ENVIRONMENTAL RELEASES OF RADIOACTIVITY AND THE INCIDENCE OF THYROID DISEASE AT THE IGNALINA NUCLEAR POWER PLANT

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Abstract – The Ignalina Nuclear Power Plant (Ignalina NPP) consists of two Russian-made RBMK-1500 reactors. The plant uses Lake Druksiai as a natural reservoir for cooling water. Within the framework of the revised radiation dose limitation system (IAEA), site-specific routine release conversion factors and maximum annual effective doses for the dominant radionuclides and pathways were evaluated for both atmospheric and aquatic releases. Using calculated release conversion factors, the locations of the highest predicted activity concentrations were determined for air and for the dilution zone of heated effluent water during the period 1984-1998. Committed effective doses for critical group members were less than 0.001 mSv for Ignalina NPP airborne releases and less than 0.05 mSv for aquatic releases. These dose estimates are lower than the 1 mSv dose limit for the adjacent population. In the case of Ignalina NPP, taking into account the uncertainties, a recommendation for the administrative dose constraint is 0.25 mSv y^{-1}. This dose level may scarcely affect human health. Interestingly, during screening for thyroid disorders, endocrinologists and pediatric-endocrinologists determined a dominance of abnormal thyroids (up to 60%) among school children in the vicinity of Ignalina NPP. The data on neonatal screening for congenital hypothyroidism and transient hyperthyrotropinemia, however, suggested a possibility that the majority of abnormal thyroid cases were related to stable iodine deficiency. Thus, the influence of Ignalina NPP on thyroid disorders is highly conjectural and unlikely to be associated with the observed levels of childhood thyroid disease.

Key words: nuclear power, release conversion factor, dose limits, radioiodine, thyroid pathology

INTRODUCTION

The Ignalina Nuclear Power Plant (Ignalina NPP) is located in northeastern Lithuania near the borders of Belarus and Latvia (inset of Fig.1). The plant consists of two RBMK-1500 reactors. (The Russian translation for RBMK is essentially "Channelled Large Power Reactor"). The first unit was put into operation in December 1983, and the second began operations in August 1987. The RBMK-1500 is a graphite moderated, channel-type, boiling water reactor. Its designed thermal rating is 4800 MW, however, for safety reasons, each reactor is currently being operated at a reduced capacity (a maximum thermal power of 4200 MW, Almenas et al. 1994).

The Plant uses Lake Druksiai as a natural reservoir for cooling water. The surface area and volume of the lake are 4.9×10^7 m^2 and 3.7×10^8 m^3, respectively. The maximum depth is 33 m while the average depth is 7.6 m. Lake Druksiai is a flow-through lake with six small creeks flowing in and one river, with a water regulation dam, flowing out.

This work involved the calculation of routine-release conversion factors and the estimation of maximum annual effective doses over all exposure pathways for the farmer and the fisherman critical receptors. The dose constraint is an upper limit of the annual dose that members of the public might receive from the planned operation of any controlled source. Following international recommendations (IAEA 1998), the existing method at Ignalina for routine release limitation (Methodical guidelines 1985) was revised. The development of a revised Ignalina NPP limitation system, for atmospheric and aquatic pathways, was initiated in 1997.

The relation of released radioiodine and the dominance of thyroid pathology among school children in the vicinity of the Ignalina NPP was also investigated (Ostrauskas et al. 1995).

METHODS

In the case of atmospheric releases, the nuclide-specific routine release conversion factors represent the ratio of the annual effective dose to a critical group member [Sv y^{-1}], at the location of the highest predicted radionuclide concentration in air, to the activity released from Ignalina NPP [Bq y^{-1}]. In the case of aquatic discharges, the highest radionuclide concentration is expected in the dilution zone of heated effluent water (Mazeika 1998). Thus, the radionuclide-specific release conversion factors and the annual effective doses were calculated for persons near this zone. Release conversion factors were estimated for two critical groups, different in their lifestyle and activities. These include farmers residing in the vicinity of Ignalina NPP, under the most unfavorable conditions, and fishermen in the dilution zone of Lake Druksiai.

