ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645
Indian Journal of Science and Technology, *Vol 8(S9), 489–500, May 2015* DOI: 10.17485/ijst/2015/v8iS9/46019

Assessment of Environmental and Human Health Impacts of a New Nuclear Power Plant using Hybrid Single-Particle Langrangian Air Dispersion Model

Abubakar Sadiq Aliyu[1,2*], Ahmad Termizi Ramli[2], Nuraddeen Nasiru Garba[3], Aminu Ismaila[3], Habu Tela Abba[4], Muneer Aziz Saleh[2] and Mustapha Aliyu[5]

[1]Department of Physics, Nasarawa State University Keffi, Nigeria; saabubakar2@live.utm.my
[2]Department of Physics, Universiti Teknologi Malaysia (UTM), Skudai - 81310, Johor, Malaysia.
[3]Department of Physics, Ahmadu Bello University Zaria, Nigeria
[4]Department of Physics, Yobe State University Damaturu, Nigeria
[5]National Space Research and Development Agency (NARSDA), Nigeria

Abstract

The processes of nuclear construction, operation and decommission require a complete safety analysis which involves the quantification of environmental and human health impacts due to releases of radionuclides into the biosphere. Accurate simulation of the atmospheric dispersion of radioactive materials is important for assessing the ecological risks of a new Nuclear Power Plant (NPP) project. The Hybrid Single-Particle Langrangian Integrated Trajectory (HYsplit) model developed by the United States Air Resource Laboratory is a state-of-the-art model for computing complex air dispersion scenarios. In this study, the HYsplit model was used to generate the representative of the scaling factors of air concentrations (in Bq m^{-3}) and surface depositions (in Bq m^{-2}) of radionuclides released from the stack of hypothetical (NPP) in Nigeria. The computed radionuclides' air concentration and surface deposition data were used to assess the environmental and human health impacts of the Nigeria's pioneer NPP. No statistically significant environmental and health impacts were predicted under normal operation conditions of the NPP. The impacts of various accident scenarios under different meteorological and release conditions were investigated. The results of this study could serve as support for decision making concerning the new nuclear energy program in Nigeria.

Keywords: Environmental Impacts, ERICA Tool, GENII, Health Risk, HYsplit, Nuclear plant

1. Introduction

According to the Nigerian Atomic Energy Commission (NAEC), the country is set to achieve at least 1 GW of electricity from its pioneer NPP in the next 10 to 12 years and the nuclear energy capacity is expected increase to 4 GW by 2030[1]. The difficulty of the issues concerning electricity crisis in Nigeria is highlighted and discussed in documented literature[2–6]. In an attempt to curtail the electricity crisis, the government of Nigeria has contacted the International Atomic Energy Agency (IAEA) to register it interest for adding nuclear energy into its energy mix. It is predicted that the interest in nuclear power will continue to grow due to the global interest in climate change mitigation[7,8].

The process of nuclear construction, operation and decommission require a complete safety analysis which involves the assessment of environmental and human health impacts due to theoretical accidental release of fission products[9]. In the past, the site assessment for NPP construction was overlooked in many countries and

*Author for correspondence

the fundamentals of nuclear safety were determined by engineering and technical issues until it was later realized that the geography of nuclear power plants is also vital for radiological protection[10].

The health and environmental consequences of any nuclear accidents depends on source term, release amount and meteorological parameters (like wind speed, wind direction, rain out and atmospheric stability). In some countries, remote siting of the nuclear infrastructures is recommended to reduce the risks associated with the any radiological incident that may occur. The remote siting of NPP have been found to be economically expensive as the facilities are sometimes built far away from the 'load' which require lengthy transmission lines. A semi-urban siting was suggested by[10,11]. Openshaw[10] and Kirkwood[11] also recommended a multidisciplinary site evaluation in order to maintain the safety standards set by regulatory authorities. Famer[12] argued that nuclear installations should not be sited in areas which protect the public against their normal operations, because any operational released from the plant are both controlled and harmless.

The use of atmospheric dispersion models for nuclear emergency planning dates back to half a century ago[9,13]; and in most dispersion problems the modeler is concerned about dispersion in the Planetary Boundary Layer (PBL) of the atmosphere[14]. In the PBL, the dispersion of effluent is affected by micro-meteorological parameters (e.g. surface roughness). The daily variations in temperature and turbulence are two important characteristics of the PBL which dictate wind fields and atmospheric dispersion. Compared with the ground surface, the turbulence over the ocean is relatively slow. This is because of the presence of trees, mountains and other irregularities (surface roughness) that increase the exchange of mass and momentum between the ground surface and the atmosphere[9,15]. Here, we seek to quantify the impacts of the routine and accidental stack discharges from the NPP with a generic reactor design on human and non-human biota. The generic reactor's annual and worst case scenario discharges (during normal operations) were adopted by the current study based on the discharge inventories of the EPR and AP1000 nuclear reactor designs. To achieve this aim, the emission of (selected) radioactive fission products into the atmosphere and the simulation of the downwind transportation and deposition using a global atmospheric dispersion model have been adopted. State-of-the-art computer codes for assessing the environmental and human health impacts have been used to statistically quantify the human health and ecological impacts of Nigeria's pioneer NPP. We have used some of these modeling scenarios in earlier studies[16–19].

2. Study Sites and Computer Simulation Codes

One of the sites selected for the Nigeria's pioneer NPP is at Itu, AkwaIbom State, Nigeria (5.20N and 7.960E). It is in Nigeria's oil producing Niger Delta region. The inhabitants are basically involved in agricultural activities.

The HYsplit4 model is a complete system for computing trajectories and complex dispersion problems using either puff or particle modeling approach. The input data are interpolated to an internal sub-grid that is centered to reduce memory requirements and increase computational speed. The calculations may be performed sequentially or concurrently on multiple meteorological grids, usually specified from fine to coarse resolution. Detailed guide concerning the computational aspect and model formulation of the HYsplit4 system are documented[20,21].

The GENII (acronym for GENeration II) computer codes were initially developed in 1988 and they were designed with the flexibility to accommodate input parameters for a wide variety of generic sites. The GENII modeling system was developed for the Environmental Protection Agency (EPA) at Pacific Northwest National Laboratory (PNNL) to incorporate the internal dosimetry models recommended by the International Commission on Radiological Protection (ICRP) and the radiological risk estimating procedures of the Federal Guidance Report 13 which are incorporated into the existing environmental pathway analysis models. The GENII system was developed to provide a state-of-the-art, technically peer-reviewed, documented set of programs for calculating radiation dose and risk from radionuclides that are released to the environment. Details of the model formulation and design documentations are available[22, 23].

