Indonesian Journal of Physics
Vol. 21 No. 1, January 2010

System Development on the Uncertainty Propagation Analysis on Estimation of Environmental Radiation Exposure

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Received 3 November 2009, Revised 15 January 2010, Accepted 21 January 2010

Abstract
This paper describes the system development to measure the uncertainty propagation analysis on estimation of environmental radiation exposure. The estimation of environmental radiation exposure is one of the important things that needs to be calculated as a result of nuclear activities in nuclear facilities from exploration and mining, nuclear fuel processing, nuclear power station, nuclear fuel repository or radioactive waste management. The nuclides that result from the radioactive waste are very hazardous to environment. One of the most hazardous materials resulted from the radioactive waste is Radon (^{222}Rn). People who are exposed to excessive Radon emission might have lung cancer. However, the estimation of the Radon exposes to the environment is quite complicated as there are many parameters to be considered. Moreover, the estimation also includes several assumptions about the process of the exposure. Therefore, the main topic of this paper is the uncertainty of the input parameters of the model to be developed. Furthermore, this paper will apply the Monte Carlo method to estimate the propagation analysis of Radon exposure in nuclear waste facility. In addition, the developed system will make use of Nuclear Regulatory Committee (NRC) Regulatory Guide model to estimate the propagation analysis from radioactive storage and waste management. Finally, the system software will be developed using open source and multiplatform environments.

Keywords*: Software System, Analysis Propagation, Uncertainty, Monte Carlo, NRC model, environmental radiation, ^{222}Rn.*

1. Introduction

The estimation of environmental radiation exposure is one of the important things that needs to be calculated as a result of nuclear activities in nuclear facilities from exploration and mining, nuclear fuel processing, nuclear power station, nuclear fuel repository or radioactive waste management. The actual danger is from the deposition of radon progenies in the lung, which receives a dose from alpha radiation emmited during subsequent decays. These decays may cause lung cancer. Several studies on mapping radon exhalation rate from soil have been reported in local, regional or national scales with different methods.

The exposed nuclides come out from the radioactive waste can have a negative impact on the environment, especially Radon (^{222}Rn) which can increase the possibility of the outbreak of lung cancer disease when the exposure is excessive. Modeling of these phenomena related to the environment has been developed. This calculation is quite complex because it involves many parameters and assumptions of the processes involved. The main problem to be addressed in this study is the uncertainty in the input parameters of the model. This paper describes the system development to measure the uncertainty propagation analysis on estimation of environmental radiation exposure based on model *Nuclear Regulatory Commitee (NRC) Regulatory Guide.*

Mathematical modeling and simulation can be applied to approach a variety of symptoms related to environmental safety, reactor safety, chemical kinetic models, dosimetric emission, ecological models and others. In this research we would develop a software to analyze the uncertainty propagation by applying the model suitable with *NRC Regulatory Guide* about Radon radionuclides (^{222}Rn) exposure from radioactive waste storage facility on the environment. Analysis of input parameters uncertainty will provide optimal results to the environmental radiation exposure calculation.

The uncertainty of parameters contained in the model and their impact on the final calculations will be analyzed using Monte Carlo method. Applying this method, the distributions represent each parameter will determined first, such as normal distribution for the parameters of initial ^{234}U contents. From this distribution then it will be generated a number of samples of relevant parameters. Sample set will be used to estimate exposure doses of radionuclides by substituting them to the above mathematical models, so that will get input parameters population and population parameters resulted from calculations. From these two populations information about the rate of radon exposure as the effects of uncertainty of each parameter on the calculated mathematical model can be obtained.

The uncertainty propagation analysis system of the calculated environmental radiation exposure will be developed in this research. Therefore, the main topic of this paper is the uncertainty of the input parameters of the model to be developed. Furthermore, this paper will apply the Monte Carlo method to estimate the propagation analysis of Radon exposure in nuclear waste facility.

