$ with a hot solution of $4M$ caustic soda and steam into large pressure vessels or digesters (Photo 8)
- Clarification: the alumina-bearing solution is separated from the insoluble impurities that were part of the original bauxite. These residues are segregated

\textsuperscript{14} A refinery in Spain has a similar size to its Irish counterpart. The largest alumina plant in the world is in Queensland (Australia) and is 3 times as big as the Irish refinery.

\textsuperscript{15} The Bayer process was discovered by Karl Bayer in 1889 and the first refinery was opened in 1893.
into 10% of sand and 90% of mud, the so-called red mud\textsuperscript{16}. The mud is pumped to a purposely built 100-hectare, 20-m high impoundment area also called bauxite residue disposal area (BRDA) where it is stacked up in terraces (Photo 9). The sand is transported by trucks to the BRDA but it is kept separate from the mud

- Precipitation: the alumina is precipitated from the solution as crystals of alumina trihydrate
- Calcination: the alumina trihydrate is washed and heated at over 1,100 °C in special calciners or kilns to obtain the final product, the white sandy alumina

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{photo_8.jpg}
\caption{A digester with a skip in front of it containing residues removed after maintenance}
\end{figure}

\textsuperscript{16} Four tonnes of bauxite are required to produce two tonnes of alumina which in turn will produce one tonne of aluminium. In total, every day, approximately $9 \times 10^3$ tonnes of bauxite ore are processed, $4 \times 10^3$ tonnes of alumina generated together with $2 \times 10^3$ tonnes of waste, heat, water effluents and water vapour.
The refinery currently holds an Integrated Pollution Control Licence (IPCL) issued by the Environmental Protection Agency (EPA). All the environmental aspects of the plant's operation are covered in this IPCL, including emissions to air, water, solid waste, ground water and noise and are closely monitored by the EPA. The IPCL does not cover radiological or radiation protection issues. Any such issue, if raised, would come under the scope of S.I. 125 of 2000 [Ireland, 2000] and would be a matter for the RPII. Therefore the radiological assessment of the Irish bauxite refining industry was carried out to determine if workers or members of the public may receive a dose in excess of 1 mSv in any 12-month period.

6.4.2 Radiological issues investigated

Bauxite ore, the waste products and residues from its refining are not regarded as radioactive materials but if they are not managed properly they could, in theory, have the potential to give rise to a significant increase in radiation exposure of workers and/or members of the public, primarily because of the very large quantities of materials being processed. Maintenance and cleaning of process equipment as well as waste management are, in most cases, the main issues to be investigated as far as NORM are concerned. Experience also shows that when occupational doses from NORM activities are found to be low members of the public are put at no significant risk from these same activities [ICRP, 1997]. Therefore, the following scenarios were investigated:

- Occupational exposure during the maintenance and cleaning of the process equipment where the build-up of residues or scales can take place as a result of the Bayer process. Scales are frequently and routinely removed from the digesters, the flash tanks, the settling tanks (or decanters) and the pipes linking these components. Maintenance work to remove the scales occurs once a year on average at all locations and is specifically carried out by the same contracted workers who are permanently onsite. A range of different techniques are used to remove the scales (pneumatic drills and water pressure jets) which are subsequently gathered in skips and transported by trucks to the BRDA. Removing scales that are encrusted onto steel walls generate large quantities of airborne
dust and particles, and this work usually takes place in confined environment. Therefore, if workers are not sufficiently protected and if the radioactive content of these scales is above an acceptable level, the inhalation of these products could be a significant cause of concern.

- Occupational exposure during waste management activities carried out on the BRDA. If it was left untouched, the accumulated red mud would naturally and slowly dry out. To prevent dusting and avoid the creation of large quantities of airborne red mud particles, the surface of the BRDA is constantly kept slightly damp with a network of sprinklers situated around the site. However, because of the vast quantities of waste that have accumulated since 1983, exposure to non-trivial external gamma radiation fields could be a potential hazard for workers and this issue was also investigated.

6.4.3 Materials and methods

Samples of bauxite slurry and scale collected in a digester, a decanter as well as red sand, fresh red mud and runoff water from the BRDA were collected and analysed by high resolution gamma spectrometry by the RPII\textsuperscript{17}. The measured activity concentrations were then compared with the IAEA and EU recommended exemption/exclusion values (Table 1). Gamma dose rate measurements were carried out on the BRDA and inside a flash tank during maintenance using a portable Mini-Rad type gamma survey monitor (1000 Series Mini-monitor Type R or 1000R) comprising an energy compensated GM tube with an integration time of 1 to 8 seconds (depending on the dose rate), a measuring range of 0.1 to 1,000 μSv/h and an energy range of 50 keV to 1.25 MeV (±20%).

6.4.4 Results

The results of the gamma spectrometry analysis of the samples collected by the RPII are shown in Table 13. For comparison purposes, published data for similar facilities in other countries are also included. The activity concentrations measured in the red mud are higher than those measured in the original bauxite ore because of the chemical reactions during the refining process which lead to various concentration enhancements, in the Th-232 decay series in particular. Both natural decay series were found to be in radioactive equilibrium in the red mud, while a disequilibrium in the U-238 decay series was found in the bauxite slurry, in the scale collected in the digester and in the red sand. A disequilibrium in the Th-232 decay chain was observed in the scale collected in the digester.

All the measured activity concentrations were found to be below the EC and IAEA indicative recommended exclusion/exemption values for NORM materials (Table 1) which provide some guidance for the implementation of the EU and IAEA Basic Safety

\textsuperscript{17} The specifications of the gamma detectors used by the RPII are mentioned in Section 6.2.3 dedicated to the coal-fired electricity production.
Standards with regard to natural radiation sources. Below these concentrations, the radiation dose received by a worker or a member of the public dealing with this type of material is unlikely to exceed 300 µSv/y.

