Energy and Power Engineering, 2010, 46-52
doi:10.4236/epe.2010.21008 Published Online February 2010 (http://www.scirp.org/journal/epe)

Valuing Health Effects of Natural Radionuclides Releases from Yatağan Power Plant

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Abstract: The objective of this paper is the valuation of radiological health effects of Yatağan Power Plant. To this aim the radiation dose calculations are carried out for the population living within 80 km radius of the plant. The average of the maximum measured specific isotopes ^{238}U, ^{232}Th and ^{226}Ra in the flying ash samples are considered as radioactive sources. Based on the dose calculations, first the stochastic health effects and then monetary health effects are estimated. The estimated total collective dose and economic value of the predicted health effects are 0.3098 man Sv/y and 14791 US$/y respectively. The results obtained from the dose calculations are lower than the limits of International Commission of Radiation Protection (ICRP) and it does not pose any risk for public health. Monetary value of health risks is also negligible in comparison to the average yearly sales revenue of the plant which is 250 million US$.

Keywords: coal-fired power plants, collective dose, atmospheric dispersion, valuing health effects

1. Introduction

Yatağan Power Plant (YPP) is one of the largest lignite-fired power plants in Turkey with a total capacity of 630 MW. It has been operated in Muğla province at the western Anatolia since 1982 [1]. Lignite in Muğla province contains some uranium as all lignite does. That uranium passes to ash with a higher concentration during the firing process in furnace chamber at 1000 ^{o}C. While well-urned ash goes to the plant chimney, the others are not burned perfectly, which are called slag ashen drops the furnace chamber floor [2,3]. The radioactive flying ash is released to the atmosphere, depending on the efficiency of the plant's chimney emission control equipment. The major potential pathway, which might result in increased radiation doses to people are inhalation of flying ash, ingestion of food grown in contaminated soil or direct radiation exposure from the increased deposited radioactivity when flying ash are released from the plant chimney [4,5].

In this study, the radiation dose calculations have been carried out using the code CAP88-PC which stands for Clean Air Act Assessment Package [6] for the population living within 80 km radius of the YPP by using the average of the maximum measured specific isotopes ^{238}U, ^{232}Th and ^{226}Ra in the flying ash samples as radioactive sources. Based on the dose calculations, the stochastic health effects have been estimated by using the risk factors, as recommended by the International Commission of Radiation Protection (ICRP) [7]. Then the predicted health effects have been monetized by using the methodology given in NucPacts model [8].

In order to estimate the average dispersion of radionuclides released from a point source, a modified plume dispersion model has been used in the calculations. Pasquill categories A-F with site-specific averaged meteorological conditions are used in the modified dispersion model. The meteorological data on atmospheric stability conditions like mean wind speed and the frequency distribution of wind direction are obtained from Turkish State Meteorological Service [9]. The population distribution around the YPP is taken from Turkish State Institute of Statistics [10].

Annual radioactivity release rate for three different radionuclides in the dose calculations is calculated by using the ash emission rate from the plant chimney, the measured activity in flying ash and the plant loading factor [11,12].

The rest of the study is organized as follows. Section 2 introduces the source terms for ^{238}U, ^{232}Th and ^{226}Ra. Section 3 deals with the assessment of radiation hazard. In Section 4 risk calculations are given in detail. Section 5 presents a monetary valuation of health effects. Finally, Section 6 gathers the main conclusions derived from this paper.

2. Source Terms

In this study, the literature related to the maximum measured specific isotopes ^{238}U, ^{232}Th and ^{226}Ra in the flying ashes of the YPP are reviewed. In those studies, the concentrations of ^{238}U, ^{232}Th and ^{226}Ra have been measured with high-resolution gamma spectroscopy. The maximum radionuclides concentrations in flying ashes of the YPP are presented in Table 1 [13–15]. As seen from Table 1 the measured concentrations are different from each other and the average of the maximum measured concentrations of different studies for ^{238}U, ^{232}Th and ^{226}Ra are 854, 191, 286 Bq/kg respectively. This is an expected result since the natural radionuclides content in the flying ashes of a coal fired power plant depend on the quality of the coals burned in the power plant. The radionuclides concentrations can be changed up to 1 and 2 orders in magnitude according to the coal types used in the power plant [2].