A number of sensitivity analysis approaches have been developed, including analysis using Monte Carlo method for the generation of random samples. The application of this method then grows to the method of *Latin Hypercube Sampling* (*LHS*). Monte Carlo simulation used several types of distribution or frequencies distribution, such as triangular distribution, rectangular distribution, normal distribution, uniform distribution, poison distribution and many others^1)^. Monte Carlo simulation is a statistical method which includes random numbers into the simulation process. The results were obtained accurately by doing repeated calculations with lots of random numbers.

The uncertainty analisis of the input parameter will give the optimal solution to be calculated as a result of nuclear activities in nuclear facilities from exploration. Finally, the system software will be developed using *open source* and *multiplatform environments*.

2. Methodology

Radon (^{222}Rn) is the gaseous radioactive products of the decay of the radium isotopes ^{226}Ra, which is present in all terrestrial material. Soil is the source of radon. In the bungalows and low buildings, the entry of radon coming from soil or rock is the main contributor to indoor radon levels2). Therefore,it is necessary to study on the sources of radon for the evaluation of atmosphere radon levels, consequently. Radon (^{222}Rn) is a radioactive inert gas produced by the decay of ^{226}Ra in the ^{238}U series with a half-life of 3.82 days. The radon escapes from the rocks and soil to be accumulated in air or dissolved in the ground water. Radon in water enters the human body by two different paths. Firstly, radon escapes from household water to the indoor air by concentration ratio of 10^{-4}. Secondly, from the ingestion of drinking water. Some measurements have been carried out to determine the concentration of radon in the soil and the release of radon from the soil, (generally 60 cm below the soil surface).

The concept taken for this analysis is the Monte Carlo method. The analysis was performed by repeated calculation model with stochastic input parameters. The model of Monte Carlo Analysis assumed as follows:

$$y = f(x_1, x_2, ..., x_n) = f(x) \qquad (1)$$

where y is the radionuclides exposures, f(x) is the model applied (in this case the model taken from *NRC Regulatory Guide*), and x_1, x_2, x_n are the inputs models.

According to the direct source of radon, the content of radium isotopes ^{226}Ra in the soil is a major factor in the calculation of radon levels influences in the soil and the release of radon from the soil surface. The previous research evaluated that the radon levels in the soil based on the assumption of 1 *Bq/kg* of radium is equivalent to 1700 Bq/m^3 radon concentration in soil. The release of radon from the soil surface directly is proportional to the radium content in soil in addition to some mathematical model was also influenced by other factors such as soil water content and others2).

The modelling radon emanation power, here denoted by ε, is the fraction of radon generated in the materials that can enter to the pore volume of the materials. It is well known that the emanation power depends on the grain size, moisture content and temperature of the material. The radon emanation power increases with soil moisture before saturation. The same phenomenon was also reported in previous literatures. It is explained as the water increases the direct recoil fraction of emanation, also increase in the indirect fraction can occur. Through the regression analysis, the moisture dependence of radon emanation power was formulated (Water saturation vs Relative emanation)3).

$$\varepsilon = \varepsilon_0[1 + k_1(1 - \exp(-k_2 S))] \qquad (2)$$

where: ε radon emanation; ε_0 radon emanation power for oven-died soil, S fraction of soil water saturation k_1 and k_2 coefficient regression for different soil textures

The value measured in oven-dried condition was taken to be 1. The dependency of radon emanation power on soil temperature had been quantified. For general utilization, the formula was reformulated in this study as below3):

$$\varepsilon = \varepsilon_0[1 + 0.01(T - T_m)] \qquad (3)$$

where ε: Radon emanation power estimated for a temperature of T, ε_0 radon emanation power measured at a temperature of T_m

