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RADIOLOGICAL CONSEQUENCES OF ATMOSPHERIC RELEASES FROM COAL-FIRED POWER PLANTS

A CRITICAL SURVEY OF CALCULATIONS REPORTED IN LITERATURE

by

Ulf Tveten

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ABSTRACT

The investigation reported here was partially funded by the Nordic Council of Ministers, via the Nordic Liaison Committee for Atomic Energy.
In literature there is a number of publications concerned with calculation of individual and collective doses resulting from the content of radioactive materials in various types of fossil fuel; primarily coal. The present project is concerned with the doses resulting from the stack releases of coal-fired power plants. The calculated doses found in literature cover a range of several decades. There is also disagreement on what exposure pathways are the most important, and what nuclides contribute most to calculated doses. These differences can only partially be explained by different composition of various types of coal and differences in design of the power plants. The purpose of the analysis is to identify possible explanations of differences in the doses calculated; and to identify possible weaknesses in methodology and/or data employed.

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1. INTRODUCTION.

The present report is prepared as part of a joint Nordic Project, partially funded by the Nordic Council of Ministers/Nordic Liaison Committee for Atomic Energy. It is a subproject (REK-4:7 Critical analysis of dose calculations in literature) under the main project REK-4 (Radiological consequences of utilization of coal for production of electricity in the Nordic countries).

In literature there is a number of publications concerned with calculation of individual and collective doses resulting from the content of radioactive materials in various types of fossil fuel; primarily coal. The present project is concerned with the doses resulting from the stack releases of coal-fired power plants. The calculated doses found in literature cover a range of several decades. There is also disagreement on what exposure pathways are the most important, and what nuclides contribute most to calculated doses. These differences can only partially be explained by different composition of various types of coal and diffences in design of the power plants.

In (Ref. ER83) are listed the most important references, and these are the references analyzed in the present report. The purpose of the analysis is to identify possible explanations of differences in the doses calculated; and to identify possible weaknesses in methodology and/or data employed.

2. POSSIBLE IMPORTANT CONTRIBUTORS TO DIFFERENCES BETWEEN REPORTS.

Calculation of doses resulting from an atmospheric release of radioactive materials involves choice of numerous data values and choice of methodologies. When it is found, in the following, that the different reports analyzed have arrived at different results, there is a large number of possible explanations. These range from differences in the release to the atmosphere, via meteorological conditions and models, via shielding and agricultural conditions, to dose relationships; and really much more.

A list has been prepared of data and conditions that are felt to be possible important contributors to differences between different dose evaluations, and this list is used as a chapter substructure in the following. These data and conditions are listed systematically in chapter 3 of this report, as far as it has been possible to identify them. Some reports are very weak on information; some are very thorough in their description; but none of the reports contain all the information needed for a real reproduction of the calculations. Just to mention one example of information that is totally lacking: The exact definition of the atmospheric stability classes employed. Without this definition, it is impossible to reproduce the calculations.

Nevertheless, it is felt that the information collected in chapter 3 provides a sufficiently solid basis for the evaluations contained in chapter 4.

3. CRITICAL SUMMARY OF REFERENCES.

3.1 CALCULATIONS OF INDIVIDUAL DOSE.

3.1.1 Aiguenerse (Ref. AI82).

This paper is in French, and some information contained in the paper may have been overlooked or misunderstood. The paper is, however, particularly well documented.

The calculations contained in this paper concerns a specific power plant; Gardanne in South-West France, 20 km North of Marseille.

Release

The calculations are performed for an existing 415 MWe power plant, divided among four units, put in operation over the time period 1953 to 1966. In addition to the information contained in table 3.1, it is assumed that the radionuclides belonging in the chains of U-238 and Th-232 are in equillibrium with these. Exceptions are Rn-222 and Rn-220. The first is assumed to have a release of 80 µCi/s, and the second is neglected. It is not quite clear, however, if this is also per 1000 MWe, or is the release from the actual plant. If the first interpretation is the correct one, the yearly release (corresponding to the other numbers in table 3.1) is 2500 Ci, which is in reasonably good agreement with the numbers in table 3.4.

Nuclide	Amount released (Ci/year)
Ra-226	0.19
U-238	0.18
Th-232	1.7
K-40	0.095

Table 3.1. Calculated radionuclide releases from the Gardanne coal-fired power plant. All values are per 1000 MWe.

Release height and plume lift

The power plant consists of four units; three of 55 MWe each, and one of 250 MWe. Correspondingly there are four stacks; three of 65 meters, and one of 142 meters height. The temperatures of the releases at the point of release are reported as 125^{0}C and 200^{0}C, and relative humidity is said to be 11%.

Weather characteristics

The weather of the region is typical Mediteranian. There is a relatively high frequency of calm winds.

Dispersion calculation

The dispersion calculations have been performed, using the model by Doury (Ref. DO80); one of the French internationally known capacities in the atmospheric dispersion field.

A dry deposition velocity of 0.5 cm/s has been used. Wet deposition has not been taken into account.

Exposure pathways

The exposure pathways considered are external exposure as well as exposure via inhalation and leaf and root vegetables. In the calculations it has been assumed that the yearly consumption of leaf vegetables is 140 kg and of root vegetables 110 kg.

Interception fraction on leaf vegetablus is assumed to be 0.25, the retention period on the leaves is set to 30 days, and the harvest period is 6 months per year.

In calculating doses via root vegetables, it is assumed that the accumulation time in soil is 30 years. Transfer factors have been taken from (Ref. US77, GA78 and KI71).

External exposure to radiation from materials deposited upon ground, is calculated assuming that the deposited activity remains on the surface one year, and thereafter is mixed evenly in the upper 30 cm of soil. The calculation method employed is taken from (Ref. BE68).

Position of individual

The position at which maximum individual dose is found, is 300 meters South-East of the release point.

Dose conversion factors

Dose conversion factors from (Ref. IC79 and IC80) have been employed.

Doses calculated

From these calculations it is concluded that inhalation is the most important exposure pathway. It is about three times as important as the nutrition pathways. External exposure is negligible in comparison with the other pathways.

The results of the calculations are given in table 3.2. Doses after operation of the power plant has been discontinued have also been calculated in this study, but the results are not given in the present report.

Nuclide	Inhalation	Leaf veget.	Root veget.	External
U-238	0.95	0.025	0.00024	
Th-234	0.00026	0.0014	0.000013	
U-234	1.1	0.028	0.00027	
Th-230	2.1	0.057	0.000056	0.053
Ra-226	0.063	0.15	0.0097	
Rn-222	0.00088	-	-	
Pb-210	0.10	0.65	0.36	
Bi-210	0.0015	0.0012	0.00043	
Po-210	0.063	0.32	0.12	
Th-232	0.62	0.029	0.000028	
Ra-228	0.0034	0.016	0.0011	0.0080
Th-228	0.25	0.0048	0.00032	
Ra-224	0.0023	0.0042	0.00028	
Total	5.5	1.3	0.49	0.061

Table 3.2. Estimated equivalent effective doses (mrem/year) received by an individual in the critical population group after the 30th year of operation of the plant.

Special aspects

In this study concentrations of radionuclides in the atmosphere were also measured. The nuclides were collected on filters in two samplers placed in opposite directions (at Le Payannet and Les Sauvaires) from the plant, at a distance of 1 km. Most of the nuclides found are fission products from nuclear weapons tests, but U-238, Ra-226, Th-232 and K-40 show concentrations several hundreds higher than normally found in the atmosphere. The results are shown in table 3.3.

In addition concentrations of radioactive nuclei were measured in rain water, soil and vegetables. The results of these measurements are not included in the present report.

Nuclide	Le Payannet	Les Sauveres
Be-7	6.3±0.7	6.3±0.7
Zr-95	0.67±0.18	0.85±0.11
Nb-95	1.2±0.2	1.5±0.1
Ru-103	0.81±0.07	1.1±0.1
Cs-137	0.07±0.04	0.04±0.02
Ce-141	0.67±0.07	1.5±0.2
Ce-144	0.15±0.04	<0.04
K-40	3.7±1.1	1.5±0.5
U-238	0.52±0.18	ND
Ra-226	0.67±0.18	ND
Th-232	0.26±0.15	0.11±0.07

Table 3.3. Measured radionuclide concentrations (mBq/m^3) in air. ND means not detected.

3.1.2 Beck (Ref. BC78).

Release

The releases from stack are given in table 3.4, for a modern and an older plant respectively, as estimated in this study, along with some values reported by other investigators. Some of the more or less volatile nuclides are enriched in fly ash compared to bottom ash. For the modern plant this enrichment is assumed to be factors of 2 for uranium, 1.5 for Ra-226, and 5 for Pb-210 and Po-210. For the older plant enrichment is assumed for the nuclides Pb-210 and Po-210 only, by a factor of 2.