In this study, the average of the maximum measured specific isotopes ^{238}U, ^{232}Th and ^{226}Ra in the flying ash samples are used as radioactive sources for the potential worst-case scenario.

3. Assessment of Radiation Hazard

The radiation dose calculations have been carried out by the code CAP88-PC for the population living within 80 km radius of the YPP by using the average of the maximum measured specific isotopes ^{238}U, ^{232}Th and ^{226}Ra in the flying ash samples as radioactive sources.

The CAP88-PC (which stands for Clean Air Act Assessment Package) computer code is a set of computer programs, databases and associated utility programs for estimation of dose and risk from radionuclide emissions to air on a personal computer. It uses a modified Gaussian plume equation to estimate the average dispersion of radionuclides released from up to six emitting sources for a circular grid of distances and directions for a radius of up to 80 km around the facility. The sources may be either elevated stacks, such as a smokestack, or uniform area sources, such as a pile of uranium mill tailings. Plume rise can be calculated assuming either a momentum or buoyant-driven plume. The plume centerline remains at effective stack height unless gravitational settling of particulates produces a downward tilt, or until meteorological conditions change. Radionuclides are depleted from the plume by precipitation scavenging, dry deposition and radioactive decay. The stored depletion fractions were calculated numerically with a Simpson's rule. Ground surface and soil concentrations are calculated for those nuclides subject to deposition due to dry deposition and precipitation scavenging. Agricultural arrays of milk cattle, beef cattle and agricultural crop area are generated automatically, requiring the user to supply only the agricultural productivity values. Only 7 organs are valid for the effective dose equivalent. They are Gonads 25 %, Breast 15%, Red marrow 12%, Lungs 12%, Thyroid 3%, Endost 3% and Remainder 30 %. Doses are provided for the pathways of ingestion and inhalation intake, ground level air immersion and ground surface irradiation. Particle size, clearance class and gut-to-blood transfer factors of the released nuclide type are further break down factors. These factors are stored in a database for use by the program.

Table 1. Concentrations of natural radionuclides in flying ashes of the YPP (Bq/kg)

Reference number	^{238}U	^{232}Th	^{226}Ra
[13]	375	253	63
[14]	1704	178	122
[15]	484	141	672
Average	**854**	**191**	**286**

3.1 Input Data

The estimate of radioactivity released annually in the environment by the YPP has been carried out for ^{238}U, ^{232}Th and ^{226}Ra that, according to average of the maximum measured concentrations given in the literature, have resulted to be the most significant. Annual nuclide release rate for the radionuclide type i [Q_i : Bq/y] is calculated from the relation given by:

$$Q_i = \dot{m} A_i L \tag{1}$$

where $\dot{m}$ is the ash emission rate from the plant chimney (kg/y), A_i is the average of the maximum measured radionuclide type i in flying ash (Bq/kg) and L is the plant loading factor.

Plume rise is calculated by using the momentum plume model since ash emission velocity at the chimney exit is known. An average lid for the assessment area is provided as part of the input data. The agricultural data like beef cattle density, milk cattle density and land fraction cultivated for vegetable crop and others for the region are inputted to the code in order to estimate of emitted radionuclides into the food chain.

The meteorological data which obtained from Turkish State Meteorological Service [9] are processed to find out the stability array file for 16 directions. The atmospheric dispersion of the radionuclides from the stack of a power plant are strongly depends on the meteorological conditions where the power plant is located. Therefore the meteorological data are annually averaged within hourly time step for the each year of the period 1975–2006. The better estimation has been made in dose calculations by this way.

