THE RADIOLOGICAL IMPACT OF COAL-FIRED ELECTRICITY GENERATION IN THE UK

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1 ABSTRACT

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 United Kingdom population, the National Radiological Protection Board has identified the need to estimate the doses received as a result of the operation of these industries in the UK. As part of this overall study an assessment of the radiological impact of coal-fired electricity generation has been carried out. Various exposure pathways were considered in the assessment. These included: discharges of ash and radon to atmosphere; disposal of ash; and the use of ash in the production of building materials. Predicted peak individual doses from atmospheric releases via stack are 1.5 μSv y^{-1} for a typical member of the hypothetical critical group and 0.1 μSv y^{-1} for "average" individuals living in the local area. The predicted doses to power station workers, landfill workers, and workers manufacturing and using building materials containing ash are, respectively, 10 μSv y^{-1}, 5 μSv y^{-1}, 35 μSv y^{-1}, and 13 μSv y^{-1}. The predicted radon concentration in buildings constructed from materials containing ash, originating from radionuclides within the structure, is 12 Bq m^{-3}. The predicted dose from inhalation of this radon is about 570 μSv y^{-1}. The predicted external dose to an individual living in a home constructed from building materials containing ash is about 900 μSv y^{-1}. The predicted peak individual risk from landfill disposal of ash is 4.2 10^{-8} y^{-1}.

Under UK legislation there are no radiological controls on the operation of coal-fired power stations, or restrictions on how waste is discharged (to the atmosphere, to landfill or being sold) which relate to its radionuclide content. With one exception this position seems entirely consistent with the low radiological impact of the industry as presented here and is also consistent with developing European Community (EC) guidance in this area. The principal exception to this is the use of ash in building materials where EC guidance indicates that future restrictions may be required

2 INTRODUCTION

All types of coal contain small levels of natural radionuclides. Combustion of coal in a coal-fired power station results in both the release of gaseous radionuclides, and the production of ash that has enhanced concentrations of natural radionuclides relative to those of coal. A fraction of the ash that is formed is released to atmosphere. The remaining ash is disposed to landfill or used in the manufacture of various products, principally for the construction industry. A study has been undertaken to assess the radiological impact of coal-fired electricity generation in the UK(1). The radiological impact of releases to atmosphere, the management and disposal of ash and the use of ash in the construction industry have all been considered.

3 PRODUCTION OF ASH

A portion of the ash produced falls to the bottom of the furnace (bottom ash). Smaller, lighter particles escape with the off gases (fly ash). These are removed from the gas stream by a range of methods, the most commonly applied being electrostatic precipitators. The bottom ash and collected fly ash are disposed to landfill or used in the manufacture of various products, primarily for the construction industry. A small fraction of fly ash is released to atmosphere through the stack. In 1998 a total of 7.4 million tonnes of ash were produced in the UK, of which approximately 51% (3.7 million tonnes) was sold and 49% (3.5 million tonnes) sent to landfill. Approximately 30,000 tonnes of ash was released to atmosphere.

4 RADIONUCLIDE CONTENT OF ASH

Coal contains trace quantities of ^{238}U, ^{235}U, ^{232}Th and their daughters and ^{40}K. When coal is burnt the majority of the non-combustible matter remains in the ash. Therefore radionuclides, which are present in the mineral constituents, tend to remain in the ash. The average ash content of coal used in the UK is around 16% (range 10% to 20%). Therefore, if all radionuclides remain in the ash, their activity concentration in the ash may be expected to increase by the reciprocal of this fraction, 6.25. At the operating temperature of coal-fired power stations it is possible for compounds containing some radionuclides to become volatilised. These compounds, in gaseous form, are free to travel with 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 activity concentrations of some radionuclides in ash released to atmosphere. This effect is most commonly associated with lead and polonium isotopes. The actual levels of enhancement of radionuclide concentrations in ashes are very variable because the effects described above are determined by the operational characteristics of a plant. For example, reported values for the concentrations of ^{210}Pb and ^{210}Po in fly ash are typically three to five times greater than those of ^{238}U and ^{226}Ra(2,3,4,5). A large number of analyses of the radionuclide content of both bottom ash and fly ash have been reported in the literature. Some of the measurements of ash, principally fly ash, indicate, as mentioned above, enhanced levels of ^{210}Pb and ^{210}Po in relation to other members of the ^{238}U decay chain(2,6,7), whilst others show no such enhancement or a deficit(4,8,9). This variation is to be expected, as enhancement in some ash fractions must, by mass balance arguments, lead to a deficit in other fractions. The conclusion of this argument is that, on average, the radionuclide concentrations in the ash sent to landfill will show no enhancement of particular radionuclide concentrations, that is, the mean radionuclide concentrations are simply those in coal divided by the ash fraction. Although the literature reports a large number of measurements of the radionuclide content of ash produced within a coal-fired power station, relatively few measurements have been taken of the ash emitted to atmosphere. A number of analyses of the radionuclide content of ash emitted to atmosphere from UK coal-fired power stations have, however, been commissioned by the Environment Agency(10).The results of these analyses are presented in Table 1.