The releases seem peculiar at first glance, since so many numbers are exactly identical. This, of course, is due to the fact that these nuclides are in natural equillibrium in the thorium, uranium and actinide decay chains. The relevant part of the thorium series is Th-232 Ra-228 Ac-228 Th-228. The uranium series is U-238 Th-234 Pa-234 U-234 Th-230 Ra-226 Rn-222 etc., and at the end of the chain

Po-210 Pb-206. The actinium series does not contain any of the nuclides in table 3.4.

Reference	MA70	MC77[1]	NC77	LE77[2]	UN77	Present study, modern[3]	Present study, older[4]
Fraction of fly ash released	~3%	1-2%	30%	0.5%	~3-5%	~1-2%	~10%
Total fly ash released (kg/y)	$4.5.10^{6}$	$\sim 3.10^{6}$	9.5×10^{7}	1.1 - 4.9 $.10^{6}$	$1.0.10^{7}$	$3.1.10^{6}$	$2.8.10^{7}$
U-238	7.2	8	133	4-11	50	28	126
U-234	7.2	8	133	4-11	50	28	126
Th-230	7.2	8	152	4-11	10	15	126
Ra-226	7.2	8	152	4-11	10	21	126
Th-232	8.1	5	171	3-10	10	11	104
Th-228	8.1	5	171	3-10	10	11	104
Ra-228	8.1	5	171	3-10	10	11	104
Pb-210	-	8	-	18-54	100	70	252
Po-210	-	8	-	18-54	100	70	252
K-40	-	-	-	18-54	150	31	280
Rn-222	-	800	-	800-2600	1000	1000-2000	1000-2000

Table 3.4. Estimates of radionuclide releases from coal-fired power plants. All values are per year per 1000 MWe. All values in the nuclide part of the table are mCi/y.

[1] Calculated on basis of 1% of all activity in $2.3.10^{9}$ kg of coal released.

[2] Range of releases reported for plants burning different types of coal.

[3] Ash released based on just meeting EPA standard of 0.1 lb/10^{6} BTU, assuming 80% utilization factor, 35% thermal efficiency.

[4] Ash released based on average releases from all U.S. plants in 1972, assuming typical 1000 MWe plant burns $2.7.10^{9}$ kg of coal per year.

Release height and plume lift

The plant upon which sample calculations have been performed, has six 52 meter stacks and two 152 meter stacks. At least some calculations have been performed for both of these release heights. Plume rise is taken into account, probably as an addition to the release height, since a very simple dispersion calculation approach has been employed.

Weather characteristics

Calculations have been performed using "average meteorological data from U.S. Weather Bureau records" for the area in which the plant is positioned.

The name of the plant is Widows Creek, and it is situated in Alabama. Nothing is said about the weather characteristics of this area; whether it is a dry or humid area, or whether it is dominated by high or low wind speeds.

Dispersion calculation

The dispersion calculations have been performed using the standard sector-averaged Gaussian plume model. The calculations evidently have been performed only for one "average" weather condition. A certain underestimation of doses can result from this.

Both wet and dry deposition is accounted for by a deposition velocity of 1 cm/s. It is not clear from the report whether dry or humid weather is characteristic of the area. Nor are other weather characteristics specified. The choise of deposition mechanisms and deposition parameter values depends upon precipitation characteristics as well as wind speed and stability distribution. One important difference between dry and wet deposition, which can not be accounted for in the simplified calculations performed here, is the fact that dry deposition decreases rapidly with increasing plume height, while wet deposition (for conditions relevant here) is independent of plume height.

Exposure pathways

Inhalation and nutrition pathways are considered, and it is concluded that the latter are of minor importance. The reason for this is the relative insolubility of the activity embedded in the fly ash particles.

The inhalation dose depends upon whether the fly ash particles are in the respiratory range or not, and upon to what extent they are soluble in body fluids. It is said that the fly ash particles from a modern plant are likely to be in the respiratory range, since this is the size range where present effluent control devices are least efficient. Even though the amount of released fly ash is larger from an older plant, a smaller proportion of the particles will be in tha respiratory range.

It is furthermore concluded that most of the radioactivity in the respirable particles will be insoluble in body fluids, an will remain in the lungs or be cleared from the body. This means that lung dose only needs to be considered.

Position of individual

The air concentrations and ground concentrations reported are calculated for the position where there will be maximum concentration, which is said to be at about 2 km from a low stack and about 6 km for a high stack. The reported individual doses are maximum doses, and they are probably for a distance from release point of 2 km, though the position of the individual is not given in the report.

Dose conversion factors

The dose conversion factors used (from air concentration to lung dose) are taken from two reports from the NCRP (Refs. NC75 and NC77).

Doses calculated

The maximum individual doses calculated are 0.14 mrem/y from the modern plant and 8.7 mrem/y from the older plant. The doses from the individual nuclides are also given.

Weaknesses

This is the only report where it is claimed that exposure is only via the lungs. If this assumption is incorrect, a serious underestimate of health consequences will result.

The dispersion characteristics are not defined at all, and this makes it somewhat difficult to compare the results from this reference with the results from the other references.

3.1.3 Bergström (Ref. BE79).

Release

Many values from literature on activity in various types of coal, in ash, and in discharges are mentioned in this report. Table 3.5 gives the discharge as given in this reference. A range is given, where "the interval is defined by the lowest and highest literature values ...". It is also said in the report that "Calculations are based upon discharges from very good cleaning equipment which result in 1000 ton dust per Mton of coal consumed". It is not clear, however, how this statement relates to the values in table 3.5. As a matter of fact, dispersion calculations have not been performed. It is said that "the doses are based on measurements of the activity concentration near Widows Creek, which has a relatively large dust discharge because of the low chimneys and limited air cleaning capacity". This statement and the previous statement seem to conflict.

Release height and plume lift

The results are said to refer to a plant with low chimneys, but the height is not given.

Nuclide	Amount released (mCi/year)
Ra-226	0.2 - 16
Ra-228	0.4 - 14
Pb-210	1.4 - 210
Th-232	0.4 - 14
Th-228	1.4 - 30

Table 3.5. Radionuclides released from a coal-fired power plant. All values are per 1000 MWe. (The values assume 2000 - 3000 ton coal used per MWe and year, and a good cleaning equipment which collects about 99% of the fly ash produced. The annual discharge per MWe and year is 2000 kg.)

Weather characteristics

No information given on this.

Dispersion calculation

No dispersion calculation performed.

Exposure pathways

No information given, but it seems that only inhalation of the passing cloud is taken into account.

Position of individual

The position of the individual is said to be near the plant, but is not quantified.

Dose conversion factors

It is said that "the dose burden has been calculated according to ICRP principles". More specific information is not given.

Doses calculated

The calculations of individual dose are based upon (Ref. MA70). The other calculation conditions are not specified.

Nuclide	Individual dose (μrem/year)
Ra-226	1.4
Ra-228	1.1
Pb-210	2.3
Th-232	1.4
Th-228	0.5
U-238	6.7

Table 3.6. Individual whole body dose from a coal-fired power plant. All values are per 1000 MWe.

Special aspects

The report has the character of a pure literature search, and no dispersion calculations have been performed.

3.1.4 Camplin (Ref. CA80).

The amount of pertinent information found in this reference about calculation conditions and models used, far exceeds that given in any of the other references. And this has been accomplished without writing a report that is particularly voluminous.

Release

The calculations are performed for a hypothetical 2000 MWe coal-fired power station sited in Great Britain. Annual discharge is calculated, conservatively based upon the measurements available in Great Britain of content in coal and flyash.

Nuclide	Amount released (mCi/year)
Actinium	series:
U-235	1.05
Th-231	1.05
Pa-231	1.05
Ac-227	1.05
Fr-223	0.015
Th-227	1.05
Ra-223	1.05
Rn-219	1.05
Pb-211	1.05
Bi-211	1.05
Tl-207	1.05
Po-211	0.003
Thorium	series:
Th-232	27.
Ra-228	27.
Ac-228	27.
Th-228	27.
Ra-224	27.
Rn-220	27.
Pb-212	27.
Bi-212	27.
Tl-208	9.5
Uranium	series:
U-238	27.
Th-234	27.
Pa-234m	27.
Pa-234	0.35
U-234	27.
Th-230	27.
Ra-226	27.
Rn-222[1]	1900.
Pb-214	27.
Bi-214	27.
Tl-210	0.0055
Po-214	27
Pb-210	27.
Bi-210	27.
Po-210	27.
Others:	
K-40	27.
C-14[2]	-12,000.

continued

continuation

Table 3.7. Discharge to atmosphere from a reference 1000 MWe coal-fired power station.