The stability array file consists of 4 different wind frequencies, one for each of the 16 wind directions and 6 Pasquill stability category (A-F). 16 records are entered for each Pasquill stability category and wind frequencies. Pasquill stability classes used in the code are A) extremely unstable, B) unstable, C) slightly unstable, D) neutral, E) slightly stable, and F) stable. Once a stability array file has been prepared, and it is converted to wind file for input to the CAP88-PC code which is namely

MUGLA. WND.

Population distribution in the 80-km radius of the plant is presented Table 2 [10] and the dose calculations are made for those population. The program uses a population file for dose calculations. The population file contains the location description, latitude, and longitude of the facility, the number of distances and population for each distance according to 16 wind directions in counter-clockwise order starting with North. The distances are edge points of each sector and are entered in the population file in km. The population distribution file which is namely MUGLA.POP is prepared for 20 distances of each wind direction. Those 20 distances are chosen closest values to the distances presented in Table 2, which are the exact values around the plant to get the sensible results for dose calculations.

Input parameters used in the calculations are given in Table 3 [1,16–18]. Calculated collective effective dose equivalent rate values including all radionuclides and pathways effect around the plant by CAP88-PC code are presented Table 4.

4. Risk Calculation

The occurrence of each of the main stochastic health effects (i.e. fatal and non-fatal cancers and severe hereditary effects) arising as a result of routine atmospheric emission from a power plant is calculated as [8],

$$N_h = HR_h \qquad (2)$$

where N_h is the total occurrence of health effect, h (cases/y), H is the total collective dose occurring via all pathways (man Sv/y), R_h is the risk factor for health effect h (cases man/Sv).

The calculated health effects by the risk factors in CAP88-PC computer code are lower than the calculated health effects by the risk factors which are recommended by the ICRP [7]. Therefore in this study, the ICRP's risk factors have been used in calculations for the potential worst-case scenario. Those values are given in Table 5. The total stochastic health effects around the YPP which are calculated from Equation (2) are given in Table 6.

Table 2. Population distribution in the 80-km radius of the YPP

Location name	Population	Distance to plant (km)	Direction
Yatağan	46252	3	N
Çine	53770	32	N
Köşk	25321	65	N
Sultanhisar	22795	66	N
Aydın, Merkez	208341	46	NNW
Koçarlı	37167	53	NNW
İncirliova	40733	70	NNW
Germencik	45821	75	NNW
Karpuzlu	13207	37	NW
Söke	137739	70	NW
Milas	112808	28	W
Didim	37395	71	W
Bodrum	97826	68	WSW
Datça	13914	77	WSW
Marmaris	79302	55	S
Muğla, (center)	83511	26	SE
Ula	21944	44	SE
Köyceğiz	29196	66	SE
Ortaca	35670	77	SE
Beyağaç	7332	72	ESE
Kale	21390	61	E
Tavas	60669	80	E
Kavaklıdere	12548	25	ENE
Babadağ	8212	80	ENE
Karacasu	21980	65	NE
Bozdoğan	35190	44	NNE
Yenipazar	15492	51	NNE
Nazilli	145963	67	NNE
Kuyucak	31094	81	NNE
Total	**1502582**		

Table 3. Input parameters used in the calculation

Explanation	Values
Grid distances, (m)	3000, 14500, 26500, 35000, 45000, 54000, 61000, 67000, 73000, 78000
Annual precipitation in Yatağan, (cm/y)	64.96
Annual ambient temperature in Yatağan, (ºC)	16.20
Annual average wind speed in Yatağan, (m/s)	2
Height of lid, (m)	642
Chimney height, (m)	120
Chimney inner diameter at the exit, (m)	6.4
Ash emission velocity at the chimney exit, (m/s)	4.1
Ash emission rate from the chimney, (kg/y)	7.55×10^6
Plant loading factor (%)	75
Average of the maximum measured activity in flying ash (^{238}U, ^{232}Th, ^{226}Ra) (Bq/kg)	854, 191, 286
Annual nuclide release rate, (Bq/y)	4.84×10^9, 1.08×10^9, 1.62×10^9
Human inhalation rate, (cm^3/hr)	9.17×10^5
Land fraction cultivated for vegetable crops	5.50×10^{-2}
Beef cattle density, (number/km^2)	3.89
Milk cattle density, (number/km^2)	1.13
Meat ingestion per person, (kg/y)	15
Leafy vegetable ingestion per person, (kg/y)	140
Cereals ingestion per person, (kg/y)	228
Milk ingestion per person, (L/y)	33

