Consequences of radiological exploitation releases from HTGR nuclear reactors for GOSPOSTRATEG-HTR project

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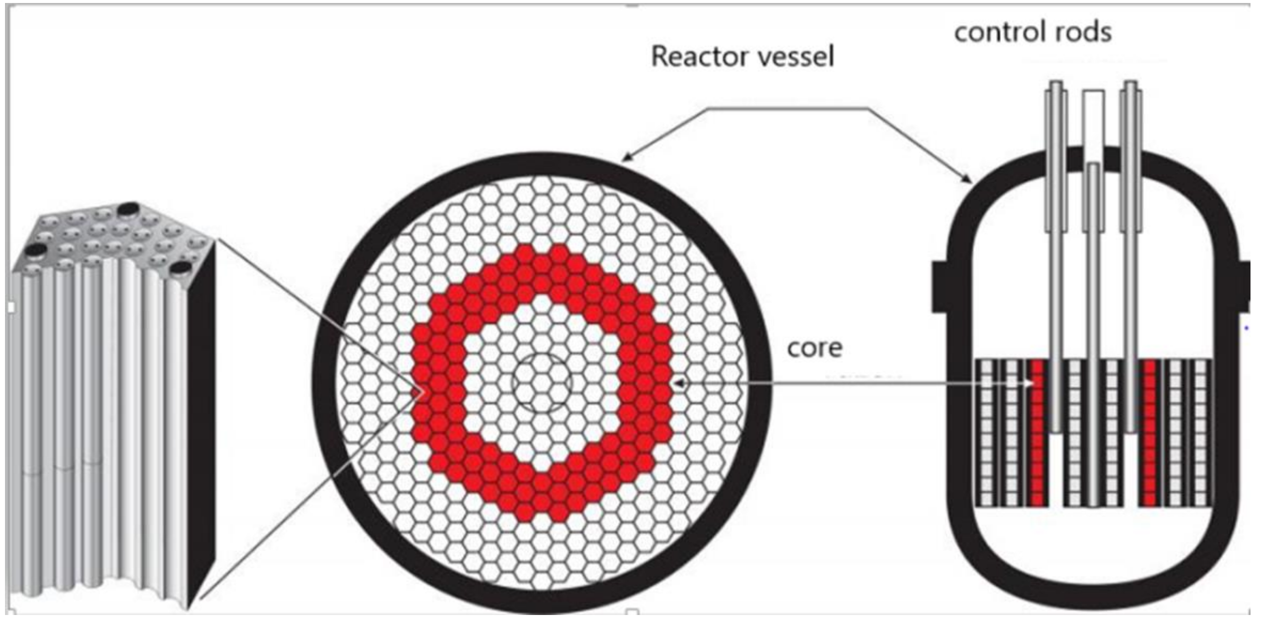
Analysis of consequences of radiological exploitation releases of High Temperature Gas-cooled Reactors (HTGR)

- Study on exploitation releases of HTGR nuclear reactors, during normal operation.
- Project GOSPOSTRATEG-HTR - in this part of project - preparing of legal, organizational and technical instruments for the implementation of HTR reactors.
- The aim of the work - calculation of radiation doses [μSv/y], basing on exploitation environmental releases, estimated before.
- Estimation of release for normal operation presented by E.Skrzypek

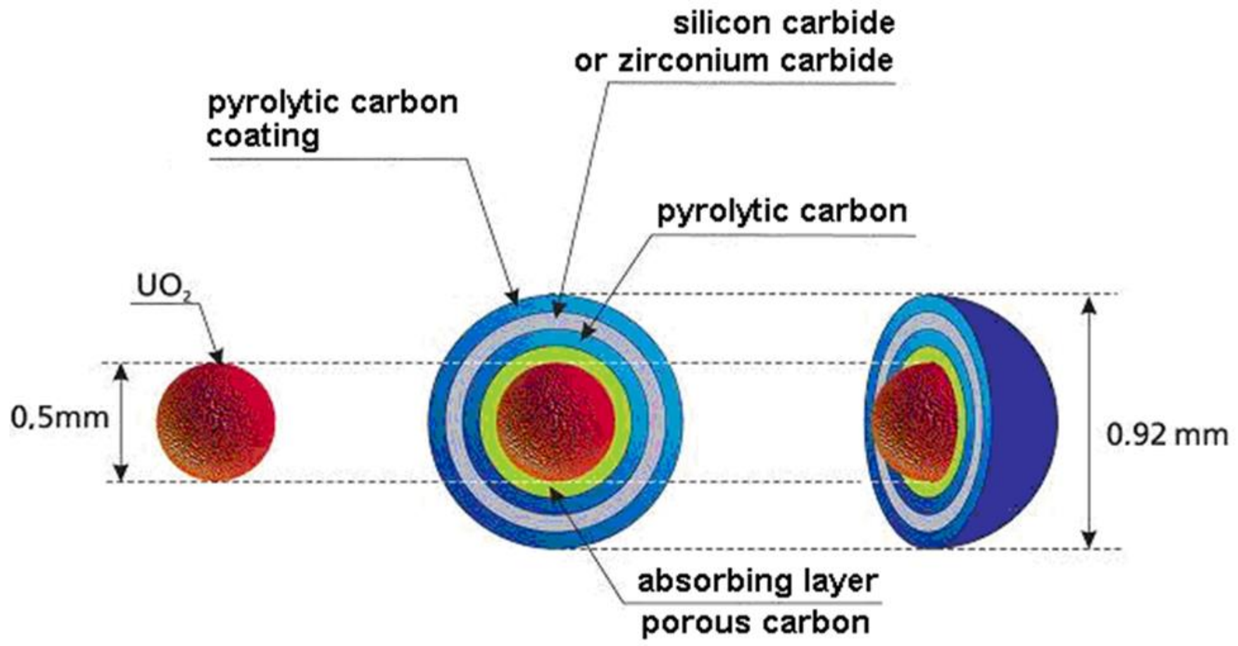
The High Temperature Gas-cooled Reactor – core construction [2]

- The High Temperature Gas-cooled Reactor (HTGR) – nuclear reactor cooled with gas – Helium.
- In a core of the reactor – hexagonal graphite blocks, constructed of graphite tubes, each containing a few fuel compacts, in each compact – about 1000 TRISO fuel particles.



TRISO – fuel [1]

- TRISO fuel - uranium oxide, covered with four coatings, made of three materials.
- 1 coating – porous carbon, absorbing fission products.
- 2 coating – pyrolytic carbon, highly resistant at high temperatures.
- 3 coating – silicon carbide, high mechanical resilience.
- 4 coating – pyrolytic carbon.



The High Temperature Gas-cooled Reactor – exploitation releases and doses

- Fission products, important for normal exploitation releases – assumed after literature studies.
- Estimating exploitation releases – considered mostly primary circuit emissions.
- Key role – volatile isotopes such as noble gases and Iodine isotopes.
- Doses calculation – based on PC-CREAM software.