Evaluation of atmospheric routine release conversion factors

The atmospheric dispersion model used in this investigation is the straight-line trajectory Gaussian plume model, which accounts for reflection from the earth's surface and from the top of the mixing layer. The model simulates quasi-continuous release, steady-state meteorological conditions and dispersion over flat, non-complex terrain. This model was used because it is relatively simple and because the results obtained for dispersion above a relatively flat surface do not differ significantly from the results of more complex models (Hosker, 1974). For calculation of annual-averaged air concentration $C_{p,i}(x)$ (Bq s^{-1}) at the height of 1 m above ground-level and across the resulting wind direction (sector p) at the distance x, the following Gaussian plume model solution was used:

$$C_{p,i}(x) = \sqrt{\frac{2}{\pi}}\,\frac{N_p Q_i}{2\pi x}\sum_{j=1}^{N_j}\frac{\exp\left(-h^2 / 2\sigma_{z,j}{}^2\right)}{\sigma_{z,j}}\sum_{k=1}^{N_k}F_{jk}(x)\frac{P_{pjk}}{u_k},$$

where

Q_I = annual average release rate for radionuclide i (Bq s^{-1});

N_p, N_k, N_j = number of wind direction sectors (16 cardinal directions), wind speed classes (10) and stability categories (6 Pasqull classes), respectively;

P_{pjk} = joint frequency of wind direction toward sector p, stability category j, and wind speed class k;

u_k = wind speed associated with wind speed class k (m s^{-1});

$\sigma_{z,j}$ = vertical diffusion coefficient (m) associated with stability category j; and

$F_{jk}(x)$ = activity reduction factor, at distance x, due to radioactive decay and wet/dry deposition.

Atmospheric stability classification follows the Pasquill-Turner method. The State-approved, long-term meteorological data (wind speed and direction, air temperature, cloudiness, cloud height and precipitation) from the nearest meteorological station with similar terrain (15 km from Ignalina NPP) were used from the period 1984 – 1997. Corrections were made for the influence of wind velocity at the stack height and plume rise. The radionuclide transfer factor in air $P_{air,i}$ (s m^{-3}) is calculated by $P_{air,i} = C_{p,i} / Q_i$.

The accumulation of radionuclides over a period of 40 years (the most probable time of Ignalina NPP operation) on an originally uncontaminated ground surface was taken into account. Radionuclide concentrations in agricultural and animal products, for the most unfavorable conditions, were calculated using a linear transfer model. The radionuclide independent (Table 1) and radionuclide dependent (Table 2) site-specific (Maceika and Tamulenaite, 1997) and generic (IAEA 1994; Simmonds et al. 1995) radionuclide transfer parameter values were used.

In the case of atmospheric releases, estimates of annual external and internal dose for the following exposure pathways were most significant for the farmer critical group: immersion in the plume, inhalation, external exposure from surface deposition, and ingestion of contaminated food. This critical group was assumed to reside in the most unfavorable conditions near the Ignalina NPP. External exposure in the plume and from contaminated soil surface was calculated using dose factors presented in Eckerman and Ryman (1993). Internal exposure from inhalation and ingestion was evaluated using the methodology of Simmons et al. (1995) and along with the appropriate dose factors (IAEA 1996; Basic Standards 1997).

Evaluation of aquatic routine release conversion factors

Radioactive substances from the NPP unavoidably enter the cooling reservoir, Lake Druksiai. Water containing radionuclides from the Ignalina NPP enters the lake through several outlets (Fig. 1). These effluents include both cooling and treated water.

The most important source of contamination of Lake Druksiai is cooling water. To cool the turbine condensers of the Ignalina NPP, water is pumped from the lake at a rate of up to 150 $m^3\ s^{-1}$. This water is then returned to Lake Druksiai through the channel. The majority of radioactive substances released from the plant (up to 98% of activity) enter Lake Druksiai with the cooling water. The contaminants that dominate offsite dose are ^{60}Co, ^{54}Mn and ^{137}Cs.

