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ENVIRONMENTAL IMPACT ASSESSMENT OF THE NUCLEAR REACTOR IN VINČA, BASED ON THE DATA ON EMISSION OF RADIOACTIVITY FROM THE LITERATURE - A MODELING APPROACH*

Article Highlights

- A study of the impact of nuclear reactor RA in Vinca on its environment using Gaussian model
- The total dose was modeled using dose factors
- Meteorological data for the six-year period were used
- Nuclear reactor RA could not affect the environment above the prescribed limit

Abstract

Research activities of Vinca Institite have been based on two heavy water research reactors: a 10 MW one, RA, and zero power, RB. Reactor RA was operational from 1962 to 1982. In 2010, spent fuel has been sent to the country of origin, and the reactor now is in decommissioning. During the operational phase of the reactor there were no recorded accidental releases into the environment, only operational ones. Results of the environmental impact assessment of the assumed emission of radionuclides from the ventilation of nuclear reactor "RA" in Vinca to the atmospheric boundary layer are presented in this paper. Evaluation was done by using the Gaussian straight-line diffusion model and taking into account characteristics of the reactor ventilation system, the assumed emission release of radioactivity (from the literature), site-specific meteorological data for six-year period and local topography around nuclear reactor, and corresponding dose factors for inventory of radionuclides. Based on the described approach, and assuming that the range of appropriate meteorological data for six year period for the application of described mathematical model is enough for this kind of analysis, it can be concluded that the nuclear reactor RA, in the course of its work from 1962 to 1982, had no influence on the surrounding environment through the air above regulatory limits.

Keywords: environment, impact, assessment, nuclear, reactor, model.

On October 15th 1958, 55 years ago, there was an accident at the nuclear reactor RB site at the Boris Kidrič Institute in Vinča [1]. Research reactor RB is a non-reflected, natural uranium, heavy water, critical assembly (zero power) reactor. In 1958, a reactivity excursion accident occurred, causing radiation over-exposure of personnel. There are no reports of environmental releases of radionuclides.

This accident is known to the world as the "Vinča accident", with the first fatal overexposure, but also successful treatment of five workers irradiated with lethal doses. The accident in Vinča led to the first bone-marrow transplant in the history of medicine, performed in the Curie hospital in Paris. Six months after the accident, the institute formed a radiation protection unit and a laboratory, and all over the

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world, strict regulations and procedures for nuclear experiments and work at reactors were introduced.

The accident was the initiationing event for the foundation of radiation protection department with meteorological and evironmental monitoring. After the accident at nuclear reactor, in order to put into the 10 MW reactor "RA" to work in 1959, classical meteorological measurements, observations, and meteorological data processing that remain to this day, had to be done.

Environmental impact assessment is a part of nuclear safety analysis for research reactors, which is mandatory for the operator for verification of the compliance with the regulations [2-6]. In different phases of the nuclear facility lifecycle, the main purpose may differ, from planning purpose to reconstruction and reevaluation of safety. In the operational phase, the main tool for controlling the environmental impact is radioactive monitoring in the vicinity of a facility. Another reason for safety reevaluation is the change of legislative framework and the need to verify that safety functions of the facility still are bellow legal limits. This paper presents the results of such reevaluation for the time period covered by automatic meteorological observations and measurements.

In 1997, meteorological measurements and data processing at a 37 m high meteorological tower, using an automatic weather station of the Institute of Physics in Zemun began. In 2008, the Slovenian company AMES built a new automatic weather station at a 40 m high meteorological tower.

Files contain ten-minute meteorological data, received from the automatic weather station that has sensors placed on a 37 m high meteorological tower. This database was used for calculations from 2001 until 2005.

Since 2009, a new automatic meteorological station was used for gathering data, and sensors were placed on several levels at the renewed meteorological tower, 40 m high.

Physical properties of the ventilation stack of reactor RA was obtained from technical documentation for the ventilation system, shown in Figure 1.

Meteorological data

From 2001-2005, meteorological data was obtained from automatic weather station of the Institute of Physics that had sensors placed on a 37 m high meteorological tower.

The station measured:

<u>Top of the tower, 38 m above ground (37 m high tower + 1 m sensor holder)</u>

- Air temperature
- Wind speed and direction

<u>2 m above ground</u>

- Air temperature
- Relative humidity
- Global solar radiation

<u>1 m above ground</u>

- Precipitation/Rainfall

In 2008, the structure of the meteorological tower was renewed and new a meteorology station, made by Slovenian company AMES, was put into operation (Figure 2).

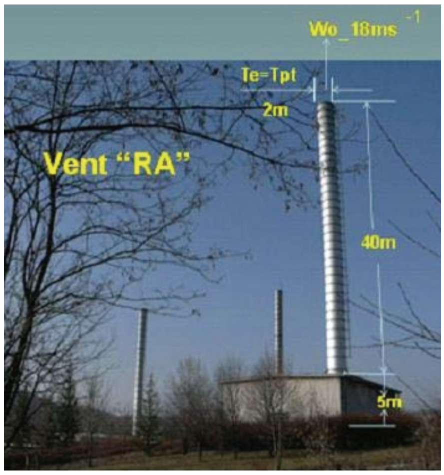

Figure 1. Ventilation stack of the reactor RA.