[1] It is assumed that all Rn-222 gas is released, which is initially present in the coal.

[2] The negative value is the dillution effect explained elsewhere in this chapter.

Release height and plume lift

The physical stack height of a modern power station is said to be about 200 meters. With plume lift taken into account, it is assumed that the effective plume height is 500 meters in weather cathegories A, B, C and D, and 280 meters in cathegories E and F.

Weather characteristics

The probabilities of each weather cathegory in the Pasquill/Smith classification scheme are given for three different sites. A "typical" wind velocity is assigned to each cathegory, as well as a "typical" inversion lid height. Furthermore it is assumed that it rains 10% of the year in C and D weather.

Dispersion calculation

The dispersion calculations are based upon the Gaussian dispersion model, assuming a uniform wind rose. Both dry deposition (deposition velocity 10^{-3} m/s) and wet deposition (wash-out coefficient 10^{-4} /s) are taken into account.

Exposure pathways

The exposure pathways considered are external irradiation from plume and from activity deposited on the ground, inhalation of material in the plume and material resuspended from land surfaces, and ingestion of contaminated foodstuffs. The nutrition pathways are found to give the highest contribution to the highest individual doses.

Position of individual

The maximum individual exposure occurs at the site boundary, which is 400 meters from the release point. This is the position of the maximum for the sum of all exposure pathways. Maximum doses from the individual exposure pathways are found at distances ranging up to 10 km.

Dose conversion factors

No information given. The results, however, indicate unconventional, probably incorrect, assumptions.

Doses calculated

The maximum annual individual committed effective dose equivalent is found to be 23 mrem. The nutrition pathways contribute 97%, and 85% of this is via consumption of liver. A rather particular diet must have been assumed. The nuclides Pb-210, Pa-231 and Po-210 dominate, giving 98% of the dose.

Special aspects

The release of carbon (not radioactive) from a coal-fired power plant will actually reduce the concentration of naturally-occurring C-14 in the atmosphere; and also the accompanying radiation exposure. This effect is taken into account in these calculations.

Weaknesses

There is something seriously wrong with the diet assumed and/or the dose conversion assumptions, as evidenced by the results obtained. In spite of the amount of detail given in this report, it seems that the results should not be trusted.

3.1.5 Halbritter (Ref. HA82).

It is said in this paper that the study is based upon (Ref. UN77), with special account taken of German technical and site conditions. The results are also compared to results from (Ref. MC78, CH80 and KO77).

Release

A rough estimate of the emission data was obtained assuming secular equilibrium of the nuclides in the uranium and thorium chains, and assumed that the content in the coal is 1 ppm of U-238 and 2 ppm of Th-232, an ash content of 10%, a heating value of 30MJ/kg and a precipitator efficiency of 99%. These assumptions are similar to the ones adopted in (Ref. MC77). The emission data obtained in this manner agree well with those reported in (Ref. UN77).

Measurements of the flyash activity, however, show higher values, especially for the U-238 chain (Ref. CH80 and KO79). On the basis of these data, an emission data set for the study was derived, and these data are presented in table 3.8. The table contains two data sets; one for dry and and one for liquid ash removal.

Release height and plume lift

Calculations have been performed for stack heights of 100 and 200 m, with and without plume lift (70 MW). The results referred to in the following are for the 200 m stack with plume lift.

Weather characteristics

The doses were calculated for a typical Northern and a typical Southern site in the Federal Republic of Germany. Furthermore the calculations are based upon (Ref. US77 and BM79).

Nuclide	Dry ash removal	Liquid ash removal
U-238	8	13
Th-234	5	7
U-234	8	13
Th-230	5	7
Ra-226	6	9
Rn-222	870	870
Pb-210	6	59
Po-210	9	150
Th-232	3	5
Ra-228	4	6
Th-228	3	5
Ra-224	4	6
Rn-220	580	580
K-40	21	21

Table 3.8. Emission data sets for radionuclide emissions (mCi/year) from (bituminous) coal-fired power plants. All values are per 1000 MWe.

Dispersion calculation

The dispersion calculations are said to be based upon a diffusion model of the Gaussian type, which also includes the influence of an upper inversion.

The dry deposition velocity assumed is 0.1 cm/s. The washout coefficient is $3.0 \cdot 10^{-9}$ A/(mm.s). "A" is, however, not defined in the text, and this is an unconventional way to present a washout coefficient. It will be neccessary to go to the original references to find the exact definition. But washout in this connection is not important. Washout contributes only 10% to total deposition.

Exposure pathways

The exposure pathways considered are external exposure, inhalation and the nutrition pathways.

Position of individual

The highest reported individual doses are at 1000 meters from the release point. Doses closer to the release point are not given, but the slope of the curves in the report indicates that the doses are somewhat higher even closer to the release point.

Individual doses have been calculated from 1000 meters up to 100 km, and the results are presented as curves, as function of distance.

Dose conversion factors

The calculations are based upon effective dose values (Ref. IC77), with dose conversion factors from (Ref. IC79).

Doses calculated

The doses are dominated by inhalation and nutrition, with inhalation slightly higher than nutrition.

The individual committed dose-equivalents are given in curves as function of distance. The highest value shown is 0.05 mrem/year normalized to a 1000 MWe plant.

Special aspects

The report points out that other releases, besides the radioactive, from coal-fired plants are important in connection with the risk, and these releases have been estimated. The resulting health impact has, however, not been assessed. This is due to the fact that the information needed is not available.

Weaknesses

In this reference it is stated explicitly that the calculations are conservative. This, however, is probably true for most of the papers and reports examined in the present report; and is not a special weakness of this particular reference.

3.1.6 van Hook (Ref. HO78).

This report covers trace and radioactive elements released during coal mining, cleaning, combustion and ash disposal, and is correspondingly bulky. The report is, however, written in the form of a state of the art report, upon the request of the President's Committee on Health and Ecological Effects of Increased Coal Utilization. At least in connection with radioactive materials it does not contain independent or new information. All information on radioactive elements in the report, including the resulting doses, is taken directly from (Ref. MC77). Other aspects will not be considered in the present report.

3.1.7 Ilyin (Ref. IL78).

Release

The releases are in this reference given for the 1200 MWe Zaporozhje fossil-fuel power plant. Various sorts of information relating to the release are given. It is said that the station burns $3.4.10^6$ tons of coal and releases $1.3.10^5$ tons of fly ash to the atmosphere annually. Nuclide content in several coal samples is given, and so is nuclide content in fly ash of one type of coal. Table 3.9, taken from this reference, contains information on the annual release to the atmosphere. It is said that the releases are estimated. One would suppose that they have been derived simply by multiplying the amount of flyash released with the nuclide content in fly ash given in the report. Simple calculations show, however, that this is not the case.

Nuclide	Amount released (Ci/year)
Ra-226	0.53
Ra-228	0.3
Po-210	2.0
Pb-210*	2.2
Th-232	0.53
K-40	5.3

Table 3.9. Radionuclides released from a coal-fired power plant. All values are per 1000 MWe.
*For estimation of Pb-210 production, it was assumed that Rn-222 is released into the atmosphere.

Release height and plume lift

No information given.

Weather characteristics

No information given. It seems probable that some sort of average characteristics have been used.

Dispersion calculation

No dispersion calculations seem to have been performed. Two clues to the mode of calculation are given: It is said that a surrounding area of 1000 km^2 is considered, and it is said that "In estimating concentrations in the air, we assume that all released ash precipitates uniformly over the territory surveyed, the constant rate of precipitation being 0.01 m/s*. This information, however, is not sufficient. The air and ground concentrations will also depend upon the wind speed.

Exposure pathways

Inhalation, nutrition and external irradiation (shielding factor 0.8 for internal organs) are considered.

Position of individual

The results given are called "average individual", and must refer to an average over the 1000 km^2.

Dose conversion factors

No dose conversion factors are given, nor any reference.

Doses calculated

Table 3.10 shows the calculated individual doses.

Irradiated organ	Total dose mrems/year
Bone tissue	114
Bone marrow	14.5
Lungs	42
Whole body	0.53

Table 3.10. Average individual radiation doses for the population near a fossil-fuel power station. Normalized to 1000 MWe.

Special aspects

The solubility of coal ash, which determines the biological accessibility, is set to 100%. This condition is also used in many of the other references, sometimes without being explicitly mentioned.

The report also contains chapters on mineral fertilizers, building materials of mineral origin, and the natural background in the USSR.

Weaknesses

The dispersion characteristics are not defined at all, and this makes it somewhat difficult to compare the results from this reference with the results from the other references. Also the doses are said to be "average doses" (but not what type of average), which means that one should expect them to be significantly lower than the "maximum doses" calculated in the other references. But this is not the case.