Table 1: Measured concentrations of radionuclides in ash emitted to atmosphere from UK coal-fired power stations (from reference 10)

	Radionuclide concentration (Bq kg^{-1})								Mass concentration (g per kg ash)	
Power station	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{235}U	^{232}Th	U	Th
Drax	109.7	121	34.5	53	188	171.3	<3.6	39.6		
Eggborough	84.9	88	30.6	74	125.4	139.8	<1.9	19.1		
Aberthaw	43.3	47.9	38.2	44.3	98	64.2	2.08	28.6		
High Marnham				<200	208	74			9 10^{-6}	1.8 10^{-2}
Drakelow				<200	220	92			1 10^{-5}	2.3 10^{-2}
West Burton				<400	290	158			8 10^{-6}	1.1 10^{-2}

There is variation in both absolute concentrations and concentrations relative to the various radionuclides considered. As discussed above, these differences will be due to both the original radionuclide content of the coal and the operating characteristics of the plant. It is clear, however, that the concentrations of ^{210}Pb and ^{210}Po are enhanced in relation to those of ^{238}U by between a factor of approximately 1.5 and 2.5. This is somewhat lower than the enhancement ratios discussed above. On the basis of these data it was assumed for this study that the concentrations of all radionuclides in the ash emitted to atmosphere in the ^{238}U decay chain to ^{226}Ra would be equal, and that the concentrations of ^{210}Pb and ^{210}Po would be higher by a factor of two. The absolute concentration of ^{238}U in ash assumed in this study is 100 Bq kg^{-1}. For radionuclides in the ^{232}Th decay chain a concentration of 50 Bq kg^{-1} in ash was assumed. The radionuclide concentrations in the ash sent to landfill are the same except no enhancement of lead or polonium was assumed. The radionuclide concentrations of ash assumed in this study are summarised in Table 2.

5 ATMOSPHERIC RELEASES

The source term used for the determination of individual doses from atmospheric releases was evaluated by multiplying the relevant radionuclide concentrations from Table 2 by the maximum quantity of ash released to atmosphere from any single coal-fired power station in 1998, 3.48 ktonnes. The quantity of ^{222}Rn released was determined by assuming that the concentration of ^{222}Rn in the coal is the same as that of the parent radionuclide, ^{226}Ra, and multiplying this concentration by the total quantity of coal burnt per year at the coal-fired power station emitting the largest quantity of ash to atmosphere in 1998 (ie 9.28 10^6 tonnes of coal).

Table 2: Assumed concentrations of radionuclides in ash and coal

	Radionuclide concentration Bq kg^{-1}				
Material	^{238}U series ^{238}U to ^{226}Ra	^{238}U series ^{210}Pb and ^{210}Po	All radionuclides in ^{235}U series	All radionuclides in ^{232}Th series	^{40}K
Ash to atmosphere	100	200	5	50	
Ash to landfill	100	100	5	50	
Ash used in building materials	100	200	5	50	900
Coal	15	15	0.75	7.5	144

6 METHODOLOGY

6.1 Atmospheric Releases

An effective release height of 300 m was assumed. Doses to members of the public were assumed to result from five exposure pathways: inhalation of radionuclides in the plume, external irradiation by radionuclides in the plume, inhalation of radionuclides resuspended from a surface deposit, external irradiation by deposited radionuclides, and ingestion of food grown on land contaminated by a deposit of radionuclides. To assess doses from these pathways, the radionuclide concentrations in air, deposition rates and external doses from gamma irradiation from the cloud were calculated using the atmospheric dispersion models ADMS(11) and PLUME (part of the PC CREAM(12) suite of models). Integrated dose rates per unit deposit were calculated for inhalation of resuspended radionuclides, external irradiation and ingestion of food using parts of the PC CREAM suite of models: RESUS, GRANIS, and the NRPB terrestrial foodchain model FARMLAND(13). Two exposed groups were considered: a group intended to represent the average exposure of local people, and a group representative of people who are assumed to be located at a place, and have habits such that they are likely to receive the highest dose from the plant (hypothetical critical group). A full description of the dose calculations and the assumptions made is given in reference 1.