Three different locations were surveyed on the BRDA with regards to the ambient gamma dose rate, two on the red mud and one on the red sand. The average of all the measurements carried out at waist height was 325 nSv/h. A background value of 100 nSv/h was subtracted from this average value\(^\text{18}\) to obtain a net average ambient gamma dose rate of 225 nSv/h. As a comparison, external gamma dose rates measured in a red mud pond in Hungary at 1 m above ground ranged from 200 to 400 nSv/h [European Commission, 2007], in total agreement with the values found in the Irish case. Using an average occupancy of 1,800 h/y for employees working on the BRDA [Hartney, 2005], a maximum and very conservative occupational radiation dose from external exposure to gamma radiation of 405 µSv/y was calculated. In comparison, the occupational dose from external gamma radiation received by employees working on a red mud disposal site located in Romania was estimated to be 270 µSv/y [Weiss et al., 2004].

Ambient gamma dose rates were also measured while maintenance work was carried out inside one of the flash tanks. The inside of the tank was scaffolded and two employees, both wearing PPE (overcoat, face mask, hard helmet, gloves, and goggles) were working to remove scales deposited on the inside walls of the tank using pneumatic drills and water-pressure jets. A red-brown scale was found to cover the entire surface of the inside of the tank, between 5 mm and a few cm thick in places and presenting a rather smooth surface. Broken pieces of scale were scattered on the floor. Ambient gamma dose rate measurements were taken at approximately 1 to 2 cm away from the surface of the scale not yet removed as well as inside the inlet and outlet pipes (80 cm in diameter) which would usually be connected to the tank. Scales were found in both pipes, thicker in the outlet pipe. All the readings were found to be between 100 and 200 nSv/h, equivalent to or just marginally above the natural background.

6.4.5 Conclusions

Analysis of red mud samples and direct measurements of external gamma dose rates to which workers are exposed to while carrying out routine and maintenance activities indicate that it is highly unlikely that doses in excess of 1 mSv/y would be received from the work activities carried out and that the bauxite refining industry does not come under the scope of the Irish regulations from a radiological point of view.

\(^{18}\) Background measurements were carried out outside the perimeter of the refinery and a value ≤ 100 nSv/h was found. The RPII country-wide gamma dose rate monitoring network also recorded an average ambient background gamma dose rate of 85-90 nSv/h during that same period of time.
7 Conclusions

Investigations of four large industries operating in Ireland have been carried out to assess the extent of exposures to natural sources of radiation of the workers involved in these particular industrial processes as well as, in some cases, members of the public, with a view to determine if any of these work activities needed to be regulated as specified by the Irish regulations.

A sector-specific approach to the dose assessments was chosen due to the wide differences in the nature of the industrial processes involved. In each case, a review of the industrial process and potential occupational radiation exposures arising from the occurrence of NORM at different stages of the process has been undertaken. Field measurements and analysis of samples have been used to estimate the radiation doses received by workers directly involved in the handling, processing and storage of NORM.

The results of these investigations are summarised in Table 14 and indicate that none of the work activities reviewed are liable to give rise to an effective dose to workers or members of the public in excess of 1 mSv above background in any 12-month period.

The first decade following the publication of the EU Directive in 1996 to deal with the regulatory aspects of work activities involving NORM and their practical implementation has seen agencies responsible for radiation protection matters in various countries focusing on the identification of those NORM industries which could potentially be of concern. From an early stage, the international community favoured a harmonised approach and many international conferences have been organised to try and fulfil this objective.

Although international consensus around some specific and critical issues is still lacking [Wymer, 2007], this first decade has allowed the international community to better define and identify the areas where real radiological problems might lie. The years to come will see a more effective use of resources to solve these problems, in particular:

- The use of different screening values between different countries for the international trading and trans-border monitoring of scrap metal;
- The lack of purpose-built facilities to dispose of the NORM waste which cannot be disposed of in landfill, mainly because nuclear waste disposal facilities are not designed to deal with the large volumes of wastes produced by some NORM industries;
- The environmental impact of unsustainable disposal options of very large volumes of NORM waste in some countries (phosphogypsum stacks in Florida for example);
- The impact of international conventions on the discharges and decommissioning of some NORM industries (oil and gas offshore installations for example);
- The identification of occurrences where occupational exposures might be unacceptable, especially in countries where occupational hygiene standards are not stringent enough or not properly enforced.

As far as Ireland is concerned, some work will be needed in the future to review the situation with regards to NORM. The RPII has identified specific areas which will have to
be examined. As with the problems identified by the international community and listed above, apart from a number of NORM items that have been detected in scrap in recent years, none of them has been identified as being of critical concern for Ireland.
8 Acknowledgements

The authors wish to thank the ESB for providing unpublished data for this report as well as Dr. Elaine Lee (now Doorly), Dr Gerard Menezes and Dr. Eric Finch from Trinity College Dublin for their valuable assistance in the assessment of the peat and coal-fired power production industries.

Further, this work would not have been possible without the assistance of staff from all four industries, and their help is gratefully acknowledged.

The draft text was reviewed by Jarlath Duffy and Alison Dowdall and by Professor Ian McAulay.

Finally, the authors wish to acknowledge the contribution from the RPII staff that provided analytical support (laboratory analysis).
9 References

AEA, 1993. Unpublished data


European Commission, 1999b. Investigation of a possible basis for a common approach with regard to the restoration of areas affected by lasting radiation exposure as a result of past or old practice or work activity. Radiation Protection 115. Luxembourg: European Commission.


European Commission, 1999d. Establishment of reference levels for regulatory control of workplaces where materials are processed which contain enhanced levels of naturally-occurring radionuclides. Radiation Protection 107. Luxembourg: European Commission.


