ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN
2019 International Nuclear Atlantic Conference - INAC 2019
Santos, SP, Brazil, October 21-25, 2019

Agência Brasileira do ISBN
ISBN 978-85-99141-08-3

ESTIMATION OF EXPOSURE LEVELS OF TERRESTRIAL BIOTA AND RADIATION EXPOSURE AROUND IPEN´S FACILITIES

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ABSTRACT

Humans are exposed to natural radiation; soil is a major source of external and internal exposure of radiation. The external exposure from the soil is associated with gamma radiation and internal exposure mainly from radon inhalation. The aim of this study is to evaluate the exposure levels of terrestrial biota and to estimate the radiation exposure around IPEN facilities. The Institute comprises several nuclear and radioactive facilities including a research reactor, cyclotrons and a radioisotope and radiopharmaceutical production plant. The ERICA Tool was used to calculate the exposure levels of terrestrial biota; the estimation of radiation exposure for humans was determined using a model proposed by UNSCEAR (Absorbed dose rate in air and Annual effective dose equivalent) and Excess Lifetime Cancer Risk. Six soil points were collected and their activity concentrations were measured by gamma spectrometry, using a HPGe detector. Two soil points showed a risk coefficient greater than 1, suggesting that the screening dose ratio of 10µGy h^{-1} might be exceeding for the most exposed species, namely lichen and bryophytes, even though the activity concentration values of the analyzed radionuclides showed no evidence of soil contamination due to the atmospheric discharges of the IPEN facilities. Thus, the radioactive discharges in the soil from all facilities are negligible. Hence, the authors concluded that the ERICA Tool can be useful in assisting environmental radiological monitoring program for decision-making, especially regarding: points collected, sample types and sampling frequency.

1. INTRODUCTION

Biota and human are exposed to natural radiation from many different sources. The external exposure from the soil is associated with gamma radiation and internal exposure with radon inhalation, soil is a major source of exposure of radiation, and the exposures of radiation are different in each region [1].

In the past, the levels of exposure to ionizing radiation was mainly focused on humans, considering that biota and the environment were also protected if human beings were adequately protected. In the last decades, this statement was proven to fail and is no longer accepted [2]. Exposure and radiological risk to biota from different ecosystems can be assessed using different risk models, such as the RESRAD-Biota and the ERICA Tool.

The Erica Integrated Approach [3] was developed by the European Union to assess the effects of radionuclides in the environment and to support decision making. The software operates in three different Tiers and provides estimation on absorbed doses (internal and external) to reference organisms from different ecosystems and perform risk characterization based on activity concentration in the environment and in biota whole body.

Estimation of Radiation Doses (Absorbed Dose Rate in air, Annual Effective Dose) and Excess Lifetime Cancer Risk (ELCR) were calculated using theoretical models [4].

2. MATERIALS AND METHODS

The Instituto of Pesquisas Energéticas e Nucleares (IPEN) is located in the city of Sao Paulo – Brazil and comprises several nuclear and radioactive facilities, including a research reactor, cyclotrons and a radioisotope and radiopharmaceutical production plant. Gaseous and Liquid radioactive effluents are acutely monitored before released into the environment and annually verified by the Environmental Radiological Monitoring Program (PMRA).

2.1. Data on soil activity concentrations from natural radionuclides

Nisti *et al.* [5] determined the activity concentrations from natural radionuclides in soil from different locations in IPEN, giving evidence of no soil contamination due to the atmospheric releases from IPEN facilities. Table 1 presents the results obtained in the referred paper:

Table 1: Average concentrations of ^{226}Ra, ^{210}Pb, ^{232}Th, ^{228}Th and ^{40}K in soil samples (Bq kg^{-1}) and sampling location[D] from Nisti *et al.* (2015)

Concentration (Bq kg^{-1})					
Sampling coordinates	^{226}Ra	^{210}Pb	^{232}Th	^{228}Th	^{40}K
1 23°33'56.66"S-46°44'07.04"O	43 ± 3	61 ± 12	92 ± 4	101 ± 4	179 ± 8
2 23°33'55.64"S-46°44'05.63"O	52 ± 1	47 ± 5	124 ± 5	134 ± 7	94 ± 10
3 23°33'59.69"S-46°44'15.48"O	42 ± 1	43 ± 6	83 ± 2	90 ± 5	200 ± 11
4 23°33'46.15"S-46°44'13.36"O	40 ± 2	62 ± 10	83 ± 7	90 ± 1	143 ± 13
5 23°33'48.21"S-46°44'16.35"O	39 ± 2	51 ± 3	70 ± 2	79 ± 6	204 ± 11
6 23°33'41.26"S-46°44'28.92"O	54 ± 5	59 ± 6	116 ± 2	127 ± 6	185 ± 18
UNSCEAR [1]	17-60		11-64		140-850
Peres [8]	1-61.8	<20-121	8-82	4.8-120	15.3-516

