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ASSESSMENT OF THE RADIOLOGICAL IMPACT OF COAL-FIRED POWER STATIONS IN THE UNITED KINGDOM

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ABSTRACT
It is well known that certain materials used and produced in a range of non-nuclear industries contain enhanced activity concentrations of natural radionuclides. As part of its periodic review of radiation doses to the UK population, NRPB has identified the need to estimate the doses received by members of the public as a result of the operation of these industries in the UK. As part of an ongoing study NRPB has performed a radiological assessment of discharges from the coal-fired electricity generating industry in the UK. Various pathways by which people could be exposed were considered in the assessment. These included discharges of fly ash and radon to the atmosphere, disposal of fly ash and recycling of fly ash in various products. Individual and collective doses to the UK population were calculated for these various routes of exposure using models developed for the assessment of discharges from the nuclear industry. The preliminary results are presented and the implications discussed.

INTRODUCTION
Certain materials used and produced in a range of non-nuclear power industries contain enhanced activity concentrations of natural radionuclides. As part of its periodic review of radiation doses to the UK population, NRPB has identified the need to estimate the doses received by members of the public as a result of the operation of these industries in the UK and has therefore initiated a study in this area. The aim of the study is to give a broad indication of the total radiological impact of each of the relevant industries. To achieve this end the study will involve identifying appropriate exposure scenarios for each of the relevant industries, considering both the primary industry, the waste streams produced and, where applicable, the use of by-products, and then determining the levels of radiation exposure from each scenario, including, as appropriate, individual and collective doses. The first industry to be considered in this study is the coal-fired power industry. Previous NRPB assessments of the radiological impact of coal-fired power stations[1,2] were concerned solely with the consequences of releases of fly ash to atmosphere. This work includes consideration of additional exposure scenarios arising from the disposal and use of fly ash. The preliminary results for coal-fired power stations are presented herein.

Coal-fired electricity generating industry in the UK
There are currently 23 coal-fired power stations operating in the UK[3], with operating capabilities between 230 and 3800 MWe with most in the range 1000 to 2000 MWe. The majority are operated by three companies: PowerGen, National Power and Eastern Generation. Coal still has the largest share of the fuel market for electricity generation in the UK accounting for just over 40% in 19963.

RADIONUCLIDE CONCENTRATIONS IN ASH
Trace quantities of natural radionuclides occur in coal. During combustion of coal there are various mechanisms by which the concentrations of these radionuclides are enhanced. When coal is burnt the majority of the non-combustible matter remains in the ash. Therefore the radionuclides which are present in the mineral constituents tend to remain in the ash. The ash content of coal varies with source but is typically 15%. Therefore if all radionuclides remained in the ash their activity concentrations in the ash would be expected to increase by approximately a factor of 7. At the operating temperature of the coal-fired power stations it is possible for some compounds containing radionuclides to be volatilised. These compounds in gaseous form are free to travel with the flue gases until they cool sufficiently to condense. Particles of ash in the gas stream then serve as condensation nuclei for the volatilised species. The result is enhanced

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building materials from reference 25. To determine doses from the radon a ventilation rate of 0.5 h^{-1} was assumed. Exposures from external irradiation were determined using data in reference 26.

RESULTS

The preliminary results of the study are presented in Table 2. These indicate that the highest doses are received as a result of the use of fly ash in building materials. Individual doses from radionuclide releases from the stack are dominated by the consumption of contaminated food-stuffs (dominated by green vegetables and grain). For the ash piles the doses from releases are again dominated by the consumption of contaminated foodstuffs, however, significant contributions to the total dose are also made by direct irradiation from the piles for the critical group and inhalation of radon for typical individuals. The maximum doses from landfill disposal arise as a result of leaching of the radionuclides from the waste and subsequent migration with ground water. As a result of the immobile nature of the radionuclides these peak doses are not predicted to occur until approximately 90 000 years following disposal.