ERICA (Environmental Risks from Ionizing Contaminants: Assessment and Management) project, which produced the ERICA tool; a software program with supporting databases, that guides users through the assessment process was co-funded by the European Union and 15 organizations in seven European Countries, between 2004 and 2007. The purpose of the project was to develop an approach whereby the impacts of ionizing radiation on the environment could be assessed and to ensure that decisions on environmental issues give appropriate weight to the exposure, effects and risks from ionizing radiation.

The project also emphasizes on safeguarding the structure and function of ecosystems.

Incorporated in the ERICA tool are databases on transfer factors, dose conversion coefficients and radiation effects on non-human biota that have been developed specifically for the purpose of the integrated approach. These are used to conduct species sensitivity study to radiation; on the basis of a universal screening dose rate criterion of 10 μGy h^{-1}. Detailed descriptions of the ERICA tool and the integrated approach for environmental impact assessment have been presented in literature[24–27].

3. Methodology

Figure 1 is a representative of the procedure adopted in this study. The red, rectangle indicates that a particular result was analytically achieved from the outputs of the air dispersion model. It represents dose-rates profile of exposure to passing radioactive plume whose contents are been deposited on the surface. The parameters in the parenthesis represent inhalation (inh.), submersion (sub.) and ground shine (g.shine).

The air dispersion models outputs are activity concentrations in air and surface depositions on the ground that are extrapolated for a particular receptor

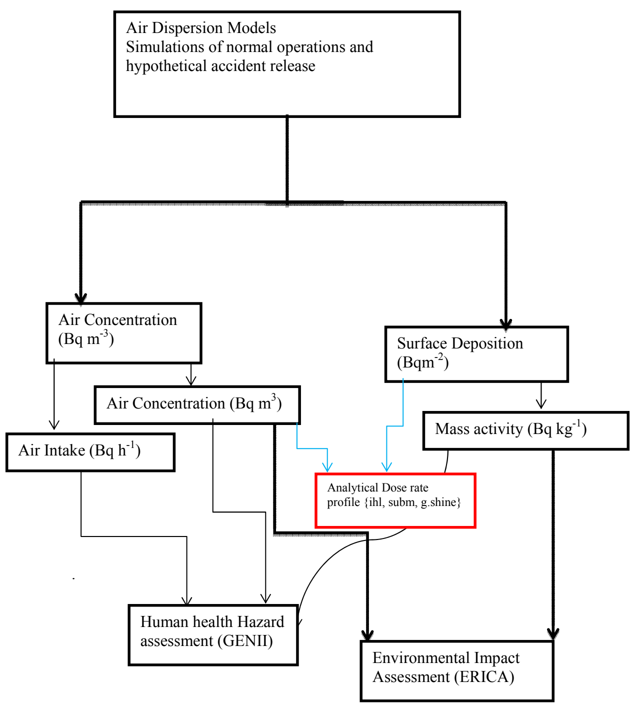

Figure 1. Schematic of the modeling and computional procedure adopted.

location in order to quantify the health and environmental hazards in that particular location. In some cases, before using the health or environmental risk model, the air modeling results had to be transformed into either inhalation intake (Bq h^{-1}) or mass concentration (Bq kg^{-1}) for the analyses.

3.1 Routine Operation Condition

To represent routine discharges, the HYsplit model was configured to simulate the dispersion of a continuous emission of just a few radionuclides. Similar approaches for long-range dispersion calculations have been presented[28–31]. The HYsplit model was configured to simulate unit (1 Bq h^{-1}) releases of the radionuclides of interest from the NPP site. In each model run, the half-life and deposition characteristics were separately entered to represent the radionuclide under consideration. The model provides the scaling factors that are used to compute the annual average concentrations (Bq m^{-3}) and total deposition (Bq m^{-2}) at the six receptor locations of interest given the actual emission rate.

The model was driven by the global NOAA-NCEP/NCAR pressure level reanalysis meteorological data that have been reprocessed into the HYsplit compatible format. The data cover a period of 20 years with spatial and temporal resolutions of 2.5 degree and 6 hours, respectively and each data file is archived as one file (122 Mb) per month. The releases were modeled using the 3-D particle distribution approach. Each (annual) simulation was done for a run duration of 8760 hours, using twelve (monthly) meteorological data files with the release starting the first day and hour of the year. The air concentration results were averaged between 0–100 m AGL (Above Ground Level). The air concentrations and depositions at stations (receptor location) [Itu (onsite), Uyo (5.05, 7.93), Calabar (4.950, 8.33), Port Harcourt (4.79,7.00), Oweri (5.49, 7.03) and the Bright of Boney/in the Atlantic Ocean (4.03, 8.13)] were extracted from the model's output.

The statistical μ (std. error) for the scaling factors of concentrations and deposition were computed for each of the sites. The μ (std. error) of the scaling factors were then multiplied by the annual discharge value of the generic reactor D_{ann}.

In order to obtain the time integrated air concentration and deposition of the respective radio nuclides at the stations, the annual discharge (D_{ann}) of the radio nuclides is computed[28] to account for periods when the discharge is likely to be higher than the predicted annual average, which is the 12 months at the end of the 18-month cycle. This is because discharge was found to increase at the end of the fuel cycle due to faulty plant operations. The Worst-Case Plant Discharge for AP1000 reactor was obtained using the following expression.

$$WCPD = 1.5 \times 1.1 \times D_{ann}$$

The factor 1.5 is as defined by the Environment Agency and 1.1 is a factor to allow for ageing of the reactor. The maximum annual activity for EPR and the Worst-Case Plant Discharge (or WCPD) for AP1000 were considered to be comparable and used to define the releases from the generic reactor (Table 1).

The annual discharges for each of the (six) radio nuclides from the site have been modeled separately to derive individual annual scaling factors for average air concentrations (Bq m^{-3}) and total depositions (Bq m^{-2}). These scaling factors (Table 3) were multiplied by the site specific annual discharge rates to assess the impact of the discharges on human and non-human biota. This approach allows future updating of the assessment once the type and number of reactors to be built at each site have been decided[28]. The advantage of the scaling technique adopted by the current study is that it is easier to facilitate future updating of the assessment once the type and number of reactors to be built at the site and the amount of radionuclide released into the air are known.

To sustainably manage computational processing resources, 'steady state' emissions were modeled using 24000 particles per radionuclide per cycle and the particles were 'killed' after 78 hours when their influence on air and surface concentrations over the area of interest could be safely assumed to be minimal.

For the population dose calculations, the 95th percentile value of 20 years simulation results for each of the radionuclide and receptor location was used.

