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# Comparison of Radiation Exposures from Coal-fired and Nuclear Power Plants

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# 석탄발전과 원자력발전에 의한 방사선피폭 비교 연구

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## Abstract

Comparison study on the radiological effects by radionuclides from hypothetical 1,000MWe coal-fired power station and nuclear power plant is made. This paper describes the radiological effects only for gaseous effluents released in normal operation. Source terms for coal-fired power station are quoted from foreign data and those for nuclear power plant are calculated for reference power plant. Gaussian plume model is used to assess atmospheric dispersion of radioactive effluents based on one year meteorological data of Kori site and individual doses are calculated at the maximum X/Q point.

Doses from nuclear power plant are slightly more than those from coal-fired power plant. In the case of coal-fired power plant, doses by ingestion of contaminated vegetation are 73.5% of total doses.

## 요 약

가상적인 1,000MWe의 석탄화력발전과 원자력발전소로부터 배출되는 방사성물질에 의한 피폭 영향을 상호 비교 연구하였다. 본 논문에서는 정상가동중에 배출되는 기체상 방사성물질에 국한하였으며 석탄화력발전소에 대한 방사선원은 국내자료가 부족하여 외국자료에 근거했고, 원자력발전소에 대해서는 표준발전소에 대해 계산된 방사선원을 사용하였다. 고리 기상탑의 1년 기상자료를 이용하여 Gaussian 모델에 의해 방사성물질의 대기확산을 평가했으며, 개인 피폭선량은 대기확산인자가 최대인 지점의 성인에 대해 계산하였다.

방사선피폭선량은 석탄화력발전소보다 원자력발전소의 경우가 약간 컸으며 석탄화력의 경우는 원자력발전소와 달리 피폭선량의 73.5%가 오염된 엽채류의 섭취에 따른 것이었다.


## 1. Introduction

Most of materials in the world contain radioactivities and there is no exception for the coal. The combustion of coal releases trace elements, including naturally occuring radionuclides, to the atmosphere as vapors and particles. The operation of coal-fired and nuclear power plants results in radiation exposure to the public.

For the former case it is caused by natural radionuclides; for the latter one by newly created nuclides.

For the detailed comparison of the radiation exposure for different types of power plants, all stages of the fuel cycles and the sequence from emission to detriment should be considered.

It is very troublesome to obtain data for all stages of the fuel cycles. So this study has been focused on radiation exposures from the radionuclides released into the atmosphere from the power plants.

The amounts of radioactive material released into the atmosphere from the power plants are calculated with the assumption that the electric power is 1, 000 MWe. Foreign data are adopted as the source terms for coal-fired power plant owing to the lack of source terms about imported coal.

In the case of nuclear power plant source terms are calculated with the GALE computer code[1] using the information of the KNU 5 plant in Kori site, Korea.

Transport and diffusion of the radioactive effluents in the atmosphere and the radiation exposure dose for some exposure pathways are calculated using the models which are described in the U.S NRC Reg. Guide 1. 109.[2] It is assumed that the two types of power plants are located in the same site, so that the collective dose equivalent has not been calculated in different situation.

In this study individual dose equivalent is calculated for individual who lives at the location of the hightest predicted ground-level concentration and who consumes only food raised or grown in the immediate area.

The exposure pathways considered in the calculation of doses are as follows;

1. external radiation exposure from radioactive effluents released into the atmosphere
2. internal radiation exposure by the inhalation of radionuclides in the atmosphere
3. internal radiation exposure by the ingestion of contaminated foodstuffs
4. external radiation exposure from the radionuclides deposited on the ground

The doses committed on bone, lung, whole body, thyroid, kidney, liver, and G.I. tract are calculated for these exposure pathways.

## II. Determination of Source Term

### II. 1. Airborne Radioactive Effluents from Coal-fired Power Plant

There are two types of radioactive materials released into the atmosphere from the coal-fired power plant in the case of normal operation. The one is gaseous radioactive effluents and the other is radioactive effluents of particulates such as Th-232, U-235, U-238, K-40 and their decay daughters.

