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Analysis of AP1000 radioactive material release accidents with MELCOR Accident Consequence Code System (MACCS)

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Abstract

The probable introduction in the medium term of nuclear energy into the Polish national power system has become a source of anxiety in society. While Poland already has a research nuclear reactor (acronym: MARIA) at the National Center for Nuclear Research in Świerk, near Warsaw, issues regarding safety and the possible consequences of an accident in the first baseload nuclear power plant have triggered public debate. As part of the licensing process of any newly designed reactor, scenarios for a range of accidents at the plant together with their consequences must be modeled, analyzed and presented in the licensing documentation. In this context a model was built based on a complex set of data—including data provided by the reactor manufacturer, location and environmental data, weather conditions and possible accident scenarios—to perform simulations with a computational tool called MELCOR Accident Consequence Code System (MACCS). MACCS is used to perform accident-related calculations, including release of radioactive material to the atmosphere and short and long-term consequences. The analysis involved releases of radioactive material from an AP1000 nuclear reactor assumed to be located on the Polish seacoast and demonstrates that the lethality and incidence of cancer caused by radioactive release are significantly lower than natural.

Keywords: MACCS; MELCOR; nuclear reactor; nuclear accident; release of radioactive materials; radioactivity; Gauss plume model

1. Introduction

This paper reports on simulations of release of radioactive materials following an accident at Poland's first nuclear power plant on the Baltic coast and its effects on the environment and people living in the affected area. The calculations were performed based on data from the AP1000 reactor designed by Westinghouse and pertain to accident types BP and CFL, as described in [1]. The accidents involve release scenarios relating to different radionuclides and various release heights and concentrations, which will be presented later on in this paper. It is assumed that the plant is located in Lubiatowo on the Polish coastline and that the plant has a single reactor which suffers an accident. Simulations were performed using the MELCOR Accident Consequence Code System (MACCS2/WINMACCS, short: MACCS) for the emergency phase, so only early stage consequences were calculated. Initially, it is assumed that no people were evacuated, relocated or sheltered and that the worse possible effects are observed.

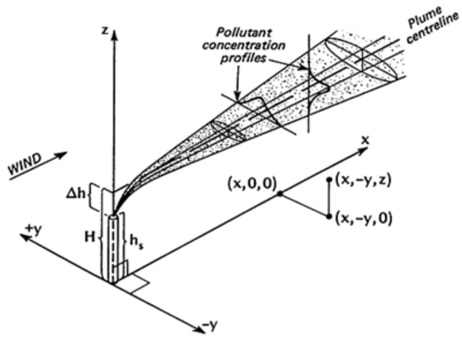

Figure 1: Gaussian plume from the elevated point source [2]

2. Methodology

2.1. Gauss plume model

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Table 1: Values of constant for equations (3) and (4) [3]

Stability Class	Constants			
	a	b	c	d
A	0.3658	0.9031	0.00025	2.125
B	0.2751	0.9031	0.0019	1.6021
C	0.2089	0.9031	0.2	0.8543
D	0.1474	0.9031	0.3	0.6532
E	0.1046	0.9031	0.4	0.6021
F	0.0722	0.9031	0.2	0.6020

In MACCS software, the Gaussian plume model is used to model the dispersion of pollution in the air. The approach assumes that the downwind dispersion of gas in the air generates the normal distribution of gas concentration in any direction. The distribution is temperature and wind speed dependent, so the curves vary significantly with altitude. The MACCS Gaussian model takes into account only vertical and crosswind distribution, neglecting the along-wind distribution. Fig. 1 presents in graphic form the assumed Gaussian plume from the elevated point source.

There are two basic equations in MACCS which describe the concentration distribution by the Gaussian model: the general Pasquill equation (1) and one which accounts for the limiting features of the ground and the capping inversion layer in the atmosphere (2) [3].

$$\chi(x,y,z) = \frac{Q}{2\pi\hat{u}\sigma_y\sigma_z} exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\cdot exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right] \quad (1)$$

$$\begin{aligned}\chi(x,y=0,z) = {} & \tfrac{Q}{2\pi\hat{u}\sigma_y\sigma_z}\left[exp\left[-\tfrac{1}{2}\left(\tfrac{z-H}{\sigma_z}\right)^2\right]+exp\left[-\tfrac{1}{2}\left(\tfrac{z+H}{\sigma_z}\right)^2\right]\right] \\ & + \textstyle\int_{i=0}^{5}\left(exp\left[-\tfrac{1}{2}\left(\tfrac{z-H-2nL}{\sigma_z}\right)^2\right]+exp\left[-\tfrac{1}{2}\left(\tfrac{z+H-2nL}{\sigma_z}\right)^2\right]\right) \\ & + \textstyle\int_{i=0}^{5}\left(exp\left[-\tfrac{1}{2}\left(\tfrac{z-H+2nL}{\sigma_z}\right)^2\right]+exp\left[-\tfrac{1}{2}\left(\tfrac{z+H+2nL}{\sigma_z}\right)^2\right]\right)\end{aligned} \quad (2)$$

The manner of dispersion of materials in air—in other words growth of the plume—depends on atmospheric turbulence, which is different for each stability class. Pasquill and Gifford defined six stability classes (A-F) [3] in which the growth of the plume in vertical and horizontal directions must be calculated. Parameters defining this growth are standard deviations in z and y directions σ_z and σ_y. On the basis of Pasquill experiments with plume dispersion, Tadmor and Gur managed to derive empirical formulas (3) and (4) to calculate the standard deviations for different atmospheric stability classes [4].

$$\sigma_y = ax^b \quad (3)$$

$$\sigma_z = cx^d \quad (4)$$

Constants a, b, c and d are different for each stability class and vary according to different authors. Values proposed in MACCS documentation are presented in Table (1).