3.1.8 Jacobi (Ref. JA81).

Doses are calculated on the basis of measurements of the radioactive emissions of a 300 MWe coal-fired power plant and a 600 MWe lignite-fired (brown coal) power plant.

This report contains very abundant information, both on data and methods employed.

Release

Measured content of radionuclides in fly ash (Ref. CH80 and JO80) are used as the basis for this study. The releases from stack are shown in table 3.11.

Nuclide	Coal-fired plant	Lignite-fired plant
U-238		
U-234	12	2.5
Th-230		
Ra-226		
Rn-222	1700	1800
Pb-210	100	6
Po-210	200	12
Th-232		
Ra-228	5.5	1
Th-228		
Ra-224		

Table 3.11. Stack release of radionuclides (mCi/year) from coal-fired and lignite-fired power plants. All values are per 1000 MWe.

Release height and plume lift

Plume rise is taken into account, and the resulting effective release heights are about 300 meters by the coal-fired plant and 200 meters by the lignite-fired plant.

Weather characteristics

The weather characteristics are not given, but are said to be representative of the site of the nuclear power plant Biblis.

Dispersion calculation

The dispersion calculations are performed in the simplest manner, by adoption of an "average" dillution factor of 3.10^{-8} s/m^3 for the coal-fired plant and 6.10^{-8} s/m^3 for the lignite-fired plant. These averages are taken from (Ref. BI79 and VO74), and apply to the position at which the ground level air concentration reaches its maximum.

Deposition is said to be mainly dry deposition, and two different deposition velocities have been employed:

1.5 cm/s for U, Th and Ra, and 0.6 cm/s for Pb and Po.

The deposited activity is assumed to accumulate in the top 1 - 2 cm of soil on an undisturbed surface, and in 20 - 30 cm on a cultivated surface.

Exposure pathways

Inhalation, nutrition and external exposure from radioactive materials deposited upon ground are considered. The dose from the passing plume is negligible in comparison, and so is the inhalation dose from resuspended materials.

Position of individual

Maximum individual inhalation dose is found at about 1 km and 1.5 km for the coal-fired and the lignite-fired plants respectively.

Dose conversion factors

Dose conversion factors are based upon (Ref. IC75, IC77, IC79 and IC80). Very detailed descriptions of the basis for the dose calculations via all the exposure pathways are given, but are too extensive to be included in the present report. It is specified that the calculated individual doses are for adults (a piece of information that is missing from the other reports).

Doses calculated

The calculated individual inhalation doses are shown in table 3.12.

Most of the nutrition dose is caused by the nuclides Po-210 and Pb-210. In the case of the coal-fired plant, these nuclides give 90% of the nutrition dose. The doses are shown in table 3.13.

When the external irradiation from radioactive materials deposited on ground is calculated, it is assumed that the plant has been in operation 50 years. The dose calculated is the outdoor dose, and will accordingly be larger than in a real situation, since it is assumed that the person exposed is outdoors continously. The only possible shielding effect is from the soil itself, as the materials migrate downwards. The migration velocity is said to be in the range 0.01 to 1 mm/year. Calculations have been performed for three different migration velocities, and the results are shown in table 3.14.

Calculated doses via all pathways summarized in table 3.15.

Organ	Weighting factor	Inhalation doses	
		Coal-fired plant	Lignite-fired plant
Lung	0.12	0.33	0.06
Bone	0.03	1.1	0.22
Bone marrow	0.12	0.1	0.02
Liver	0.06	0.02	0.003
Kidney	0.06	0.04	0.005
Spleen	0.06	0.05	0.004
G.I. tract	0.24	0.002	0.0002
Other	0.31	0.002	0.0002
Effective equivalent dose		0.1	0.02

Table 3.12. Maximum individual equivalent doses (mrem/year) via inhalation. From coal-fired and lignite-fired power plants. All dose values are per 1000 MWe. Weighting factors for the different body organs also included.

Nuclide	Coal-fired plant	Lignite-fired plant
U-238	0.6	0.26
U-234	0.7	0.30
Th-230	1.1	0.41
Ra-226	2.0	0.76
Pb-210	34	3.5
Po-210	14	1.4
Th-232	1.8	0.68
Ra-228	0.6	0.22
Th-228	0.2	0.1
Total	53	8

Table 3.13. Maximum individual equivalent doses (μrem/year) via nutrition. From coal-fired and lignite-fired power plants. All values are per 1000 MWe.

Nuclide	Coal-fired plant			Lignite-fired plant		
	0.01	0.1	1	0.01	0.1	1
U-238 - Ra-226	1.0	0.8	0.4	0.4	0.32	0.16
Rn-222 - Tl-210	10	8.0	6.0	4.0	3.2	2.4
Pb-210 - Po-210	0.2	0.15	0.1	0.08	0.06	0.04
Th-232 - Ra-224	4.4	3.0	1.6	1.8	1.2	0.6
Rn-220 - Tl-208	20	15	7.0	8.0	6.0	2.8
Total	36	27	15	15	11	6

Table 3.14. Maximum individual equivalent doses (μrem/year) via exposure to radiation from materials deposited upon ground. From coal-fired and lignite-fired power plants. All values are per 1000 MWe.

Exposure pathway	Coal-fired plant	Lignite-fired plant
Inhalation	0.1	0.02
Nutrition		
-direct	0.01	0.002
-indirect (via soil)	0.04	0.008
External γ-exposure	0.015-0.04	0.005-0.015
Total	0.2	0.04

Table 3.15. Summary of maximum individual equivalent doses (mrem/year) via all exposure pathways. From coal-fired and lignite-fired power plants. All dose values are per 1000 MWe.

3.1.9 Kolb (Ref. KO79).

Release

The releases are in this reference given for a modern coal power plant in West Germany (no name given), of 300 MW (it is not said whether this is MWe or MWth, but considering the numerical value, it is assumed that it is MWe). The releases given are based upon analysis of the flyash. In addition the content of Po-210 is set equal to the content of Pb-210, with reference given to (Ref. JL77). The releases, scaled to 1000 MWe, are given in table 3.16. It is evident from the numbers in the table that they were determined by analysis, and not by calculations; as numbers that should be expected to have the same value, because they are in balance in the natural decay chains (like Th-232 and Ra-228), actually have slightly different values.

Release height and plume lift

Release height is 150 meters, and plume lift has evidently not been taken into account.

Weather characteristics

A wind velocity of 5 m/s seems to have been assumed. Other weather characteristics are not specified.

Nuclide	Amount released (mCi/year)
U-238	10
Ra-226	15
Pb-210	90
Po-210	90
Th-232	6.0
Ra-228	6.3

Table 3.16. Radionuclides released from a coal-fired power plant. All values are per 1000 MWe.

Dispersion calculation

Dispersion calculations have not been performed, but a maximum integrated "Langzeitausbreitungsfaktor" is given. This factor is taken from (Ref. AL77). The value is $1.4 \cdot 10^{-7}$ s/m^3, assuming a 20% wind direction frequency in the 30^0 sector around the main wind direction; and this maximum is found at a distance of 750 meters from the release point.

Dry and wet deposition has been taken into account, although in a rather uncommon fashion. Wet deposition is evidently based upon a yearly precipitation of 500 liters/m^2, which is equivalent to 500 mm. The deposition is calculated using some factors from (Ref. AL77), whose exact meaning is not explained. They are a "Fall-out-faktor" which is set equal to $1.4 \cdot 10^{-7}$ m^{-2} and a "Wash-out-faktor" which is set equal to $7 \cdot 10^{-10}$ m^{-2}. It is necessary to go to the original reference, if it is of importance to obtain an exact definition.

Exposure pathways

Inhalation and ingestion are the two dominant exposure pathways, and are the only ones included in the calculations.

Position of individual

The individual is placed at the point of maximum integrated concentration, which is 750 meters from the release point.

Dose conversion factors

The dose conversion factors are taken from (Ref. AL77), and it is necessary to go to the original reference, if it is important to determine the basis for the conversion factors.

Doses calculated

The maximum individual doses (to bone) are 0.97 mrem/year via inhalation and 63 mrem/year via ingestion, when they are scaled up to an effect of 1000 MWe. The doses from the individual nuclides are also given, and it is said that the dominant nuclides are Th-232 (actually the exposure from Th-228 further down in the decay chain) for the inhalation pathway and Ra-226 for the ingestion pathway.

Weaknesses

Only the dose to bone is given. The reason is not explained, and almost all the other references put the main emphasis on whole body dose. It is true that the bone dose from this release is probably larger than the whole body dose, but the whole body dose will still have the larger health impact.