2.2. Risk characterization for terrestrial biota using Erica Tool

Data on radionuclide concentrations on soil were used as input to calculate the Risk Quotient (RQ) for all terrestrial reference organisms. The assessment was run using Tier 1, once this is more conservative and only requires media concentration activities.

Whenever the calculations of RQ´s present a value equal to or higher than 1, it indicates that there is a significant probability that the activity concentration of a particular radionuclide exceeds the screening dose value (10μGy/h) for the most exposed organism. The Tool suggests that the user carry on with the assessment, using Tier 2 or Tier 3.

The assessment using Tier 2 requires the activity concentrations in biota whole body in order to estimate the total absorbed dose (from internal and external sources). Once estimated, the Tool employs these results to calculate a new value for the Risk Quotient.

According to Brown J.E. *et al* (2008), if adequate measured values of activity concentrations in biota whole body are not available, one can infer them using the Concentration Ratio (CR) given by the following equation:

$$CR = \frac{Activity\ concentration\ in\ biota\ whole\ body\ (Bq.kg^{-1}\ fresh\ weight)}{Activity\ concentration\ in\ soil\ (Bq.kg^{-1}\ dry\ weight)} \quad (1)$$

There is a wide set of CR´s values stored in the Tool for each radionuclide and reference organism.

2.3. Estimation of Radiation Doses and Excess Lifetime Cancer Risk

The ^{226}Ra, ^{232}Th and ^{40}K activity concentrations of soil samples were used for the calculation of outdoor external absorbed dose rate in air at 1m above the ground surface to the population [1]. The absorbed dose rate in air was obtained by the equation 2:

$$DR = [(CRa\ x\ CFRa) + (CTh\ x\ CFTh) + (CK\ x\ CFK)] \quad (2)$$

Where:
DR is external absorbed dose rate (nGy h^{-1}),
C_{Ra} is the activity concentrations of ^{226}Ra (Bq kg^{-1}),
C_{Th} is the activity concentrations of ^{232}Th (Bq kg^{-1}),
C_k is the activity concentrations of ^{40}K (Bq kg^{-1}),
CF_{Ra} is conversation factor of ^{226}Ra 0.462 (nGy h^{-1} per Bq kg^{-1}),
CF_{Th} is conversation factor of ^{232}Th 0.604 (nGy h^{-1} per Bq kg^{-1}),
CF_k is conversation factor of ^{40}K 0.0417 (nGy h^{-1} per Bq kg^{-1}),

The conversation factors were defined by the UNSCEAR [B].

The annual effective dose (outdoor) to the population were calculated using the following equation 3:

$$AED = (DR\ x\ T\ x\ OF\ x\ CF) \quad (3)$$

Where:
AED is annual effective dose (outdoor) (mSv y^{-1}),
DR is external absorbed dose rate (nGy h^{-1}),

T is annual average time for exposure to radiation (h),
OF is outdoor occupancy factor 0.2,
CF is conversion factor 0.7 ($Sv\ Gy^{-1}$).

The occupancy factor and conversion factor was proposed by the UNSCEAR [6].

The Excess Lifetime Cancer Risk is calculated using the following equation 4.

$$ELCR = AED \times DL \times RF \tag{4}$$

Where:
ELCR is Excess Lifetime Cancer Risk,
AED is annual effective dose (outdoor) ($mSv\ y^{-1}$),
DL is duration of life 70 (years),
RF is risk factor 0.05×10^{-3} (Sv^{-1}).

The duration of life and risk factor for stochastic effect was defined by the ICRP [7].

3. RESULTS

3.1. Risk analysis and absorbed dose rates for terrestrial biota

Tier 1 was initially used to calculate the RQ for terrestrial organisms, using data from Table 1 as input. The results for each studied radionuclide and the most exposed organism are presented in Table 2, using the highest value for each radionuclide concentration.