The stability classes are attributed to weather conditions on the basis of time of day or night, insolation, cloudiness and wind speed. The division is presented in Table (2).

Table 2: Stability classes depending on wind speed and time of day [4]

Windspeed [m/s]	Day—Insolation			Night—Cloudiness	
	Strong	Medium	Weak	$\geq 4/8$	$\leq 3/8$
2	A	A–B	B	E–F	F
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
> 6	C	D	D	D	D

Figure 2: Computational grid around the NPP

2.2. Computational grid

The location assumed in the model, Lubiatowo, was selected because the Polish Energy Group (Polska Grupa Energetyczna S.A.) believes it is a site with real potential for a nuclear power plant. The coordinates of the nuclear power plant in the model are: 54°48'43"N, 17°51'39"E. In MACCS software the grid for which all the parameters are calculated takes the form of concentric circles split into segments, as presented on the map in Fig. (2). The simulations performed cover the area of a circle with a radius of 170 km, so about 91000 km^2 in total. It is split into 14 zones, each containing 16 sectors. Table (3) presents the areas of each of these zones and sectors. The 16 sectors each have an attributed wind rose direction.

Table 3: Zone and segments area

Zone	Radius, km	Zone area, km^2	Sector area, km^2
1	0.5	0.05	0.79
2	1	0.15	2.36
3	5	4.71	75.40
4	10	14.73	235.62
5	15	24.54	392.70
6	20	34.36	549.78
7	30	98.17	1570.80
8	40	137.44	2199.11
9	50	176.71	2827.43
10	70	471.24	7539.82
11	90	628.32	10053.10
12	110	785.40	12566.37
13	130	942.48	15079.64
14	150	1099.56	17592.92

2.3. Population and surface water fractions

For each sector defined in the previous subsection the fractions of surface water and population must be defined. The directions of sector placement from the power plant location are in accordance with the wind rose directions presented in the previous subsection.

The surface water fractions are to be indirectly defined in the site file by the land fractions. They were estimated on the basis of the fraction of each sector which is occupied by the Baltic Sea or lakes.

In order to estimate the population in each sector, in close vicinity to the power plant the population of the villages concerned was used, while in the bigger and more remote sectors the population data of districts (Polish: gmina) was used. Uniform population distribution was assumed in those sectors, which is obviously a source of uncertainty in the results obtained.

2.4. Meteorological data

The largest population density in the target area—the Gdansk area—accounts for about one million people. These circumstances in combination with adverse weather conditions makes it the most affected area in the event of a containment failure accident and the number of possible health consequences is potentially enormous. Since it is important to know the full range of danger, the meteorological data are assumed so as to obtain the worst case scenario.

MACCS2 code gives the option of selecting an external meteorological file with yearly measurements of wind speed, wind direction, atmospheric stability class and precipitation. This model assumes pessimistic steady weather conditions, without precipitation, and wind of 14 m/s blowing in the direction of big cities (SE) and a corresponding D class of stability. These assumptions deliver a relatively high concentration over the big cities and maximize the health impact.

2.5. AP1000 core inventory

The Westinghouse AP1000 reactor contains many radioactive nuclides which pose a threat in the event of major accidents that result in significant releases of radioactivity directly into the environment. Relying on knowledge of nuclides content, the release fractions of each nuclide group may be approximated. This data is important in terms of determining the possible environment and health consequences.

AP1000 core inventory is available in Westinghouse documentation. It contains nuclides and inventory with the following assumptions [5]:

- Core thermal power of 3468 MWt (2 percent above the design core power of 3400 MWt). The main feedwater flow measurement supports a 1-percent power uncertainty; use of a 2-percent power uncertainty is conservative.
- Three-region equilibrium cycle core at end of life.

Table 4: Classification of isotopes for the AP1000

	Group name	Isotopes
1	Noble Gases	Kr, Xe
2	Cs Group	Cs, Rb
3	Sr & Ba Group	Sr, Ba
4	Iodines	I
5	Te Group	Te, Sb
6	Noble Metals	Ru, Rh, Mo, Tc
7	Ce Group	Ce, Pu, Np
8	La Group	Y, Nb, Zr, La, Pr, Nd, Am, Cm

The radionuclides are divided into groups, which basically contain isotopes with similar chemical properties, for example the noble gases. A summary of the classification of radionuclides in the AP1000 core inventory is presented in Table (4). In the simulation, the isotopes classified in a single group are all released in the same fractions with regard to their initial activity. Due to specific chains of reactions implemented in MACCS, some additional isotopes had to be added to the core inventory with zero level activity.