European Commission, 2001b. Radiological considerations with regard to the remediation of areas affected by lasting radiation exposure as a result of a past or old practice or work activity. Radiation Protection 124. Luxembourg: European Commission.


Hartney, Th., 2005. Personal communication.


ICRP, 1996. **Age-dependent doses to the members of the public from intake of radionuclides. Part 5 Compilation of ingestion and inhalation coefficients.** Annals of the ICRP, 26(1), Publication 72, International Commission on Radiological Protection.


McCarthy, F., Electricity Supply Board, personal communication.


NORM IV (Szczyrk, Poland, 16-21 May, 2004), IAEA-TECDOC-1472, Vienna: International Atomic Energy Agency.


10 Glossary of Terms

**Absorbed Dose**
Quantity of energy imparted by the ionising radiation to unit mass of matter such as tissue. It is measured in grays (Gy). One Gy produces different biological effects on tissue depending on the type of radiation (alpha, beta or gamma).

**Activity**
Activity is a measure of the rate at which nuclear disintegration occurs. The unit of activity is the becquerel (Bq). One Bq is equivalent to one disintegration per second.

**Collective Effective Dose**
Total dose over a population group exposed to a given source. It is represented by the product of the average effective dose to the individuals in the group by the number of persons comprising the group. It is measured in man sieverts (manSv).

**Committed Effective Dose**
Total dose gradually delivered to an individual over a given period of time by the decay of a radionuclide following its intake into the body. The integration time is usually taken as 50 years for adults and 70 years for children.

**Effective Dose**
Weighted sum of the equivalent doses to the various organs and tissues. The weighting factor for each organ or tissue takes account of the fractional contribution of the risk of death or serious genetic defect from irradiation of that organ or tissue to the total risk from uniform irradiation of the whole body. The unit of effective dose is the sievert (Sv).

**Equivalent Dose**
The quantity obtained by multiplying the absorbed dose by a factor representing the different effectiveness of the various types of radiation in causing harm to tissues. It is measured in sieverts (Sv). One Sv produces the same biological effect irrespective of the type of the radiation.

**Half-life**
The time taken for the activity of a radionuclide to lose half its value by decay.

**Radionuclide**
An unstable nuclide that emits ionising radiation. The emissions may be either alpha, beta or gamma radiation.

**Radiotoxicity**
A measure of the dose per becquerel resulting from the ingestion of a particular radionuclide.
Appendix A

Amount of radioactivity discharged by the stack of the studied coal-fired power plant used to estimate the radiological impact of the atmospheric discharges.

Collecting the alpha and beta terms marked in the table below (symbols $¥$ and $¶$, respectively) and allowing for the polonium (Po) and lead (Pb) enhancements on the smaller emitted particles (factor 20 and 10, respectively), the activity emitted was calculated as follows:

**Total alpha activity:**

- In the $^{232}$Th series:
  - 6 alpha $\rightarrow$ 6 x 53 Bq/kg
- In the $^{238}$U series – above radon:
  - 4 alpha $\rightarrow$ 4 x 134 Bq/kg
- In the $^{238}$U series – below radon:
  - 3 alpha, including $^{210}$Po (enriched 20 times) $\rightarrow$ 2 x 92 + 1 x (92x20) Bq/kg
- In the $^{235}$U series:
  - 7 alpha $\rightarrow$ 7 x 6 Bq/kg
- In the $^{40}$K series:
  - 0 alpha

Therefore, total alpha = $6 \times 53 + 4 \times 134 + 2 \times 92 + 1 \times (92 \times 20) + 7 \times 6 = 2920$ Bq/kg of ash emitted

**Total beta activity:**

- In the $^{232}$Th series:
  - 5 beta $\rightarrow$ 5 x 53 Bq/kg
- In the $^{238}$U series – above radon:
  - 2 beta $\rightarrow$ 2 x 134 Bq/kg
- In the $^{238}$U series – below radon:
  - 4 beta, including $^{210}$Pb (enriched 10 times) $\rightarrow$ 3 x 92 + 1 x (92x10) Bq/kg
- In the $^{235}$U series:
  - 5 beta $\rightarrow$ 5 x 6 Bq/kg
- In the $^{40}$K series:
  - 1 beta $\rightarrow$ 1 x 650 Bq/kg

Therefore total beta = $5 \times 53 + 2 \times 134 + 3 \times 92 + 1 \times (92 \times 10) + 5 \times 6 + 1 \times 650 = 2409$ Bq/kg of ash emitted.
Single underlined: measured radionuclide and measured activity concentrations (in Bq/kg) in the coal fly ash [McAulay, 1986 and 1988], see Table 6.

Double underlined: radionuclide activity concentrations used in the ESB model (calculated on the basis of measurements by McAulay [1986 and 1988] plus 1.65 standard deviation, see Table 6, except for the U-235 series (§) for which the concentrations were estimated on the basis of the ratio of natural abundance of uranium isotopes $^{235}U / ^{238}U = 0.046$. 

α alpha emitters
β beta emitters

................. In the U-238 series, the dotted line symbolises the fact that elements above and below Rn-222 are considered to form two separate equilibrium series.
### Tables

Table 1  Comparison of exclusion / exemption levels (Bq/kg) recommended by the EC and the IAEA for use in NORM industries

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>EC (all types of NORM material)</th>
<th>EC (for wet sludge, from oil and gas industry only)</th>
<th>IAEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238 sec (assumed to be in natural equilibrium with the U-235 chain) §</td>
<td>500</td>
<td>5,000</td>
<td></td>
</tr>
<tr>
<td>Ra-226+</td>
<td>500</td>
<td>5,000</td>
<td></td>
</tr>
<tr>
<td>Pb-210+</td>
<td>5,000</td>
<td>100,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Po-210</td>
<td>5,000</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>Th-232 sec</td>
<td>500</td>
<td>5,000</td>
<td></td>
</tr>
<tr>
<td>Ra-228+</td>
<td>1,000</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>Th-228+</td>
<td>500</td>
<td>5,000</td>
<td></td>
</tr>
<tr>
<td>K-40</td>
<td>5,000</td>
<td>100,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

§ NORM processes do not cause a shifting of the natural isotope relation between U-238 and U-235. The dose contributions of these nuclides are considered in the results for the U-238 chain according to the natural isotope relation between U-328 and U-235. The specific activity of the nuclides of the U-235 chain amounts to 4.6% of the specific activity of the nuclides of the U-238 chain.