Table 2. Risk Quotient for each radionuclide and limiting reference organism

Isotopes	RQ [unitless] (M_{n-max})	Limiting Reference Organism
Ra-226	1.88 E0	Lichen & Bryophytes
Pb-210	9.92 E-3	Lichen & Bryophytes
Th-232	3.99 E-1	Lichen & Bryophytes
Th-228	3.47 E0	Lichen & Bryophytes
∑ RQ	5.76 E0	

Calculations have shown that the concentrations of Ra-226 and Th-228 measured in soil may provide absorbed doses higher than the screening dose value (10μGy/h) for the most exposed organism (lichen and bryophytes). The Tool indicates the need to further investigate these concentrations, which was done using Tier 2.

As mentioned before, Tier 2 requires the activity concentrations in biota whole body in order to estimate the total absorbed dose (from internal and external sources) and calculates a new set of Risk Quotient values. Activity concentration in biota whole body were not available in this work, therefore, the authors addressed to the default values of CR within the Tool (Table 3).

Table 3. Concentration Ratio values and their Standard Deviation, for elements studied in this work, considering terrestrial biota

	Pb		Ra		Th	
	CR	SD	CR	SD	CR	SD
Amphibian	1,2E-01	5,2E-01	4,4E-02	1,2E-01	3,9E-04	9,4E-05
Annelid	4,8E-01	7,3E-01	4,3E-02	1,0E-02	9,2E-03	7,0E-03
Arthropod - detritivorous	4,0E-01	4,6E-01	4,3E-02	1,0E-02	5,1E-03	5,9E-03
Flying insects	4,0E-01	4,6E-01	4,3E-02	1,0E-02	5,1E-03	5,9E-03
Bird	6,1E-02	1,7E-01	3,6E-02	5,1E-02	3,9E-04	9,4E-05
Grasses & Herbs	1,2E-01	2,9E-01	1,8E-01	4,1E-01	1,6E-01	4,3E-01
Lichen & Bryophytes	2,6E+00	3,3E+00	7,1E-01	1,6E+00	3,8E-01	8,2E-01
Mammal - large	3,7E-02	3,6E-02	4,4E-02	1,2E-01	1,4E-04	1,3E-04
Mammal - small-burrowing	3,7E-02	3,6E-02	4,4E-02	1,2E-01	1,4E-04	1,3E-04
Mollusc - gastropod	7,3E-03	1,3E-02	4,8E-02	4,8E-02	9,2E-03	7,0E-03
Reptile	3,9E-02	1,7E-01	4,4E-02	1,2E-01	2,2E-03	5,2E-04
Shrub	3,2E-01	4,9E-01	3,3E-01	8,3E-01	6,1E-02	1,4E-01
Tree	7,0E-02	1,6E-01	1,2E-02	1,8E-02	1,3E-03	1,1E-03

Using equation 1 and data from Table 3, the activity concentration in biota whole body was than inferred for selected organisms (Table 4) and are shown next in Figure 1:

Table 4. Whole body activity concentration for terrestrial biota, inferred from default CR values and measured soil activity concentrations.

Whole Body Activity Concentrations [Bq/kg f.w.]						
Isotope	Lichen & Bryophytes	Grasses & Herbs	Bird	Flying insects	Shrub	Tree
Ra-226	38.34	9.4	1.9	2.3	17.0	0.6
Pb-210	160.0	7.4	3.8	25.0	20.0	4.31