It is important to stress that a large quantity of fission products that are formed in the reactor of NPPs and released have little impact on the environment due to their extremely short half-lives (<24 h)[32]. The choice of these (six) radionuclides was due to their volatility and their long term importance in radiation protection.

The time integrated air concentrations and ground depositions of the respective radionuclides served as input for the human risk model (GENII) and environmental assessment model (ERICA tool). The total human doses (due to inhalation and food ingestion) and the corresponding cancer risk were computed. For the non-human biota, the risk quotients and doses to reference organisms were calculated by working through the tiers 1 and 2 of the ERICA assessment tool.

Table 1. Emission parameters of the generic reactor

Isotope	EPR maximum annual activity (GBq y^{-1})	WCPD for AP1000 (GBq y^{-1})	D_{ann}. Generic reactor (GBq y^{-1})	Modeling technique adopted	Dry deposition velocity (m/s)	In cloud (l/l) and below cloud (/s) coefficients
^{3}H	3000	3081	3080	Mostly released as triturated water vapor or HTO. Modeled as a gas (no deposition)[1].	0	0
^{14}C	95	7.3	95	80% released in organic form (CH_4) and 20% as CO_2 Modeled as gas and no deposition was considered.	0	0
^{131}I	0.05	0.0328	0.05	It exist in both gaseous [element (I_2) and organic (ICH_3) form] and particulate form. During routine discharged only gases are released as the particles are filtered.	1 x 10^{-3}	In cloud: 3.2×10^4 Below cloud: 5.0×10^{-6}
^{137}Cs	0.0252	0.00220	0.071	Modeled as aerosol particulate (1 μm particle size).	1 x 10^{-3}	In cloud: 3.2×10^4 Below cloud: 5.0×10^{-6}
^{90}Sr	–	0.000733	0.00073	Modeled as aerosol particulate (1 μm particle size).	1 x 10^{-3}	In cloud: 3.2 v 10^4 Below cloud: 5.0×10^{-6}

3.2 Hypothetical Accident Condition

In an attempt to define the source term for the hypothetical accident, a concise literature review of the source term and the global impact of the FNPA (Fukushima Nuclear Accident) was conducted. In order to verify the accuracy of our modeling approach, the release amount of the 12th March to 6th April of the FNPA as reported by the NSCJ (Nuclear Safety Commission of Japan) were considered for the simulation. The cesium (^{137}Cs) and iodine (^{131}I) released were estimated to be $1{:}2 \times 10^{16}$ and $1{:}3 \times 10^{16}$Bq, respectively. Based on these figures, a simulation of the Fukushima NPP accident has been considered and some of the obtained results shown in Figures 2 and 3.

The results obtained by the current study were in agreement with those reported by the MEXT (Ministry of Education, Culture, Sports, Science and Technology) from the environmental measurements at the Ibaraki Prefecture[33].

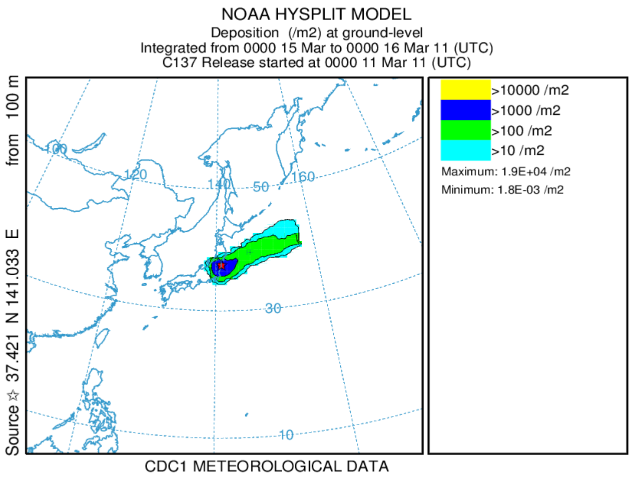

Figure 2. Deposition of ^{137}Cs after Fukushima nuclear accident.

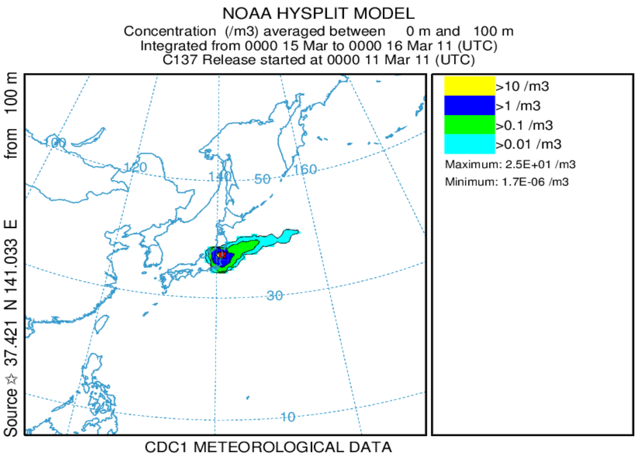

Figure 3. Air concentration of ^{137}Cs from Fukushima nuclear accident.

The average concentration and deposition for the Ibaraki Prefecture (36.2333, 140.2833) were extracted from our simulation result. No significant values were recorded until the period of 00Z of March 15th and 12Z of 16th March, 2011 which shows ^{137}Cs concentrations of ~3445 Bq m^{-3} and a surface deposition of ~ 3.4 Bq m^{-2}. The other significant results were those of 00Z March 21st and 12Z of March 22nd (i.e. ~ 6334 Bq m^{-3} and ~ 7.4 Bq m^{-2}) and 32 h later, i.e. by 00Z March 24th the values changed to ~ 2471 Bq m^{-3} and 1.8 Bq m^{-2}. The constant emission rate used for this simulation was 2.4×10^{13} Bq h^{-1} of ^{137}Cs. This value was obtained by considering the average value of the total ^{137}Cs released reported by the NSCJ which happens to be consistent with the average monthly release rate (Bq h^{-1}) reported by Ten Hoeve and Jacobson[34].

To compare our results with the monitoring data at the Ibaraki Prefecture[33], the concentration and deposition of particulate iodine (^{131}I) were obtained and the DCFs (Dose Conversion Factors) for submersion and ground shine for the cesium and iodine isotopes available in[35] were used for dose calculation. The total dose rate was 1.4 μSv h^{-1} (~12.3 mSv y^{-1}) with 53% of the dose rate contributed by the particulate iodine. The ratio of the computed result to that of the MEXT is ~0.31. The discrepancy may not be unconnected to the fact that only the contributions of two fission products were considered in our analysis. Of importance is the similarity in the spatiotemporal pattern between our data and the MEXT report for the Ibaraki Prefecture in Japan.