PC CREAM

- PC-CREAM is a Radiological Impact Assessment Software, prepared for UK Health Security Agency.
- Individual yearly radiation effective doses, from complex external and internal exposition.
- Model analysing various ways of radiation exposition, such as radiation absorbed directly from radioactive cloud, from inhalation and digestive pathways and from suspension.
- A suite of models and data which can be used to perform the radiological impact assessments of routine, continuous discharges from virtually any type of installation.
- Typical use - performing prospective assessments as a key input to discharge authorizations and waste management decisions. [3]

PC-CREAM functions and capabilities

- Modelling of discharges to atmospheric, marine and river environments.
- Calculations of activity concentrations in environmental media.
- Calculations of effective doses to individuals and population groups.
- Inclusion of comprehensive sets of default data for all model parameters.
- Ability to model atmospheric discharges from multiple stacks.
- Inclusion of data on the spatial distribution of agricultural production and population for input to collective dose assessments.
- Taking to account the contribution to collective dose from radionuclides that become globally circulated. [3]

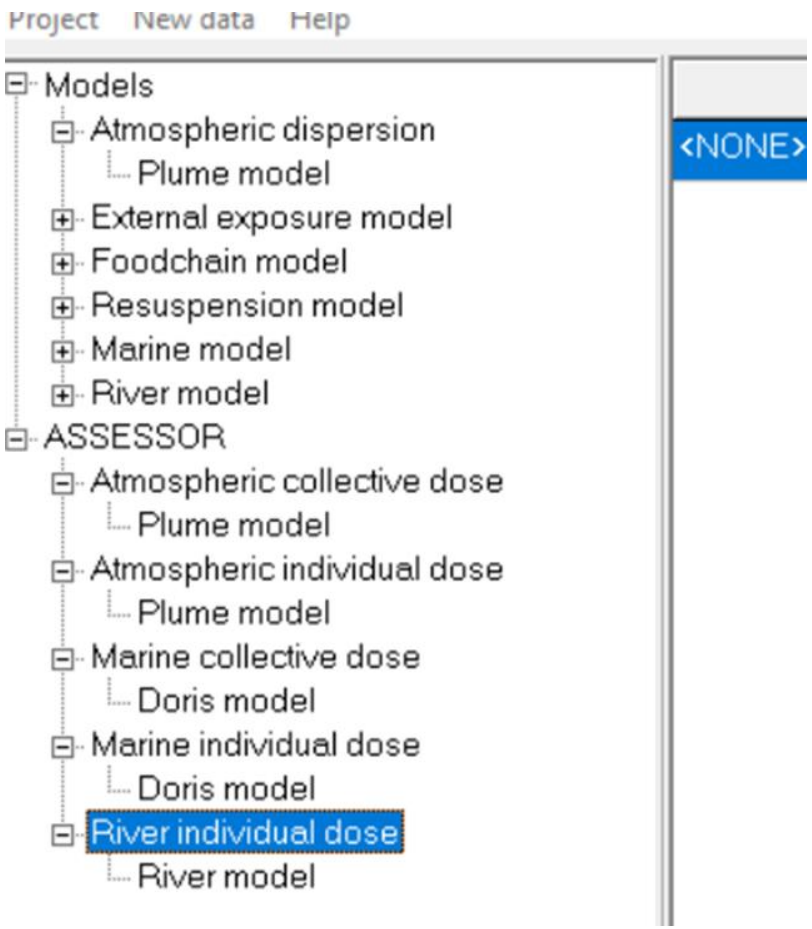
PC CREAM limitations

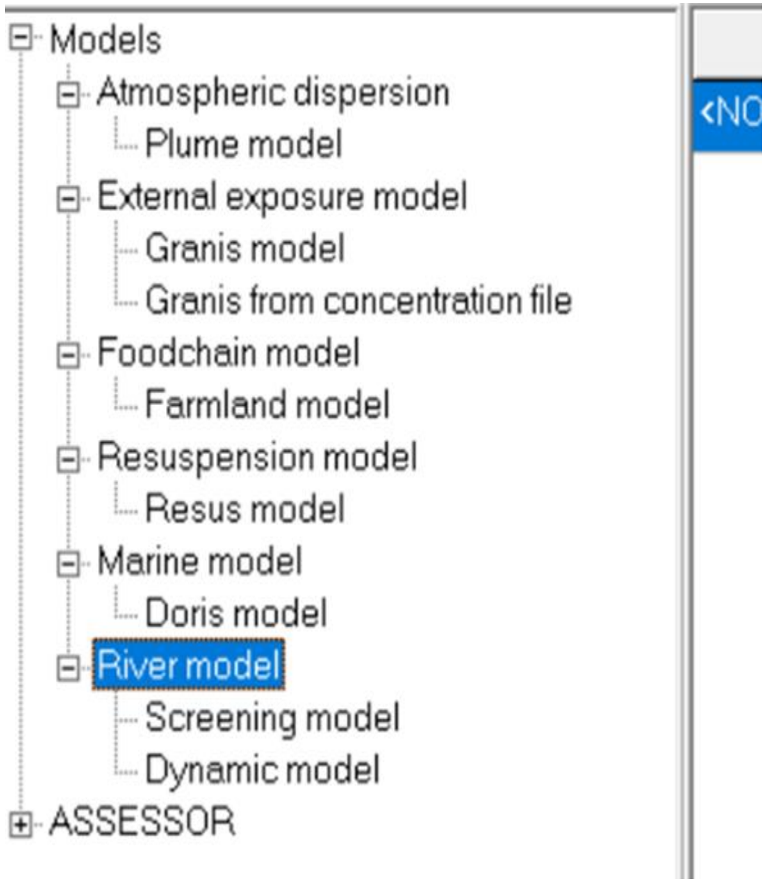
- PC-CREAM can only be used if it can be assumed that discharges of radionuclides to the environment are continuous and constant.
- PC-CREAM can not be used to model short duration releases unless these occur with sufficient frequency, so they can be approximated to a continuous release. [3]

PC CREAM requirements

- The current version of PC-CREAM 08 will run under Windows XP, Vista, 7 and 10 on 32 and 64 bit computers.
- The database must be installed on a local drive and typically requires several tens of Mbytes of storage space [3]
- Current base - 70 MB.