The concentration of radionuclide i in lake water $C_{w,i}$ can be described by a first-order linear differential equation. In the case of equilibrium conditions (when t is sufficiently large) this equation has the asymptotic solution:

$$C_{w,i} = \frac{Q_{w,i}}{V\Lambda_i},$$

where

$Q_{w,i}$ = radionuclide activity discharge rate (Bq y^{-1});

V = lake volume (m^3); and

Λ_i = water self-cleaning constant (y^{-1}).

If the radionuclide concentration in lake water is described using a two-compartment model (water and bottom sediments), a water self-cleaning constant may be evaluated as:

$$\Lambda_i = \lambda + \lambda_s + \lambda_{of},$$

where

λ = radionuclide decay constant;

λ_s = radionuclide transfer (with solid particles to bottom) constant; and

λ_{of} = water outflow constant.

The constant λ_s is defined by the following equation:

$$\lambda_s = \frac{K_d v_s}{(1 + K_d m_s)H},$$

where

K_d = radionuclide distribution coefficient between soluble and solid particles;

v_s = solid-particle sinking rate;

m_s = concentration of sinking particles; and

H = average lake depth.

The radionuclide independent parameter values are presented in Table 3. Desorption of radionuclides and resuspension of bottom sediments are temporarily neglected. However, resuspension, increasing the concentration of those radionuclides with a half-life exceeding 200 days, is taken into account (Motiejunas et al., 1999). The radionuclide transfer factor in water $P_{w,i}$ (a m^{-3}) is calculated by $P_{w,i} = C_{w,i} / Q_{w,i}$.

The radionuclide concentration in the cooling-water dilution zone exceeds that calculated for the whole volume of the lake. Under steady-state conditions the radionuclide concentration in the dilution zone is calculated considering only dilution and decay. Radionuclide dependent aquatic release transfer factors $P_{w,i}$, factors describing radionuclide concentration in the dilution zone, and factors for radionuclide transfer from water to the bank sediments are presented in Table 4 (Mazeika 1998).

In the Lake Druksiai system the concentration of long-lived radionuclides, primarily ^{137}Cs and ^{90}Sr, is influenced by globally distributed radionuclides due to atmospheric nuclear tests and the Chernobyl accident, as well as migration from the water catchment area. The research of Mazeika et al. (1998) indicates that the fraction of activity in the lake, due to discharges from the Ignalina NPP, is about 50% for ^{137}Cs and only 3% for ^{90}Sr.

In the case of aqueous releases, the annual effective dose to the fishermen critical group was determined via the following exposure pathways: immersion in the plume, inhalation, external exposure due to the accumulation of radionuclides on the lake shore, and ingestion of fish. Radiation doses to gardeners in small suburban gardens, situated close to Lake Druksiai and using its water for irrigation, were also estimated. For most radionuclides, the release conversion factors for exposure of fishermen is greater compared to exposure of gardeners.

RESULTS AND DISCUSSION

Revised limitation system parameter values

The Ignalina NPP site-specific atmospheric and aqueous release conversion factors, and maximum annual total effective doses for 1997, are presented in Table 5. Technical and organizational changes have been implemented over the past decade to improve the operational safety of Ignalina NPP. Partly, this has been done according to bilateral agreements with other countries (especially active is Sweden). Improvements in plant operation, without additional reactor down time, are principally responsible for the decreasing trend in release amounts over the past several years.