Soil water saturation, defined as the fraction of soil pore space filled with water, is the ratio of of volumetric water content to total porosity of the soil. In this study, for roughly estimating the volumetric water content from the meteorological data, the relationship between the volumetric water content (θ_v) in the top 20 cm of soil and the estimated annual aridity (*D*) was analyzed. The annual aridity is defined as the ratio of potential evapotranspiration (E_t) to precipitation (P) by multiplied and adjusted factor (f). An empirical formula for estimating seasonally volumetric water content in top 20 cm of soil, the power regression analyses are derived as below3),

$$\theta_v = k_3[f\,\frac{E_t}{P}]^{-k_4} \qquad (4)$$

where f is a factor (0.6-0.8) adjusted for different seasons[3)], the coefficients of k_3 and k_4 as well as the square of their correlation coefficient (r^2) for different land use patterns.

Based on the porous media transport theory, and we assumed the soil as a homogeneous media including temperature and moisture, several one-dimensional, steady-state models for radon flux density from the soil have been developed. In this study, two representative models were combined. The empirical function of effective radon diffusion coefficient derived, was used, and temperature dependency of the kinetic diffusion $[D = (\frac{T}{273})^{0.75} D_0]$, suggested by reff[3)] was taken into account. The combined model for radon flux density used in this study is as below[3)],

$$F = R\,\rho_b\,\varepsilon\,(\frac{T}{273})^{0.75}\sqrt{\lambda\,D_0\;p\exp(-6S - 6S^{14p})} \quad (5)$$

where R is the ^{226}Ra content in soil ($Bq\ kg^{-1}$), ρ_b is the soil bulk density $(kg.m^{-3})$, T is the soil temperature (^{o}K), λ is the decay constant of ^{222}Rn (s^{-1}), D_0 is the ^{222}Rn diffusion coefficient in air ($1.1 \times 10^{-5}\ m^2\ s^{-1}$). S is the fraction of pore space filled with water (%), and P is the total porosity of soil (%).

Some types of sampling procedure are used to generate the sample in Monte Carlo analysis, such as *Simple Random Sampling (SRS), Sratified Sampling* and *Latin Hypercube Sampling (LHS).* With random sampling, there is no assurance that a sample element will be generated from any particular subset of the sample space. In particular, important subsets of sample with low probability but high consequences are likely to be missed. Stratified sampling has the advantage of forcing the inclusion of specified subsets of sample space while maintaining the probabilistic character of random sampling but there is a problem with stratified sampling, the necessity of defining the strata and calculating their probablities, when the dimensionality of sample space is high, the determination of strata and strata probabilities become a major undertaking. The determinations are further complicated when many analysis outcomes are under consideration, in particular, strata definitions that are appropriate for one analysis outcome may be inappropriate for other analysis outcomes. Latin hypercube sampling is based on a combination of simple random sampling and stratified sampling techniques that leads to statistically significant result with substantially fewer realizations[1)]. *LHS* display properties between *SRS* and *Stratified Sampling*, which stratifies on the sample space.

The basis of *LHS* is a full stratification of the sampled distribution with a random selection inside each stratum, sample values are randomly shuffled among different parameters. To generate probability distributions, the *LHS* was performed using the following steps[4)];

(i) Assign an inverse *cumulative distribution function* (*cdf*) for each input parameter.
(ii) Choose the number of simulations (N) to be performed.
(iii) Divide the *cdf* for each parameter into N equi-probable intervals.
(iv) For each interval, choose a random sample x, from the inverse *cdf* and develop a data set for each parameter.
(v) Randomly select from each parameter input data set to create N model input sets.
(vi) Use an analytical or numerical model to determine a realization for each model input set.

The current development accomodates uniform, triangular, and normal distributions which are commonly used in practice. The particular difference of the *LHS* and standard random sampling is in the third step of the above steps.

There are five basic components that underlie the implementation of a sampling-based uncertainty and sensitivity analysis[5)]:

(i) Definition of distributions $D_1, D_2, ...,$ for each parameter $\boldsymbol{x_j}$.
(ii) Samples generating using *Monte Carlo* method (*Latin Hypercube Sampling*):

$$x_i = [x_{i1}, x_{i2}, ..., x_{in}], \quad i = 1, 2, ..., m \qquad (6)$$

where n is the number of input parameters and m is the sample size.