Even more at variance with the other references is the fact that the nutrition pathway is found to be the dominant one, while the other references find inhalation to be the most important exposure pathway. The yearly nutrition dose determined in this reference, is far from insignificant; as it is of the same order of magnitude as the natural background.

Since only the bone doses are given (possibly because of a misjudgement of the relative importance of the body organs), the results from this reference can not be compared to the results from the other references. The relative importance of exposure pathways found, also makes one doubt the validity of the results.

3.1.10 Krieger (Ref. KR78).

This study is almost exclusively concerned with experimental determination of the content of radioactive materials in coal and combustion products from a coal-fired power plant. The dose calculations performed are rather simplified.

Release

The content of γ-emitting materials was determined with a spectrometer and a Ge(Li) detector. The content of other radioactive materials was determined by radiochemical analysis.

The content in fly ash of K-40, Ra-226, U-234, U235, U-238, Th-228, Th-230 and Th-232 is reported, but only for Ra-226 has the annual stack release been estimated. Determination of this quantity has evidently not been the principal aim of the study, since it is said that direct measurement of the activity in the stack effluent would give a more reliable estimate than the one obtained.

The annual release of Ra-226 is estimted to 0.02 Ci. And the reason for only estimating the release of this nuclide is that it is found to contribute the major part of the dose. The doses from U-238 and Th-232 have evidently also been calculated (no numbers contained in the report), but found to give insignificant contributions.

Release height and plume lift

Stack height is 150 meters. No plume rise.

Weather characteristics

The calculations are performed for "average stability - neutral conditions". Wind speed is set to "average wind speed - 8.4 mph", which is 3.8 m/s.

Dispersion calculation

No information given.

Exposure pathways

No information given.

Position of individual

It is said that the maximum concentration is found at 5.5 km from release point.

Dose conversion factors

No information given.

Doses calculated

The maximum individual dose due to atmospheric release from a coalfired power plant of 1000 MWe is estimated to 0.037 mrem/year to the bone. Doses to other body organs are not given. This dose is from Ra-226 only, and other nuclides are said to give only insignificant contributions to the dose.

Weaknesses

There are good reasons to doubt that bone is the critical organ. The dose may be higher to bone than to other body organs, but the resulting health consequences may be larger in other organs, even when they receive significantly smaller doses. Whole body dose is a better measure of the health impact in most instances, or alternatively the bone marrow dose.

Nor is Ra-226 found to be the critical nuclide in the other references analyzed in the present report.

The maximum ground level air concentration is found at a distance from release point of 5,5 km, which is very far, when compared to the findings of the other reports. This may reflect on the quality of the dispersion calculation.

There seem to be several reasons for doubting the validity of the results reported in this reference.

3.1.11 McBride (Ref. MC77).

Release

The evaluations are performed for a 1000 MWe model coal-fired steam plant, assuming that 1% of the ash is released to the atmosphere.

The releases to atmosphere were estimated, using the following assumptions:

- The coal contains 1 ppm uranium and 2 ppm thorium.
- Ash release is 1%.
- Rn-220 is produced from Th-232 in the combustion gases at the rate of $1.38.10^{-9}$ Curies per second per gram of thorium.
- The annual release of natural uranium is $2.32.10^{4}$ g and of Th-232 is $4.64.10^{4}$ g.
- 15 seconds are required for the gases to travel from the combustion chamber to the top of the stack.

The estimated releases are shown in table 3.17.

Release height and plume lift

Calculations are performed for stack heights of 50, 100, 200 and 300 m. Plume rise is calculated according to (Ref. BR69).

Nuclide	Amount released (mCi/year)
Actinium	series:
U-235	0.35
Th-231	0.35
Pa-231	0.35
Ac-227	0.35
Th-227	0.35
Ra-223	0.35
Rn-219	0.35
Pb-211	0.35
Bi-211	0.35
Tl-207	0.35
Thorium	series:
Th-232	5.
Ra-228	5.
Ac-228	5.
Th-228	5.
Ra-224	5.
Pb-212	5.
Bi-212	5.
Tl-208	1.8

continued

continuation

Uranium	series:
U-238	8.
Th-234	8.
Pa-234m	8.
Pa-234	8.
U-234	8.
Th-230	8.
Ra-226	8.
Po-218	8.
Pb-214	8.
Bi-214	8.
Po-214	8.
Pb-210	8.
Bi-210	8.
Po-210	8.
Radon	releases:
Rn-220	0.4
Rn-222	0.8

Table 3.17. Discharge to atmosphere from a reference 1000 MWe coal-fired power station.
[†]It is assumed that all Rn-222 gas is released, which is

Weather characteristics

The calculations are based upon weather characteristics of St. Louis, Missouri, using annual-average meteorological data in terms of joint frequencies of wind-speed categories, atmospheric stabilities and wind direction.

Dispersion calculation

The dispersion calculations were performed using the AIRDOS computer program (Ref. MO77), which is a Gaussian-type program, using the equation of Pasquill (Ref. SL68 and PA61), as modified by Gifford (Ref. GI61).

The dry deposition velocity was assumed to be 1 cm/s, and a scavenging coefficient of 2.10^{-5} per second was used for all particulates. The scavenging coefficient is said to represent an average over the year. The rainfall rate is 89 cm/year.

Exposure pathways

The exposure pathways taken into account are inhalation, nutrition, exposure to external irradiation from immersion in the cloud, and from materials deposited upon ground.

The computer program TERMOD (also incorporated in the AIRDOS program), used for estimating the nutrition doses, is described in (Ref. BO71 and KI76). The latter reference contains the input values used in the analysis. It should be mentioned here that the daily intakes assumed for calculation of maximum individual dose is 250 g vegetables, 300 g beef and 1 liter of milk.

Position of individual

The highest individual doses were found at site boundary, at 500 meters from the release point. This is true for all stack heights, the reason being that the nutrition dose is dominating.

Dose conversion factors

Dose conversion factors are based upon dosimetric criteria given in (Ref. IC59), with the exception of the factors used for radium isotopes, which are based on recommendations in (Ref. IC68).

Dose estimates via inhalation and nutrition are 50-year dose commitments accrued from 1 year of exposure to the releases from the plant. Deposited nuclides are assumed to build up for a period of 50 years (and to stay on the surface), for the purpose of estimating doses from surface exposure.

Doses calculated

The calculated maximum whole body individual dose commitment is found to be 1.9 mrem/year. Contrary to most of the other references the nutrition pathway is found to be dominant, contributing 93.6% of the whole body dose.

Weaknesses

The report does not contain sufficient information for understanding why the nutrition pathway is found to be dominant. Even the high daily vegetable and meat consumption, which it is quite impossible to afford in the Nordic countries, can not explain this. There seems to be reason to doubt the validity of the results of even this reference, although it comes from a reputable institution like Oak Ridge National Laboratory.

3.1.12 Miller (Ref. MI81).

This reference is very weak on information, since it is less than two pages long. It is actually a summary of a presentation at a workshop.

However, Miller is in the "et al" of (Ref. BC78); the report by Beck, and I assume that it is really the same piece of work.

In (Ref. MI81) are given some values of lung and ingestion doses, along with some very incomplete information on the releases. No details of calculation methods or assumptions are given, and there is no way in which the validity of the results can be assessed. Two references only are given; the first is the above-mentioned (Ref. BC78), and the second is a short publication (5 pages) by Beck and Miller (Ref. BC80).

The doses from atmospheric release are reported to be as follows:

"For a typical older plant, releasing 10% of its fly ash from a 50 meter stack, the dose equivalent to the lung would be less than 10 mrem/year. However, for a modern plant meeting EPA emission standards and releasing from a 150 meter stack, the dose would be less than 0.2 mrem/year."

"Although many investigators have suggested the ingestion pathway could result in doses of up to 20 mrem/year from ingestion of crops grown on surrounding land, we feel this is more unrealistic due to available evidence that indicates extremely low solubility of the radionuclides when bound in fly ash."

3.1.13 Styron (Ref. ST83).

The calculations are performed for the George Neal power plant, located near Sioux City, Iowa, on the Missouri River.

The study is mainly a programme of measurements of the content of radioactivity. Coal, fly ash and bottom ash were sampled and measured, and soil, vegetation and airborne particulate samples were also collected and measured. The radiological assessment was performed as a secondary task.

(Ref. ST83) is a summary report, and the information contained in this reference is limited. (Ref. ST79a and ST82) are only concerned with radioactivity from ash piles. (Ref. ST79), however, contains the relevant information, described in considerable detail. It was unexpected that this should be the correct source of information, since it is in the title described as "preliminary"; but none of the other three references contain newer information on atmospheric dispersion of stack effluents and resulting environmental effects.