PC-CREAM – GUI and menu





PC-CREAM - 'Models' and 'ASSESSOR' modes

- Complex model divided into several parts for ease of use. The main division of the program into 'Models' and 'ASSESSOR' modes .
- ASSESSOR – the dose assessment part of PC-CREAM 08, for effective doses calculations. Activity concentrations in environmental media calculated using the various models – can be used in ASSESSOR mode as an input.
- Five parts of ASSESSOR – for calculations of individual and collective doses from discharges to the atmosphere and sea and individual doses from discharges into rivers. Each part of ASSESSOR – displaying all the model runs that are available for use including the default set.
- Results of these models – combined with actual discharge rates, site specific data, habit data and dose coefficients for effective doses calculations for various exposure pathways. [3]

PC-CREAM– Models

- PLUME - The atmospheric dispersion model. A Gaussian plume model takes into account the meteorological conditions during the release, the roughness of the land surface and the physical characteristics of the radionuclides being released.
- RESUS - Activity concentrations estimations, in air arising from the resuspension of previously deposited radionuclides. A formula independent of the radionuclide considered with the exception that differences in radioactive decay are taken into account. The activity concentrations are calculated for a unit deposition rate.
- GRANIS - Models the external gamma dose from radionuclides deposited on the soil - models the transfer of radionuclides through the soil. Taken into account the shielding properties of the soil when estimating doses one metre above the soil surface. The doses – calculated based on a unit deposition rate. Some organ doses included, as well as effective dose.
- FARMLAND - Predicting activity concentrations of radionuclides in terrestrial foods following deposition onto the ground; a suite of models.
- DORIS - The marine dispersion model. The model can be used to predict the activity concentrations in sea water, sediments and marine biota for user-defined discharge rates.
- River models - Two models for calculating the dispersion of radionuclides released to rivers. [3]

PC-CREAM– Models

- Series of mathematical models, predicting the transfer of radionuclides through the environment.
- Providing estimates of activity concentrations in various environmental media following a continuous release.
- The output of these models is then used as input to the dose assessment part of the program ASSESSOR. [3]

Doses calculations - assumpions

- Meteorological conditions taken into account – characterising areas near Otwock-Świerk.
- A set of meteorological data prepared – basing on a couple of sets of meteo statistics collected from the stations nearby within several years.
- Assumed stack height – 60m.
- Calculations prepared for 56 receptor points – points situated in a given distance at a given angle from the source, whose analyzed inhabited population groups would absorbe estimated effective radiation dose.

Receptor points

- Receptor points placed in distances of 100m, 250m, 500m, 1000m, 1500m, 2000m, 2500m and 3000m, on circles of radius mentioned above; for distances up to 1000m, points were selected every 45°, for distances above – every 60°.

Receptor points, with distance form source and radius

	Angle [°]	Distance from source [m]
Receptor 1	0	100
Receptor 2	45	100
Receptor 3	90	100
Receptor 4	135	100
Receptor 5	180	100
Receptor 6	225	100
Receptor 7	270	100
Receptor 8	315	100
Receptor 9	0	250
Receptor 10	45	250
Receptor 11	90	250
Receptor 12	135	250
Receptor 13	180	250
Receptor 14	225	250
Receptor 15	270	250
Receptor 16	315	250
Receptor 17	0	500
Receptor 18	45	500
Receptor 19	90	500
Receptor 20	135	500
Receptor 21	180	500
Receptor 22	225	500
Receptor 23	270	500
Receptor 24	315	500
Receptor 25	0	1000
Receptor 26	45	1000
Receptor 27	90	1000
Receptor 28	135	1000
Receptor 29	**180**	**1000**
Receptor 30	225	1000
Receptor 31	270	1000
Receptor 32	315	1000
Receptor 33	0	1500
Receptor 34	60	1500
Receptor 35	120	1500
Receptor 36	180	1500
Receptor 37	240	1500
Receptor 38	300	1500
Receptor 39	0	2000
Receptor 40	60	2000
Receptor 41	120	2000
Receptor 42	180	2000
Receptor 43	240	2000
Receptor 44	300	2000
Receptor 45	0	2500
Receptor 46	60	2500
Receptor 47	120	2500
Receptor 48	180	2500
Receptor 49	240	2500
Receptor 50	300	2500
Receptor 51	0	3000
Receptor 52	60	3000
Receptor 53	120	3000
Receptor 54	180	3000
Receptor 55	240	3000
Receptor 56	300	3000

Calculations - population

- Doses estimated for 3 age groups – infants, children and adults. Higher doses absorbed by infants and children taken into account.
- Doses from all groups of nutrients considered, such as: cow liver, cow meat, cow milk, dairies, fruits, grains, green vegetables, root vegetables, lamb, lamb liver.
- Nutrition doses assumed as critical – higher than default average. As a consequence – calculations performed for higher consumption index than for average data.

Nutrition doses – critical and average doses for groups of nutrients

Group of nutrients	Consumption index for adults		Consumption index for children		Consumption index for infants	
	Index – critical dose [kg/yr]	Index – average dose [kg/yr]	Index – critical dose [kg/yr]	Index – average dose [kg/yr]	Index – critical dose [kg/yr]	Index – average dose [kg/yr]
Cow liver	10	2.75	5	1.5	2.75	0.5
Cow meat	45	15	30	15	10	3
Cow milk	240	95	240	110	320	130
Dairies	60	20	45	15	45	15
Fruits	75	20	50	15	35	9
Grains	100	50	75	45	30	15
Green vegetables	80	35	35	15	15	5
Root vegetables	130	60	95	50	45	15
Lamb liver	10	2.75	5	1.5	2.75	0.5
Lamb	25	8	10	4	3	0.8

Input data

- Sources of HTR reactors exploitation releases – mostly additional systems, such as regenerative helium purification system or primary cooling circuit unseals, during breakdown.
- Estimates of environmental releases – based on literature and exploitation data studies, from other HTGR projects; mostly – data gained for GEMINI+ project.
- Primary circuit emissions mostly considered.

Input data

- Estimations of all fission products, important for radiological hazard for normal exploitation estimation.
- Key role – Iodine isotopes and noble gases.
- Releases estimated as 1010 Bq/(hMW) for noble gases and 109 Bq/(hMW) for Iodine isotopes. For highly volatile fission products, such as Sr90, Cs134, Cs137 and Silver Ag110m estimated about 105 Bq/(hMW). Tritium primary circuit release estimated about 107 Bq/(hMW). For Carbon C14 - 105 Bq/(hMW).

Input data

- Very conservative fuel release rates for Iodines - environmental releases overestimation.
- Finally – use of filters during normal exploitation considered – filtration coefficients for all nuclides released.
- Filtration coefficients – assumes basing on experiments and performance of Maria reactor. [16]
- Finally - filtration coefficient 0.04 for Iodines, 0.01 for other nuclides, except noble gases and Carbon (without filters).