3.3 Determination of Worst Case Accident Scenario for Nigeria's Pioneer NPP

The time series plot of the MM5 generated meteorological parameters (precipitation rate, wind speed and wind direction) of the Nigeria's NPP site are presented in Figure 4.

Because the severity of a NPP accident depends on the source term, duration of release, period releases as well as the meteorological conditions like the wind vector and precipitation, some of these factors have been considered in the determination of a worst case scenario accident based on the meteorological conditions of the year 2011. The worst case scenario was determined from the surface deposition data of long lived radionuclide (^{137}Cs). In order to consider a

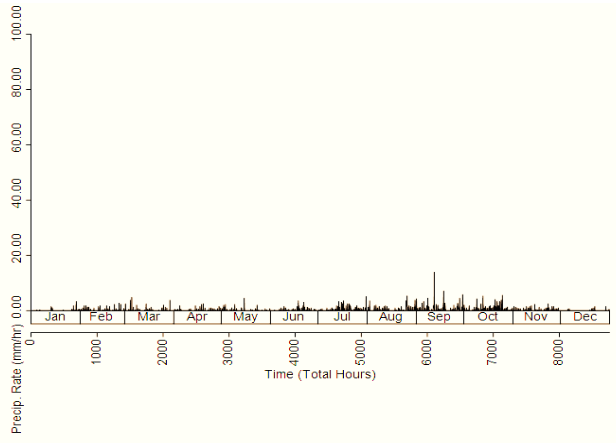

Figure 4. MM5 generated on site annual precipitation rate for 2011.

unique meteorology for each month, a single release period was considered at the midpoint of each month using a unit release rate for duration 48 hours. Deposition is computed at the Uyo which is shown in Figure 5.

The maximum deposition (a measure of the WCS) was on the JD (Julian Day) 197.958 (which is the 23h June 16th).

Based on this WCS information, two hypothetical accidents conditions with source terms that are analogous

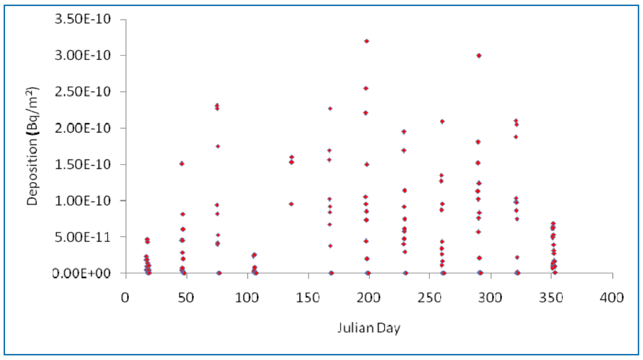

Figure 5. Hourly deposition in Uyo for worst case scenario (WCS) determination.

to that of the Fukushima NPP (^{137}Cs and ^{131}I) were considered. The accidents released times were 48 hours before the JD of the WCS (i.e. 23Z June 14th 2011). The release duration was 48 hours and the release amount considered were 2.4×10^{13}Bq h^{-1} and 9.06×10^{13}Bq h^{-1} of ^{137}Cs and ^{131}I, respectively.

4. Results and Discussion

Table 2 presents the μ (standard error) and the {95th percentile values} of the scaling factors of air concentrations

Table 2. The representative of the annual scaling factors for air concentration and surface deposition at the receptor locations

Receptor (Distance away)	^{3}H	^{14}C	^{137}Cs		^{131}I		^{90}Sr	
	Concentration (Bq m^{-3})	Concentration (Bq m^{-3})	Concentration (Bq m^{-3})	Deposition (Bq m^{-2})	Concentration (Bq m^{-3})	Deposition (Bq m^{-2})	Concentration (Bq m^{-3})	Deposition (Bq m^{-2})
ITU (1km)	4.13E-11 (9.90E-13) {4.87E-11}	4.88E-11 (7.76E-13); {5.316E-11}	4.13E-11 (6.62E-13); {4.53E-11}	7.47E-06 (1.30E-07); {8.26E-06}	2.50E-08 (2.44E-08); {2.50E-08}	4.71E-07 (2.80E-08); {6.09E-07}	4.15E-11 (6.56E-13); {4.53E-11}	7.48E-06 (1.26E-07); {8.27E-06}
Uyo (<20 Km)	5.08E-13 (5.26E-14); {8.86E-13}	5.35E-13 (5.90E-14); {1.0945E-12}	2.96E-13 (3.59E-14); {6.22E-13}	3.21E-08 (3.64E-09); {6.26E-08}	6.35E-14 (8.66E-15); {1.31E-13}	1.35E-09 (4.09E-10); {5.02E-09}	2.96E-13 (3.59E-14); {6.22E-13}	3.24E-08 (3.63E-09); {6.27E-08}
Calabar (<50 km)	1.94E-13 (5.26E-14); {8.86E-13}	2.27E-13 (2.47E-14); {4.0725E-13}	8.32E-14 (1.25E-14); {1.81E-13}	1.34E-08 (1.84E-09); {2.70E-08}	2.51E-14 (7.38E-15); {5.47E-14}	1.44E-10 (1.02E-10); {6.35E-10}	8.35E-14 (1.25E-14); {1.81E-13}	1.37E-08 (1.82E-09); {2.73E-08}
P. Hacourt (< 120 Km)	4.90E-15 (2.44E-14); {3.24E-13}	1.21E-14 (4.17E-15); {5.179E-14}	7.24E-15 (2.21E-15); {2.92E-14}	9.27E-10 (2.34E-10); {3.41E-09}	1.38E-15 (6.17E-16); {8.38E-15}	2.44E-11 (2.37E-11); {2.44E-11}	7.09E-15 (2.22E-15); {2.92E-14}	9.45E-10 (2.32E-10); {3.42E-09}
Oweri (< 110 Km)	1.73E-14 (2.03E-15); {2.42E-14}	3.70E-14 (6.76E-15); {8.279E-14}	2.46E-14 (5.34E-15); {6.73E-14}	2.25E-09 (5.28E-10); {6.56E-09}	2.62E-15 (5.93E-16); {8.16E-15}	1.41E-11 (1.37E-11); {1.41E-11}	2.49E-14 (5.35E-15); {6.73E-14}	2.24E-09 (5.24E-10); {6.56E-09}
Bright of Boney (135 km)	5.47E-15 (4.72E-15); {5.79E-14}	7.13E-15 (3.56E-15); {2.87E-14}	2.42E-15 (6.64E-16); {8.61E-15}	3.72E-10 (6.93E-11); {7.71E-10}	8.52E-16 (5.12E-16); { 2.73E-15}	4.80E-16 (1.44E-16); {1.82E-15}	7.42E-15 (5.23E-15); {1.36E-14}	3.64E-10 (7.00E-11); {7.98E-10}

and surface depositions for respective fission products at each receptor location.