Release

The plant consists of three units of 150, 330 and 540 MWe respectively. The release has been determined from stack measurements on one of the units, and subsequent scaling to determine the source terms for the other two units. A different approach, however, was used for Rn-222; assuming secular equillibrium with U-234 in the coal, and release of all Rn-222 contained in the coal. In the report the releases are given per second for each of the three units. In the present report transformation to release per year and 1000 MWe has been performed, to ease comparison with the releases specified in the other references.

Nuclide	Release
U-234	0.252
U-238	0.254
Po-210	0.309
Pb-210	0.492
Rn-220	1.702

Table 3.18. Source terms used in the dispersion calculations (Ci/year). All values are per 1000 MWe.

Release height and plume lift

The physical stack heights are 76.2 m, 91.4 m and 121.9 m respectively for the three units. The plume rise was calculated, using Holland's equation (Ref. TU70), as 69.4 m, 121.5 m and 148.0 m respectively.

Weather characteristics

The meteorological data used in the dispersion calculations were obtained from the National Climatic Center in Asheville, North Carolina. These data were based on observations covering the 5-year period January 1970 through December 1974, at the Sioux City weather station. These data were processed to yield two tables. In both tables the horizontal lines represent wind directions (16 directional sectors); and the columns represent atmospheric stability classes (Pasq. A to F). The first table is a frequency table, and shows the percentage of the time when there is a particular atmospheric stability in a particular direction. The numbers for all directions and atmospheric stabilities add up to 100%. The second table shows wind speed (m/s) for the specific stabilities and wind directions. This is an unusual approach, as it allows only one possible wind speed (a sort of average wind speed?) for a particular stability and direction. A result of this approach is that low wind speeds are excluded.

Another peculiarity of these data is that there is zero probability of stability class Pasquill F, in all directions.

Dispersion calculation

The dispersion calculations were carried out using the computer program AIREM (Ref. MA74), which is a Gaussian dispersion plume model. The actual computer output is included in the report as an appendix.

A deposition velocity of 1 cm/s was assumed, and wet deposition was not taken into account. The deposited materials were assumed to be homogenously mixed in the 15 cm thick top layer of soil. The doses were calculated assuming 20 years of continous deposition, and ingrowth of daughter nuclides was taken into account.

Air concentrations were measured, but as these are short-time average values, and the calculated values are averages over 5 years, a comparison is not meaningful. Soil samples were also measured, and here the calculated and measured values can more easily be related. The measured values were, however, 500 - 1000 times higher than the calculated values. No explanation is given.

Exposure pathways

The inhalation and nutrition pathways are considered, but not the exposure to radiation from radioactive materials deposited on ground. In other references it is found, however, that this exposure pathway is not important.

Position of individual

Maximum individual inhalation and nutrition doses were calculated. However, the maximum inhalation doses and nutrition doses may be found in different positions, so that the total dose is not neccessarily the sum of the two.

Dose conversion factors

The doses are actually 50-year dose commitment equivalent.

The dose conversion factors for inhalation are taken from (Ref. HO77), and the breathing rate of 8000 m^3/year is taken from (Ref. US77).

Dose conversion factors for the nutrition pathways were also taken from (Ref. HO77), and the usage factors were taken from (Ref. US77). It is mentioned that the individual annual consumption of stored vegetables (including grain and fruit) is assumed to be 520 kg and of fresh vegetables 64 kg. This is about two kilos of vegetables every day, which must be highly unusual.

Doses calculated

The calculated maximum individual inhalation doses and nutrition doses are shown in tables 3.19 and 3.20. Doses to bone, liver, total body, kidney, G.I. tract, lung and bronchial epithelium were calculated. Only the total body doses are presented here.

Nuclide	Dose
U-234	$3.36.10^{-4}$
U-238	$2.95.10^{-4}$
Po-210	$6.05.10^{-5}$
Pb-210	$8.51.10^{-4}$
Total	$1.5.10^{-3}$

Table 3.19. Maximum annual inhalation dose commitment (mrem), calculated for the three units and added (Total effect 1020 MWe).

Nuclide	Dose
U-234	$3.50.10^{-3}$
U-238	$3.10.10^{-3}$
Po-210	$3.97.10^{-3}$
Pb-210	$1.45.10^{-1}$
Po-218	$1.16.10^{-7}$
Pb-214	$1.52.10^{-7}$
Bi-214	$1.40.10^{-8}$
Total	$1.6.10^{-1}$

Table 3.20. Maximum annual ingestion dose commitment (mrem), calculated for the three units and added (Total effect 1020 MWe).

Weaknesses

The weather statistics used in the calculations seems to neglect the weather conditions that will give the highest doses (low wind speeds and/or Pasquill F), making the annual doses somewhat low.

3.1.14 UNSCEAR (Ref. UN77 and UN82).

Release

The reports give surveys of atmosperic releases. Table 3.21 contains the estimated atmospheric discharges as best estimates from UNSCEAR. These estimates are based upon values taken from references from France, Fed. Rep. Germany, India, Italy, USSR, United Kingdom and the United States.

It is said in the report that by and large there are two types of coal-fired plants throughout the world. Those which release about 10% of the total ash produced to the atmosphere, and those, equipped with sophisticated retention devices, which release only about 1% of the ash. The normalized discharges (UNSCEAR estimates) contained in table 3.21 are taken to be representative of the current situation on the world-wide scale.

Nuclide	UNSCEAR 1977	UNSCEAR 1982
K-40	0.15	0.11
U-238	0.05	0.04
Ra-226	0.01	0.04
Pb-210	0.10	0.14
Po-210	0.10	0.14
Th-232	0.01	0.04
Ra-228	0.01	0.04
Th-228	0.01	0.04

Table 3.21. Estimated atmospheric discharges from a coal-fired power plant. All values in units (Ci/year) and per 1000 MWe.

Release height and plume lift

The individual dose is estimated assuming an effective stack height of 100 meters. It is not said how much of this height is due to plume rise.

Weather characteristics

A uniform wind rose is assumed.

Dispersion calculation

The individual dose calculation is based upon the maximum "annual average of the ground level air concentration per unit release rate" from (Ref. CL79). In other words, no dispersion calculation has been performed specifically for the UNSCEAR report, which is reasonable, since it shall not refer to any specific site. But the calculations in (Ref. CL79) must be based upon some assumptions regarding weather characteristics, and they probably refer to some specific or generic site in the United Kingdom.

Exposure pathways

The actual estimate refers to inhalation only, but in addition it is said that the dose "due to ingestion and external irradiation could be of about the same importance", with reference given to (Ref. JA81).

Position of individual

Maximum individual dose will be received about 1 kilometer from the stack.

Dose conversion factors

Based upon (Ref. IC79 and IC80).

Doses calculated

The maximum individual annual effective dose equivalent resulting from inhalation during cloud passage will be about 0.5 mrem per 1000 MWe.

Special aspects

The report aims at being representative of the world-wide situation. Due to the limitations in available information, it is rather representative of the situation in the temparate zone, and in the industrialized countries.

Weaknesses

Because of the generic character of the report, the evaluations are performed with more simplifications than in most of the other reports.

3.2 CALCULATIONS OF COLLECTIVE DOSE.

3.2.1 Bergström (Ref. BE79).

This report has the character of a pure literature search, and the reported collective doses are said to be taken from (Ref. UN77). However, it is also said that "The calculation of the collective dose committment for α-emitting nuclides is for the long term collective dose burden in a zone within 80 km from the discharge source (Ref. UN75)". This short distance will result in an underestimation. The reported collective doses are given in table 3.22, together with the amounts released (identical to the numbers in table 3.5, except for Th-228. Must be an error here).

Nuclide	Amount released (mCi/year)	Collective dose (manrem/year)
Ra-226	0.2 - 16	1.6 - 124
Ra-228	0.4 - 14	1.6 - 56
Pb-210	1.4 - 210	2.4 - 357
Th-232	0.4 - 14	0.1 - 4.2
Th-228	1.4 - 14	0.1 - 3
U-238	14	1.2

Table 3.22. Radionuclides released from a coal-fired power plant, and collective dose committments, whole body (manrem/year of operation). All values are per 1000 MWe.

3.2.2 Camplin (Ref. CA80).

Consult chapter 3.1.4 for additional information.

Dose conversion factors

Truncated at 500 years.

Doses calculated

The collective effective dose equivalent commitment is found to be $1.8.10^{4}$ manrem per year of operation, for a 1000 MWe plant. The largest contribution to the dose is via inhalation (78%). Via nutrition comes 18%, distributed as follows: grain 47%, root vegetables 25%, green vegetables 14%, liver 10%, and only 3% via meat and 2% via milk.

Weaknesses

The individual dose calculations in this report seem to have deficiencies. It is difficult to judge whether the same doubts to the validity of the results should be extended to the collective dose calculations.