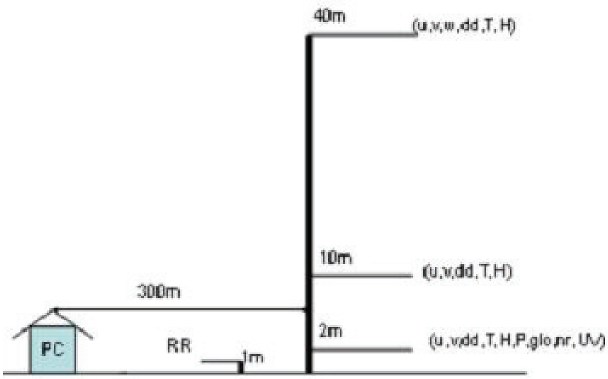

Figure 2. Scheme of measurements at meteorological tower in NFS in Vinča, AMES Ljubljana.

u,v,w-components of the wind vector
dd-wind direction [°]
ww-wind speed [m s^{-1}]
T-air temperature [°C]
H-relative humidity [%]
P-air pressure [h Pa]
Glo-global sun radiation [W m^{-2}]
Nr-net radiation [W m^{-2}]
RR-precipitation/rainfall [l m^{-2}]
PC-computational room

Data from the station is recorded every minute or ten-minutes, to a file automatically created for each new minute or ten-minute data set, in the format shown in the example below:

1211080835 15.5 95.5 734 321 7.3 313 3.1 22.1 10.1 323 24.9 15.4 343 1.5 -1.2345E-06 4

where **1211080835** day, month, year, hour, minute (two numbers each), **15.5** temperature (at 2 m above the ground), **95.5** relative humidity (at 2 m), **734** global solar radiation (at 2 m), **321** NR (net radiation) (at 2 m), **7.3** wind speed (at 2m), **313** wind direction (at 2 m), **3.1** precipitation/rainfall (at 1 m), **22.1** temperature (at 10 m), **10.1** wind speed (at 10 m), **323** wind direction (at 10 m), **24.9** temperature (at 40 m), **15.4** wind speed (at 40 m), **343** wind direction (at 40 m), **1.5** vertical component of wind speed (at 40 m), **-1.2345E-06** Monin Obukhov length, **4** stability class.

Modeling environmental effects of reactor RA

In The Public Company for Nuclear Facilities of Serbia (NFS), we established a meteorological program that depends on the computer codes we developed for modeling dispersion of pollutants in the atmospheric boundary layer and it is primarily based on measurements done with automatic meteorological station on the meteorological tower.

We also established a program for classical measurements and observations for the computer code for routine work, based on the Gaussian model of atmospheric diffusion and on the Pasquill original theory [7,8]. This program provides basic meteorological input data for every hour of meteorological measurements and observations: cloudiness in total and by type, predominant cloud base height, wind speed and direction at a height of 10 m above the ground, and precipitation. Insolation for each one-hour term and the beginning of the day and night (sunrise and sunset for any location sources) are determined by the computer code we developed based on spherical trigonometry equations that define the relationship between coordinates of the Sun in the horizon and equatorial coordinate astronomical system. The basic program for meteorological measurements and observations in PC NFS serves as a backup system and is used when the automatic weather station is out of service.

In this paper, we used meteorological program based on measurements obtained from automatic meteorological station which, among other benefits, allows fast determination of stability class at Turner's scheme, practically in real-time, and allows just as fast access to the values of σ_z and σ_y. The integral part of the automatic station is our own computer code based on the well-known equation of Gaussian straight line plume model [7-14]:

$$C(x,y,z)=\frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\times \left\{\exp\left[-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right]+\exp\left[-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right]\right\} \quad (1)$$

where *C (x, y, z)* is concentration of pollutants at the point (x, y, z), *Q* strength source (emission rate) (kg s^{-1}, Bqs^{-1}...), σ_z standard deviation of the Gaussian cloud in the direction of *z* axis, which define its dimensions in terms of time *t* or distance downwind. $x = ut$, (m), σ_y standard deviation of the Gaussian plume in the direction of y-axis (m), *H* the effective source height (m), *u* wind speed at effective source height (m s^{-1}).

Initial information, in addition to the above-mentioned meteorological data, is the emission of activity/radionuclides per unit of time (source strength, *Q*) and duration of releases. Monitoring of activity releases at the exit of chimney ventilation should provide this input data to the mathematical model, but at the institute Vinča this data could not be obtained. Because of the inability to acquire adequate data on the inventory of radionuclides during routine operation of the reactor, RA in NI Vinča, we used publicly available data on the assumed annual emissions of radionuclides into the atmosphere from Brookhaven National Laboratory, USA [15] (Table 1).