The scaling factors (Table 2) are the air concentrations and deposition values calculated using the unit (1 Bq h^{-1}) discharge from the nuclear power plant. These values were then multiplied up by the actual annual discharges for the generic reactors to obtain the actual air concentrations and surface depositions (Figure 6 and 7). Note the log scale.

The maximum average annual concentration was at the NPP site for tritium (1.27×10^{-2}Bq m^{-3}) and carbon-14 (4.63 Bq m^{-3}), the isotope with the least onsite air concentration is strontium-90. The onsite most deposited nuclides were caesium-137, iodine-131 and strontium-90 in that order. The values for the onsite isotopes depositions were 530, 23.5 and 5.46 Bq m^{-2} for ^{137}Cs, ^{131}I and ^{90}Sr, respectively.

The least depositions of particulate fission products due to routine discharges form the generic reactor were at the Bright of Boney (Atlantic Ocean). The essence of selecting this receptor location is to quantify the surface deposition on the marine environment.

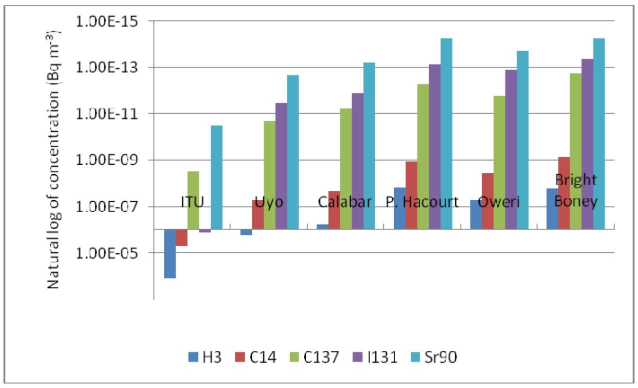

Figure 6. Average annual air concentrations for the generic reactor.

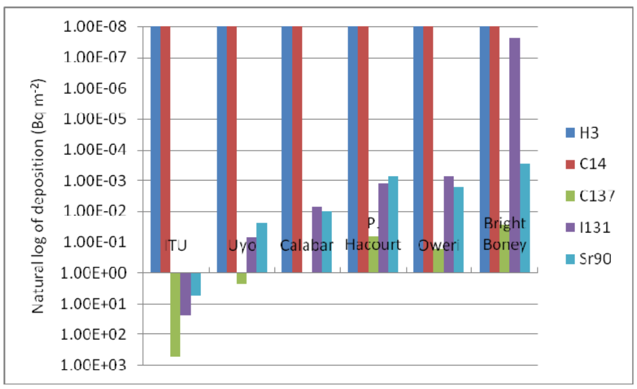

Figure 7. Average annual surface deposition for the generic reactor.

To quantify the human health impact, the EDE (Effective Dose Equivalent) from the intake of the radio nuclides in air was computed using the GENII code. In this case, the total risk to all organs and the effective dose due to assumed (no shielding) annual exposure were computed using the average annual breathing rate of 22.2 m^3 d^{-1} for the conversion of air concentrations (Bq m^{-3}) of radionuclides to intake (Bq y^{-1}).

The ICRP (International Commission on Radiological Protection) publication-60[36] and the US EPA (US Environmental Protection Agency) report 12/13[37] were adopted in the health risks calculations.

The EDE and the per capita risk incidence and risk fertility from intake of the release radionuclide in air due to annual routine discharges are presented in Table 3.

In line with previous results, the maximum values for the risks and EDE were found to be at Itu (onsite). There were 7 to 8 chances in a billion of cancer related incidence due to inhalation of all the radionuclides and a 2 to 3 chances of cancer related mortality in a billion (Table 5). A measure of the onsite radiological dose equivalent indicated a value of ~ 0.27 μSv. The US NRC (US Nuclear Regulatory Commission) standard for member of the public is an effective dose of 1 mSv per annum[38].

Table 3. Average annual inhalation dose and cancer risk for a reference person (20–70 yrs) from normal operation release

Isotopes	Per capita risk of cancer morbidity	Per capita risk of cancer Mortality	EDE (Sv)
Receptor 1: Itu			
All	7.61E-09	2.67E-09	2.67E-07
Receptor 2: Uyo			
All	5.50E-11	3.94E-11	1.13E-09
Receptor 3: Calabar			
All	2.01E-11	1.44E-11	4.14E-10
Receptor 4: P. Harcourt			
All	1.53E-12	1.09E-12	3.14E-11
Receptor 5: Oweri			
All	1.53E-12	1.09E-12	3.14E-11
Receptor 6: Bright of Boney			
All	No human Population (Atlantic Ocean)	No human Population (Atlantic Ocean)	On Occupied

Table 4. Average annual effective dose for terrestrial food ingestion

Isotopes	Effective Dose (Sv)
Receptor 1: Itu	
All	6.346E-09
Receptor 2: Uyo	
All	4.811E-11
Receptor 3: Calabar	
All	2.076E-11
Receptor 4: P. Harcourt	
All	2.63E-12
Receptor 5: Oweri	
All	5.032E-12

Table 5. Inhalation dose and cancer risk for a reference person (20–70 yrs) for 48 hrs exposure after hypothetical accident

Isotopes	Per capita risk of cancer Morbidity	Per capita risk of cancer Mortality	EDE (Sv)
Receptor 1: Itu			
All	5.54E-07	3.95E-07	1.18E-05
Receptor 2: Uyo			
All	5.54E-07	3.95E-07	1.18E-05
Receptor 3: Calabar			
All	5.54E-07	3.95E-07	1.18E-05
Receptor 4: P. Harcourt			
All	0.0	0.0	0.0
Receptor 5: Owerri			
All	0.0	0.0	0.0
Receptor 6: Bright of Boney			
All	0.0	0.0	0.0

This shows that the obtained value for the EDE is thousands of times less than the regulatory standard. It has been confirmed by nationwide study in the US[32], that during routine operations the releases of NPPs in the country results in impacts that are thousands of times less than the regulatory standards. Some experts believed that in the US, the nuclear industry is over-regulated while the coal energy is under-regulated[39].

Because the maximum air concentrations at Itu (onsite) resulted in no significant health impact, it can be argued that the health impacts at the other receptor locations with are also not significant. This is due to the fact that the onsite concentrations are higher than that of any other receptor location.