3.2.3 Halbritter (Ref. HA82).

Release

See the information in chapter 3.1.5.

Release height and plume lift

Calculations have been performed for stack heights of 100 and 200 m. with and without plume lift (70 MW). It is not clear which case is the basis for the collective dose calculations, but this is also of minor importance, where collective doses are concerned.

Weather characteristics

The doses were calculated for a typical Northern and a typical Southern site in the Federal Republic of Germany. Furthermore the calculations are based upon (Ref. US77 and BM79). But this may apply to the individual dose calculations only. In connection with the collective dose calculations, it is said that they are based upon the same model assumptions as in (Ref. UN77). Only one set of results are given, so that the Northern and Southern sites do not seem to apply in this case.

Exposure pathways

The exposure pathways considered are external exposure, inhalation and the nutrition pathways.

Dose conversion factors

The calculations are based upon effective dose values (Ref. IC77), with dose conversion factors from (Ref. IC79).

Doses calculated

The largest contribution to collective dose comes via the nutrition pathways. Inhalation is somewhat less important, and exposure to radiation from material deposited upon ground is not important. The total collective dose is 400 manrem/year normalized to a 1000 MWe plant.

It is then assumed that the nuclides deposit within a radius of 500 km from the release point, and accumulate in the upper 20 cm of soil. More detailed results are given in table 3.23.

Nuclide	Nutrition	Inhalation	From ground
U-238	0.1	8.5	
Th-234	-	-	
U-234	0.2	17.0	
Th-230	2.3	13.7	
Ra-226	8.3	0.5	
Pb-210	154	7.8	
Po-210	90.8	9.8	
Th-232	3.2	31.5	
Ra-228	5.5	-	
Th-228	0.5	10.5	
Ra-224	0.3	0.3	
K-40	-	-	8
Total	265	99.6	8

Table 3.23. Collective dose-equivalent commitment (manrem/year of operation) from coal-fired power plants. All values are per 1000 MWe.

Special aspects

In this paper is drawn a (too hasty) conclusion regarding comparison between collective doses from nuclear and coal-fired power production. The conclusion is invalid, since the dose from nuclear includes the dose from the power plant, reprocessing plant, mining, milling, fuel fabrication and transportation, and it is compared to a dose from coal-fired which is restricted to the power plant itself. The invalid conclusion is that the dose by nuclear power production is about ten times higher than by coal-fired power production.

3.2.4 Ilyin (Ref. IL78).

In this reference (Ref. IL78) are given population doses from a fossil-fuel power station to the whole of the USSR. All other relevant information given in the report is summarized in chapter 3.1.7. It is not possible from this reference to understand in any detail how the population doses have been calculated.

Irradiated organ	Population dose
Bone tissue	5250
Bone marrow	700
Lungs	1950
Whole body	15

Table 3.24. Population doses (manrem/year of operation) due to releases from USSR fossil-fuel power stations. Normalized to 1000 MWe.

3.2.5 Jacobi (Ref. JA81).

The collective doses calculated in this reference are the collective exposure of the population of the Federal Republic of Germany, but normalized so that the doses represent the ones following from production of 1000 MWe. For additional information see chapter 3.1.8.

Population

A homogenous population density of 250 persons/km^2, which represents the average population density of the FRG, is used.

Area considered

The area included in the collective dose calculations is equal in magnitude to the area of the FRG, but is represented by a circle with radius 280 km^2.

Doses calculated

The dose calculations are performed in a simplified manner. It is e.g. assumed that all material released to the atmosphere is deposited entirely on the area in the FRG, and the nutrition dose calculations are based upon the average ground concentration. For the purpose of this report, however, the simplifications seem to be acceptable.

An important, but undetermined, parameter in the nutrition dose calculation is the "half-life" of the deposited materials; which represents the fact that the materials slowly become unavailable to the plants, either because of chemical changes or physical removal from the area (run-off or migration out of the root zone). The nutrition doses have been calculated using four different half-lives. This "half-life" comes in addition to the radioactive half-life. The doses calculated are shown in table 3.25.

The nutrition doses and doses from exposure to radiation from material deposited upon ground are integrated over infinite time.

The calculated doses via all exposure pathways are shown in table 3.26.

Half-life (years)	Coal-fired plant	Lignite-fired plant
50	28	1.8
100	35	2.4
200	41	2.8
500	52	5.0

Table 3.25. Collective effective nutrition doses (personrem/year of operation). From coal-fired and lignite-fired power plants. All dose values are per 1000 MWe.

Exposure pathway	Coal-fired plant	Lignite-fired plant
Inhalation	40	8
Nutrition	30 - 50	2 - 5
External γ-exposure	10 - 100	2 - 20
Total	80 - 200	12 - 35

Table 3.26. Summary of collective effective equivalent doses via all exposure pathways, in (personrem/year of operation). From coal-fired and lignite-fired power plants. All dose values are per 1000 MWe. The two values are values with vertical migration velocity in soil of 0.1 mm/year and 1 mm/ year respectively.

3.2.6 McBride (Ref. MC77).

For additional information see chapter 3.1.11.

Exposure pathways

In calculations of the collective dose, it is assumed that daily intake of milk is 0.3 liters. The other assumptions are identical to the ones adopted in the individual dose calculation.

Nuclide	Contrib.(%)
Ra-226	67
Ra-228	21
Th-228	0.7
Th-230	3.5
Th-232	0.7
Po-210	2.5
Pb-210	2.1
Ac-227	1.0

Table 3.27. Percentage contributions of radionuclides to population doses from the airborne releases of a 1000 MWe coal-fired power plant. 50 meter stack height.

Exposure pathway	Contrib.(%)
Inhalation	5.5
Surface exposure	0.9
Nutrition	93.6

Table 3.28. Percentage contributions of exposure pathways to population doses (whole body) from the airborne releases of a 1000 MWe coal-fired power plant. 50 meter stack height. (Increased stack height will result in a larger percentage via nutrition.)

__Doses calculated__

The population dose commitment calculations include only the area within a 88.5 km radius of the release point. The population densities assumed (in persons per km^2) were 37 within 8 km, 49 between 8 km and 40 km, and 170 between 40 km and 88.5 km. This is a total of 3.5 million persons. The distribution is based upon (Ref. FI77), and is the average population distribution around three midwestern population centers.

The calculated population whole body dose commitments (per 1000 MWe) range from 23 to 18 manrem per year of operation, for the different stack heights. Contributions from the various radionuclides are shown in table 3.27, and from the various exposure pathways in table 3.28.

__3.2.7 UNSCEAR (Ref. UN82).__

For additional information see chapter 3.1.14.

Nuclide	*Inhalation*	*Internal due to deposited activity*	*External due to deposited activity*
U-238	4.5	0.6	
U-234	5.2	0.6	
Th-230	18.	0.9	
Ra-226	0.4	0.9	35.
Rn-222*	0.1	20.	
Pb-210	2.3	22.	
Po-210	2.5		
Th-232	86.	0.3	
Ra-228*	0.2	1.6	54.
Th-228	18.	-	
Rn-220*	-	9.4	
Total	140.	56.	90.

Table 3.29. Estimates of collective effective dose commitments resulting from atmospheric releases from coal-fired power plants. All values in units (manrem/year of operation) and per 1000 MWe.

* - and daughters.

Doses calculated

The collective dose commitments due to inhalation are calculated, as described in chapter 3.1.14, and the results are shown in table 3.29.

The collective dose commitments incurred after deposition are crudely evaluated by comparison with doses from natural soil activity. It has also been assumed that the deposited activity becomes unavailable to the vegetation with a halflife of 100 years, and that only the upper 30 cm of soil are involved in the uptake of radionuclides by vegetation. The evaluated doses, external and internal are shown on the previous page, in table 3.29.

4. SUMMARY OF RESULTS, AND ROUGH EVALUATION.

Table 4.1 contains a summary of the calculated maximum individual doses esimated in the references analyzed in chapter 3. Table 4.2 contains a summary of the estimated collective doses.

Reference	Dose (mrem/year)
AI82	7.4 (whole b.)
BC78[1]	0.14 - 8.7 (lung)
BE79[3]	0.013 (whole b.)
CA80	23. (whole b.)
HA82	0.05 (whole b.)
IL78	0.53 (whole b.)
JA81[2]	0.2 - 0.04 (w.b.)
KO79	64. (bone)
KR78	0.037 (bone)
MC77	1.9 (whole b.)
ST83	0.16 (whole b.)
UN82[3]	0.5 (whole b.)

Table 4.1. Maximum individual dose estimates, due to the airborne releases of a *1000 MWe coal-fired power plant.*

[1] Doses *for a modern* and older plant.
[2] Doses for a coal-fired and lignite-fired plant.
[3] Only inhalation.