Table 2: **Individual effective doses from releases from reference coal-fired power station.**

Exposure scenario	Total effective dose (Sv y^{-1})	Dominant exposure pathways and radionuclides (% contribution to total effective dose)
Stack releases		
critical group	5.5 10^{-5}	^{210}Pb and ^{210}Po ingestion (99%)
typical	1.1 10^{-6}	^{210}Pb and ^{210}Po ingestion (83%)
Ash piles		
critical group	6.9 10^{-8}	^{210}Pb and ^{210}Po ingestion (49%) ^{238}U series and ^{232}Th series direct external (34%)
typical	2.2 10^{-10}	^{210}Pb and ^{210}Po ingestion (62%) ^{220}Rn and ^{222}Rn inhalation (20%)
Landfill disposal		
critical group	1.6 10^{-5}	^{232}Th series (56%) and ^{238}U series (44%), radionuclide migration, peak occurring at 9 104 years
Building materials		
critical group	2.5 10^{-4}	^{222}Rn and ^{220}Rn inhalation (96%), external (4%)

SUMMARY

Preliminary results of a study to investigate the radiological consequences to the UK population of coal-fired power stations have been presented above. Additional work will include a more detailed analysis of assumptions made in the assessment of doses from ash piles and further investigation of the radiological consequences of the use of fly ash in building materials. Collective doses to the UK population for each exposure pathway will also be evaluated.

This work forms part of a broad study to assess the radiological impact on the UK population of non-nuclear industries within the UK involved in the production or processing of materials containing enhanced levels of naturally occurring radionuclides. Currently there is much interest in developing regulatory approaches for these industries. It is hoped that the results of this study will also provide useful background information to inform discussions in this area.

Atmospheric releases from the stack and ash piles

The exposure pathways considered for the release to atmosphere from the stack and ash piles were: inhalation of radionuclides in the plume; external irradiation by radionuclides in the plume; external irradiation by radionuclides from the plume deposited on the ground; inhalation of radionuclides resuspended from ground deposits and the ingestion of food grown on land contaminated by deposited radionuclides. For the ash piles direct external irradiation from the piles was also considered. The general methodology adopted was developed for use in the assessment of the radiological impact of radionuclide releases from the nuclear industry. Concentrations of radionuclides in air and deposited on land were determined using the ADMS model[15] and PLUME (part of the PC-CREAM[16] suite of codes). The assumed stack height was 200 m, however, the effective release height is greater because of the continued vertical rise of the plume due to the initial buoyancy and momentum of the flue gases. Predictions of plume rise indicate an effective release height in the range of 300 to 500 m[2]. For this study an effective release height of 300 m was assumed. Effective doses from external irradiation by radionuclides in the plume were determined using PLUME. Effective doses from inhalation, external irradiation by radionuclides deposited on the ground and ingestion of contaminated food were determined using elements of the PC-CREAM[16] suite of codes (RESUS and GRANIS) and the NRPB terrestrial foodchain model FARMLAND[17]. Effective doses from external irradiation by the ash piles were determined using the code QAD-CGP[18], assuming that the ash has buildup and attenuation characteristics approximately the same as concrete, with an assumed density of 0.75 tm^{-3}. Individual doses to two groups were considered, typical individuals and the critical group. The habits of the typical exposed individual were based on the assumptions described in references 19 and 20. It was assumed that an adult lives 5 km from the stack or piles and is inside for 10% and outside for 90% of the year at that location. It was further assumed that they consume all foodstuffs at average rates and obtain 25% of their food from the local area. The assumptions used to characterise the typical critical group member were based on those described in reference 21. The individual was assumed to live 500 m from the stack or ash piles and to be outside for 50% and inside for 50% of the year at that location. They were further assumed to obtain all food from local sources eating the two most significant foodstuffs at critical rates and all others at average rates.

Disposal of ash to landfill

A significant proportion of the ash produced by coal-fired power stations in the UK is disposed of in landfills. Exposure of members of the public from radionuclides in the disposed ash can occur in two principal ways. Leaching of radionuclides from the waste into groundwater will occur over time. Radionuclides will then migrate from the landfill in the groundwater, leading to their distribution in the environment from where they may expose individuals by various routes. It is also possible that individuals may be exposed to the radionuclides in the ash following intrusion into the landfill, for example, during the construction of foundations for buildings. For this study it has been assumed that the ash is placed in a basic landfill of the type typically used in the UK for inert industrial wastes, which has no lining and limited capping (0.5 m of soil). The implications of this are that water may enter the landfill relatively easily. Such landfills usually cover a substantial area as the trenches are generally shallow. The landfill has therefore been assumed to have a capacity of 5 10^6 m^3, cover an area of 100 ha and have an average depth of 5 m. The methodology adopted for determining the radiological consequences of ash disposal in such a facility has been described elsewhere[22].