Table 1. Supposed power source based on Brookhaven National Laboratory (1997)

Nuclide	Ar41	Al26	As76	Ba128	Ba140	Br82	Ce141
Emission, Bq/y	8.2×10^{13}	4.5×10^{2}	1.7×10^{7}	6.9×10^{6}	5.8×10^{6}	3.2×10^{8}	6.7×10^{3}
Nuclide	Ce144	Co60	Fe59	Hg203	I124	I131	I133
Emission, Bq/y	5.3×10^{4}	9.8×10^{4}	1.4×10^{5}	2.2×10^{6}	7.0×10^{5}	1.2×10^{6}	1.3×10^{7}
Nuclide	La140	Mo99	Na24	Sb122	Sc46	Se75	Sr91
Emission, Bq/y	3.0×10^{7}	5.7×10^{3}	8.5×10^{6}	1.8×10^{4}	7.9×10^{2}	7.5×10^{3}	1.2×10^{7}
Nuclide	Tc99m	Ti44	Xe133	Xe135	Zn65	Zn69m	
Emission, Bq/y	2.2×10^{6}	4.8×10^{6}	3.8×10^{6}	4.0×10^{7}	7.2×10^{5}	5.3×10^{4}	

Along with the given emission data, we used the available data on the properties of the RA reactor ventilation, data from automatic weather station with meteorological sensors placed on tower near the reactor RA, 3D topography of the area around the Institute Vinča, the physical properties of pollutants and dose factors (dose conversion factors) available from international publications, ICRP (1990), ICRP (1991), ICRP (2007), ICRP (1991b), EPA (1993), IAEA (1996), IAEA (2000), Health Canada (1999), Council Directive 96/29/(1996) [16-24], etc.

This paper started from the conservative assumptions that the emission of radionuclides in the atmospheric boundary layer was continuous - 24 h a day, 365 days a year, and that the hypothetical resident was continuously exposed to radiation throughout the year, by inhalation, radiation from dry and wet deposition of radionuclides on the ground, and by staying in a "radioactive cloud".

RESULTS

Results of the mathematical modeling of the dispersion of radionuclides through the atmospheric boundary layer are the fields of mean annual activity 1 m above the ground, fields of annual activity of dry and wet deposition and the fields of total annual dose to a hypothetical inhabitant of the selected computational domain.

Fields of annual averages of air activity concentrations in the five years periods 2001-2005 and 2009

Emitted radionuclides carry activity, which represents the number of decays per sec (Bq). Initial activity at the source, depending on the radionuclides half-life, changes with time and with distance from the source to calculating point. Fields of annual averages of concentration of activities, obtained by the presented emission of radionuclides, taking into account characteristics of sources, weather conditions and soil characteristics are shown graphically in Figure 3.

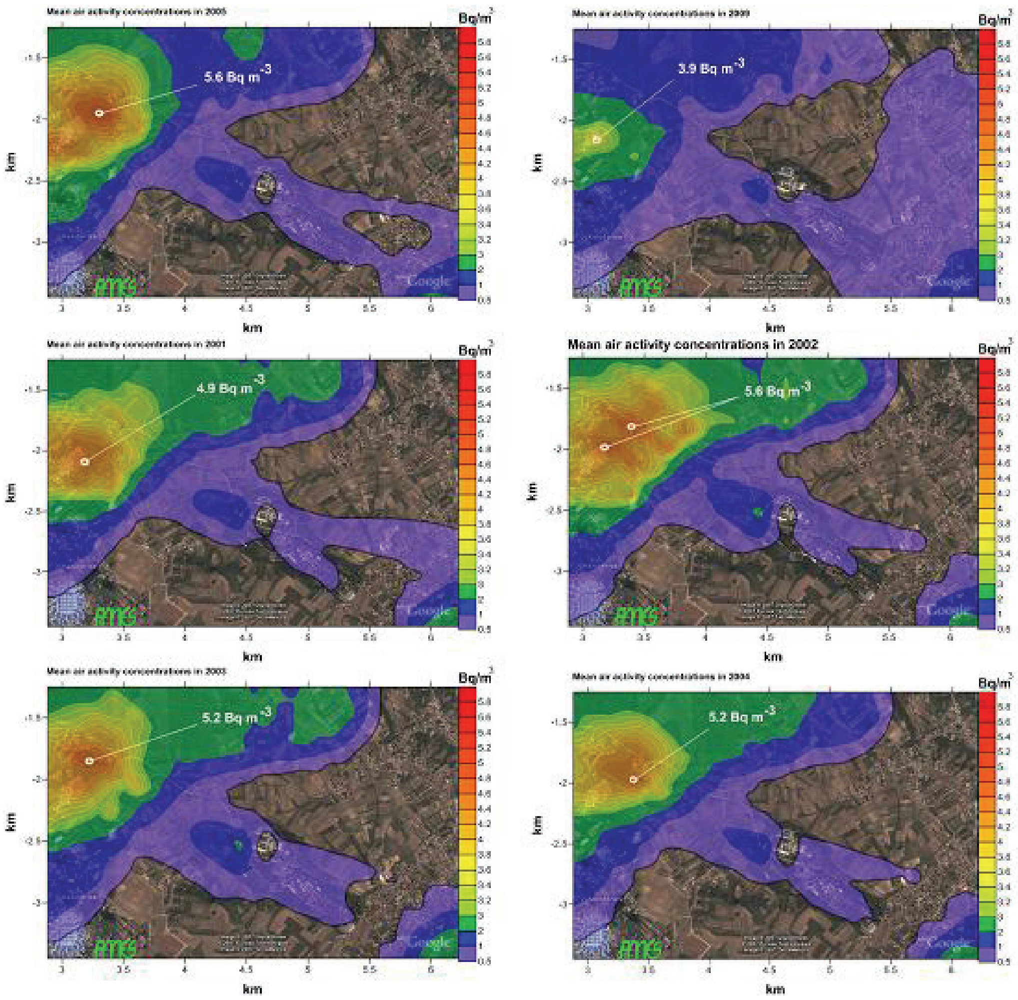

Figure 3. Fields of average annual concentration activity for assumed annual emission of radionuclides in period 2001-2005 and 2009.