Table 4. Collective effective dose equivalent (man Sv/y)

Distance, km	N	NNW	NW	WNW
3.00	0.0480	0.0000	0.0000	0.0000
14.50	0.0000	0.0000	0.0000	0.0000
26.50	0.0000	0.0000	0.0000	0.0000
35.00	0.0081	0.0000	0.0040	0.0000
45.00	0.0000	0.0390	0.0000	0.0000
54.00	0.0000	0.0060	0.0000	0.0000
61.00	0.0000	0.0000	0.0000	0.0000
67.00	0.0050	0.0000	0.0000	0.0000
73.00	0.0000	0.0110	0.0230	0.0000
78.00	0.0000	0.0000	0.0000	0.0000
Distance, km	W	WSW	SW	SSW
3.00	0.0000	0.0000	0.0000	0.0000
14.50	0.0000	0.0000	0.0000	0.0000
26.50	0.0510	0.0000	0.0000	0.0000
35.00	0.0000	0.0000	0.0000	0.0000
45.00	0.0000	0.0000	0.0000	0.0000
54.00	0.0000	0.0000	0.0000	0.0000
61.00	0.0000	0.0000	0.0000	0.0000
67.00	0.0000	0.0120	0.0000	0.0000
73.00	0.0055	0.0000	0.0000	0.0000
78.00	0.0000	0.0015	0.0000	0.0000
Distance, km	S	SSE	SE	ESE
3.00	0.0000	0.0000	0.0000	0.0000
14.50	0.0000	0.0000	0.0000	0.0000
26.50	0.0000	0.0000	0.0260	0.0000
35.00	0.0000	0.0000	0.0000	0.0000
45.00	0.0000	0.0000	0.0048	0.0000
54.00	0.0150	0.0000	0.0000	0.0000

Distance, km	N	NNW	NW	WNW
61.00	0.0000	0.0000	0.0000	0.0000
67.00	0.0000	0.0000	0.0045	0.0000
73.00	0.0000	0.0000	0.0000	0.0012
78.00	0.0000	0.0000	0.0050	0.0000
Distance, km	E	ENE	NE	NNE
3.00	0.0000	0.0000	0.0000	0.0000
14.50	0.0000	0.0000	0.0000	0.0000
26.50	0.0000	0.0027	0.0000	0.0000
35.00	0.0000	0.0000	0.0000	0.0000
45.00	0.0000	0.0000	0.0000	0.0039
54.00	0.0000	0.0000	0.0000	0.0016
61.00	0.0034	0.0000	0.0000	0.0000
67.00	0.0000	0.0000	0.0023	0.0140
73.00	0.0000	0.0000	0.0000	0.0000
78.00	0.0077	0.0009	0.0000	0.0027

Table 5. Risk factors for main stochastic health effects for whole population (case/man Sv)

Health Effect	Risk factor
Fatal cancer	5.0×10^{-2}
Non fatal cancer	1.0×10^{-2}
Severe hereditary effects	1.3×10^{-2}

Table 6. The total stochastic health effects (cases/y)

Health effect type	Number of cases
Fatal cancer	1.549×10^{-2}
Non fatal cancer	3.098×10^{-3}
Severe hereditary effects	4.027×10^{-3}