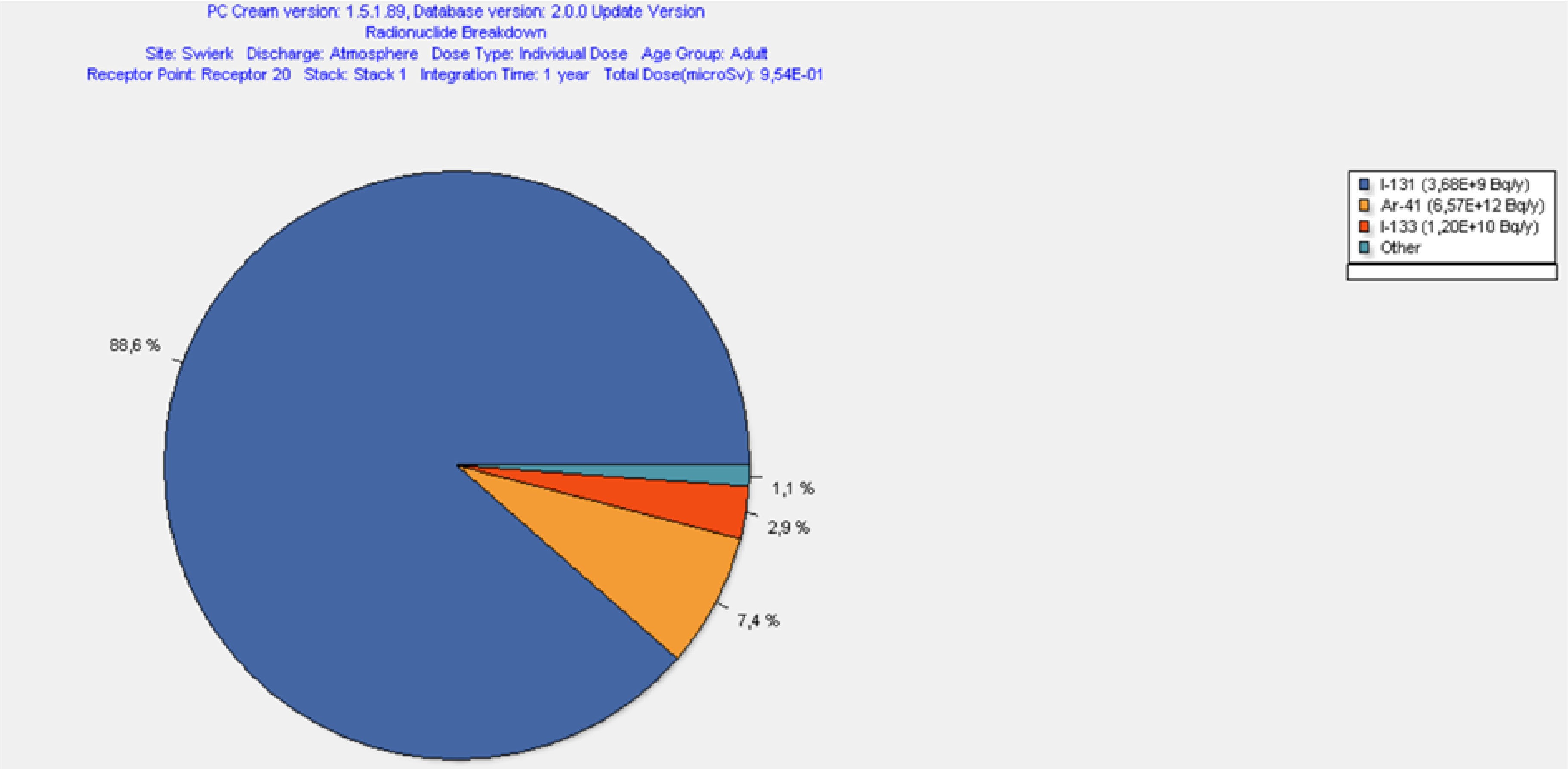
NUCLIDES CONSIDERED FOR CALCULATIONS OF RADIATION DOSES, WITH RADIATION EMISSIONS

Nuclide	Radiation emission [Bq/yr]	Nuclide	Radiation emission [Bq/yr]
H-3	4.09E+08	I-132	2.17E+08
Kr-83m	5.32E+10	I-133	3.17E+08
Kr-85	1.27E+06	I-134	3.63E+08
Kr-85m	1.32E+11	I-135	2.99E+08
Kr-87	2.42E+11	Rb-88	3.27E+08
Kr-88	3.23E+11	Sr-89	9.06E+04
Xe-131m	4.03E+09	Sr-90	4.25E+03
Xe-133	7.98E+11	Cs-134	4.36E+02
Xe-133m	2.39E+10	Cs-137	5.05E+02
Xe-135	1.68E+11	Ag-110m	6.55E+05
Xe-135m	1.61E+11	Ar-41	6.57E+12
I-131	1.47E+08	C-14	1.02E+07