The areal maximum values of annual averages of activity concentration in the air, 2 m above the ground, were in the range 3.9-6 Bq m^{-3}.

Fields of annual dry deposition of activity (2001-2005 and 2009)

Dry deposition was calculated from the activity concentrations in air, deposition rate for the selected terrain and the radionuclide emission inventory. Speed of dry deposition is obtained from the literature [23] and was based on the recommendation for the deposition rate of 0.008 m s^{-1}. Fields of dry deposition correspond to fields of activities concentration, both in shape and by zones with maximum values. Maximum annual values for dry deposition of activities for the selected period 2001-2005, and 2009 are in the interval 12-17 kBq m^{-2} (Figure 4).

Fields of annual wet deposition of activity (2001-2005 and 2009)

Wet deposition is calculated as washing with precipitation. The intensity of rainfall was measured by an automatic station every ten minutes. Fields of annual activities of wet deposition are calculated based on the activity distribution in a radioactive cloud and on the intensity of rainfall. Maximum values for wet deposition vary in the interval 120-630 Bq m^{-2} (Figure 5).

Dose

Doses are calculated by the algorithm in accordance with IAEA recommendations IAEA (2013) [24] based on dose conversion factors (Table 2).

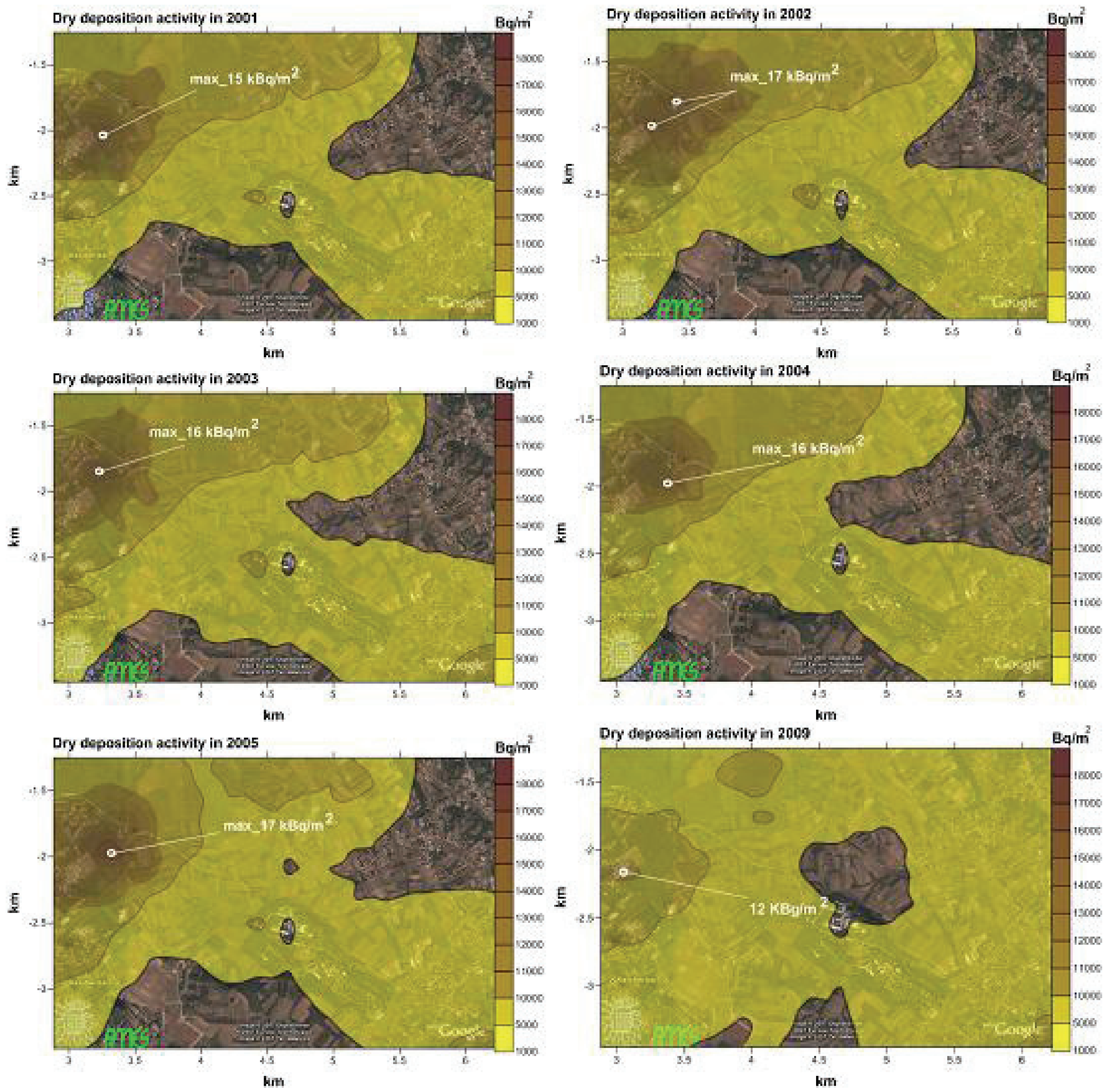

Figure 4. Dry deposition of activity (2001-2005 and 2009).