(iii) *NRC Regulatory Guide* model is calculated for every element in equation (5)

$$y_i = f(x_{i1}, x_{i2}, ... x_{in}) = f(x_i), \qquad i = 1,2, ...m \quad (7)$$

(iv) The mean and variance as a descriptive statistics of y are obtained from equation (7),

$$E(y) = \sum_{i=1}^{m} y_i / m \qquad (8)$$

$$V(y) = \sum_{i=1}^{m} [y_i - E(y)]^2 / (m-1) \qquad (9)$$

(v) The calculation of correlation analysis[6)] is performed to determine the sensitivity of the parameters x_i againts the function of y.

3. Disccussion

Observations were conducted on the area of radius 0.5 *km* up to 1 *km* in Nuclear Energy Research Center (PPTN) area Serpong. Based on observation, concentration data of the Radium ^{226}Ra obtained during the rainy season and dry season are shown in the following table.

Table 1. Radium ^{226}Ra concentration data during the rainy season and dry season

Number of observation	Sample code of location	Radium Content (Bq/kg) Rainy Season	Radium Content (Bq/kg) Dry Season
	P01TP	17.57	20.58
2	**P02TP**	25.72	34.39
3	**P03TP**	27.82	33.47
4	**P04TP**	29.31	12.82
5	**R01TP**	25.30	38.64
6	**R02TP**	29.04	46.03
7	**R03TP**	24.80	30.03
8	**R04TP**	26.91	16.98
	Mean	25.81	29.12
	Standard Deviation	3.724	11.402

The values of parameters and the types of distribution are described in Table 2 for rainy season, and Table 3 for dry season.

Tabel 2. The parameters and distributions for Rainy Season

No.	Types of Parameters	Types of Distribution	The values of distribution parameters
1	Radium Content (R)	Normal	(25.81;3.724)
2	Soil Bulk Density (ρ_b)	Triangular	($1.50 \mathrm{x} 10^3$; $1.60 \mathrm{x} 10^3$;$1,55 \mathrm{x} 10^3$)
3	Radon Emanation (ε)	Triangular	(30%;35%;30%)
4	Temperature (T)	Uniform	(295 ^{0}K; 296 ^{0}K)
5	Total Porosity of Soil (P)	Uniform	(0.39;040)
6	Fraction of pore space filled with water (S)	Triangular	(0.08;0.13;0.10)
7	Decay ^{222}Rn (λ)	Constant	$2.1 \mathrm{x} 10^{-6}$
8	Diffusion Coeficient (D_0)	Constant	$1.1 \mathrm{~x} 10^{-5}$

Table 3 . The parameters and distributions for Dry Season

No.	Type of Parameters	Types of Distribution	The value of distribution parameters
1	Radium Content (R)	Normal	(29.12;11.402)
2	Soil Bulk Density (ρ_b)	Triangular	($1.50 \mathrm{x} 10^3$; $1.60 \mathrm{x} 10^3$;$1,55 \mathrm{x} 10^3$)
3	Radon Emanation (ε)	Triangular	(30%;35%;30%)
4	Temperature (T)	Uniform	(299 ^{0}K; 300 ^{0}K)
5	Total Porosity of Soil (P)	Uniform	(0.39;040)
6	Fraction of pore space filled with water (S)	Triangular	(0.08;0.13;0.10)
7	Decay ^{222}Rn (λ)	Constant	$2.1 \mathrm{x} 10^{-6}$
8	Diffusion Coeficient (D_0))	Constant	$1.1 \mathrm{~x} 10^{-5}$

Based on the model, with the uncertainty of applied parameters and the given distributions, the simulation results are obtained for the radon flux rate. The sensitivity between each parameter with radon flux rate were indicated by the correlation value. The result of radon flux rate in rainy season and dry seasons are described below, based on equation (5). The first step in the application of created software was to give the parameter types (Fig. 1) with their distribution types, and also provide the amount of trials to be conducted to obtain the desired amount of data (Fig. 2).