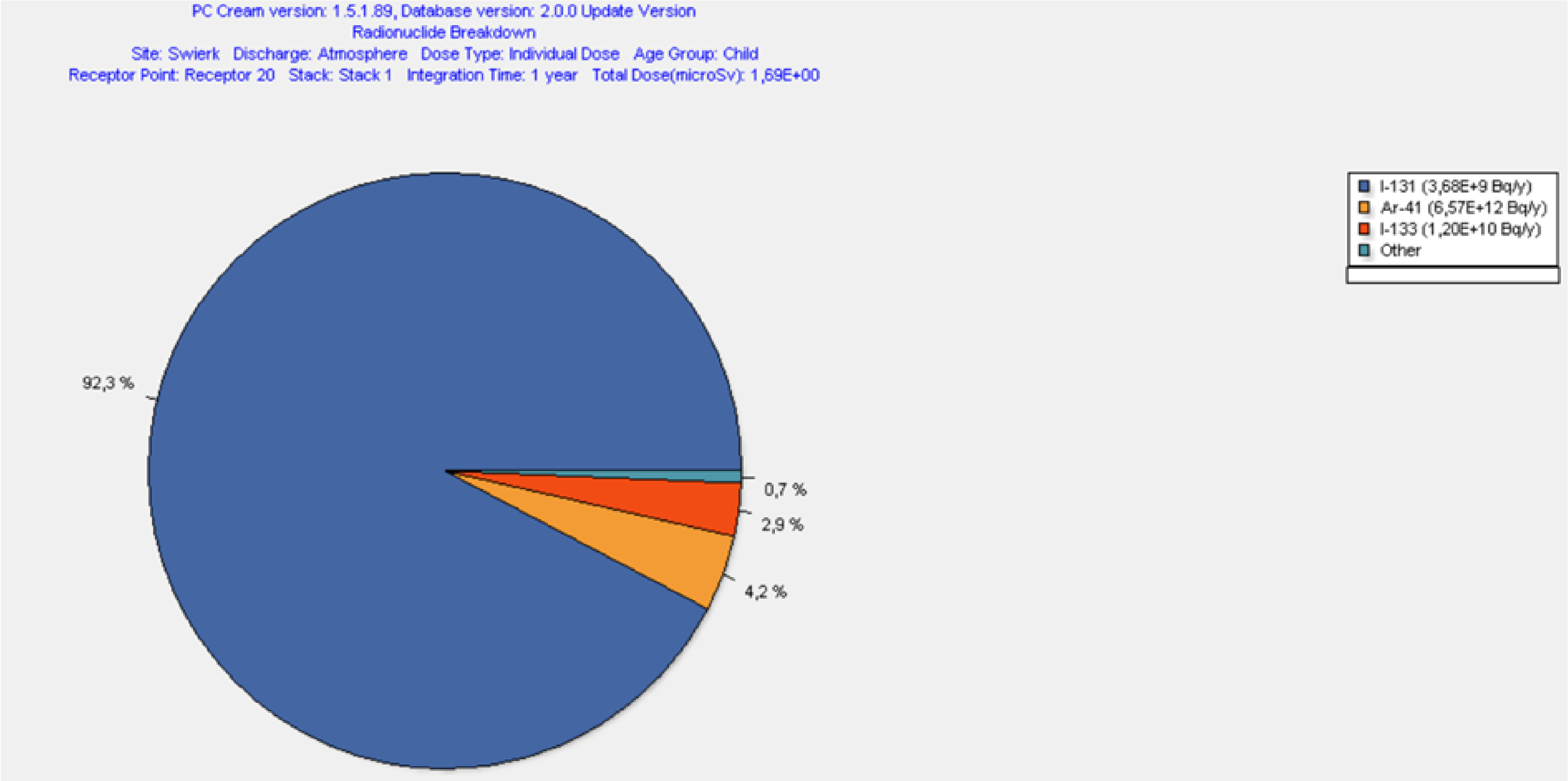
Results of calculations

- According to corresponding law, limiting effective dose for the area of restricted zone, for habitants during normal exploitation is 0.3 mSv/yr, for all pathways.
- Maximum individual radiation dose calculated by model for points considered – 9.54E-1 μSv (9.54E-4 mSv) for adults, 1.69 μSv (1.69E-3 mSv) for children and 5.95 μSv (5.95E-3 mSv) for infants.
- Maximum doses – significantly more than 100 Times smaller than limiting effective dose defined by law.
- Maximum doses – absorbed by population near Receptor 20, placed 500 m from emission source, at an angle of 135°.

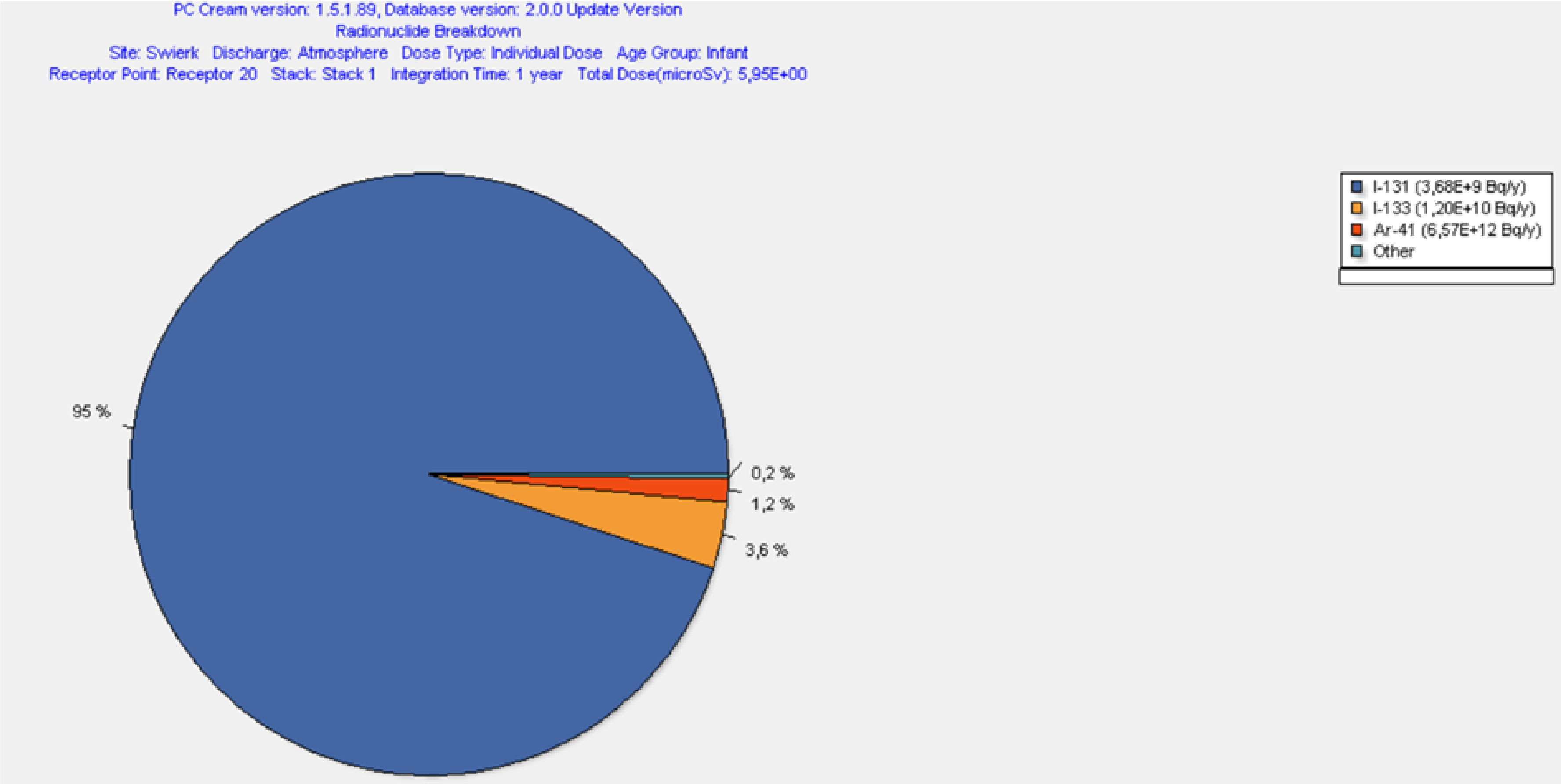
Radiation doses from all nuclides considered in overal dose for Receptor 20, for adults.



Radiation doses from all nuclides considered in overal dose for Receptor 20, for children.