6.2 Landfill disposal

In order to give an indication of the maximum individual risks arising from the disposal of ash produced in a single year (1998), the disposal inventory was determined using the radionuclide concentrations in Table 2 and the maximum quantity of ash disposed to any *single* site in 1998, ie 587,000 tonnes. Following the disposal of radioactive material there are two main scenarios in which exposure to people could occur. The most likely occurrence (migration scenario) is the gradual migration of radionuclides with ground water from the waste through the surrounding rock and soil (geosphere) into the local environment (biosphere). From here, people could be exposed by a wide variety of routes including direct external irradiation from contaminated soil and the consumption of contaminated food. This type of exposure has a probability of occurrence close to unity. The second way (probabilistic scenarios) involves events that disturb the natural evolution of the site, and has a lower probability of occurrence. One example is excavation of the site for development. This study considered the following scenarios for exposure of members of the public: migration, borehole water extraction, excavation during development of the site, and residence on the site. Doses to landfill workers were also determined. For the study, modelling of the migration of radionuclides in the geosphere was performed using GEOS(14) and transfer in the biosphere using BIOS(15), both models were developed at NRPB.

6.3 Production and use of building materials containing ash

Ash is used in the production of a number of building materials. It has been assumed in this study that ash comprises 30% of the building material(16). This is a conservative but not untypical value for the UK. The use of ash in building materials will lead to the exposure of a number of groups. The three most significant, and those considered in this study, are workers manufacturing building products containing ash, workers constructing buildings using these products, and members of the public living in houses built from these materials.

The doses received by individual workers at plants manufacturing building materials will vary depending in detail on their work activities, with the majority receiving trivial doses. The aim of this part of the study was to determine doses typical of those received by the most exposed workers. These workers would typically be those directly involved in the management of ash. It was assumed that workers were exposed by the following pathways: inhalation of ash, inadvertent ingestion of ash, external irradiation from contamination of exposed skin areas, and external irradiation from piles of ash and building materials. Workers constructing buildings will also be exposed by the same pathways. The methodology used for the determination of doses to both sets of workers was developed from that used in previous studies, and is described in more detail in reference 1.

Doses to residents of buildings from radionuclides within the building materials will arise from the following exposure pathways: inhalation of ^{220}Rn and ^{222}Rn and external irradiation. Concentrations of radon in homes and doses from the inhalation of radon were determined using the methodology described in reference 17. Doses from external irradiation were determined using the approach outlined by the EC(18,19). A detailed description of the methodology, assumptions and data used to estimate doses from these pathways is given in reference 1.

6.4 Coal-fired power station workers

The doses received by individual workers at coal-fired power stations will vary depending in detail on their work activities, with the majority receiving trivial doses. The aim of this part of the study was to determine doses typical of those received by the most exposed workers. These workers would typically be those directly involved in the management of ash and would be exposed by the same pathways as those discussed above. The methodology, assumptions and data used for the determination of doses to these workers are described in more detail in reference 1.

7 RESULTS

Predicted individual doses and risks are presented in Tables 3 and 4. Risks are defined as those from cancer or serious hereditary defects, for which ICRP recommends a risk factor of 0.06 Sv^{-1} (20). Predicted peak individual doses from atmospheric releases from the stack are 1.5 μSvy^{-1} for a typical member of the hypothetical critical group and 0.1 μSvy^{-1} for "average" individuals in the area. The hypothetical nature of the critical group characteristics assumed in this study should be stressed at this stage. No consideration has been given to actual distributions of housing or agricultural production around a site. Instead conservative assumptions, such as occupation of a farm 500m from the stack, have been made. It is therefore probable that the predicted doses are overestimates of the actual levels of exposure.

For scenarios involving the use of ash in building materials a number of sets of doses are presented in Table 4: doses from all radionuclides in the building materials containing ash; doses from radionuclides in similar building materials that do not contain ash; and the excess dose due to the use of ash as a component in the building materials. The second set of doses were estimated by making reasonable assumptions about the concentrations of naturally occurring radionuclides in the general constituents of building materials in the UK(18). These three doses allow the overall impact of the use of ash to be evaluated. It is important to note that the assumed concentrations of radionuclides in building materials were based on those for modern composite building materials. The results are clearly dependent upon the assumptions made regarding concentrations of activity in building materials, which can vary significantly, and the use of a 30% ash content. Nevertheless, they serve to provide a useful overall indication of the radiological impact of using ash in building materials.