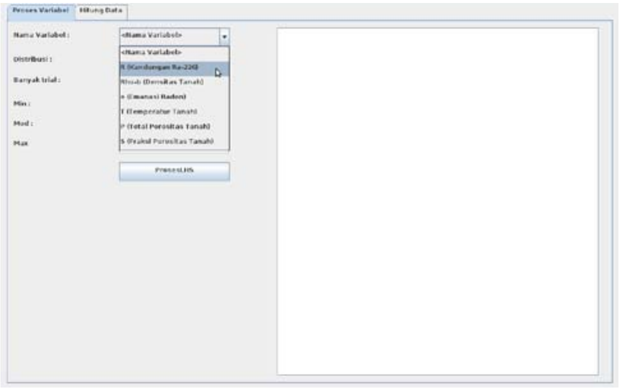


Figure 1. Provide the names of the parameters

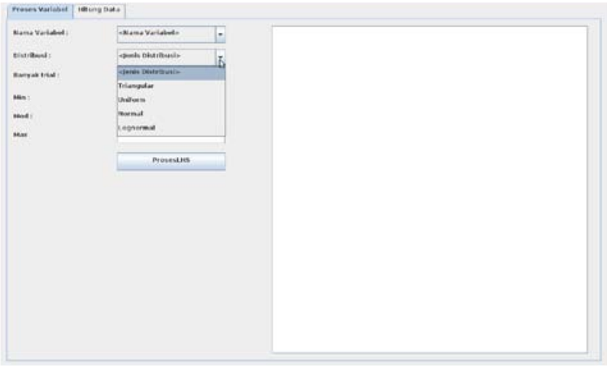
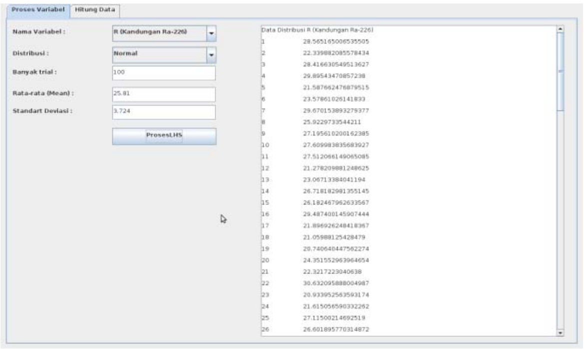


Figure 2. Determining the types of parameter distributions

Based on the results of field measurements during the rainy season, the radium content *^{226}Ra* parameters have a normal distribution, where its mean is 29.12 and its standard deviation is 3.724 (Fig. 3). The same way was done for the other parameters with the desired types of distribution according to information obtained in Table 2 (for rainy season) and Table 3 (for dry season).



Nama Variabel : R (Kandungan Ra-226)
Distribusi : Normal
Banyak trial : 100
Rata-rata (Mean) : 25.81
Standart Deviasi : 3.724

```
Data Distribusi R (Kandungan Ra-226)
1            28.565165006535505
2            22.339882085578434
3            28.416630549513627
4            29.89543470857238
5            21.587662476879515
6            23.57861026141833
7            29.670153893279377
8            25.9229733544211
9            27.195610200162385
10           27.609983835683927
11           27.512066149065085
12           21.278209881248625
13           23.06713384041194
14           26.718182981355145
15           26.182467962633567
16           29.487400145907444
17           21.896926248418367
18           21.05988125428479
19           20.740640447562274
20           24.351552963964654
21           22.3217223040638
22           30.632095888004987
23           20.933952563593174
24           21.615056590332262
25           27.11500214692519
26           26.601895770314872
```

Figure 3. Determining the Number of Trial, R parameter (^{226}Ra content) of normal distribution and the data generated by *LHS*