The concept of a 1 mSv annual dose limit for members of the public was set forth in the International and National Basic Safety Standards (IAEA 1996; Basic Standards 1997). According to the 1997 data presented in Table 5, the maximum annual effective dose to the critical group members is less than 0.001 mSv for Ignalina NPP airborne releases and less than 0.05 mSv for aquatic discharges. These values are far below the 1 mSv dose limit for the adjacent population. A comparison of doses from different sources of human exposure is presented in Fig. 2. Average radiation doses from the main sources of ionizing exposure in the vicinity of Ignalina NPP include natural background (2.4 mSv y^{-1}), medical exposures (0.48mSv y^{-1}) (Atkocius et al. 1995), and the INPP (0.05 mSv y^{-1} aquatic; 0.001 mSv y^{-1} atmospheric).

Thus, the annual average dose to the population from natural background and medical exposures (Atkocius et al. 1995) constitutes the major portion of annual radiation dose.

In setting the dose constraint near nuclear facilities, several factors must be taken into account, e.g., dose contributions from other sources and practices on a regional and global scale, changes in operational status, alternative exposure pathways, modification of critical groups, etc. Optimized discharge limits should never lead to source-related doses exceeding the dose limit. Many countries have already set maximum levels of individual exposure that effectively optimize protection from various sources (IAEA 1998). In the case of the Ignalina NPP, the recommended dose limit is 0.25 mSv y^{-1}, including both atmospheric and aqueous releases.

Thyroid disease in the vicinity of Ignalina NPP

The interest in health risks of the population around Ignalina NPP coincided with the building and licensing of this facility. Common to all studies of health effects near nuclear facilities is the debate whether the public health has been placed at risk and the quantification of that risk, especially in terms of radioiodine exposures. It is necessary to stress that the Ignalina NPP radioiodine-release value peaked at nearly 150 GBq y^{-1} in 1986 and has subsequently decreased to less than a few GBq y^{-1} since that time (Fig. 3).

The distribution of chronic doses to the infant thyroid (Fig. 4), performed using the LIETDOS computer code (Filistovic and Nedveckaite 1999) and specific dose assessment methods (Nedveckaite and Filistovic 1995), shows that thyroid doses in the Ignalina NPP region have been as small as a few μSv y^{-1}. The historical trends of infant, children, and adult thyroid equivalent doses are presented in Fig. 5.

The situation occurring in the town of Zarasai, located at a distance of 22 km from Ignalina NPP, is of special note. During the screening for thyroid disorders, endocrinologists and pediatric-endocrinologists determined a dominance of abnormal thyroids (up to 60%) among school children in Zarasai. However, levels in the town of Visaginas (located only 8 km west of Ignalina) were found to be consistent with levels throughout the country (Ostrauskas et al. 1995). First, it was assumed that thyroid diseases in Zarasai were attributable to the radioiodine released to the atmosphere by Ignalina NPP operations. Subsequent examination suggests, however, that the main reason for thyroid diseases in Zarasai can be related to stable iodine deficiency.

The European program of systematic screening for congenital hypothyroidism in the neonate (Delange et al. 1992) provided clear evidence that a moderate degree of iodine deficiency, although insufficient to induce endemic goiter or gross abnormalities of thyroid function in adults, could critically affect thyroid function and possibly brain development in the neonate. In 1994, the World Health Organization (WHO), the United Nations Children's Fund (UNICEF), and the International Council for Control of Iodine Deficiency Disorders (ICCIDD) jointly proposed the neonatal thyroid stimulating hormone to be one of the indicators for the iodine deficiency status. In the Human Genetics Centre of Vilnius University, neonatal screening for congenital hypothyroidism and transient hyperthyrotropinemia was based on the assessment of thyroid stimulating hormone in peripheral blood sampled during the first week of life (Kucinskas et al. 1996). The thyroid stimulating hormone concentration was estimated by means of immunoassay with fluorometric detection using "Labsystem" (Finland) kits. The most frequent thyroid abnormalities encountered were hyperplasia of the thyroid gland, autoimmune thyroiditis and uni- or multi-nodular goiters. Morphological abnormalities were investigated by means of palpation, thyroid ultrasonography and fine needle aspiration biopsy (FNAB). Blood samples were taken for determining thyroid stimulation hormone (TSH), free thyroxine (fT4), performed by radioimmunoassay *in vitro*, and the presence of thyroid microsomal antibodies. Results of the screening are convincing proof for the stable iodine deficiency level in Lithuania.