Th-228	51.0	21.0	0.052	0.68	8.2	0.17
Th-232	47.0	2.0	0.048	0.63	7.6	0.16

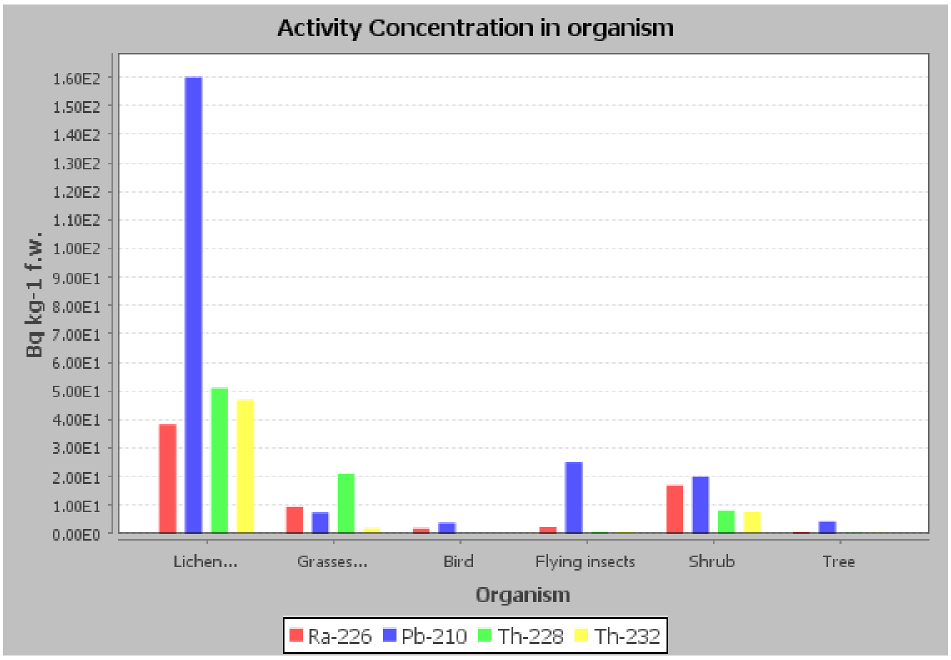

Figure 1. Activity concentration in organism whole body, due to internal and external exposures of radionuclides in soil.

In agreement with the results obtained in Tier 1, the activity concentration in the most exposed organism, lichen and bryophytes, are higher, specially for Pb-210, as expected Once Rn-222 is easily released to the air from soil surfaces, some of their radioactive daughters (such as Po-210) can be deposited on the surface of vegetation.

The estimated values presented in Table 4 were used as input to calculate the internal (Table 5) and external (Table 6) dose rates and a new set of RQ's (Table 7) for each radionuclide and exposed organism.

Table 5. Internal absorbed doses for selected organisms.

Internal absorbed doses [µGy/h]						
Isotope	Lichen & Bryophytes	Grasses & Herbs	Bird	Flying insects	Shrub	Tree
Ra-226	5.31	1.28	0.27	0.31	2.32	0.084
Pb-210	0.031	0.002	9.88E-4	0.005	0.0045	0.0011
Th-228	9.451	3.881	0.01	0.126	1.51	0.03
Th-232	1.081	0.04	0.001	0.014	0.17	0.004

Table 6. External absorbed doses for selected organisms.

External absorbed doses [μGy/h]						
Isotope	Lichen & Bryophytes	Grasses & Herbs	Bird	Flying insects	Shrub	Tree
Ra-226	0.018	0.018	0.012	0.0189	0.01728	0.014
Pb-210	1.80E-5	2.48E-5	1.736E-5	1.80E-5	1.24E-5	8.06E-6
Th-228	0.039	0.04	0.03886	0.03886	0.036	0.03082
Th-232	5.42E-6	1.36E-5	5.33E-6	5.45E-6	6.2E-6	2.604E-6

Table 7. Expected RQ's for each selected organism.

Organism	Total Dose Rate per organism [μGy/h]	Screening Value [μGy/h]	Risk Quotient (expected) [uniteless]
Lichen & Bryophytes	1.59E1	1.00E1	1.59E0
Grasses & Herbs	5.27E0	1.00E1	5.27E-1
Bird	3.41E-1	1.00E1	3.41E-2
Flying insects	5.17E-1	1.00E1	5.17E-2
Shrub	4.07E0	1.00E1	4.07E-1
Tree	1.67E-1	1.00E1	1.67E-2

The Tool points out three different results: for lichen & bryophytes, the screening dose rate is exceeded and requires further investigation; for grasses & herbs and shrubs, there is a significant probability that the screening dose rate might be exceeded; for birds, flying insects and tress, the probability that the screening dose rate is exceed is low. Further investigation (including area characterization and environmental sampling) in the area with the highest soil activity concentration is currently under consideration and will be addressed in future papers.

3.2. Radiation Doses and Excess Lifetime Cancer Risk

Two scenarios were used to estimate the assumption of annual average time for exposure to radiation of Annual Effective Dose of the population in IPEN. The first scenario, more conservative, considered the time of 8,766 hours (Table 8). The second scenario, more realistic, considered the hours that the individual (worker) is inside IPEN, estimated at 2,277 hours (Table 9).

Table 8. Estimation of Radiation Doses (Absorbed Dose Rate in air (DR), Annual Effective Dose (AED)) and Excess Lifetime Cancer Risk (ELCR) (first scenario).