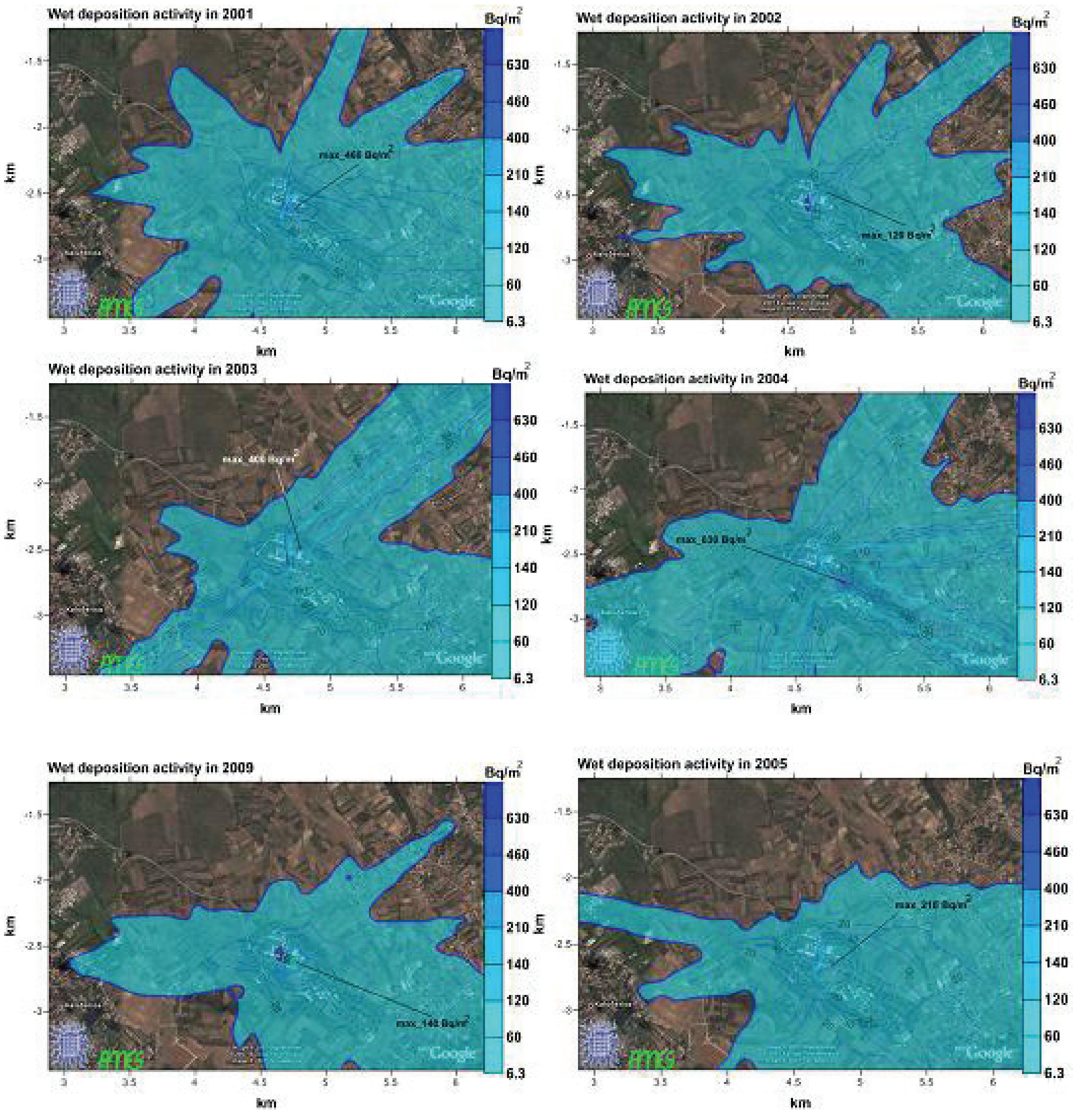

Figure 5. Wet deposition of activity (2001-2005 and 2009).

Table 2. Densities, dose coefficients for the adult population, time constants for radionuclides

Radionuclide	Density, g/cm^3	$g_{inh}\times10^9$ / Sv Bq^{-1}	$g_{obl}\times10^{14}$ / Sv·m^3 (Bq·s)$^{-1}$	$g_{dep}\times10^{16}$ / Sv·m^2 (Bq·s)$^{-1}$	$t_{1/2}$
Ar41	1.784	0	6.13	0	1.8 h
Al26	2.702	12	12.8	24.7	7.2×10^{5} y
As76	5.72	0.92	2.06	5.24	2.43 d
Ba128	3.51	0	0.254	0.678	12.8 d
Ba140	3.51	0	0.807	1.90	35 h
Br82	3.119	0	12.1	24.8	32.5 d
Ce141	6.77	3.2	0.310	0.693	284 d
Ce144	6.77	36	0.0763	0.184	5.27 y
Co60	8.9	10	11.9	23.0	44.5 d
Fe59	7.874	3.7	0.562	11.0	46 d
Hg203	13.456	2.4	1.04	2.22	4.2 d
I124	4.933	0	5.04	10.4	8.04 d
I131	4.933	0	1.69	3.64	20.8 h
I133	4.933	0	2.76	6.17	1.68 d