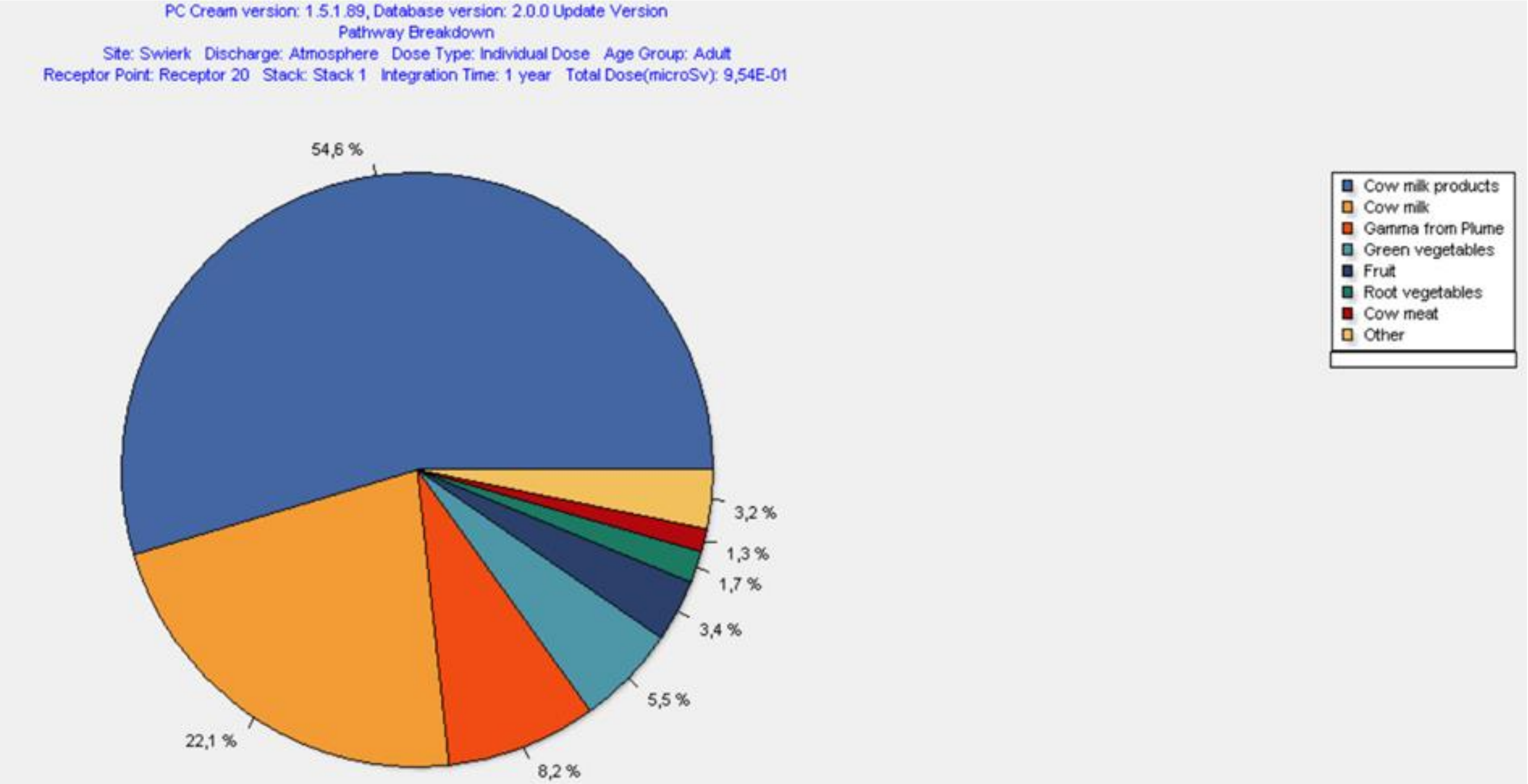
Radiation doses from all nuclides considered in overal dose for Receptor 20, for infants.



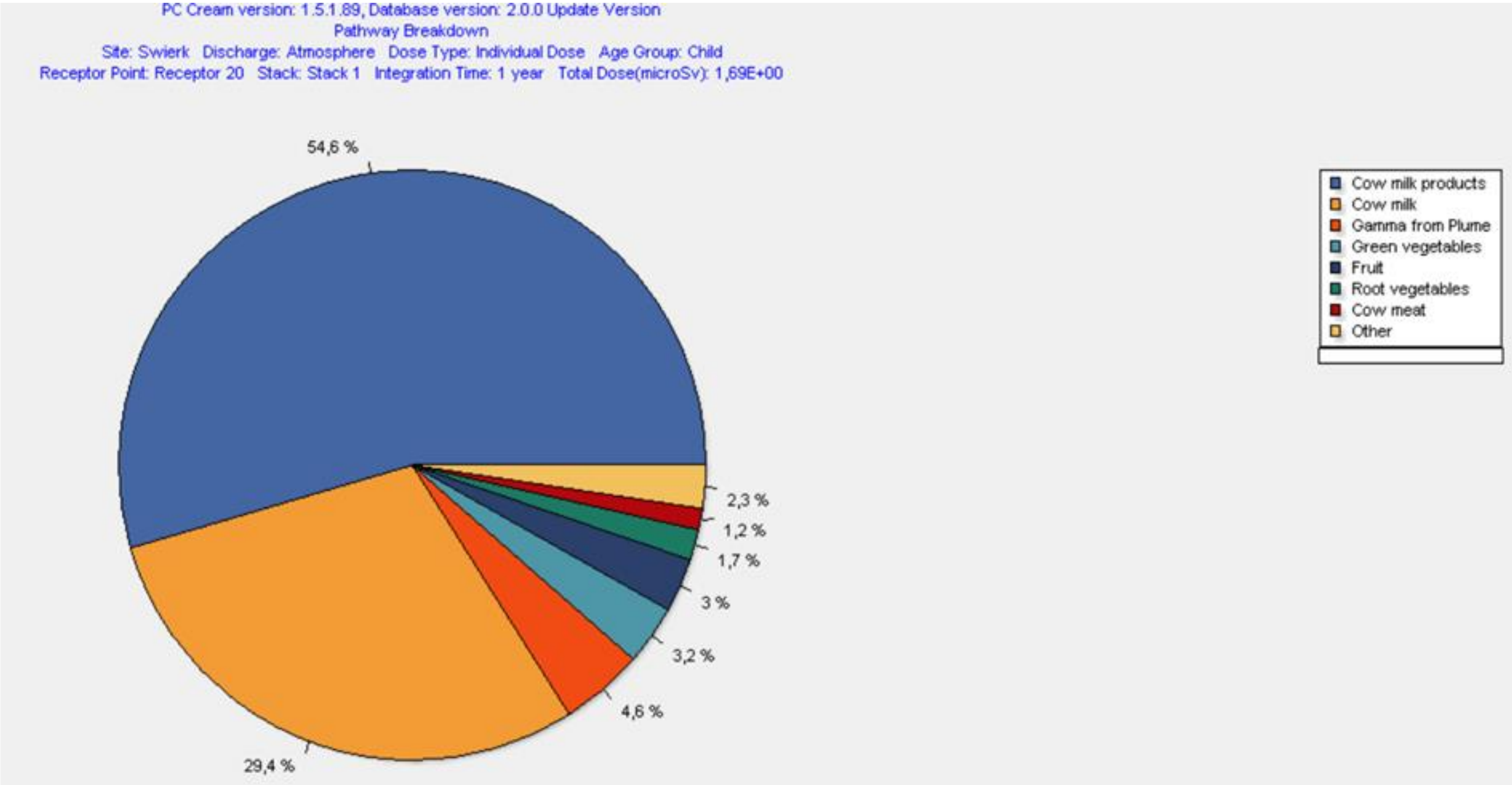
Radiation doses from all nuclides considered in overal dose for Receptor 20, for adults, children and infants, with nuclides releases.

Nuclide	Release value[Bq/yr]	Percentage of dose for adults [%]	Dose from the nuclide for adults [µSv]	Percentage of dose for children [%]	Dose from the nuclide for children [µSv]	Percentage of dose for infants [%]	Dose from the nuclide for infants [µSv]
I 131	3.68E+9	88,6	0,83727	92,3	1,55987	95	5,6525
Ar 41	6.57E+12	7,4	0,06993	4,2	0,07098	3,6	0,2142
I-133	1.20E+10	2,9	0,027405	2,9	0,04901	1,2	0,0714
Reszta	7.18E+11	1,1	0,010395	0,7	0,01183	0,2	0,0119