These radioactive materials are released into the atmosphere as the form of fly ash. Generally 15 W/O of coal is transformed into fly ash in the process of combustion. In modern power stations this bulk of ash is collected in hoppers from the flue gas stream by gravitational settling and electrostatic precipitators. Fly ash from coal-fired power plant escapes into the atmosphere in quantities of about 0. 5% to 2% of the total ash produced, depending upon the efficiency of the electrostatic filters applied.[3]

The amount of radioactivity released into the atmosphere can be calculated if we know the amount of the fly ash escaped from plant through the stack and the concentrations of radionuclides in the fly ash.

Owing to the lack of these data for imported coal in Korea, informations of several countries are compared[4~10] and then the data of Germany are adopted as the source term.[11]

The specific activity in coal and fly ash is shown in Table 1, and the amount of radioa-

**Table 1. Specific Activity in Coal & Fly Ash** (nCi/kg)[11]

| Radionuclide | Coal | Fly ash |
|---|---|---|
| U-238(U-234, Th-230) | <1 | 8 |
| Ra-226 | 0.5 | 8 |
| Pb-210 | 0.7 | 80 |
| Po-210 | 0.8 | 150 |
| Th-232(Th-228) | <0.5 | 3 |

**Table 2. Activity Released into the Atmosphere for Coal-fired Power Plant** (mCi/GWe. yr)[11]

| Radionuclide | Activity |
|---|---|
| U-238 | 10 |
| U-234 | 10 |
| Th-232 | 10 |
| Ra-226 | 10 |
| Pb-210 | 100 |
| Po-210 | 200 |
| Th-232 | 5 |
| Th-228 | 5 |

ctivity released into the atmosphere from 1,000 MWe power plant in one year is described in Table 2.

### II.2. Airborne Radioactive Effluents from Nuclear Power Plant

In nuclear power plant radioactive materials are formed by fission and activation. The released amount of radioactive materials depends on type of plants, operating condition, failure rate of fuel cladding, and characteristics of waste treatment system. Several different types of plants have been diverse such as AGR, HTGR, BWR, PWR and CANDU.

In Korea there is only one CANDU type reactor and all the others are PWR, so in this study the amounts of radionuclides released from 1,000MWe PWR is adopted as the reference source term.

PWR has primary and secondary coolant loops. The radionuclides generated in fuel enter the primary coolant loop by the failure of fuel cladding and then enter the secondary coolant loop by the failure of steam generator. Some of the contained radionuclides may escape from the primary and/or secondary coolant loops with any water leak or steam release. Such release paths include pressurizers, air ejectors, steam valves, gland seals, turbine seals and any other dripping pipes. The gaseous and volatile components end up in the containment vessel atmosphere and the liquids go to various floor drains, sumps, and retention tanks.

**Table 3. Annual Releases of Gaseous Effluents for Reference Nulcear Power Plant**(NPP)

| Nuclide | Release quantity(Ci/year) |
|---|---|
| I-131 | 1.749E−2 |
| I-133 | 5.869E−2 |
| H-3 | 1.110E+3 |
| Ar-41 | 34.0 |
| Kr-85M | 8.80E+1 |
| Kr-85 | 7.01E+2 |
| Kr-87 | 4.90E+1 |
| Kr-88 | 1.39E+2 |
| Xe-131M | 9.80E+1 |
| Xe-133M | 1.70E+1 |
| Xe-133 | 3.46E+2 |
| Xe-135M | 1.60E+1 |
| Xe-135 | 4.86E+2 |
| Xe-137 | — |
| Xe-138 | 1.30E+1 |
| Cr-51 | 9.40E−5 |
| Mn-54 | 5.60E−5 |
| Co-57 | 8.20E−6 |
| Co-58 | 4.60E−4 |
| Co-60 | 1.10E−4 |
| Fe-59 | 2.70E−5 |
| Sr-89 | 1.50E−4 |
| Sr-90 | 6.00E−5 |
| Zr-95 | 1.10E−6 |
| Nb-95 | 4.20E−5 |
| Ru-103 | 1.60E−5 |
| Ru-106 | 7.20E−7 |
| Sb-125 | 5.70E−7 |
| Cs-134 | 4.30E−7 |
| Cs-136 | 3.20E−5 |
| Cs-137 | 8.30E−5 |
| Ba-140 | 6.30E−7 |
| Ce-141 | 1.30E−5 |