Table 2. Continued

Radionuclide	Density, g/cm^3	$g_{inh}\times10^9$ / Sv Bq^{-1}	$g_{obl}\times10^{14}$ / Sv·m^3 (Bq·s)$^{-1}$	$g_{dep}\times10^{16}$ / Sv·m^2 (Bq·s)$^{-1}$	$t_{1/2}$
La140	6.7	0	11.1	21.6	40 h
Mo99	10.289	0.89	0.699	1.78	66 h
Na24	0.971	0.27	2.08	35.9	15 h
Sb122	6.684	1.0	2.02	4.85	2.7 d
Sc46	2.989	0	9.36	18.8	83.6 d
Se75	4.79	1.1	1.68	3.61	119 d
Sr91	2.54	0	3.27	7.27	9.5 h
Tc99m	11.5	0.019	5.25	1.14	6.02 h
Ti44	4.549	0	0.470	1.18	47.3 y
Xe133	5.897	0	0.139	0	5.27 d
Xe135	5.897	0	1.11	0	9.1 h
Zn65	7.133	1.6	2.72	5.41	244 d
Zn69m	7.133	-	1.84	3.98	13.8 h

Inhalation dose

Inhalation dose is calculated from speed of breathing, activity concentrations in the air and appropriate inhalation dose conversion coefficients [24]:

$$D_{inh} = g_{inh} C(x,y,z,t) V_{br} \tag{2}$$

where: g_{inh} is inhalation dose coefficient for radionuclide observed (Sv Bq^{-1}), $C(x,y,z,t)$ activity concentration in the air (Bqm^{-3}) and V_{br} speed of breathing air (3.33×10^{-4} m^3 s^{-1}).

Dose of the cloud (immersion)

The dose from external radiation of observer wrapped with radioactive cloud, formed in accidental situations, is calculated according to the relation [24]:

$$D_{obl} = g_{obl,r}\, C(x,y,z,t) \tag{3}$$

where : $g_{obl,r}$ is the coefficient of dose from external radiation from radionuclides clouds, r (Sv·m^3 Bq^{-1}·s^{-1}).

A dose of dry and wet deposition

External radiation dose from the total radioactivity deposited on the ground that hypothetical inhabitant receives from age 18 until age 70 is calculated according to the model [24]:

$$D_{dtot} = \left[(1-\vartheta) g_{b,r}^{>17a} + (1-\vartheta^{52}) b g_{b,r}^{>17a}\right]\times \times\frac{1}{\lambda_r}\left(Dry_{dep,r} + Wet_{dep,r}\right) \tag{4}$$

$$\vartheta = \exp(-\lambda_r t_1) \tag{5}$$

where: t_1 is time period 1 year (s), λ_r coefficient for radionuclide dissolution r (s^{-1}), $g_{b,r}^{\rangle 17a}$ dose deposition coefficient for the resident older than 17 years for the radionuclide r (Sv·m^{3}Bq^{-1}·s^{-1}), $Dry_{dep,r}$ dry radionuclide deposition r (Bq m^{-2}), $Wet_{dep,r}$ wet radionuclide deposition r (Bq m^{-2}), b dimensionless coefficient.

Fields of annual radiation dose for a hypothetical resident are calculated from inhalation, dose of staying in radioactive cloud (dose of immersion) and a dose of radioactive material deposited on the ground in the form of dry and wet deposition. Total annual dose is calculated as sum of the doses listed above. The model is started for each year separately. Limit value of total annual dose coming from artificial sources shall not exceed 1% of the annual dose limit received by a resident from natural background sources, which is 1 mSv a year. This way, the contribution of artificial sources to total annual dose should not be greater than 10^{-5} Sv or 10 μSv. Total annual dose to a hypothetical resident around nuclear reactor RA for the assumed, hypothetical radionuclides emission were in the range of 9.4–11 μSv. On two occasions, in 2002 and 2005, these values were 10 % larger than the limit values for artificial sources (10 μSv), *i.e.*, they were 11 μSv.

Inhalation doses were calculated from the volume of breathing rate, exposure time, inhalation dose coefficients (dose conversion factor) and activity concentration of each radionuclide from the emissions inventory. Exposure time was equivalent of the annual or monthly period for which the doses are calculated, at the speed breathing air for a grown man, to 3.33×10^{-4} m^3 s^{-1}.

External radiation dose received by the observer at the ground, which is immersed in a cloud of radionuclide/activities for observed monthly and annual periods, is proportional to the activity concentration in the air near ground, the exposure time and the corresponding dose coefficients for radionuclides present in the cloud.

The total annual dose

The total annual doses are the sum of the inhalation dose, dose from clouds and dose of dry and wet deposition (Figure 6).