Table derived from: [European Commission, 2001a] [IAEA, 2004]. Nuclides for which the progeny is already accounted for in the dose calculations are marked with the sign “+”; when the equilibrium between nuclides of one decay chain is disturbed, the data on activity concentrations refer to the nuclide with the highest individual activity.
Table 2  Specific activity concentrations of radionuclides from the U-238 and Th-232 series, K-40 and Cs-137 measured in peat, peat ash and ash pond effluent samples by gamma spectrometry.

<table>
<thead>
<tr>
<th></th>
<th>U-238</th>
<th>Ra-226</th>
<th>Pb-210</th>
<th>Th-232</th>
<th>K-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Detectable Limit MDL (in Bq/kg)</td>
<td>0.29</td>
<td>0.41</td>
<td>0.05</td>
<td>0.90</td>
<td>0.008</td>
</tr>
<tr>
<td>Raw peat (in Bq/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arriving at plant</td>
<td>3.1±0.7</td>
<td>&lt; MDL</td>
<td>21.6±2.8</td>
<td>&lt; MDL</td>
<td>6.2±5.8</td>
</tr>
<tr>
<td>Arriving at plant</td>
<td>8.4±0.7</td>
<td>6.0±0.5</td>
<td>5.8±0.9</td>
<td>&lt; MDL</td>
<td>&lt; MDL</td>
</tr>
<tr>
<td>In tippler</td>
<td>12.3±2.9</td>
<td>3.6±0.6</td>
<td>31.4±3.6</td>
<td>&lt; MDL</td>
<td>6.6±3.0</td>
</tr>
<tr>
<td>In bunker</td>
<td>8.5±1.8</td>
<td>1.6±0.3</td>
<td>43.5±5.3</td>
<td>&lt; MDL</td>
<td>&lt; MDL</td>
</tr>
<tr>
<td>Dust sampled in bunker</td>
<td>7.1±1.6</td>
<td>3.2±0.5</td>
<td>27.4±3.3</td>
<td>&lt; MDL</td>
<td>&lt; MDL</td>
</tr>
<tr>
<td>Average (rounded up)</td>
<td>8</td>
<td>4</td>
<td>26</td>
<td>1 (assumed)</td>
<td>7</td>
</tr>
<tr>
<td>Peat fly ash (in Bq/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (rounded up)</td>
<td>36.7±4.1</td>
<td>4.4±0.6</td>
<td>357.4±39.3</td>
<td>11.1±1.3</td>
<td>70.2±3.5</td>
</tr>
<tr>
<td>Peat bottom ash (in Bq/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average (rounded up)</td>
<td>342.0±17.1</td>
<td>81.0±4.4</td>
<td>17.8±2.0</td>
<td>&lt; MDL</td>
<td>7.9±0.9</td>
</tr>
<tr>
<td>Effluent ash pond (in Bq/l)</td>
<td>0.31±0.3</td>
<td>&lt; MDL</td>
<td>7.4±1.0</td>
<td>&lt; MDL</td>
<td>&lt; MDL</td>
</tr>
</tbody>
</table>

Errors quoted are the counting uncertainties at one standard deviation from the mean count.
Table 3  Activity concentrations (Bq/kg) of radionuclides in other NORM materials and in Irish soils.

<table>
<thead>
<tr>
<th></th>
<th>U-238</th>
<th>Ra-226</th>
<th>Pb-210</th>
<th>Th-232</th>
<th>K-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw peat - Finland (1)</td>
<td>16</td>
<td>11</td>
<td>30</td>
<td>6</td>
<td>28</td>
</tr>
<tr>
<td>Coal – UK average (2)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>7.5</td>
<td>144</td>
</tr>
<tr>
<td>Peat fly ash – various Irish peat-fired plants (3)</td>
<td>133</td>
<td>71</td>
<td>7</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>121</td>
<td>11</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td></td>
<td>74</td>
<td>68</td>
<td>14</td>
<td>263</td>
<td></td>
</tr>
<tr>
<td></td>
<td>121</td>
<td>127</td>
<td>8</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>31</td>
<td>10</td>
<td>153</td>
<td></td>
</tr>
<tr>
<td>Coal fly ash – UK average (2)</td>
<td>100</td>
<td>100</td>
<td>100-200</td>
<td>50</td>
<td>900</td>
</tr>
<tr>
<td>Irish soils - Average (4)</td>
<td></td>
<td>46</td>
<td></td>
<td>25</td>
<td>418</td>
</tr>
<tr>
<td>Peaty soils - Donegal (5)</td>
<td>79 (3-788)</td>
<td>104 (4-479)</td>
<td>35 (3-135)</td>
<td>526 (8-1088)</td>
<td></td>
</tr>
<tr>
<td>Other NORM materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite (6)</td>
<td></td>
<td>78</td>
<td></td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Bauxite (7)</td>
<td>250</td>
<td></td>
<td>200</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Red mud (8)</td>
<td>260-540</td>
<td>340-500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red mud (9)</td>
<td>250</td>
<td></td>
<td>300</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Phosphate ore (7)</td>
<td>40-4800</td>
<td>7-110</td>
<td>10-230</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphogypsum (10)</td>
<td>1000</td>
<td></td>
<td></td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Zircon sands (7)</td>
<td>&gt;500</td>
<td></td>
<td></td>
<td>&gt;500</td>
<td></td>
</tr>
</tbody>
</table>