The radwaste system is designed to extract and retain as much of these residual activity as possible so that released amount to environment is kept as low as reasonably achievable.[12] In this study with the data of KNU 5, the amount of radionuclides released into the atmosphere from the 1,000MWe PWR is calculated using the GALE computer code, and shown in Table 3.

## III. Atmospheric Dispersion of Radioactive Effluents.

Radioactive effluents are transported in downwind direction and diffused by turbulent mixing. The Gaussian plume model is adopted appropriately for a long-term atmospheric diffusion analysis.

The concentration of radionuclides at the downwind distance $x$ from the release point is represented as the Sagendorf equation based on a Gaussian model,

$$X(x)=\frac{f}{2\pi x/n}\int_{-\infty}^{\infty}\frac{Q}{\pi\sigma_y\sigma_z\bar{u}}\exp\left[-\left(\frac{y^2}{2\sigma_y^2}+\frac{he^2}{2\sigma_z^2}\right)\right]dy \qquad (1)$$

where

$X(x)$ : concentration [Ci/m$^3$]

$Q$ : source strength [Ci/sec]

$\sigma_y$, $\sigma_z$ : lateral and vertical dispersion parameter [m]

$f$ : fraction of time that wind occurs in the sector

$n$ : number of the sectors in direction

$he$ : effective release height [m]

$\bar{u}$ : mean wind speed [m/sec]

$x$ : downwind distance [m]

16 kinds of wind directions are considered, and then the Eq. (1) is modified as follow;

$$X/Q=2.032\sum_{i=1}^{M}\frac{f_i}{\sigma_{zi}u_i x}\exp\left(-\frac{he^2}{2\sigma_{zi}^2}\right) \qquad (2)$$

where the subsctipt $i$ denotes Pasquill category on stability and $M$ is the number of every category.

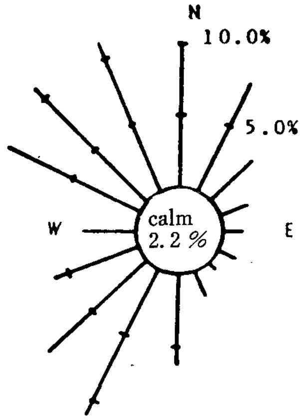


**Fig. 1. Wind Rose Roreference Site for One Year.**

Meteorological data used to calculate the diffusion factor are the annual 15-minute average of wind speeds, directions and stabilities taken from Kori-site meteorological tower. With these data wind rose is obtained and represented in Fig. 1.

Radionuclides in the atmosphere are deposited on the ground surface by wet and dry deposition.

Only the dry deposition is considered in this study.

For each radionuclide, deposition velocity is different according to the properties of impingement on ground surface and electrostatic attraction. The relative concentration of radionuclides on the ground surface is described as

$$D/Q=Vd(X/Q)$$

where $Vd$ is deposition velocity.

## IV. Analysis of Exposure Pathways and dose Calculation

Four pathways described in intoduction are adopted to assess exposure dose and shown schematically in Fig. 2. In calculation of radiation dose induced by the gaseous radioactive effluents from nuclear power plant, models which

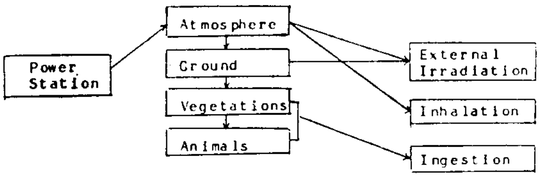


**Fig. 2. Exposure Pathways** (summary).

are described in US NRC Reg. Guide 1.109 is widely used in normal operation.