Exposure from building products

A proportion of the ash produced by coal-fired power stations in the UK is sold and used in the production of building materials. It is used mainly as a constituent of cement or a light weight filler for concrete. To assess the radiological consequences of the use of ash in building materials it was assumed that an individual lived in a house constructed of such materials and spent 90%[20] of their time in the house. The proportion of ash used in building materials varies, generally between 5 and 30%[23], depending on the detailed specifications. For this study it was assumed that the building material was 25% ash by mass, a typical value for cement[24]. Two exposure pathways were considered: external irradiation from radionuclides contained in the building structure and the inhalation of radon emanating from the walls. In both cases only the doses arising from the presence of radionuclides originating in the ash were evaluated. The rate of exhalation of radon from the walls of the building was calculated using the general approach described in reference 14, using diffusion coefficients and emanating fractions appropriate for activity concentrations of some radionuclides on fly ash. This effect is most commonly associated with lead and polonium isotopes (boiling points of 1740 and 962 °C respectively). Relatively little enhancement by volatilisation has been reported for other elements[4]. However it has been suggested that significant fractions of uranium and thorium isotopes are volatilised[5]. For lead and polonium isotopes in fly ash measured enhancement factors in relation to ^{226}Ra of between 3 and 5 have been widely reported[4,6]. This variation arises in part because the effects described above are dependent on the operational characteristics of a plant, such as operating temperature. It is also not clear for some studies whether the fly ash analysed was a sample from that released to atmosphere or collected from precipitators. It is possible that the distribution of particle sizes would be different for these two sample types and it has been noted that activity concentrations vary with particle size[6,7]. The actual concentrations of radionuclides in the fly ash released to atmosphere for a particular plant will vary significantly depending upon the initial radionuclide concentrations in the coal and the enhancement mechanisms discussed above. For this study the radionuclide concentrations used were based on recent measurements of samples of fly ash released to atmosphere from UK power plants. On the basis of this data the following concentrations were assumed: ^{238}U series to ^{226}Ra 100 Bq kg^{-1} (each), ^{210}Pb and ^{210}Po 200 Bq kg^{-1} (each) (an enhancement factor of 2), ^{232}Th series 50 Bq kg^{-1} (each) and ^{235}U series 5 Bq kg^{-1} (each).

RADIOLOGICAL ASSESSMENT

The radiological consequences to members of the public of the following exposure pathways have been assessed: releases to atmosphere from the stack, releases to atmosphere from ash piles, the use of ash in building materials, and the disposal of ash in landfills. In order to determine the maximum individual doses which may be received from stack releases a reference plant with the highest UK operating capacity of approximately 4000 MWe was considered.

Radionuclide release terms

On the basis of information on operating characteristics of UK coal-fired power stations[9,10,11] it was assumed that the plant operated at a load factor of 80%, producing 2.8 10^4 GWhy^{-1}, consuming 1 10^7 ty^{-1} of coal and generating 1.7 10^6 ty^{-1} of ash. It was further assumed that 8 10^3 ty^{-1} of ash was released to atmosphere, about 0.5% of the total ash produced. On the basis of the quantity of ash released to atmosphere and the radionuclide concentrations discussed above annual releases were estimated for the majority of the radionuclides. Releases of radon were determined assuming that all the radon in the coal is released. Radionuclide concentrations in the coal were derived from the concentrations in fly ash discussed above assuming an average ash fraction of 16.5%[9,10,11]. The assumed releases used in the study are presented in Table 1.

***Table 1:* Estimated stack emissions of radionuclides from reference coal-fired power station.**

Radionuclide	Stack Release (Bqy^{-1})
^{238}U series to ^{226}Ra	8.0 10^8 each
^{210}Pb and ^{210}Po	1.6 10^9 each
^{232}Th series	4.0 10^8 each
^{235}U series	4.0 10^7 each
^{222}Rn	1.7 10^{11}

Large piles of ash are often stored close to power stations awaiting disposal or sale. In order to determine atmospheric releases from such piles it has been preliminarily assumed that 1 10^5 m^3 of ash is stored on site. This pile is assumed to be on average 10 m deep and have a surface area of approximately 1 10^4 m^2. Annual releases of the majority of radionuclides were determined assuming a concentration of resuspended ash above the piles of approximately 1 10^{-7} kg m^{-3} [12]. Annual radon releases were determined from rates of radon exhalation by diffusion determined using a method described in reference 13. The exhalation rate depends on two parameters, the emanating fraction and the diffusion coefficient. Although these parameters have been studied extensively for building materials few data are available for fly ash piles. An emanating fraction of 5.4 10^{-3} was used based on data in reference 14. The diffusion coefficient was assumed to be 5 10^{-6} m^2 s^{-1}, based on the value for typical soil[4].

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