Estimating the risk due to deposition requires the conversion of the activity concentrations of the radio nuclides (Bq m^{-2}) to mass unit (Bq kg^{-1}) of radionuclide in the top soil. To achieve this, more information on the soil (soil depth and density) are required. For convenience, the redistribution factor of the soil was assumed to be unity. The soil density value used was 1.63×10^{3}kg m^{-3}, and the soil depth was assumed to be 1 m. The mass concentrations in the top soil were obtained using [Equation (1)].

$$C_m = {C_a}/{\rho d} \tag{1}$$

Where Cm is the mass concentration, C_a is the area concentration, ρ is the density of soil, and d is the depth of soil (1 m).

The total effective dose due to ingestion of terrestrial food like fruits, leafy vegetables and grains grown at each of the receptor location is presented in Table 6. The age group considered in this analysis is 0–70 years.

Figures 8 and 9 are the representative of the post accident's air concentration and total surface deposition respectively. Within the simulation run time (48 h) the plume traveled over 400 km towards north central states like Benue and Taraba. The deposition had shown similar pattern compared with the downwind plume transportation.

The maximum air and surface contamination were within few kilometers of the NPP sites, which are probably within the EPZ (Emergency Planning Zone). In this case more than 90% of the fission products were transported

Table 6. Total effective dose for terrestrial food ingestion after hypothetical accidents.

Isotopes	Effective Dose (Sv)
Receptor 1: Itu	
All	3.374E-07
Receptor 2: Uyo	
All	3.374E-07
Receptor 3: Calabar	
All	3.374E-07
Receptor 4: P. Harcourt	
All	9.228E-12
Receptor 5: Owerri	
All	9.228E-12

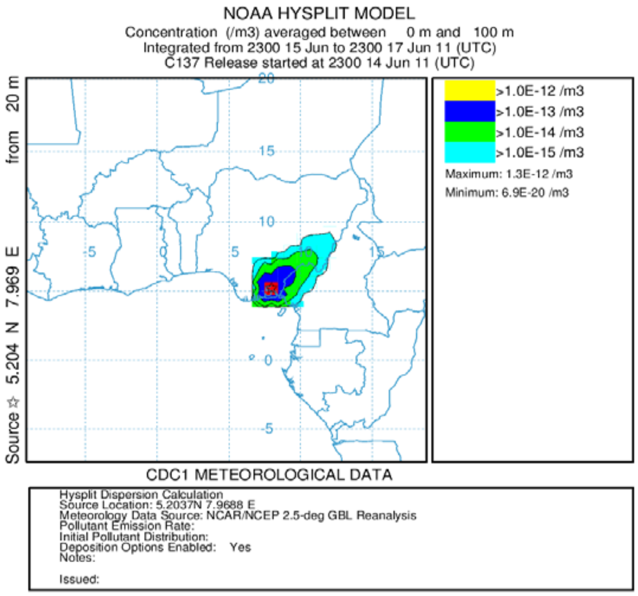

Figure 8. Representative of the hypothetical accident's scaling factor concentration of ^{137}Cs.

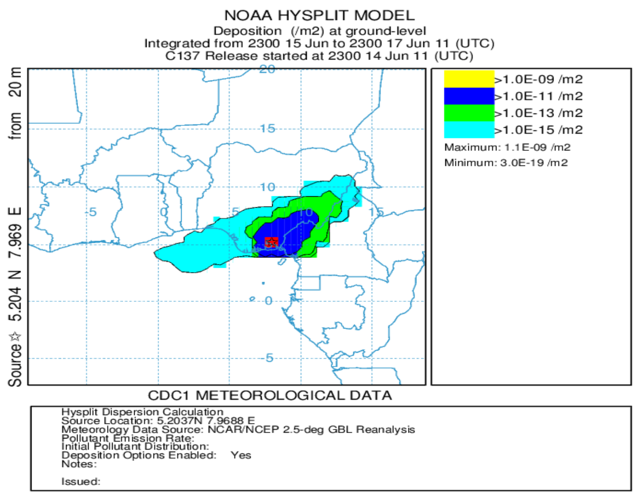

Figure 9. Representative of the hypothetical accident's scaling factor for surface deposition ^{137}Cs.

and deposited over land in Nigeria and the neighboring Cameroon.

Figure 10 shows the values of the air concentration and deposition of ^{137}Cs at each of the receptor locations.

Within the first 48 h, the concentrations at the first three receptor locations were equal and similar pattern is shown for the deposited fission products. The concentration and deposition at the Bright of Boney were zero and this indicates that the radioactive plume is directed away from the sea towards the inland of Nigeria. The concentration and deposition values of ^{131}I are shown in Figure 11.

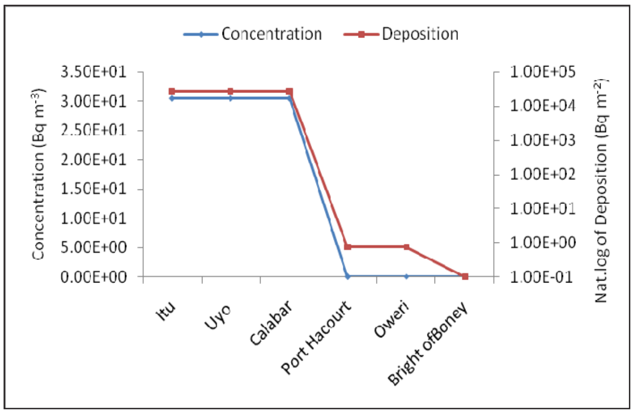

Figure 10. Hypothetical accidents' concentration and deposition of ^{137}Cs at each of the receptor locations.

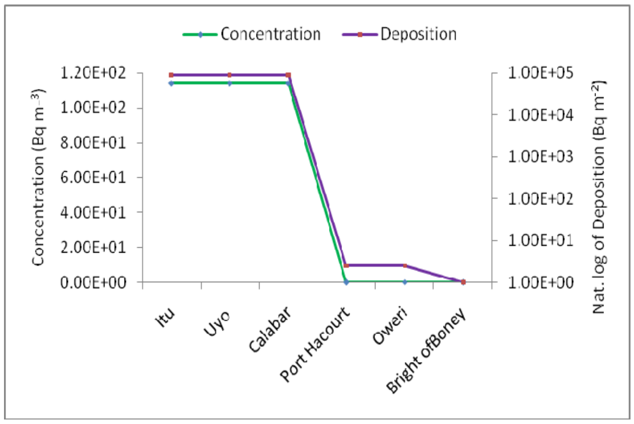

Figure 11. Hypothetical accident's concentration and deposition of ^{131}I at each of the receptor locations.