Table derived from: (1) [Mustonen and Jantunen, 1985], (2) [Smith et al., 2001], (3) [Finch, 1998], (4) [Marsh, 1991], (5) [O’Dea and Dowdall, 1999], (6) [Von Philipshorn and Kuhna st, 1992], (7) [IAEA, 1996b], (8) [European Commission, 2001a], (9) [Hofmann et al., 2000], (10) [O’Grady, 1992].
Table 4  Maximum (with no respiratory protective equipment) effective dose from inhalation of airborne peat dust (total fraction) in the bunker area.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Ra-226</th>
<th>Pb-210</th>
<th>Po-210</th>
<th>Ra-228</th>
<th>Th-228</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity concentration in the peat dust §</td>
<td>3.2</td>
<td>27.4</td>
<td>27.4</td>
<td>1</td>
<td>1</td>
<td>Bq/kg</td>
</tr>
<tr>
<td>Dust concentration ¥</td>
<td></td>
<td></td>
<td>25.6</td>
<td></td>
<td></td>
<td>mg/m³</td>
</tr>
<tr>
<td>Ambient air activity concentration c, †</td>
<td>8.2x10⁵</td>
<td>7.0x10⁻⁴</td>
<td>7.0x10⁻⁴</td>
<td>2.6x10⁻⁵</td>
<td>2.6x10⁻⁵</td>
<td>Bq/m³</td>
</tr>
<tr>
<td>Inhalation dose factor g_{inh,r}, #</td>
<td>1.2x10⁵</td>
<td>1.1x10⁶</td>
<td>2.2x10⁻⁶</td>
<td>1.7x10⁻⁶</td>
<td>3.2x10⁻⁵</td>
<td>Sv/Bq</td>
</tr>
<tr>
<td>c_r x g_{inh,r}</td>
<td>9.8x10⁻¹⁰</td>
<td>7.7x10⁻¹⁰</td>
<td>1.5x10⁻⁹</td>
<td>4.4x10⁻¹¹</td>
<td>8.2x10⁻¹⁰</td>
<td>Sv/m³</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.2x10⁻⁹</td>
</tr>
<tr>
<td>Exposure duration t_{exp}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Breathing rate B ‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.18</td>
</tr>
<tr>
<td>t_{exp} x B x \sum (c_r x g_{inh,r})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>

§ See Table 2. Pb-210 and Po-210 are assumed to be in equilibrium; Ra-228 and Th-228 are assumed to be in equilibrium with Th-232.

¥ Dust concentration is equal to (A/V) where A is the amount of peat dust breathed in during an 8-h shift (23.78 mg) and V is the flow rate of the pump used for the experiment (2 l/min) multiplied by the duration of the experiment (465 min) and divided by 1000.

† Equals to the product of the activity concentration in the peat dust by the dust concentration.

# AMAD 5 μm [ICRP, 1994].

‡ [Smith et al., 2001].
Table 5  Summary of the occupational radiation doses calculated at the studied peat-fired power plant.

<table>
<thead>
<tr>
<th>Location and exposure duration</th>
<th>Dust inhalation (µSv)</th>
<th>External gamma radiation (µSv)</th>
<th>Total dose (rounded up) at given location for given exposure duration (µSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tippler / 100 h/y</td>
<td>Undetermined</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Bunker / 100 h/y</td>
<td>0.5</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Boiler area / 680 h/y</td>
<td>Undetermined</td>
<td>19.8</td>
<td>20.0</td>
</tr>
<tr>
<td>Inactive bottom ash pile / 50 h/y</td>
<td>Undetermined</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Active bottom ash pile / 500 h/y</td>
<td>Undetermined</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Wet ash pond / 400 h/y</td>
<td>Undetermined</td>
<td>7.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Maintenance duties / 170 h/y</td>
<td>Undetermined</td>
<td>Undetermined</td>
<td>undetermined</td>
</tr>
<tr>
<td>Total exposure = 2000 h/y</td>
<td></td>
<td></td>
<td>49 µSv/y</td>
</tr>
</tbody>
</table>
### Table 6  Activity concentrations (Bq/kg dry weight) of radionuclides measured in samples collected at the studied coal-fired power plant