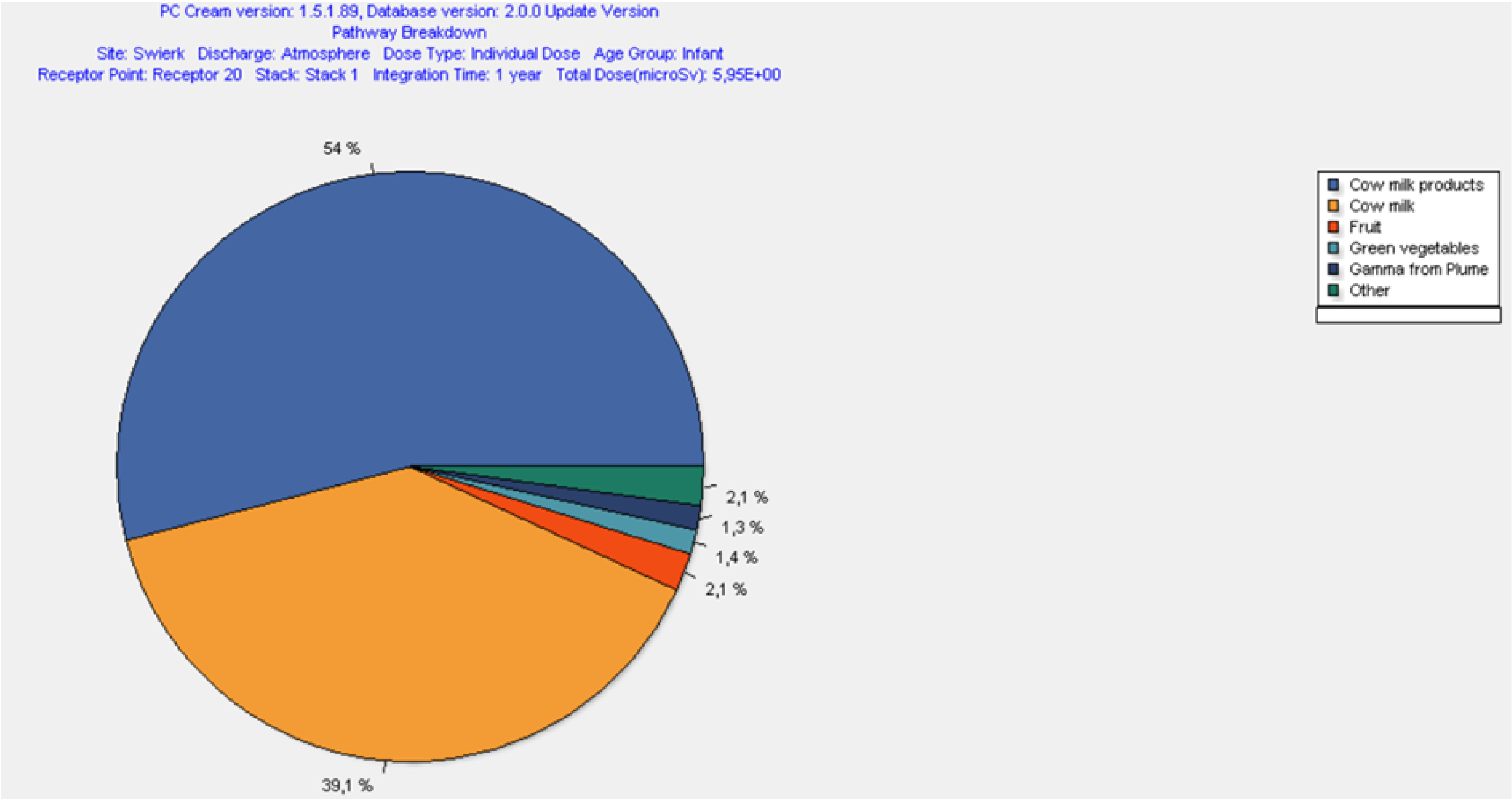
Radiation doses from all pathways considered in overall dose for Receptor 20, for adults



Radiation doses from all pathways considered in overall dose for Receptor 20, for children



Radiation doses from all pathways considered in overall dose for Receptor 20, for infants.



Radiation doses from all pathways considered in overall dose for Receptor 20, for adults, children and infants.

Group of nutrients	Percentage of dose from pathway for adults [%]	Dose from pathway for adults [µSv]	Percentage of dose from pathway for children [%]	Dose from pathway for children [µSv]	Percentage of dose from pathway for infants[%]	Dose from pathway for infants [µSv]
Dairies	54,6	0,51597	54,6	0,92274	54	3,213
Cow milk	22,1	0,208845	29,4	0,49686	39,1	2,32645
Gamma from plume	8,2	0,07749	4,6	0,07774	1,3	0,07735
Green vegetables	5,5	0,051975	3,2	0,05408	1,4	0,0833
Fruits	3,4	0,03213	3	0,0507	2,1	0,12495
Root vegetables	1,7	0,016065	1,7	0,02873	0	0
Cow meat	1,3	0,012285	1,2	0,02028	0	0
Other	3,2	0,03024	2,3	0,03887	2,1	0,12495

Conclusions

- Nuclides considered the most significantly affecting doses – Iodine 131, Argon 41 and Iodine 133.
- At all receptors considered – highest impact of radiation from Iodine 131 – about and above 90% of overall dose.
- In receptors most distant the source – the highest domination of doses from Iodine 131 (above 90% for the most distant points, for adults). The more distant point, the more marginal impact of the rest of nuclides (for the most distant – less than 1%).
- Points placed in angle of 120-135° - considered those with the highest doses absorber by population, in all distances from source.