A total of 133,259 newborns were screened for congenital hypothyroidism and transient hyperthyrotropinemia from August 1993 to June 1998. The frequency of transient hyperthyrotropinemia cases in various districts of Lithuania varied from 0.0 to 43.4 per 10,000 newborns tested, the majority of which did not exceed 25 per 10,000. The district of Zarasai appeared to be distinguishable from other districts of Lithuania by the evidently greater frequency of cases (43.4 per 10,000 newborn tested). From this it is inferred that one of the peculiarities of Zarasai region is the highest iodine deficiency level in Lithuania. Thus, the great number of abnormal thyroids among school children in Zarasai, as compared with background thyroid disease levels in Visaginas, is connected with stable iodine deficiency, not releases of radioiodine from the Ignalina NPP.

CONCLUSIONS

Following international recommendations, the revised Ignalina NPP routine-release limitation system has been developed. The site-specific dose conversion factors were estimated for atmospheric and aquatic pathways separately. According to the calculations, the committed effective dose for all exposure pathways is less than 0.001 mSv for the farmer critical receptor and less than 0.05 mSv for the fisherman critical receptor, i.e., below the 1 mSv dose limit imposed on the adjacent population (IAEA). Almost without exception, the foodchain and external (ground) pathways dominate total dose. External (cloud) exposure was dominant for noble gases. In the case of Ignalina NPP, the recommended administrative dose limit should be established at a value of 0.25 mSv y^{-1}.

The data demonstrate that a great number of cases of hyperthyroidism among school children in the vicinity of the Ignalina NPP, namely in the Zarasai region, were associated with stable iodine deficiency, and the influence of Ignalina NPP radioiodine releases are insignificant. This conclusion is based on an investigation of the neonatal thyroid stimulating hormone and the frequency of transient hyperthyrotropinemia in Lithuania. It was shown that the district of Zarasai appeared to be distinguishable from other districts of Lithuania by the evidently greater frequency of transient hyperthyrotropinemia (43.4 per 10,000 newborn tested). The influence of Ignalina NPP on thyroid disorders is thus unlikely to be associated with the observed levels of childhood thyroid disease.

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Table 1. Radiouclide-independent atmospheric release parameter values (individual food consumption was based on data (Household Income 1998) obtained from the Lithuanian Department of Statistics).

Parameter definition	Parameter value
Stacks height (m)	150
Thickness of root zone (m):	
Food crops,	0.3
Grass.	0.15
Bulk density of root zone soil (kg m^{-3})	1.46×10^{3}
Dry deposition velocities (m s^{-1}):	
Elementary iodine,	1.0×10^{-2}
Organically bounded iodine,	1.0×10^{-4}
Aerosols.	1.5×10^{-3}
Washout coefficients (s^{-1}):	
Elementary iodine	7.0×10^{-5}
Organically bound iodine	7.0×10^{-7}
Aerosols.	7.0×10^{-5}
Yield (kg fw m^{-2}):	
Grains,	0.4
Potatoes,	3.0
Other root crops,	0.4
Leafy vegetables,	0.7
Fruits,	1.0
Grass.	0.65
Consumption rates (kg fw d^{-1}):	
Grains,	0.60
Potatoes,	0.74
Other root crops,	0.36
Leafy vegetables,	0.10
Fruits,	0.15
Eggs,	0.13
Milk (L d^{-1}),	2.58
Meat (kg d^{-1}),	0.52
Freshwater fish (kg d^{-1}).	0.06
Inhalation rate (m^{3} d^{-1})	22.4

Table 2. Radionuclide-depended atmospheric release parameter values.