5. Monetary Unit Costs for Health Impact Assessments

The final stage of the impact pathway analysis is to value the health endpoints in money terms. In literature there are two approaches that may be used in health risk assessments; the first is based on the Value of a Statistical Life (VOSL) and the second is based on the Value of a Life Year Lost (VLYL) [19]. The latter differs from the former in that it takes into account the latency period of different types of cancers. A component related to the cost of illness has also been included in VLYL. Estimates for the economic unit value of radiological health effects have been made for several countries. Ideally, economic unit values should be based on local economic valuation of a country. However, in the absence of such information economic unit values for specific to a country may be transferred to another country after making some adjustments on the basis of real per capita income. This adjustment is required to reflect differences in income and hence, willingness-to-pay regarding the valuation of the health damages of two countries. The following formula can be used to arrive at economic unit values of radiological health effects for countries where there are no studies [19]:

$$D_Y = D_X \left(\frac{PPPGNP_Y}{PPPGNP_X} \right)^E \quad \textbf{(3)}$$

where D_Y economic unit values of radiological health damages for country *Y*, D_X economic unit values of radiological health damages for country *X*, $PPPGNP_Y$ and $PPPGNP_X$ is real Gross National Product per capita in purchasing power parity terms for country Y and X respectively, *E* is the elasticity of income.

Once the total occurrence of health effect and economic unit values are calculated from Equation (2) and Equation (3) respectively; the total damage in terms of health effect *h* is valued using *VOSL* or *VLYL* approach. $V_h(VOSL, VLYL)$ can be calculated from the following formula [19]:

$$V_h(VOSL, VLYL) = N_h \, D_h(VOSL, VLYL) \quad (4)$$

In this study, the economic unit values for Turkey are estimated by using Canadian economic unit values of radiological health impacts since the Canada is the country that the recent economic unit values of radiological health impacts are available [8]. $PPPGNP_{Turkey}$ and $PPPGNP_{Canada}$ 8600 US$ and 27630 US$ respectively, in 2000 [20]. The elasticity (*E*) of income is assumed to be

Table 7. Economic unit values of radiological health impacts (US$/case)

	Canada	Turkey
Fatal cancer VOSL	1.73×10^{6}	5.38×10^{5}
Fatal cancer VLYL	7.73×10^{5}	2.41×10^{5}
Non-fatal cancer	5.77×10^{5}	1.80×10^{5}
Severe hereditary effect	1.73×10^{6}	5.38×10^{5}

Table 8. The monetary value of the predicted health effects (US$/y)

Health effect type	Damage cost
Fatal cancer VOSL	8334
Fatal cancer VLYL	3733
Non fatal cancer	558
Severe hereditary effects	2167
Total	**14791**

equal to 1 [8,21]. Economic unit values of radiological health impacts for Canada and estimated values for Turkey are given in Table 7.

Based on the economic unit values of radiological health impacts (see Table 7), the valuation of the predicted health effects are calculated from Equation (4). The calculated damage costs of the radiological health effects are given in Table 8.

6. Conclusions

In this study, the radiation dose calculations have been carried out by the code CAP88-PC for the population living within 80 km radius of the Yatağan coal-fired power plant (YPP). The average of the maximum measured specific isotopes ^{238}U, ^{232}Th and ^{226}Ra in the flying ash samples are considered as radioactive sources. Based on the dose calculations, the stochastic health effects and predicted health effects have been estimated. It is seen that the total and the maximum collective effective dose equivalent rate is 0.3098 man Sv/y and 0.0510 man Sv/y respectively. Those values are lower than recommended by the ICRP and it does not pose any risk for public health.

The total monetary value of health risk is 14791 US$/y. The yearly total revenue of the YPP from the sales of electricity is approximately 250 million US$ [1,22]. The results indicate that the predicted health effects are negligible in comparison to the economic value of the YPP.

YPP was stopped between 20 February and 20 March 1993 because of the speculations on radionuclide emissions from the plant. It was a big occasion for news media [23]. The speculations on the radionuclide emissions from the YPP and their health effects have continued since 1993. Against the speculations, there is no significant literature on the stochastic health effects and the cost of the predicted health effects from the YPP [24]. Therefore, the results of this study are very useful for ending up the speculations on the health effects and the costs of those effects.

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