The GASPAR code based on this guide[13] is used to calculate dose for nuclear power plant, and a computer program is made in accordance with this guide for coal-fired power plant.

And the radionuclides are categorized into two groups; nobles gases and the other radionuclides.

**VI. 1. Doses from Noble gases Discharged to the Atmosphere.**

Whole body dose from noble gas release is calculated at the depth of 5 cm and skin dose is calculated at the depth corresonding to 7 mg/cm$^2$ of tissue.[14]

Equations for dose from free-standing stacks more than 80 meter high are

$$D^T(r,\theta)=1.11S_F\sum_k D_k^r(r,\theta)\exp[-\mu_a^T(E_k)t_d] \quad (4)$$

$$D^S(r,\theta)=1.11S_F D^r(r,\theta)+\sum_i X_i(r,\theta)DFS_i \quad (5)$$

where superscript $T$ means whole body and $S$ means skin, and $S_F$ is the attenuation factor that accounts for the dose reduction due to shielding. $Dk^r$ is the annual gamma air dose associated with the k-th photon energy group, $\mu_a^T(E_k)$ is air energy absorption coefficient dependent on the energy of k-th photon energy group, and $t_d$ is the product of tissue density and depth. $X_i(r,\theta)$ is the annual average concentration of radionuclide $i$ at the distance $r$ in the sector $\theta$ and $DFS_i$ is the beta skin dose factor of radionuclide $i$.

For all other releases,

$$D_\infty^T(r,\theta)=S_F\sum_i X_i(r,\theta)DFB_i \quad (6)$$

$$D^S(r,\theta)=1.11S_F\sum_i X_i(r,\theta)DF_i^r+\sum_i X_i(r,\theta)DFS_i \quad (7)$$

where $DFB_i$ is the whole body dose factor of radionuclide $i$.

**IV. 2. Doses from Other Radionuclides Released to the Atmosphere.**

The ground concentration of radionuclide $i$ at the location $(r,\theta)$ is determined by

$$C_i^G(r,\theta)=\frac{1.0\times10^{12}\delta_i(r,\theta)Q_i}{\lambda_i}[1-\exp(-\lambda_i t_b)] \quad (8)$$

where $t_b$ is the time period over which the accumulation is evaluated and $\delta_i(r,\theta)$ is the annual average relative deposition of effluent species $i$ at location $(r,\theta)$. And $\lambda_i$ is decay constant of radionuclide $i$.

Annual dose from external irradiation from radionclides deposited on the ground is expressed as follow;

$$D_j^G(r,\theta)=8760\ S_F\sum_i C_i^G(r,\theta)DFG_{ij} \quad (9)$$

where $DFG_{ij}$ is the dose conversion factor on open field ground for organ $j$ from radionuclide $i$.

Annual dose from inhalation of radionuclides is calculated using the following equation;

$$D_{ja}^A(r,\theta)=R_a\sum_i X_i(r,\theta)DFA_{ija} \quad (10)$$

where $R_a$ is the annual inhalation rates for individuals in age group $a$, and $DFA_{ija}$ is the inhalation dose factor for radionuclide $i$, organ $j$, and age group $a$.

The equation for calculating the annual dose from ingestion of radionuclide in contaminated food is represented as,

$$D_{ja}^D(r,\theta)=\sum_i DFI_{ija}[U_a^V f_g C_i^V(r,\theta)+U_a^M C_i^M(r,\theta)+U_a^F C_i^F(r,\theta)+U_a^L f_l C_i^L(r,\theta)] \quad (11)$$

where superscripts $V, M, F$ and $L$ represent produce, milk, leafy vegetable, and meat, respectively. *DFIija* is the ingestion dose factor for radionuclide $i$, organ $j$, and age group $a$. $C_i(r, \theta)$ is the concentration of radionuclide $i$ in each food at location $(r, \theta)$. $U_a$ is the annual intake of each food for individuals in the age group $a$, and $f_g$ and $f_l$ are the respective fractions of the ingestion rates of produce and leafy vegetables.