Nuclide	Partition coefficient of radionuclide in root zone soils ($m^3\ kg^{-1}$)		The accumulation (over a period of 40 years) factors of radionuclides in soils ($s\ kg^{-1}$)		Transfer coefficient for cow milk ($d\ L^{-1}$)	Transfer coefficients for beef ($d\ kg^{-1}$)
	Sand	Loam	Sand	Loam		
^{3}H	-	-	-	-	112.5[a]	87.5[a]
^{14}C	-	-	-	-	267.0[a]	800.0[a]
^{51}Cr	6.7×10^{-2}	3.0×10^{-2}	3.8×10^{-3}	3.8×10^{-3}	1.0×10^{-5}	9.0×10^{-3}
^{54}Mn	4.9×10^{-2}	7.2×10^{-1}	4.2×10^{0}	4.3×10^{0}	3.0×10^{-5}	5.0×10^{-4}
^{59}Fe	2.2×10^{-1}	8.1×10^{-1}	6.3×10^{-1}	6.3×10^{-1}	3.0×10^{-5}	2.0×10^{-2}
^{58}Co	6.0×10^{-2}	1.3×10^{0}	9.8×10^{-1}	9.3×10^{-1}	1.0×10^{-3}	1.3×10^{-2}
^{60}Co	6.0×10^{-2}	1.3×10^{0}	2.3×10^{1}	2.7×10^{1}	1.0×10^{-3}	1.3×10^{-2}
^{89}Sr	1.3×10^{-2}	2.0×10^{-1}	6.8×10^{-1}	7.0×10^{-1}	2.8×10^{-3}	8.0×10^{-3}
^{90}Sr	1.3×10^{-2}	2.0×10^{-1}	3.3×10^{1}	1.2×10^{2}	2.8×10^{-3}	8.0×10^{-3}
^{95}Zr	6.0×10^{-1}	2.2×10^{0}	9.1×10^{-1}	9.1×10^{-1}	5.5×10^{-7}	1.0×10^{-6}
^{95}Nb	1.6×10^{-1}	5.4×10^{-1}	4.8×10^{-1}	4.8×10^{-1}	4.1×10^{-7}	3.0×10^{-7}
$^{99}Mo/^{99m}Te$	7.4×10^{-3}	1.3×10^{-1}	3.8×10^{-2}	3.8×10^{-2}	1.7×10^{-3}	1.0×10^{-3}
^{131}I	1.0×10^{-3}	4.5×10^{-3}	2.8×10^{-1}	2.8×10^{-1}	1.0×10^{-2}	4.0×10^{-2}
^{132}I	1.0×10^{-3}	4.5×10^{-3}	3.2×10^{-3}	3.2×10^{-3}	1.0×10^{-2}	4.0×10^{-2}
^{133}I	1.0×10^{-3}	4.5×10^{-3}	3.0×10^{-2}	3.0×10^{-2}	1.0×10^{-2}	4.0×10^{-2}
^{134}Cs	2.7×10^{-1}	4.4×10^{0}	1.0×10^{1}	1.1×10^{1}	7.9×10^{-3}	5.0×10^{-2}
$^{137}Cs/^{137m}Ba$	2.7×10^{-1}	4.4×10^{0}	1.3×10^{2}	1.5×10^{2}	7.9×10^{-3}	5.0×10^{-2}

[a] – in $Bq\ kg^{-1}$ per $Bq\ m^{-3}$ (air conc.) (Simmonds at al, 1995)

Table 3. Radionuclide-independent aquatic release main parameter values.