<table>
<thead>
<tr>
<th></th>
<th>U-238</th>
<th>Ra-226</th>
<th>Pb-210</th>
<th>Th-232</th>
<th>K-40</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal (1) - 16 samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 (5-45)</td>
<td>30 (6-67)</td>
<td>8 (2-13)</td>
<td>61 (20-100)</td>
<td></td>
</tr>
<tr>
<td><strong>PFA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) – 5 samples</td>
<td>120</td>
<td>134</td>
<td>53</td>
<td>650</td>
<td></td>
</tr>
<tr>
<td>(2) – 4 samples</td>
<td>116</td>
<td>118</td>
<td>69</td>
<td>545</td>
<td></td>
</tr>
<tr>
<td>This study – 5 samples</td>
<td>269 (172-317)</td>
<td>305 (254-387)</td>
<td>80 (40-107)</td>
<td>377 (191-625)</td>
<td></td>
</tr>
<tr>
<td><strong>Bottom ash</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) – 2 samples</td>
<td>78</td>
<td>80 (60-100)</td>
<td>38 (29-47)</td>
<td>240 (180-300)</td>
<td></td>
</tr>
<tr>
<td>(2) – 4 samples</td>
<td>68 (48-91)</td>
<td>88 (73-94)</td>
<td>48 (39-61)</td>
<td>375 (310-460)</td>
<td></td>
</tr>
<tr>
<td>This study – 2 samples</td>
<td>163 (105-220)</td>
<td>73</td>
<td>366</td>
<td>62 (58-65)</td>
<td>374 (353-394)</td>
</tr>
<tr>
<td><strong>Boiler residues</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This study – 2 samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Effluents (Bq/l)</strong></td>
<td>&lt; 2</td>
<td>&lt; 4</td>
<td>&lt; 1</td>
<td>8.5 (8.1-8.9)</td>
<td></td>
</tr>
<tr>
<td>This study – 2 samples</td>
<td>&lt; 2</td>
<td>&lt; 4</td>
<td>&lt; 1</td>
<td>8.5 (8.1-8.9)</td>
<td></td>
</tr>
<tr>
<td><strong>Building materials (this study)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement with PFA – 1 sample</td>
<td>123</td>
<td>502</td>
<td>25</td>
<td>273</td>
<td></td>
</tr>
<tr>
<td>Cement without PFA – 3 samples</td>
<td>107 (87-128)</td>
<td>1601 (963-1951)</td>
<td>15 (14-17)</td>
<td>232 (210-264)</td>
<td></td>
</tr>
<tr>
<td>Concrete with PFA – 1 sample</td>
<td>73</td>
<td>306</td>
<td>7</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td>Concrete without PFA – 1 sample</td>
<td>62</td>
<td>766</td>
<td>9</td>
<td>205</td>
<td></td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>¶</td>
<td>Maximum values + 1 standard deviation</td>
</tr>
</tbody>
</table>

Table derived from: (1) [McAulay, 1986 and 1988 - unpublished], (2) [AEA, 1993 - unpublished].
Table 7  Activity concentrations (Bq/kg) of radionuclides in coal and PFA as found in the literature

<table>
<thead>
<tr>
<th></th>
<th>U-238</th>
<th>Ra-226</th>
<th>Pb-210</th>
<th>Th-232</th>
<th>K-40</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UK (1)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>7.5</td>
<td>144</td>
</tr>
<tr>
<td>Poland (2)</td>
<td>20-30</td>
<td>15-23</td>
<td>20-26</td>
<td>12-18</td>
<td>106-150</td>
</tr>
<tr>
<td>Brazil (3)</td>
<td>24-35</td>
<td>24-35</td>
<td>24-35</td>
<td>27-48</td>
<td>351-447</td>
</tr>
<tr>
<td>Belgium (4)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>World (5)</td>
<td>10-25</td>
<td>10-25</td>
<td>10-25</td>
<td>10-25</td>
<td></td>
</tr>
<tr>
<td>World (6)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td><strong>PFA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UK (1) – emitted ash</td>
<td>79</td>
<td>57</td>
<td>188</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Poland (2) – trapped ash</td>
<td>38-185</td>
<td>54-119</td>
<td>43-264</td>
<td>47-264</td>
<td>448-758</td>
</tr>
<tr>
<td>Belgium (4) – emitted ash</td>
<td>700</td>
<td>700</td>
<td>2800</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Greece (7) – trapped ash (lignite)</td>
<td>964</td>
<td>904</td>
<td>1158</td>
<td>53</td>
<td>454</td>
</tr>
<tr>
<td>Romania (8) – trapped ash</td>
<td>114-121</td>
<td>77-97</td>
<td>617-729</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hungary (9) – trapped ash</td>
<td>1053-1519</td>
<td>1356-1470</td>
<td>77-97</td>
<td>617-729</td>
<td></td>
</tr>
<tr>
<td>Australia (10) – trapped ash</td>
<td>96</td>
<td>96</td>
<td></td>
<td>170</td>
<td>203</td>
</tr>
<tr>
<td>World (5)</td>
<td>200-400</td>
<td>200-400</td>
<td>200-400</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

Table derived from: (1) [Smith et al., 2001], (2) [Bem et al., 2002], (3) [Flues et al., 2002], (4) [Zeevaert et al., 2006], (5) [UNSCEAR, 2000], (6) [Corbett, 1983], (7) [Karangelos et al., 2004], (8) [Pantelica et al., 2001], (9) [Papp et al., 2002], (10) [Beretka and Mathew, 1985].
Table 8  Annual effective dose from inhalation of radionuclides emitted by the stack of the studied power plant

<table>
<thead>
<tr>
<th></th>
<th>Inhalation dose for the studied power plant (µSv/y)</th>
<th>Inhalation dose in the UK [Smith et al., 2001] (µSv/y) - for comparison purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>1.04·10^{-2}</td>
<td>2.08·10^{-2}</td>
</tr>
<tr>
<td>Pb-210</td>
<td>5.06·10^{-3}</td>
<td>3.28·10^{-3}</td>
</tr>
<tr>
<td>Th-232</td>
<td>7.91·10^{-3}</td>
<td>2.59·10^{-2}</td>
</tr>
<tr>
<td>U-235</td>
<td>2.35·10^{-5}</td>
<td>2.59·10^{-2}</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2.34·10^{-2}</td>
<td>7.58·10^{-2}</td>
</tr>
</tbody>
</table>

* Includes contributions from all members of the $^{238}$U decay chain assumed to be in secular equilibrium.
‡ Includes contributions from $^{210}$Pb and all daughters assumed to be in secular equilibrium.
* Includes contributions from all members of the $^{232}$Th decay chain assumed to be in secular equilibrium.
§ Includes contributions from all members of the $^{235}$U decay chain assumed to be in secular equilibrium.

Table derived from: Smith et al. [2001] Parameters used: exposure duration 8760 h/y; inhalation rate 0.83 m$^3$/h; fraction spent outdoor 0.1 and indoor 0.9; effective dose coefficients for inhalation of radionuclide for adult members of the public, default absorption types used [ICRP, 1996].