DISCUSSION

For environmental impact assessment of the reactor RA in routine practice, at short distances from the source, we used the most commonly applied mathematical model for this type of analysis – the Gaussian straight-line diffusion model. The advantage of mathematical models is that they can give results on a very dense network of points in the chosen domain. The results are given in the form of fields of concentrations of activity in the air, fields of activity due to dry/wet deposition of radionuclides or fields of the doses received by the real or hypothetical resident in the vicinity of the source. Another good property of mathematical models is that they can also asses impact to the environment for a large number of combinations of variable meteorological parameters in the atmospheric boundary layer with a large number of radio-nuclides, and a large number of 3D topography points for certain computational domain. In the paper we used a six-year series of ten-minute meteorological data, 3D topography of the terrain with marked populated areas and presented inventory of radionuclides, to assess the impact of the reactor RA on environment.

The reactor is placed on a slightly hilly terrain, which results in a specific microclimate of the site.

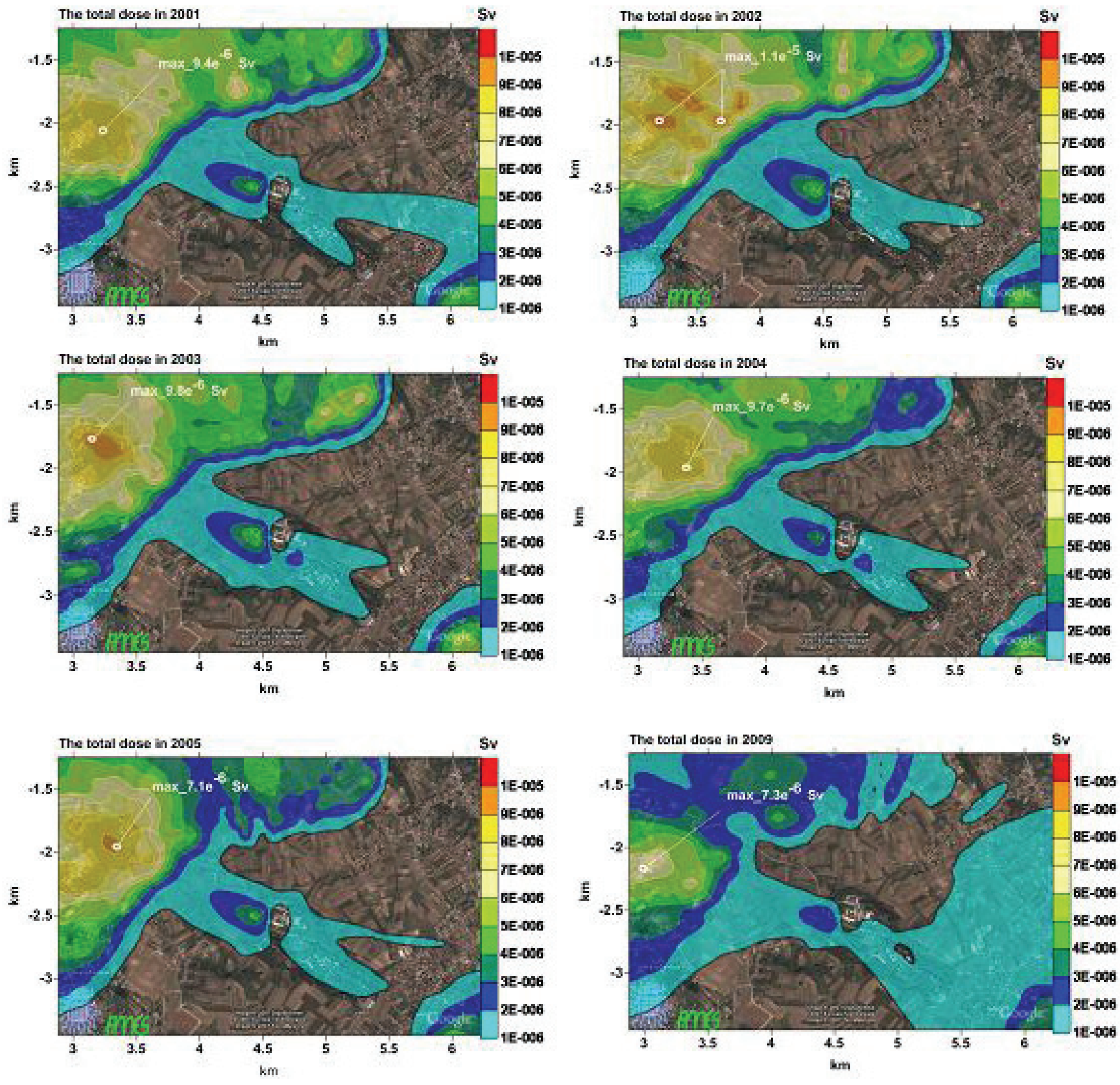

Figure 6. Fields of total annual dose of internal (inhalation) and external radiation (immersion and groundshine), for assumed emission activity/radionuclides, in period 2001-2005 and 2009.

Night weather condition is characterized by high frequency of appearance of clear weather and wind speed below 2 ms^{-1}. In the Pasquill-Gifford classification of atmospheric stability, this phenomenon is known as stable atmosphere, *i.e.*, class stability F. According to the Wittek theory [25], Gaussian-type mathematical model for atmospheric diffusion at distances up to 10 km from the source, can be used on these types of terrain.