Parameter definition	Mean value
Lake water volume (m^3)	$3.69x10^8$
Average depth of the lake (m)	7.6
Water outflow from lake (m^3 y^{-1}):	
Average,	$9.4x10^7$
Maximal.	$1.6x10^8$
Particles sinking rate (kg m^{-2} y^{-1})	0.4
Concentration of particles (kg m^{-3})	0.002
Water volume in dilution zone (m^3)	$1.5x10^7$
Flow of heated water (m^3 s^{-1})	70
Amount of fish consumed per year (kg)	100
Time spent fishing (hr y^{-1})	1500
Irrigation (m^3 y^{-1})	300
Resuspension factor (m^{-1})	$1x10^6$
Time spent in watered territory (hr y^{-1})	4500
Time of watering season (d y^{-1})	110
Time spent on the bank (hr y^{-1})	1500
Amount of precipitation (mm y^{-1})	640
Silt accumulated on flooded soil (kg m^2 y^{-1})	0.5

Table 4. Radionuclide-dependent aquatic release parameter values.

Nuclide	Radionuclide Partition coefficient (m^3 kg^{-1})	Concentration factors for freshwater fish (L kg^{-1})	Radionuclide transfer into water (Bq m^{-3})/(Bq y^{-1})	Radionuclide concentration in the dilution zone (Bq m^{-3})/(Bq y^{-1})	Radionuclide transfer from water to the bank sediments (Bq m^{-2})/(Bq m^{-3})
^{3}H	0.0003	0.9	$8.7x10^{-9}$	$4.5x10^{-10}$	$4.8x10^{0}$
^{14}C	2	4550	$7.5x10^{-9}$	$4.5x10^{-10}$	$1.2x10^{1}$
^{51}Cr	20	40	$2.6x10^{-10}$	$4.3x10^{-10}$	$3.3x10^{-2}$
^{54}Mn	50	100	$7.9x10^{-10}$	$4.5x10^{-10}$	$3.7x10^{-1}$
^{59}Fe	10	100	$4.3x10^{-10}$	$4.4x10^{-10}$	$5.5x10^{-2}$
^{58}Co	20	300	$5.6x10^{-10}$	$4.4x10^{-10}$	$8.4x10^{-2}$
^{60}Co	20	300	$1.9x10^{-9}$	$4.5x10^{-10}$	$2.3x10^{0}$
^{89}Sr	2	60	$5.0x10^{-10}$	$4.4x10^{-10}$	$5.9x10^{-2}$
^{90}Sr	2	60	$7.1x10^{-9}$	$4.5x10^{-10}$	$7.7x10^{0}$
^{95}Zr	60	3.3	$3.9x10^{-10}$	$4.4x10^{-10}$	$7.6x10^{-2}$
^{95}Nb	0.1	30000	$3.6x10^{-10}$	$4.3x10^{-10}$	$4.1x10^{-2}$
^{131}I	0.3	200	$8.5x10^{-11}$	$3.7x10^{-10}$	$9.5x10^{-3}$
^{134}Cs	80*	2000	$6.5x10^{-10}$	$4.5x10^{-10}$	$8.9x10^{-1}$
^{137}Cs/^{137m}Ba	80*	2000	$6.9x10^{-10}$	$4.5x10^{-10}$	$7.8x10^{0}$

* estimated ***in situ*** (Mazeika, 1998); others K_d and B_F - generic

Table 5. Site-specific routine release conversion factors estimated for the farmer (airborne release) and fishermen (aquatic release) critical groups, and calculated maximum annual effective dose due to releases from Ignalina NPP.