Place marks of the receptor locations are presented in Figure 12. It can be seen from the map that the last three locations (Owerri, Port Harcourt and Bright of Boney) are not in the plume's direction.

The results of the concentrations and depositions after the hypothetical accident served as input for the GENII and ERICA tool models for impacts analysis.

The EDE for the three receptor locations (Table 7) are ~0.01 mSv (this results in 1.83 mSv yr^{-1}) and in attempt to further calculate the radiation detriment, the population effective dose [Equation (2)] is calculated using the 2011 projected population of each of the cities.

The population annual collective effective dose in the cities due to routine releases was assessed according to[36]. Using the 2006 population data (www.geohive.com) from the National Bureau of Statistics, and a 2.5% population growth rate, the population as of 2011 were

Figure 12. Receptor locations.

Table 7. A measure of the health detriment at each receptor location

Receptor Location	CEDE (man-Sv)	Health Detriment
Itu	1.70	~ 0.1
Uyo	4.13	~ 0.21
Calabar	2.45	~ 0.12

143 728, 350 255, and 207 740 for Itu, Uyo and Calabar, respectively.

$$S_E = H \times N \tag{2}$$

where *SE* is the collective effective dose equivalent, *H* is the annual effective dose equivalent for the city of interest and *N* is the projected 2011 population of that city based on the latest census. Adopting a Liner No-Threshold model (LNT), the total health risks due to radiological exposure were assessed by Equation (3) assuming a homogeneous group of *N* persons.

$$G = R_k \times S_E \tag{3}$$

where *G* is the collective health detriment , which was assumed to be proportional to the collective dose equivalent; *Rk* is the radiation risk factor given as $5 \times 10^{-2}\ Sv^{-1}$[40]. This value represents the number of individuals to that of cancer related health issues. This *G*-value represents the number of individuals to that of cancer related health issues[41]. The Collective Effective Dose Equivalent (CEDE) and the health detriment for the three locations are presented in Table 7.

For impact assessment, of the hypothetical accident on the non-human terrestrial habitat, only the onsite receptor location was considered for the ERICA integrated approach for environmental risk assessment considering the onsite activity concentrations in soil, which are 16.6 and 54.7 Bq kg^{-1} for ^{137}Cs and ^{131}I, respectively. The result of the Tier 2 assessment is presented in Figure 13.

The reference organism that received the maximum dose rate is bird egg. And a dose rate of 1.05 is by far less than the standard screening dose rate (of 10 μGy h^{-1}) adopted by this study. Adopting a UF (Uncertainty Factor) of 3, which tests for 5% probability of exceeding the screening dose rates the RQ_s (Risk Quotients); both conservative and expected have been found to be less than unity, which is an indication that there is no substantial probability that the screening dose rate has been exceeded Figure 14.

For all the reference organisms, $RQ_{cons}<1$, which indicates that there is low probability that the screening dos rate has been exceeded. This indicates that the environmental impact of the accident risk is arguably negligible.

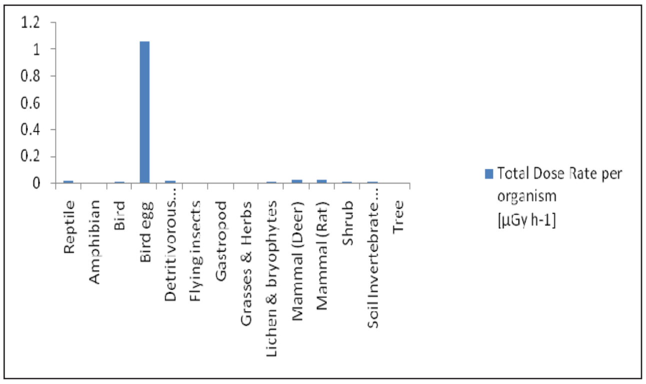

Figure 13. Total dose rate per organism for the hypothetical accident scenario.

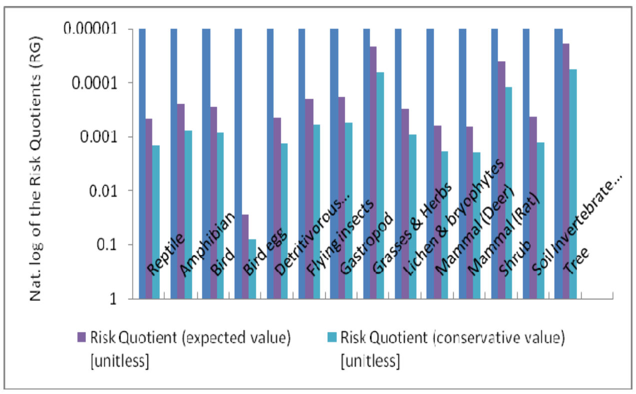

Figure 14. Plot of RQ_s for each terrestrial organism.

5. Conclusions

This paper predicted the environmental and health impacts of Nigeria's pioneer NPP using deterministic models for radio ecological impact analysis. Atmospheric dispersion modeling of radiological emergency was adopted to quantify these impacts. The results indicate that under routine operations, the NPP's air discharges does not present discernible environmental and health impacts, even though conservative values of annual air discharge were adopted.

Twenty years simulations of the air discharges have shown that the predominant downwind direction is the north-east of the NPP site. This information is important in nuclear emergency preparedness for situations in which evacuation is necessary or in a situation where residents will be asked to stay indoors.

A hypothetical accident with source terms that are analogous to that of the Fukushima nuclear accident but with assumed release duration of 48 h was simulated and the obtained results indicate a hundred-fold increase in human dose and cancer risk.

6. Acknowledgements

Dr. A.S. Aliyu wishes to acknowledge the support of the Research Management Center of Universiti Teknologi Malaysia for its support through the Post Doc fellowship scheme, project number (Q.J130000.21A2.01E98). The authors thankfully acknowledge the support of Dr. Roland Draxler of NOAA Air Resources Laboratory, USA and Ciara McMahon of Radiological Protection Institute of Ireland for advice in configuring HYsplit model. Our sincere appreciation goes to Dr. Kilian Smith of Radiological Protection Institute of Ireland for introducing HYSPLIT model and their report[28] to us.