The ventilation exhaust of the reactor RA in routine practice is treated as a cold source. This means that the temperature of the emitted gases and particles at the top of the stack is equal to the ambient air temperature. Result of modeling with the frequent occurrence of stability class F characterized by wind speeds below 2 m s^{-1}, was the expected geometry of fields of activity concentration in the air, as well as the geometry of the fields of the dose received by the hypothetical adult resident. Maximum annual concentration of activities and doses, and their spatial distribution, are mostly influenced by the strength of source, microclimate of location, frequency of direction and wind speed, frequency of F-class stability, and topography.

In a stable atmosphere, the plume of the activities carried by the wind is spread out horizontally from the vent, and when reaches an obstacle passes it at low altitude [25], which causes high concentrations of activity in the soil.

For all the above-mentioned reasons, zones with maximum activity concentration in the air and maximum values of dry deposition are consistent with the tops of the hills surrounding the ventilation chimney RA.

Maximum aerial values of the mean annual concentration in air at the height 2 m above the ground after prolonged routine emissions, ranging from 3.9 to 5.6 Bq m^{-3} may be compared, as a result of chronic exposure scenario, with exposure to natural radon outdoor concentrations which ranges up to 57 Bq m^{-3}, according to survey results [26].

Similar chronic exposure scenario for the population in Serbia may be result of widespread global dispersion of radionuclides due to distant nuclear accidents such as ones that have happened in Chernobyl and Fukushima. Comparing published results of contamination monitoring after Fukushima accident obtained in Serbia [27] and in neighbouring regions [28,29] which are up to 2.7±0.1 mBq m^{-3} in Serbia [27], in Greece 0.497 mBq m^{-3} [28] and 1.2 mBq m^{-3} in Austria [29] it may be concluded that the influence of routine emissions from a nuclear facility is the most significant exposure scenario in chronic exposure situations. In the case of research reactor RA, this contribution to population exposure is still significantly lower than contribution of natural radon exposure levels.

CONCLUSION

Gaussian straight line model of atmospheric diffusion, with modules for deposition (dry, wet) and the dose, was used to analyse the impact of the reactor RA on the environment during operation in Vinča, near Belgrade, due to assumed operational releases.

Maximum values for the mean annual concentration in air at the hight 2 m above the ground and for annual activities of dry and wet deposition, were in the range of:

3.9 to 5.6 Bq m^{-3}, 2 m above ground in the air,
12 to 17 kBq m^{-2}, dry deposition and
120 to 630 Bq m^{-2}, wet deposition.

The total annual dose that would be received by hypothetical resident in the vicinity of RA through the air was estimated from dose factors for the inventory of radionuclides. Maximum values for total annual doses had values between 7.3 and 11 μSv.

In addition to very conservative assumptions, assuming that the meteorological data from six years period is appropriate for this type of analysis, it can be concluded that the nuclear reactor RA, during its work from 1962–1982, could not have impacted the environment through the air above the prescribed limit of 10 μSv/year [6]. This limit is a one of the criteria for the assessment of nuclear safety of nuclear facility for regular operation. Another criteria, the prescribed limit for accidental conditions, with the probability of occurrence ones in lifetime of the facility, is 5 mSv. Various scenarios can be used for the assessment of the consequences of accidental releases, and obtained results are dependent on reactor construction and inventory as well. Due to diversities in circumstances it is difficult to directly compare results of the assessments for different reactors and different scenarios. However, it can be concluded that the environmental impact of routine emissions is three orders of magnitude lower than in the case of accidental releases [30].

Acknowledgments

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NAUČNI RAD

PROCENA UTICAJA NA OKOLINU NUKLEARNOG REAKTORA U VINČI NA OSNOVU PODATAKA O EMISIJI RADIOAKTIVNOSTI IZ LITERATURE – MODELSKI PRISTUP

Deo istraživanja u Institutu Vinča zasnivao se na dva teškovodna istraživačka reaktora od 10 MW RA i nulte snage RB. Reaktor RA je bio u funkciji od 1962. do 1982. U 2010. godini istrošeno gorivo je poslato u zemlju porekla (Rusija), a reaktoru predstoji faza dekomisije. Tokom operativnog rada reaktora nije bilo akcidentalnih emisija radioaktivnosti u životnu sredinu. U radu su prikazani rezultati procene uticaja na okolinu nuklearnog reaktora RA u Vinči, za pretpostavljenu emisiju radionuklida (literaturni podatak) u granični sloj atmosfere preko ventilacije reaktora. Za procenu je primenjen Gausov pravolinijski model dimne perjanice sa karakteristikama reaktorskog ventilacionog sistema, sa šestogodišnjim nizom časovnih meteoroloških podataka na lokaciji reaktora RA, lokalnom topografijom terena oko reaktora i odgovarajućim doznim faktorima za radionuklide iz korišćenog inventara o emisiji u atmosferu. Na osnovu navedenih pretpostavki o emisiji radionuklida, primenom opisanog difuzionog modela, sa nizom časovnih meteoroločkih podataka, dovoljnim za ovakvu vrstu analiza, u radu je zaključeno da nuklearni reaktor RA u periodu od 1962. do 1982, preko vazduha nije uticao na svoju okolinu iznad propisanih granica.

Ključne reči: uticaj na okolinu, procena, nuklearni, reaktor, model.