Release pathway	Nuclide	Release conversion factor, Sv/Bq	Dominating pathways	Released activities and doses (1997 data values)	
				Released activity, Bq	Dose, Sv
Atmospheric	$^{3}H^{a}$	$6.7x10^{-22}$	Food chain, inhalation	$5.2x10^{11}$	$3.5x10^{-10}$
	$^{14}C^{a}$	$1.8x10^{-19}$	Food chain	$4.0x10^{11}$	$7.2x10^{-8}$
	$^{41}Ar^{b}$	$1.0x10^{-21}$	External (cloud)	$2.8x10^{8}$	$2.8x10^{-13}$
	^{51}Cr	$1.6x10^{-20}$	Food chain, external (ground)	$1.9x10^{7}$	$3.0x10^{-13}$
	^{54}Mn	$3.2x10^{-18}$	External (ground)	$4.6x10^{8}$	$1.5x10^{-9}$
	^{59}Fe	$1.3x10^{-18}$	Food chain, external (ground)	$5.9x10^{6}$	$7.7x10^{-12}$
	^{58}Co	$1.1x10^{-18}$	Food chain, external (ground)	-	-
	^{60}Co	$5.7x10^{-17}$	External (ground)	$2.1x10^{9}$	$1.2x10^{-7}$
	^{89}Sr	$1.2x10^{-18}$	Food chain	$3.2x10^{8}$	$3.9x10^{-10}$
	^{90}Sr	$7.0x10^{-17}$	Food chain	$1.5x10^{7}$	$1.0x10^{-9}$
	^{95}Zr	$6.4x10^{-19}$	External (ground)	$7.8x10^{7}$	$5.0x10^{-11}$
	^{95}Nb	$3.6x10^{-19}$	External (ground)	$2.6x10^{8}$	$9.3x10^{-11}$
	$^{99}Mo/^{99m}Te$	$4.3x10^{-20}$	Food chain	$7.0x10^{6}$	$3.0x10^{-13}$
	^{131}I	$5.6x10^{-17}$	Food chain	$6.0x10^{9}$	$3.4x10^{-7}$
	^{132}I	$2.4x10^{-20}$	Food chain	$5.5x10^{6}$	$1.3x10^{-13}$
	^{133}I	$1.9x10^{-18}$	Food chain	$7.4x10^{7}$	$1.4x10^{-10}$
	^{134}Cs	$8.4x10^{-17}$	Food chain	$4.0x10^{7}$	$3.4x10^{-9}$
	$^{137}Cs/^{137m}Ba$	$1.2x10^{-16}$	Food chain, external (ground)	$5.3x10^{8}$	$6.3x10^{-8}$
Aquatic	$^{3}H^{a}$	$3.5x10^{-20}$	Food chain	$1.3x10^{11}$	$4.6x10^{-9}$
	$^{14}C^{a}$	$3.1x10^{-15}$	Food chain	$1.2x10^{9}$	$3.7x10^{-6}$
	^{51}Cr	$1.3x10^{-19}$	Food chain	$1.9x10^{6}$	$2.5x10^{-13}$
	^{54}Mn	$8.2x10^{-17}$	Food chain	$6.2x10^{7}$	$5.1x10^{-9}$
	^{59}Fe	$1.7x10^{-17}$	Food chain	$3.6x10^{7}$	$6.1x10^{-10}$
	^{58}Co	$2.6x10^{-17}$	Food chain	$2.6x10^{6}$	$6.8x10^{-11}$
	^{60}Co	$1.2x10^{-15}$	External (ground)	$6.1x10^{8}$	$7.3x10^{-7}$
	^{89}Sr	$1.5x10^{-17}$	Food chain	$1.7x10^{8}$	$2.6x10^{-9}$
	^{90}Sr	$1.9x10^{-15}$	Food chain	$7.0x10^{8}$	$1.3x10^{-6}$
	^{95}Zr	$5.3x10^{-18}$	External (ground)	$2.3x10^{7}$	$1.2x10^{-10}$
	^{95}Nb	$1.4x10^{-15}$	Food chain	$8.7x10^{7}$	$1.2x10^{-7}$
	^{131}I	$2.0x10^{-17}$	Food chain	$9.1x10^{8}$	$1.8x10^{-8}$
	^{134}Cs	$7.4x10^{-15}$	Food chain	$7.1x10^{7}$	$5.3x10^{-7}$
	$^{137}Cs/^{137m}Ba$	$2.4x10^{-15}$	Food chain, external (ground)	$4.5x10^{9}$	$1.1x10^{-5}$

[a] - ^{3}H and ^{14}C released activity was not evaluated. Routine release conversion factor calculations has been performed using data for RBMK reactors presented in Kosinski (1987) and Vokal (1997)

[b] - Assumed as total activity of noble gases.

List of Figures