The references that give doses to bone or lung only can not be compared to the others. Help in converting these results to comparable entities may, however, be obtained from e.g (Ref. JA81) where doses to the different organs, as well as weighted whole body doses are given. This reference gives the following rough relationships between the doses (whole body/bone/lung) = (1/10/3). Another reference, (Ref. IL78), however, gives the following relationship: (whole body/bone/lung) = (1/200/80). The doses calculated by these two references, as shown in table 4.1, are not very different, but there are evidently more serious disagreements underneath; possibly explained by differences in the composition of the releases assumed.

Some results in table 4.1 stand out as exceptionally high (AI82, CA80) and some as exceptionally low (BE79, KR78). The results from (HA82) are somewhat low. The probable reasons for diverging results are:

- AI82 Large releases; roughly ten times higher than many of the other references.

- CA80 Peculiar, and probably faulty, assumptions concerning dose relationships and calculations of nutrition doses.

- BE79 Includes only the inhalation pathway; but this can only be part of the explanation, since the other references find inhalation to be the dominating pathway. The report contains too little information for further evaluation.

- KR78 Only Ra-226 included in the calculation. Since the calculated dose is to bone, this result is probably more than a factor 100 smaller, when compared to the results from the other references.

- HA82 It seems that doses closer to the release point (than 1000 meters) are higher, but they are not given.

A most probable value of 0.5 mrem/year for the maximum individual effective dose equivalent commitment is indicated. It must be kept in mind, however, that agreement between results from different studies does not prove that the result is correct.

Reference	Collective dose
BE79	550
CA80	18000
HA82	370
IL78	15
JA81	200
MC77	23
UN82	290

Table 4.2. Collective doses (whole body) (manrem/year of operation), due to releases from a 1000 MWe coal-fired power plant.

One of the values in table 4.2 is extremely high (CA80), and two are rather low (IL78, MC77). The probable explanations are:

- CA80 Peculiar, and probably faulty, assumptions concerning dose relationships and calculations of nutrition doses.

- IL78 Impossible to evaluate from the available information. Does not have any evident flaws.

- MC77 Includes only the population out to 88.5 km from the release point.

The references point to a most probable value of about 300 manrem per year of operation, for the collective dose commitment.

<u>Rn-222 and daughters</u>

When this report was reviewed in the Steering Group, a desire was expressed for knowing how much of the doses was due to radon and daughters. This information has been found in two of the references (AI82 and JA81). Since the part of the doses due to radon and daughters is quite insignificant, time has not been wasted on searching for this type of information in the remaining references.

Exposure to radon takes place via inhalation only. In (Ref. AI82) it is said that 0.00088 mrem/year is due to Rn-222 and daughters, while the individual inhalation dose from all nuclides is 5.5 mrem/year. In (Ref. JA81) it is said that 0.0005 mrem/year is due to Rn-222 and daughters, while the individual inhalation dose is 0.1 mrem/year, when summed over all nuclides. In (Ref. JA81) the collective dose due to Rn-222 and daughters is found to be 0.2 manrem/year of operation, while the collective dose via inhalation is 40 manrem/year of operation, when summed over all nuclides. The collective dose via all pathways and summed over all nuclides is 80 - 200 manrem/year of operation (depending upon the value chosen for vertical migration velocity in soil).

5. CONCLUSION.

A first look at the different reports analyzed in the present report, shows a very wide range in doses calculated. There is, however, also a wide range in the assumptions adopted. In some cases some of the assumptions can be criticized; while in other cases they are chosen to represent situations different from the ones calculated in the other reports.

Strong variations in maximum individual doses will result from neglecting plume rise, and also from differences in actual stack height. Refs. CA80 and HA82 have relatively high stacks, which should result in low doses. But CA80, on the contrary gives a high dose. Refs. KO79, KR78 and probably UN77 and UN82 do not take plume rise into account. This should result in high doses, which it does in Ref. KO79, but not in the other references.

In the situation analyzed, the full range of meteorological conditions should be used to obtain the exposure over the whole year. In some of the references calculations have only been performed for an "average" condition. The calculated dose is then probably too low. This error may on the other hand be smaller than the error (or difference between results from two references) resulting from use of different quantification of the dispersion characteristics.

The position of the individual is of course important. Most references have attempted to place the individual in the position where the dose will be highest (several kilometers from the release point). Because of the height of the release, and plume rise when included, this position can really only be determined by carrying out the calculations for all weather conditions and many different distances. It is not clear whether it is actually the maximum individual dose that has been determined in most of the references. In Ref. IL78 it is specified that the dose is an "average individual" over 1000 km^2, and must as such be expected to be considerably lower than the doses from the other references. It is, however, quite near the "most probable value" predicted by these references.

Most of the references have found that inhalation and nutrition are the two most important exposure pathways. However, BC78 finds that nutrition is negligible. BE79 seems to consider inhalation only. CA80 finds nutrition completely dominant, but it is hard to believe the results in this report. In KO79, MC77 and ST83 nutrition is found to be much more important than inhalation.

In AI82 the most important nuclides are found to be Th-230 and U-234. In BE79 U-238 is found to be the most important nuclide, but Pb-210, Th-232, Ra-226, Ra-228 and Th-228 (in this order) are not much less important. In CA80 it is claimed that Pb-210, Pa-231 and Po-210 dominate. In JA81 the most important nuclides are found to be Po-210 and Pb-210. In KO79 the most important nuclide is said to be Th-228 (coming from decay of Th-232). In KR78 the nuclide Ra-226 is said to be completely dominant. In ST83 the dose is completely dominated by Pb-210. The agreement between the references on this point is in other words exceptionally bad.

Several of the reports contain less information than they ought to, in order to assure a proper understanding of the work performed. The results from these reports will tend to be rejected, if they are at variance with the results from other, better documented reports.

It is concluded that the maximum individual dose is about 0.5 mrem/year per 1000 MWe, and that the collective dose is about 300 manrem per year of operation, and per 1000 MWe.

The doses are at least of the same order of magnitude as those resulting from atmospheric release from nuclear power plants of the same capacity; probably considerably larger, if compared to real releases from operating nuclear power plants in the Nordic countries.

It seems that agreement between the different references is worse than would appear from only comparing the calculated doses. This becomes especially clear when one examines what nuclides are considered to be the most important by the respective references.

6. RECENT PUBLICATIONS

The literature search which formed the basis for the present report was performed in 1982. A new search was performed in May 1985, and the following potentially interesting new references were found:

Chatterjee, B. et al: Radionuclides in soil and vegetation from the environment of a coal-fired power plant. (In German) GSF-S-940. München. May 1983.

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The available resources in the present project have been exhausted, and examination of these references can not be carried out at the present time.

The two last references have, however, been obtained and briefly looked at, and the rough impressions will be given here:

The Yugoslavian work has consisted of measurements of the total alpha activity in air one meter above ground level (in two positions at 1.5 km and 5 km from the plant respectively), and of measurements of concentrations of Pb-210 and Ra-226 in rain and washout. Potential resulting doses have not been estimated.

The report from Los Alamos is somewhat unconventional in its approach, and from the very brief progress report obtained, it is difficult to see just what sort of work has been performed as part of the project. It is said in the report that: "The largest incremental dose of radioactivity from coal is likely to come from airborne radioactivity, largely from elevated Pb-210 and Po-210 on escaping fly ash. However, in the vicinity of a modern 1000-MW coal-fired power plant, other nuclides contribute to the total dose, which is estimated to be 0.14 mrem/y for the maximally exposed individual." This information seems to have been taken from other references. The dose is about a factor three lower than what is taken as the "most probable value" in the present report, in chapter 4. The unconventional part is, however, the claim that such doses are of no concern, since many common voluntary situations may differ as much in radiation exposure. A couple of examples are "2 days over bare ground" compared to "2 days over ground covered with snow", and "12 hours in wind from the continent" compared to "12 hours in wind from the ocean".

Finally, it should be mentioned that the INIS data base was not as much help as it ought to have been. It is not by far as up to date as hoped and expected.

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MAIN ACTIVITY AREAS

- Petroleum technology
- Nuclear power
- Process control
- Energy systems, energy conservation
- Isotope technology
- Industrial process technology
- Materials technology
- Basic research in physics

SPECIAL ACTIVITIES

- Nuclear fuel technology
- Process supervision and -control
- Industrial mathematics
- Reservoir modelling
- Petroleum geology and -chemistry
- Flow technology
- Nuclear instrumentation
- Gas technology
- Oil corrosion
- Advanced welding methods
- Radioactive pharmaceuticals
- Radiation technology
- Physical-chemical analyses
- Solid state physics

The Institute has 500 employees, 300 at Kjeller and 200 in Halden.

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