## V. Results and Discussion

Individual exposure doses caused by normal operation of 1,000 MWe coal-fired and nuclear power plants are calculated seperately using 15-minute meteorlogical data obtained for one year at the Kori meteorological tower.

Individual doses are calculated for adult at the midpoint of each 160 sector which is composed of 10 distance intervals and 16 directions, and then the maximum values are compared. The maximum dose is found at the first interval (804m distant from source) in NE direction.

In the case of coal-fired power plant, stack heights of 100m, 200m and 300m are considered. In PWR nuclear power plants, gaseous effluents are released from vent, so that ground level release is considered conservatively for nuclear power plant. In Table 4, the maximum X/Q values are represented for each stack height, and the maximem values of relative deposition are shown in Table 5.

Individual doses calculated with these maximum values are shown in Table 6 and 7 for nuclear power plant. Doses from coal-fired power plant are represented in Table 8 to 11 for each exposure pathway and each target organ.

**Table 4. Maximum Atmospheric Diffusion Factor** (X/Q)

| Stack height(m) | X/Q(sec/m$^3$) |
|---|---|
| 0 | 3.88 E−06 |
| 100 | 2.51 E−08 |
| 200 | 8.06 E−09 |
| 300 | 4.84 E−09 |

**Table 5. Maximum Relative Deposition** (D/Q)

| Stack height(m) | D/Q(1/m$^2$) |
|---|---|
| 0 | 1.36 E−08 |
| 100 | 2.51 E−10 |
| 200 | 8.06 E−11 |
| 300 | 4.84 E−11 |

**Table 6. Individual Doses for Each Organ for NPP** (mrem/yr)

| Organ \ Pathway | External | Inhalation | Ingestion |
|---|---|---|---|
| W.B* | 3.30 E−01 | 1.73 E−01 | 6.31 E−01 |
| GI-Tract | 3.30 E−01 | 1.73 E−01 | 6.27 E−01 |
| Bone | 3.30 E−01 | 7.95 E−04 | 2.14 E−02 |
| Liver | 3.30 E−01 | 1.73 E−01 | 6.30 E−01 |
| Thyroid | 3.30 E−01 | 4.65 E−01 | 6.30 E−01 |
| Kidney | 3.30 E−01 | 2.12 E−01 | 1.25 E+00 |
| Lung | 3.34 E−01 | 1.73 E−01 | 6.26 E−01 |
| Skin | 7.52 E−01 | 1.73 E−01 | 6.26 E−01 |

*W.B: whole body

**Table 7. Individual Doses for Each Pathway for NPP**

| Pathway | Doses (mrem/yr) |
|---|---|
| External | 3.06 E+00 |
| Inhalation | 1.54 E+00 |
| Ingestion | 5.04 E+00 |

**Table 8. External Doses for Coal-fired Power Plant**(CPP), (mrem/yr)

| Organ \ Height | 100m | 200m | 300m |
|---|---|---|---|
| Whole body | 6.04 E−03 | 1.94 E−03 | 1.16 E−03 |
| Skin | 2.91 E−00 | 9.35 E−01 | 5.61 E−01 |

**Table 9. Inhalation Doses for CPP** (mrem/yr)

| Organ \ Height | 100m | 200m | 300m |
|---|---|---|---|
| Bone | 2.57 E−01 | 8.26 E−02 | 4.96 E−02 |
| Liver | 1.35 E−02 | 4.33 E−03 | 2.60 E−03 |
| W. Body | 1.06 E−02 | 3.41 E−03 | 2.05 E−03 |
| Thyroid | 5.92 E−02 | 1.90 E−02 | 1.14 E−02 |
| Lung | 1.24 E−01 | 3.98 E−02 | 2.39 E−02 |
| GI-tract | 8.88 E−05 | 2.85 E−05 | 1.71 E−05 |