Sampling coordinates	DR (nGy h-1)	AED (mSv y-1)	ELCR

1 23°33'56.66"S-46°44'07.04"O	83	0.10	0.36x10^{-3}
2 23°33'55.64"S-46°44'05.63"O	103	0.13	0.44 x10^{-3}
3 23°33'59.69"S-46°44'15.48"O	78	0.10	0.33 x10^{-3}
4 23°33'46.15"S-46°44'13.36"O	75	0.09	0.32 x10^{-3}
5 23°33'48.21"S-46°44'16.35"O	69	0.08	0.30 x10^{-3}
6 23°33'41.26"S-46°44'28.92"O	103	0.13	0.44 x10^{-3}
mean ± st. dev.	85±15	0.10±0.02	(0.36±0.06) x10^{-3}

The results obtained for the absorbed dose in air from soil varied from 69 to103 nGy h^{-1} in soil samples of IPEN, with an average value of 85 ± 15 nGy h^{-1}.

The Annual Effective Dose (outdoor) from soil varied from 0.08 to 0.13 mSv y^{-1}, with an average value of 0.10 ± 0.02 mSv y^{-1}.

The Excess Lifetime Cancer Risk (outdoor) from soil varied from 0.30x10^{-3} to 0.44x10^{-3}, with an average value of (0.36 ± 0.06)x10^{-3}.

Table 9. Estimation of Radiation Doses (Absorbed Dose Rate in air (DR), Annual Effective Dose (AED)) and Excess Lifetime Cancer Risk (ELCR) (second scenario).

Sampling coordinates	DR (nGy h-1)	AED (mSv y-1)	ELCR
1 23°33'56.66"S-46°44'07.04"O	83	0.03	0.09x10^{-3}
2 23°33'55.64"S-46°44'05.63"O	103	0.03	0.11x10^{-3}
3 23°33'59.69"S-46°44'15.48"O	78	0.02	0.09x10^{-3}
4 23°33'46.15"S-46°44'13.36"O	75	0.02	0.08x10^{-3}
5 23°33'48.21"S-46°44'16.35"O	69	0.02	0.08x10^{-3}
6 23°33'41.26"S-46°44'28.92"O	103	0.03	0.11x10^{-3}
mean ± st. dev.	85±15	0.03±0.01	(0.01±0.02) x10^{-3}

The Annual Effective Dose (outdoor) from soil varied from 0.02 to 0.03 mSv y^{-1}, with an average value of 0.03 ± 0.01 mSv y^{-1}.

The Excess Lifetime Cancer Risk (outdoor) from soil varied from $0.08x10^{-3}$ to $0.11x10^{-3}$, with an average value of $(0.10 \pm 0.02)x10^{-3}$.

The results obtained for the absorbed dose in air (outdoor) are in good agreement with the value reported from UNSCEAR [1] for the range worldwide of 18 to 93 nGy h^{-1}.

The Annual Effective Dose (outdoor) and Excess Lifetime Cancer Risk in the present studies are of the same order of magnitude of the mean worldwide of 0.07 mSv y^{-1} and $0.29x10^{-3}$, respectively [1, 8].

4. CONCLUSIONS

Risk Quotients calculations using Tier 1 have shown that the concentrations of Ra-226 and Th-228 measured in soil may provide absorbed doses higher than the screening dose value (10µGy/h) for the most exposed organism (lichen and bryophytes). Using Tier 2, the Tool provided a new set of Risk Quotients as well as the internal and external dose rates for selected organisms. For lichen & bryophytes, the screening dose rate is exceeded and requires further investigation; for grasses & herbs and shrubs, there is a significant probability that the screening dose rate might be exceeded.

According to these results, the authors believe that the Tool can be used to justify further investigation of the area with the highest soil activity concentration. Therefore, the authors conclude the ERICA Tool can be useful in assisting environmental radiological monitoring program for decision-making, especially regarding: points collected, sample types and sampling frequency.

The results obtained for Estimation of Radiation Doses (Absorbed Dose Rate in air (DR), Annual Effective Dose (AED)) and Excess Lifetime Cancer Risk (ELCR) in the soil samples for both scenarios; indicate that the exposure around IPEN facilities is of the same order of magnitude of the mean worldwide.

Finally, the results of this paper can be used for a database on soil radioactivity in the São Paulo city.

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