Table 9  Radon concentrations in the Irish natural gas extracted from the studied gas field - Grab sampling technique.

<table>
<thead>
<tr>
<th>Measurement date</th>
<th>Concentration (Bq/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/09/03</td>
<td>865</td>
</tr>
<tr>
<td>18/12/03</td>
<td>680</td>
</tr>
<tr>
<td>8/04/04</td>
<td>918</td>
</tr>
<tr>
<td>5/08/04</td>
<td>660</td>
</tr>
<tr>
<td>14/12/04</td>
<td>525</td>
</tr>
<tr>
<td>19/04/05</td>
<td>777</td>
</tr>
<tr>
<td>20/07/05</td>
<td>116</td>
</tr>
<tr>
<td>18/10/05</td>
<td>562</td>
</tr>
</tbody>
</table>
Table 10  Radon concentrations in the Irish natural gas extracted from the studied gas field – 3-month continuous measurements.

<table>
<thead>
<tr>
<th>Measurement period</th>
<th>Concentration (Bq/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/09/03 to 18/12/03</td>
<td>411</td>
</tr>
<tr>
<td>18/12/03 to 8/04/04</td>
<td>270</td>
</tr>
<tr>
<td>8/04/04 to 5/08/04</td>
<td>310</td>
</tr>
<tr>
<td>5/08/04 to 13/12/04</td>
<td>266</td>
</tr>
<tr>
<td>13/12/04 to 19/04/05</td>
<td>259</td>
</tr>
<tr>
<td>19/04/05 to 20/07/05</td>
<td>225</td>
</tr>
<tr>
<td>20/07/05 to 18/10/05</td>
<td>275</td>
</tr>
</tbody>
</table>

Table 11  Radon concentrations in the Irish natural gas extracted from the studied gas field – 8-month continuous measurements.

<table>
<thead>
<tr>
<th>Measurement period</th>
<th>Concentration (Bq/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18/12/03 to 5/08/04</td>
<td>269</td>
</tr>
<tr>
<td>8/04/04 to 13/12/04</td>
<td>228</td>
</tr>
<tr>
<td>5/08/04 to 19/04/05</td>
<td>277</td>
</tr>
<tr>
<td>13/12/04 to 20/07/05</td>
<td>285</td>
</tr>
</tbody>
</table>

Table 12  Radionuclide activity concentrations (Bq/kg dry weight, unless specified) in the two sludge samples collected on the offshore platform (gas extraction industry).

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Sludge A</th>
<th>Sludge B</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>&lt; 0.2</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Ra-226</td>
<td>&lt; 10</td>
<td>5.55±1.78</td>
</tr>
<tr>
<td>Pb-210</td>
<td>2900±65 (wet weight)</td>
<td>130±3 (wet weight)</td>
</tr>
<tr>
<td>Th-232</td>
<td>5.4±0.2</td>
<td>15.7±0.3</td>
</tr>
<tr>
<td>Ra-228</td>
<td>5.0±1.2</td>
<td>15.4±1.2</td>
</tr>
<tr>
<td>Th-228</td>
<td>10.1±0.2</td>
<td>5.4±0.2</td>
</tr>
<tr>
<td>K-40</td>
<td>18.8±4.3</td>
<td>22±3</td>
</tr>
</tbody>
</table>
Table 13  Radionuclide activity concentrations (Bq/ kg dry weight) in samples collected in the bauxite refinery and comparison with other published data.