7. References

1. Aduba O. Nigeria to attain 4000 MW from nuclear power plants by 2030. Guardian Newspaper. 2012 Jul 18.
2. Aliyu AS, Ramli AT, Saleh MA. First nuclear power in nigeria: an attempt to address the energy crisis? Int J of Nucl Gov Econ and Ecol. 2013; 4(1):1–10.
3. Aliyu AS, Ramli AT, Saleh MA. Nigeria electricity crisis: power generation capacity expansion and environmental ramifications. Energy. 2013; 61:345–67.
4. Kennedy-Darling J, Hoyt N, Murao K, Ross A. The energy crisis of nigeria: An overview and implications for the future. Chicago, USA: The University of Chicago; 2008.
5. Obadote D. Energy crisis in nigeria: technical issues and solutions. Proceedings of the Power Sector Prayer Conference; 2009 Jun 25–27.
6. Aliyu AS, Dada JO, Adam IK. Current status and future prospects of renewable energy in nigeria. Renew Sustain Energ Rev. Forthcoming 2015.
7. WNA. Comparison of lifecycle greenhouse gas emissions of various electricity generation sources. Lodon: World Nuclear Association; 2011.
8. y Leons SB. Panel on safety, health and the environment: Implications of nuclear power growth. Health Phys. 2011; 100:12–3.
9. Jilani AB. Atmospheric dispersion and consequence modeling of radiological emergencies [PhD thesis]. Pakistan Institute of Engineering and Applied Sciences; 2009.
10. Openshaw S. Nuclear power: Siting and safety. Routledge and K. Paul; 1986.
11. Kirkwood CW. A case history of nuclear power plant site selection. J Oper Res Soc. 1982; 33(4):353–63.
12. Farmer FR. Reactor safety and siting: A proposed risk criterion. Nucl Saf. 1967; 8:539–48.
13. Yao R. Atmospheric dispersion of radioactive materials in radiological risk assessment and emergency response. Prog in Nucl Sci and Technol. 2011; 1:7–13.
14. Turner DB. Workbook of atmospheric dispersion estimates. US Department of Health, Education and Welfare, National Center for Air Pollution Control; 1970.
15. Marshall J, Plumb RA. Atmosphere, ocean and climate dynamics: An introductory text, Vol. 8. Academic Press; 1965.
16. Aliyu A, Ramli A, Saleh M. Environmental impact assessment of a new Nuclear Power Plant (NPP) based on atmospheric dispersion modeling. Stochastic Environmental Research and Risk Assessment. 2014; 27(7):1897–911.
17. Aliyu AS. Atmospheric dispersion analysis for potential radiological impact assessement of nigeria's pioneer nuclear power plant. Malaysia: Univesriti Teknologi; 2014.
18. Aliyu AS, Ramli AT, Garba NN, Saleh MA, Gabdo HT, Liman MS. Fukushima nuclear accident: preliminary assessment of the risks to non-human biota. Radiat Prot Dosimetry. 2015; 162(2):238–50.
19. Aliyu AS, Ramli AT, Saleh MA. Assessment of potential human health and environmental impacts of a nuclear power plant (npp) based on atmospheric dispersion modeling. Atmosfera. 2015; 28(1):13–26.
20. Draxler RR, Hess G. Description of the HYSPLIT4 modeling system. 1997.
21. Draxler RR, Stunder B, Rolph G, Taylor A. HYSPLIT4 user's guide. NOAA Technical Memorandum ERL ARL. 1999; 230:35.

22. Napier BA. GENII version 2 users' guide. Pacific Northwest National Laboratory report. Rev 2006; PNNL-14583.
23. Napier BA, Strenge DL, Ramsdell JV, Eslinger PW, Fosmire C. GENII version 2: software design document. Pacific Northwest National Laboratory; 2004.
24. Larsson CM. An overview of the erica integrated approach to the assessment and management of environmental risks from ionising contaminants. J Environ Radioact. 2008; 99(9):1364–70.
25. Torrud J, Saetre P. Assessment of long-term radiological effects on plants and animal from deep geological respiratory: no discernible impact detected. AMBIO. 2013; 42:506–16.
26. Beresford N, Brown J, Copplestone D, Garnier-Laplace J, Howard B, Larsson C, Oughton D, Prohl G, Zinger I. D-ERICA: an integrated approach to the assessment and management of environmental risks from ionising radiation. description of purpose, methodology and application. Brussels: European Commission; 2007. EC contract number FI6R-CT-2004-508847.
27. Torudd J. Long term radiological effects on plants and animals of a deep geological repository: sr-site biosphere. Svensk Karnbranslehantering AB, Swedish Nuclear Fuel and Waste Management Company; 2010.
28. McMahon C, Kelleher K, McGinnity P, Organo C, Smith K, Currivan L, Ryan T. Proposed nuclear power plants in the UK – potential radiological implications for Ireland. Radiological Protection Institute of Ireland; 2013.
29. Nelson N, Kitchen K, Maryon R. Assessment of routine atmospheric discharges from the sellafield nuclear installation–cumbria uk. Atmos Environ. 2002; 36(19): 3203–15.
30. Khandakar HA, Moritomi H. Assessment of ambient mercury deposition fluxes by numerical air quality modeling. Air Quality, Atmosphere and Health. 2013; 6(3):629–40.
31. Smith K, Organo C, Somerville S, Hanley O, McMahon C. Comparison of atmospheric dispersion model outputs and radioactivity measurements made in ireland following the fukushima nuclear emergency. 13th International Congress of the International Radiation Protection Association, Glasgow; 2012.
32. Harris JT. Radiological releases and environmental monitoring at commercial nuclear power plants. In: Tsvetkov DP. Nuclear Power - Operation, Safety and Environment. In Tech; 2011.
33. MEXT. Monitoring data at ibaraki prefecture. 2011 Mar 15th–18th. Japan: Ministry of Education, Culture, Sports, Science and Technology.
34. Ten Hoeve JE, Jacobson MZ. Worldwide health effects of the fukushima daiichi nuclear accident. Energ Environ Sci. 2012; 5(9):8743–57.
35. Homann SG. HotSpot-Health physics codes for the pc. Lawrence Livermore National Laboratory; 2011. UCRL-MA-106315.
36. ICRP. ICRP publication 60. Annals of ICPR. 1990; 21(1–3).
37. Eckerman KF, Ryman JC. External exposure to radionuclides in air, water and soil. Federal guidance report. 1993.
38. USNRC. Subpart D-Radiation dose limits for individual members of the public. US Nuclear Regulatory Commission. 2013.
39. Vujic J, Antic DP, Vukmirovic Z. Environmental impact and cost analysis of coal versus nuclear power: The us case. Energy. 2012; 45(1):31–42.
40. ICRP. ICRP publication 103. Ann ICRP. 2007; 37(2–4):2.
41. ICRP. The 2007 recommendations of the international commission on radiological protection: ICRP publication 103. Ann ICRP. 2007; 37(2–4):1–332.