The parameter soil density (ρ_b) with a triangular distribution, has the minimum value is 1.50x10^3 kg/m^3, the maximum value is 1.60x10^3 kg/m^3 and the mode value is 1.55x10^3 kg/m^3 for the rainy season and the dry season. That value based on the previous information and the results from laboratory measurement[7,8)] (Fig. 4). The parameter radon emanation (ε) with a triangular distribution, based on the results of laboratory measurements, a minimum of 30%, maximum of 35% and 30% mode values from dry season and rainy season are given to. Meanwhile, based on the results of the field measurements, the minimum value 295^{0}K to maximum 296^{0}K for rainy season and minimum 299 ^{0}K to maximum 300 ^{0}K for dry season are given to the temperature (*T*) parameter with uniform distribution. Similarly, based on laboratory measurements, the minimum value 0,39 and maximum value 0,40, both for the rainy season and dry season are given to the parameters total soil porosity (*P*) with uniform distribution. Based on laboratory measurement[7,8)] for the rainy season and dry season, fraction of total porosity parameter *(S)* with a triangular distribution has a minimum, maximum and mode values respectively 0:08; 0:13 and 0:10.

After generating each parameter and samples with a number of trials *n = 100* obtained, then performed the calculation of radon flux rate (*F*) according to the model determined previously (Fig. 4).

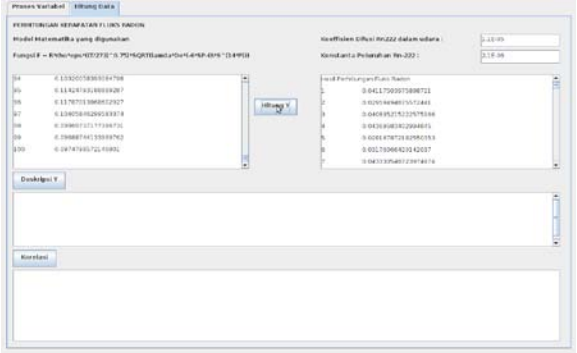
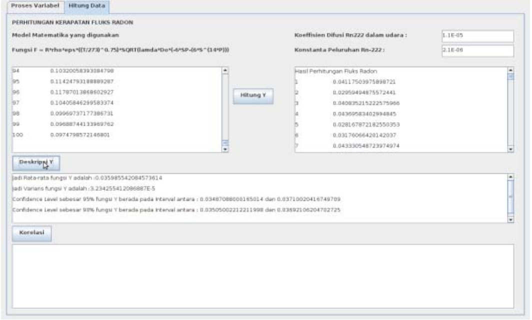


Figure 4. The results of Radon flux rate calculations

Before performing calculations, specify first the ^{222}Rn diffusion coefficient constant value (D_0) of 1.1x10^{-5} and ^{226}Rn decay constant(λ) of 2.1x10^{-6}. The calculation of mean and standard deviation for the radon flux rate was expressed with a confidence level of 95% and 90% (Fig. 5)[9)].



PERHITUNGAN KERAPATAN FLUKS RADON

Model Matematika yang digunakan

Fungsi F = R*rho*eps*((T/273)^0.75)*SQRT(lamda*Do*(-6*SP-(6*S^(14*P)))

Koeffisien Difusi Rn222 dalam udara : 1.1E-05

Konstanta Peluruhan Rn-222 : 2.1E-06

```
94           0.10320058393084798
95           0.11424793188889287
96           0.11787013868602927
97           0.10405846299583374
98           0.09969737177386731
99           0.09688744133969762
100          0.0974798572146801
```

```
Hasil Perhitungan Fluks Radon
1            0.04117503975898721
2            0.02959494875572441
3            0.040835215222575966
4            0.04369583402994845
5            0.028167872182550353
6            0.03176066420142037
7            0.043330548723974974
```

```
Jadi Rata-rata fungsi Y adalah :0.035985542084573614
Jadi Varians fungsi Y adalah :3.234255412086887E-5
Confidence Level sebesar 95% fungsi Y berada pada interval antara : 0.03487088000165014 dan 0.03710020416749709
Confidence Level sebesar 90% fungsi Y berada pada interval antara : 0.03505002212211998 dan 0.03692106204702725
```