**Table 10. Ingestion Doses for CPP** (mrem/yr)

| Organ \ Height | 100m | 200m | 300m |
|---|---|---|---|
| Bone | 4.95 E+00 | 1.59 E+00 | 9.53 E−01 |
| Liver | 4.28 E−01 | 1.37 E−01 | 8.24 E−02 |
| W. Body | 2.72 E+00 | 8.73 E−01 | 5.24 E−01 |
| Thyroid | 1.26 E+00 | 4.04 E−01 | 2.43 E−01 |
| GI-tract | 1.85 E−01 | 5.94 E−03 | 3.56 E−03 |

**Table 11. Individual Doses for CPP** (mrem/yr)

| Pathway \ Height | 100m | 200m | 300m |
|---|---|---|---|
| External | 2.92 E+00 | 9.37 E−01 | 5.62 E−01 |
| Inhalation | 4.64 E−01 | 1.49 E−01 | 8.96 E−02 |
| Ingestion | 9.54 E+00 | 3.01 E+00 | 1.81 E+00 |

**Table 12. Individual Doses for Both Power Plants** (mrem/yr)

| Pathway | NPP | CPP |
|---|---|---|
| External | 3.06 E+00 | 9.37 E−01 |
| Inhalation | 1.54 E+00 | 1.49 E−01 |
| Ingestion | 5.04 E+00 | 3.01 E+00 |

The typical stack height is 200m in modern 1,000MWe coal-fired power plant, so the doses obtained in case of 200m stack height are compared with those of nuclear power plant. The results are shown for each pathway in Table 12. Individual doses from nuclear power plant are slightly more than those from coal-fired power plant, and doses by ingestion of contaminated food are similiar in the both cases. The doses by ingestion are shown for each organ in Table 13. And Table 14 shows that dose for every organ is different for both types of power plants. Thyroid receives the most exposure for nuclear power plant and bone receives the most exposure

**Table 13. Doses by Ingestion** (mrem/yr)

| Organ | NPP | CPP |
|---|---|---|
| W.B. | 6.31 E−01 | 8.73 E−01 |
| GI-tract | 6.27 E−01 | 5.94 E−03 |
| Bone | 2.14 E−02 | 1.59 E+00 |
| Liver | 6.30 E−01 | 1.37 E−01 |
| Kidney | 6.30 E−01 | — |
| Thyroid | 1.25 E+00 | 4.04 E−01 |
| Lung | 6.26 E−01 | — |
| Skin | 6.26 E−01 | — |

for coal-fired power plant. It is because the doses from nuclear power plant are mainly devoted by noble gases and iodine but the doses from coal-fired power plant are mainly devoted by long-lived alpha-emitters such as Ra-226.

Even though the doses from nuclear power plant are slightly more than those from coal-fired power plant, it can't be said that coal-fired power plant have less environmental effects than nuclear power plant. It is because the environmental effects are only by the radiation in the case of nuclear power plant, but its effects are by the SOx, NOx, and particulates as well as the radiation in the case of coal-fired power plant.

In this study, the comparisons are carried out only for the radioactive effluents in normal operation, but every step of fuel cycle and accident case should be considered for more detailed comparisons.

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**Table 14. Dose Comparison for Every Organ** (mrem/yr)

| | T. body | Thyroid | Bone | Liver | lung | Kidney | GI-tract | Skin |
|---|---|---|---|---|---|---|---|---|
| NPP | 1.13 E−00 | 1.79 E−00 | 3.53 E−01 | 1.13 E−00 | 1.13 E−00 | 1.43 E−00 | 1.13 E−00 | 1.55 E−00 |
| CPP | 8.79 E−01 | 0 | 1.67 E−00 | 1.41 E−01 | 3.98 E−02 | 4.24 E−01 | 5.98 E−03 | 9.36 E−01 |

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