The additional dose to a worker manufacturing building materials containing ash (as compared to a worker manufacturing building materials that do not) is in the region of 5 μSvy^{-1}. Similarly, the additional dose to workers using materials containing ash is 2 μSvy^{-1} and the additional dose to an individual living in a home constructed from materials containing slag is in the region of 200 μSvy^{-1}

The most exposed workers at a coal-fired power station are estimated to receive a dose of about 10 μSvy^{-1}. The predicted doses to landfill workers are approximately 5 $\mu Sv y^{-1}$.

The predicted peak dose to members of the public from landfill disposal of ash is approximately 130 $\mu Sv\ y^{-1}$ from the excavation scenario. This scenario has, however, a low probability of occurrence giving an individual risk of 5 10^{-9} y^{-1}. The migration scenario gives a predicted peak individual dose of 0.7 $\mu Sv\ y^{-1}$, corresponding to a risk of 4.2 10^{-8} y^{-1}.

Table 3: Peak annual individual doses and risks

Exposure scenario	Exposed group	Peak individual effective dose $\mu Sv\ y^{-1}$	Peak individual risk y^{-1}	Dominant exposure pathways (% contribution to total dose in brackets)
Stack releases	Critical group	1.5 10^{0}	9.0 10^{-8}	Ingestion of food (88%)
	Typical individual	1.1 10^{-1}	6.6 10^{-9}	Plume inhalation (69%)
Landfill disposal	Worker	4.7 10^{0}	2.8 10^{-7}	External irradiation
Power station	Worker	1.0 10^{1}	6.2 10^{-7}	External (90%)

Table 4: Peak annual individual doses from building materials

Component	Individual dose $\mu Sv\ y^{-1}$				
	Manufacturer	Construction worker	Resident Radon	Resident External	Resident Total
Building materials containing ash	35	13	574 (11.6)*	893	1467
Building materials not containing ash	30	11	508 (10.3)*	758	1266
Excess dose from use of ash	5	2	66 (1.3)*	135	201

* Radon concentrations, Bqm^{-3}, in parentheses

8 SUMMARY AND CONCLUSIONS

IAEA has concluded(21) that a level of dose of some tens of microsieverts a year could reasonably be regarded as trivial by regulatory authorities, and recommended the use of a 10 $\mu Sv\ y^{-1}$ dose criterion for the derivation of exemption levels. The maximum predicted doses to members of the public from stack releases are, at approximately 1.5 μSv y^{-1}, significantly lower than the IAEA 'trivial' level. The predicted doses to power station workers, landfill workers, and workers manufacturing and using building materials containing ash are in the range of a few to a few tens of μSv y^{-1}. These are significantly lower than 1 mSv y^{-1}, which EC guidance indicates is the dose level below which regulation is not necessary for workplaces processing materials with enhanced levels of naturally occurring radionuclides(22). The doses are also at or below the IAEA 'trivial' level.

The predicted radon concentration in buildings constructed from materials containing ash, originating from radionuclides within the structure, is approximately 12 Bq m^{-3}. This therefore satisfies EC guidance(18) that the amount of radium in building materials should be restricted at least to a level where it is unlikely that it would be a major cause for exceeding the design level for indoor radon introduced in the EC recommendations (200 Bq m^{-3}). The predicted external dose arising from building materials containing ash is about 900 μSv y^{-1}. Subtracting the outdoor external background dose gives a net dose of approximately 600 μSv y^{-1}. This is within the range of 0.3 mSv y^{-1} to 1 mSv y^{-1} (excess external irradiation dose to that received outdoors) within which EC guidance indicates that controls on the use of such building materials should be instituted(18). In the UK the acceptability of purpose built disposal facilities for radioactive waste would be judged against a risk target(23) of 10^{-6} y^{-1}. The predicted peak individual risk from landfill disposal at the largest site is 4.2 10^{-8} y^{-1}, clearly below the risk criterion.

Under UK legislation there are currently no radiological controls on the operation of coal-fired power stations, or restrictions on how waste is discharged that relate to its radionuclide content. With one exception this position seems entirely consistent with the low radiological impact of the industry as presented above, and is also consistent with developing EC guidance in this area. The principal exception to this is the use of ash in building materials, where EC guidance indicates that future restrictions may be required to control doses to individuals. More detailed analyses and investigations in this area may therefore be useful.

9 ACKNOWLEDGEMENTS

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