Figure 5. Description of the calculated radon flux rate

Based on the types of uncertainty parameters, the sensitivity of each parameter and the rate of radon flux are expressed by the result of calculated correlation between radon flux rate below with their parameters respectively (Fig. 6)

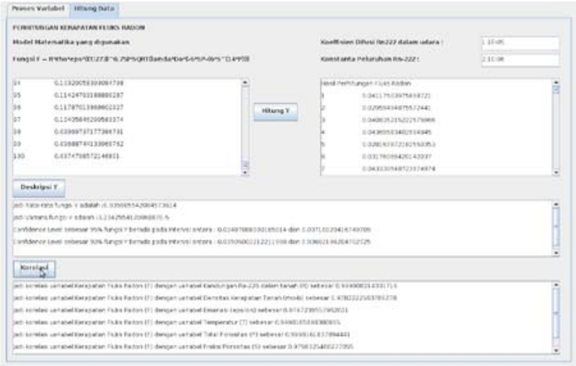


Figure 6. The calculated radon flux rate function and the correlation value

The mean value for radon flux rate obtained is 0.035981 Bq/m2sec with standard deviation 0.005695 Bq/m2sec during rainy season. 95% confidence level located on the interval (0.034865; 0.037098) Bq/m2sec. 90% confidence level located in the interval (0.035045; 0.036918) Bq/m2sec. Whereas, in the dry season the mean value obtained for radon flux rate is 0.041358 Bq/m2sec with standard deviation 0.014761 Bq/m2sec. 95% confidence level located in the interval (0.038467; 0.044246) Bq/m2sec. 90% confidence level located in the interval (0.038931; 0.043782) Bq/m^{2}sec.

The sensitivity analysis of radon flux rate and each parameter on rainy season expressed in correlation values. The correlation betweento radon flux rate with radium content are worth 0.9999; soil bulk density value 0.9776; radon emanation power value 0.9801; soil temperature value 0.9998; total porosity of soil is worth 0.9998 and the fraction of pore space filled with water is worth 0.9795. While the correlation between radon flux rate with each of the parameters of radium contents in the dry season are worth 0.9997; soil bulk density value 0.9746; radon emanation power value 0.9823; Soil Temperature value 0.9996; total porosity of soil is worth 0.9996 and the fraction of pore space filled with water is worth 0.9835.

4. Conclusion

Radon (^{222}Rn) is the most hazardous material resulted from the radioactive waste. The estimation of the Radon exposes to the environment is quite complicated as there are many parameters to be considered. The estimation also includes several assumptions about the process of the exposure. The uncertainty of the input parameters of the model has applied the *Monte Carlo* method. *Latin Hypercube Sampling (LHS)* is the type of sampling procedure that is used to generate the sample in Monte Carlo analysis. Latin hypercube sampling is based on a combination of simple random sampling and stratified sampling techniques that leads to statistically significant result with substantially fewer realizations. The uncertainty propagation analyses system of the calculated environmental radiation exposure has developed in this research especially in nuclear waste facility. The Simulation using LHS method for calculating radon flux rate are close to the conducted experiments result. Sensitivity analysis between radon exhalation rate and each of that parameters have the strong corelation. The software has been developed using open source and multi platform environments Java.

Acknowledgments

The authors would like to thanks to :Mr. Dadong Iskandar, Mr. Untara, Mrs. Sri Widayati, Mr. Wahyu, Mr. Adi Wardoyo, Mr. Noer Agus Salim, Mrs. Ruliyanti Pardewi and Mr. Topan Setiadipura, for their support to this written material. This research is funded by DIKNAS and RISTEK grants.

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