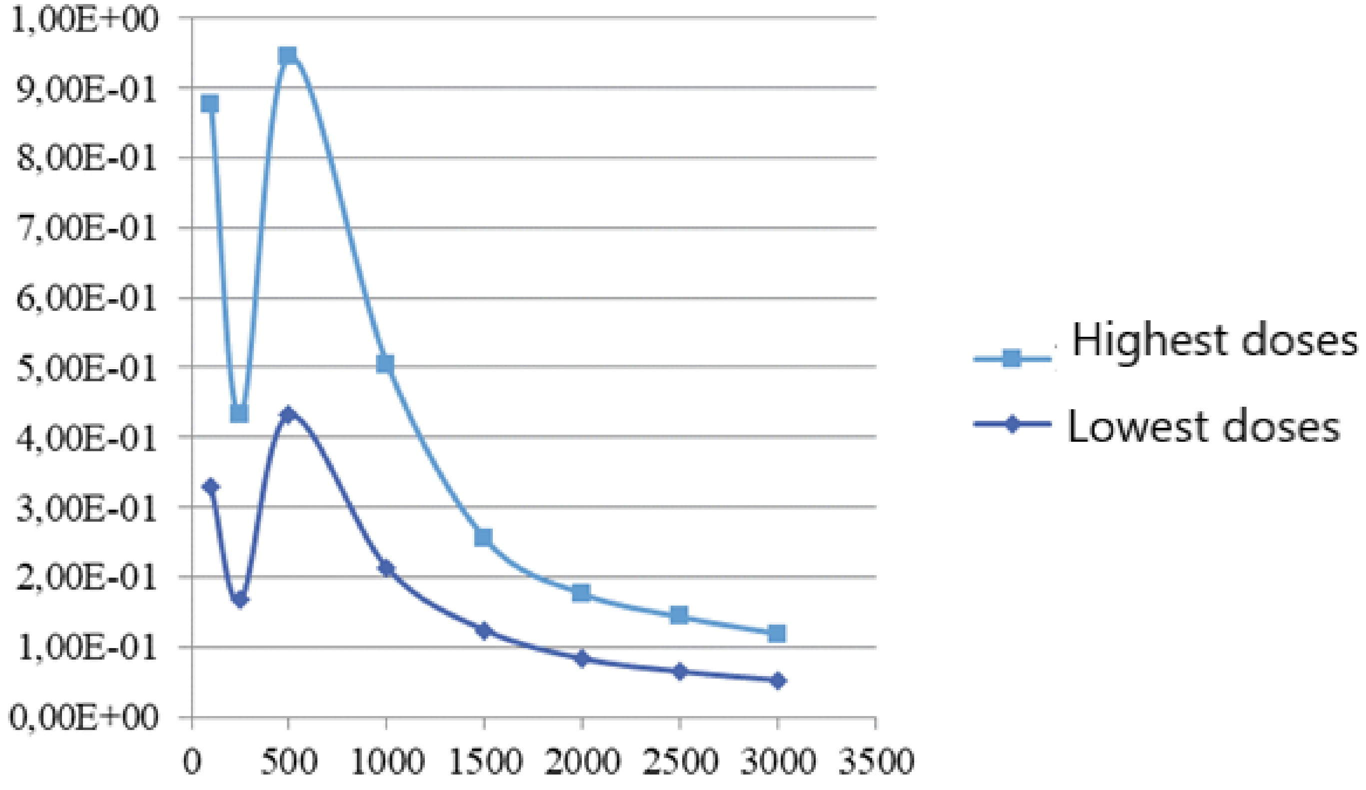
Conclusions

- Radiation doses generally decrease with the distance. Although among the same distances – highest doses for angles of 135°, lowest for 0°.
- Probably huge impact on doses of meteorological conditions and height of stack.
- Largest part of dose for adults – from milk and dairies and gamma from plume, considerable also doses from green vegetables and fruits.
- Largest part of dose for infants and children – from milk and dairies.

Radiation doses for all receptor points, with distance from source and angles

	Adults – dose [μSv]	Children – dose [μSv]	Infants – dose [μSv]	Radius [°]	Distance from source [m]
Receptor 1	3.28E-01	5.14E-01	1.59E+00	0	100
Receptor 2	5.96E-01	9.38E-01	2.91E+00	45	100
Receptor 3	4.42E-01	6.91E-01	2.13E+00	90	100
Receptor 4	8.77E-01	1.37E+00	4.21E+00	135	100
Receptor 5	5.76E-01	9.04E-01	2.81E+00	180	100
Receptor 6	6.53E-01	1.04E-00	3.26E+00	225	100
Receptor 7	5.13E-01	8.12E-01	2.54E+00	270	100
Receptor 8	6.17E-01	9.66E-01	2.99E+00	315	100
Receptor 9	1.67E-01	2.64E-01	8.30E-01	0	250
Receptor 10	2.99E-01	4.75E-01	1.49E+00	45	250
Receptor 11	2.23E-01	3.52E-01	1.10E+00	90	250
Receptor 12	4.33E-01	6.82E-01	2.12E+00	135	250
Receptor 13	2.83E-01	4.47E-01	1.40E+00	180	250
Receptor 14	3.22E-01	5.15E-01	1.63E+00	225	250
Receptor 15	2.56E-01	4.09E-01	1.29E+00	270	250
Receptor 16	3.14E-01	4.98E-01	1.56E+00	315	250
Receptor 17	4.32E-01	7.71E-01	2.73E+00	0	500
Receptor 18	7.14E-01	1.27E+00	4.49E+00	45	500
Receptor 19	5.16E-01	9.18E-01	3.23E+00	90	500
Receptor 20	9.45E-01	1.69E+00	5.95E+00	135	500
Receptor 21	5.90E-01	1.05E+00	3.68E+00	180	500
Receptor 22	7.11E-01	1.27E+00	4.46E+00	225	500
Receptor 23	5.90E-01	1.05E+00	3.71E+00	270	500
Receptor 24	8.17E-01	1.46E+00	5.16E+00	315	500
Receptor 25	2.13E-01	3.81E-01	1.35E+00	0	1000
Receptor 26	3.53E-01	6.31E-01	2.23E+00	45	1000
Receptor 27	2.58E-01	4.60E-01	1.62E+00	90	1000
Receptor 28	5.05E-01	8.99E-01	3.17E+00	135	1000
Receptor 29	3.15E-01	5.61E-01	1.98E+00	180	1000
Receptor 30	3.70E-01	6.60E-01	2.33E+00	225	1000
Receptor 31	3.04E-01	5.44E-01	1.92E+00	270	1000
Receptor 32	4.03E-01	7.20E-01	2.55E+00	315	1000
Receptor 33	1.24E-01	2.21E-01	7.82E-01	0	1500
Receptor 34	2.07E-01	3.70E-01	1.31E+00	60	1500
Receptor 35	2.55E-01	4.54E-01	1.60E+00	120	1500
Receptor 36	1.92E-01	3.41E-01	1.20E+00	180	1500
Receptor 37	2.21E-01	3.95E-01	1.40E+00	240	1500
Receptor 38	1.87E-01	3.34E-01	1.18E+00	300	1500
Receptor 39	8.32E-02	1.49E-01	5.26E-01	0	2000
Receptor 40	1.42E-01	2.53E-01	8.93E-01	60	2000
Receptor 41	1.76E-01	3.14E-01	1.11E+00	120	2000
Receptor 42	1.35E-01	2.40E-01	8.47E-01	180	2000
Receptor 43	1.53E-01	2.72E-01	9.62E-01	240	2000
Receptor 44	1.27E-01	2.26E-01	8.01E-01	300	2000
Receptor 45	6.49E-02	1.16E-01	4.11E-01	0	2500
Receptor 46	1.14E-01	2.04E-01	7.20E-01	60	2500
Receptor 47	1.43E-01	2.56E-01	9.05E-01	120	2500
Receptor 48	1.12E-01	2.00E-01	7.07E-01	180	2500
Receptor 49	1.23E-01	2.20E-01	7.78E-01	240	2500
Receptor 50	9.97E-02	1.78E-01	6.31E-01	300	2500
Receptor 51	5.25E-02	9.41E-02	3.34E-01	0	3000
Receptor 52	9.44E-02	1.69E-01	5.98E-01	60	3000
Receptor 53	1.19E-01	2.13E-01	7.56E-01	120	3000
Receptor 54	9.51E-02	1.70E-01	6.01E-01	180	3000
Receptor 55	1.02E-01	1.82E-01	6.46E-01	240	3000
Receptor 56	8.12E-02	1.45E-01	5.15E-01	300	3000

Highest and lowest doses [μSv], for distances considered, in a function of distance from the source [m]



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[3] https://www.ukhsa-protectionservices.org.uk/pccream/

[4] RAPORT GOSPOSTRATEG-HTR „Oszacowanie emisji eksploatacyjnych i ich skutków radiacyjnych”; E. Skrzypek, E. Kowalik-Pilarska, M. Skrzypek, J. Malesa