<table>
<thead>
<tr>
<th>Reference and material</th>
<th>U-238 (maximum)</th>
<th>Th-232 (maximum)</th>
<th>U-235</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>This study</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite slurry</td>
<td>140</td>
<td>120</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Scale top digester</td>
<td>250</td>
<td>260</td>
<td>20</td>
</tr>
<tr>
<td>Scale decanter</td>
<td>40</td>
<td>40</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Red sand</td>
<td>150</td>
<td>170</td>
<td>7</td>
</tr>
<tr>
<td>Red mud</td>
<td>240</td>
<td>460</td>
<td>7</td>
</tr>
<tr>
<td>Liquid effluent (Bq/l)</td>
<td>3</td>
<td>0.3</td>
<td>&lt; 10</td>
</tr>
<tr>
<td><strong>[Von Philipsborn and Kühnast, 1992]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite ore (Sierra Leone)</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Bauxite ore (Boké – Rep. Guinea)</td>
<td>130</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Bauxite ore (Queensland – Australia)</td>
<td>90</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Red mud (unspecified origin)</td>
<td>120</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td><strong>[Beretka and Mathews, 1985]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red mud (Australia)</td>
<td>330</td>
<td>1130</td>
<td></td>
</tr>
<tr>
<td>Red sand (Australia)</td>
<td>50</td>
<td>390</td>
<td></td>
</tr>
<tr>
<td><strong>[FNCA, 2005]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite (Australia)</td>
<td>120</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Red mud (Australia)</td>
<td>400</td>
<td>1300</td>
<td></td>
</tr>
<tr>
<td><strong>[Cooper, 2005]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite (Western Australia)</td>
<td>120-350</td>
<td>450-1050</td>
<td></td>
</tr>
<tr>
<td>Red sand (Western Australia)</td>
<td>5-200</td>
<td>300-800</td>
<td></td>
</tr>
<tr>
<td>Red mud (Western Australia)</td>
<td>150-600</td>
<td>1000-1900</td>
<td></td>
</tr>
<tr>
<td><strong>[European Commission, 2007]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red mud (Hungary)</td>
<td>250-570</td>
<td>260-400</td>
<td>7-11</td>
</tr>
<tr>
<td>Red mud (Bosnia and Herzegovina)</td>
<td>72</td>
<td>190</td>
<td>3</td>
</tr>
<tr>
<td><strong>[European Commission, 2001a]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite</td>
<td>50-500</td>
<td>50-500</td>
<td></td>
</tr>
<tr>
<td>Red mud</td>
<td>260-540</td>
<td>340-500</td>
<td></td>
</tr>
<tr>
<td><strong>[Timmermans and van der Steen, 1996]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite</td>
<td>500</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td><strong>[IAEA, 2003]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite</td>
<td>10-9000</td>
<td>35-1400</td>
<td></td>
</tr>
<tr>
<td>Red mud</td>
<td>100-3000</td>
<td>100-3000</td>
<td></td>
</tr>
<tr>
<td><strong>[Marsh, 1991]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average in Irish soils</td>
<td>46</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
Table 14  Range of doses to workers and members of the public from each of the four industries reviewed in this report.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Workers</th>
<th>Members of the public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat-fired power production</td>
<td>• 50 μSv/y from all exposure pathways except maintenance duties not investigated</td>
<td>• less than 300 μSv/y from exposure to building materials containing peat ash used in house construction</td>
</tr>
<tr>
<td></td>
<td>• less than 300 μSv/y for workers involved in manufacture of building materials (concrete and cement) containing peat ash</td>
<td>• effluents would be exempted if peat-fired power production was considered a practice</td>
</tr>
<tr>
<td>Coal-fired power production</td>
<td>• less than 300 μSv/y from exposure to boiler residues when carrying out maintenance duties</td>
<td>• less than 300 μSv/y from exposure to building materials containing coal ash used in house construction</td>
</tr>
<tr>
<td></td>
<td>• less than 300 μSv/y for workers involved in manufacture of building materials (concrete and cement) containing coal ash</td>
<td>• 20 nSv/y from atmospheric emissions through the stack (radon, total alpha and total beta)</td>
</tr>
<tr>
<td></td>
<td>• for other exposure scenarios, see NRPB report [Smith et al., 2001]</td>
<td>• effluents would be exempted if coal-fired power production was considered a practice</td>
</tr>
<tr>
<td>Natural gas extraction</td>
<td>• less than 100 μSv/y from exposure to sludge residues (maintenance duties)</td>
<td>• 8 μSv/y received by domestic gas users (from inhalation of radon contained in gas supplies)</td>
</tr>
<tr>
<td></td>
<td>• no other significant exposures (all measurements below background)</td>
<td></td>
</tr>
<tr>
<td>Bauxite refining</td>
<td>• 300 to 600 μSv/y for workers involved in bauxite residue (red mud) management</td>
<td>• less than 300 μSv/y (from effluents and bauxite residue disposal area)</td>
</tr>
<tr>
<td></td>
<td>• no other significant exposures (all measurements below background)</td>
<td></td>
</tr>
</tbody>
</table>
Figures

Figure 1  Uranium 238 decay series.

Figure 2  Thorium 232 decay series.
1. Incoming milled peat from the bog – two peat samples
2. Peat in tippler – one peat sample and one gamma dose rate measurement
3. Peat in bunker – two peat samples, two gamma dose rate measurements and one air sampling test
4. Boiler area - two gamma dose rate measurements
5. Dry bottom ash pile – four ash samples and two gamma dose rate measurements
6. Stack
7. Fly ash – two ash samples
8. Wet ash pond – one gamma dose rate measurement
9. Effluent from the ash pond – two samples
10. Control site (small church at the main entrance of the plant) – one gamma dose rate measurement

---

> peat and ash movement through the process
Figure 4  Coal combustion cycle at the studied coal-fired power plant. (The numbers refer to the types of samples analysed - see next page)

Gaseous Pb and Po escape in the gas flue and progressively condense attached on fly ash particles

1\textsuperscript{st} GENERATION LOW-NO\textsubscript{x} BOILER Pb/Po volatilisation

Pulverised coal (2x10\textsuperscript{6} t/y or 315 t/h)

\textbf{Bottom Ash} (15% of total ash) (landfilled at rate of 3x10\textsuperscript{4} t/y or 3.4 t/h)

\textbf{ESP} 99.5\% of PFA trapped (17x10\textsuperscript{4} t/y or 19.4 t/h)

0.5\% of PFA not trapped

\textbf{Trapped PFA} 1x10\textsuperscript{6} t/y sold, 7x10\textsuperscript{4} t/y landfilled

\textbf{Landfill}

\textbf{Effluent}

\textbf{Atmospheric discharges} (finest particles/near gaseous form at approximately 1.1x10\textsuperscript{6} m\textsuperscript{3}/h)

Dispersion, Dilution, Deposition, Inhalation/Ingestion

\textbf{Bottom Ash} (15\% of total ash)
Legend for Figure 4
1. pulverised coal samples – results from 1986 and 1988 unpublished data (16 samples)
2. bottom ash samples – results from 1986, 1988 and 1993 unpublished data (6 samples)
3. two samples of boiler residues – this study
4. PFA - results from 1986, 1988 and 1993 (unpublished data – 9 samples) and from this study (5 samples)
5. building materials: four samples of cement (one with, three without PFA) and two samples of concrete (one with, one without PFA) – this study
6. two samples of the runoff from the coal ash landfill – this study
7. atmospheric discharges – unpublished results from 1986-1990 model study

Figure 5  Radon levels measured in the Irish natural gas.

![Graph showing radon levels measured in the Irish natural gas.](image-url)
Mission Statement

In the three year period from 2008 to 2010 the RPII will grow the level of awareness and implementation of the measures needed to protect people in Ireland from the harmful effects of ionising (and non-ionising radiation) through scientifically based regulation, monitoring and advice.

Contact us

Radiological Protection Institute of Ireland (RPII)
3 Clonskeagh Square
Dublin 14,
Ireland
Tel:   +353 1 2697766
Fax:  +353 1 2697437
Email: rpii@rpii.ie
Web:  www.rpii.ie