2.6. Dry and wet deposition

A scenario envisages a release of radioactive material contaminating the ground around the nuclear power plant. Deposition of radionuclides can occur in two ways: dry deposition and wet deposition. The only group of isotopes presented in Table 4. which does not undergo this process are the noble gases. The models used to calculate both types of deposition are presented in the following subsections.

Chamberlain's source depletion method is used for dry deposition modeling. In the MACCS software it is modified to account for particle size distribution and limiting of vertical expansion by an inversion layer. The fraction of plume material which undergoes dry deposition can be expressed by equation (5) [3].

$$\frac{Q}{Q_0} = \exp\left(\frac{v_d\, t}{F'}\right) \tag{5}$$

F' is the height of the column from which the deposition occurs [m] and may be expressed by following equation:

$$F' = \sqrt{\frac{\pi}{2}}\sigma_z \frac{1}{F} \tag{6}$$

F is the sum of all of the exponential terms that contain σ_z in the equation for calculating the ground level air concentration:

$$\mathbf{F} = \left[\exp -\frac{\mathrm{H}^2}{2{\sigma_z}^2} + \sum_{\mathrm{n}=1}^{5}\left(\exp -\frac{(\mathrm{H}+2\mathrm{nL})^2}{2\sigma_z^2} + \exp -\frac{(\mathrm{H}-2\mathrm{nL})^2}{2{\sigma_z}^2}\right)\right] \tag{7}$$

Wet deposition accounts for the influence of rainfall on the deposition of radioactive material on the ground surface. The precipitation of part of the isotopes depends on the intensity and duration of rainfall and may be calculated as the fraction of the radioactive material which is deposited after the rainfall on the basis of equation (8).

$$\frac{Q}{Q_0} = \exp\left(a\, I^b\, t\right) \tag{8}$$

Here a and b are the coefficients of the washout function, which by derivation of equation (8) is as follows:

$$\frac{dQ}{dt} = -\Lambda Q = -aI^b \tag{9}$$

Equations (8) and (9) represent the Brenk and Vogt model for wet deposition implemented in the MACCS software. Exemplary values of constants a and b may be, according to NUREG/CR-6244, equal to 1.89e-5 and 0.664 respectively for particles of diameter of 1 μm.

2.7. Dose calculation

Five pathways are considered as regards dose calculation: cloudshine, cloud inhalation, groundshine, resuspension inhalation and dose from radionuclides deposited on skin. Equation (10) is used to calculate the dose received due to cloudshine. The code implements a "semi-infinite cloud" approximation, which is accounted for by using a conversion factor in the formula [6].

$$DC_k = \left(\sum_i AC_i^c \cdot DFC_{\infty ik}\right) C \cdot F \cdot SFC \tag{10}$$

Next, the groundshine dose is governed by equations (11) and (12). The phenomenon involves two types of exposure: (i) the plume segment passes in the specific spatial element, when the ground contamination is a linear ramping up function, and (ii) the plume has already passed and the contamination drops exponentially. These two types correspond to the following two equations respectively.

$$DG_k^1 = GDR_k(t_o) \cdot \int_{t1}^{t2} \frac{(t-t_e)}{(t_0-t_e)} dt \tag{11}$$

For the time when the plume segment has already left the area and the exponential drop in activity occurs, the following equation holds:

$$DG_k^2 = D2 \cdot \left[\frac{e^{-\lambda_e(t_1-t_0)} - e^{-\lambda_e(t_2-t_0)}}{1-e^{-\lambda_e T2}}\right] J \cdot SFG \tag{12}$$

Equation (13) is used for exposure from inhalation. This dose is calculated for two different time periods: the acute exposure period and the lifetime dose commitment period—lasting 50 years.

$$DI_k = \left(\sum_i AC_i \cdot DFI_{i\,k}\right) BR \cdot F \cdot J \cdot SFI \tag{13}$$

Resuspension inhalation is calculated by equation (14).

$$DR_k = \left(\sum_i GC_i \cdot DFI_{i\,k}\right) BR \cdot J \cdot RF \cdot SFI \tag{14}$$

Equation (15) is used for the fifth pathway of exposure: deposition on the skin. The code assumes that the material is deposited on the skin through dry deposition, with dry velocity of 0.01 m/s.

$$DR_k = \left(\sum_i GC_i \cdot DFI_{i\,k}\right) BR \cdot J \cdot RF \cdot SFI \tag{15}$$

2.8. Health effects

The human health impact is assessed on the basis of the doses received. The cases of specific health effects are estimated on the basis of multiplication of the average individual risk of experiencing this effect r_i by the number of people who receive a similar dose. This approach is reflected in equation (16).

$$N_i = r_i \cdot f_i \cdot P \tag{16}$$

The risk of early harm caused by excessive exposure to radiation in the initial period of several weeks from the event occurring is modeled by equation (17).

$$r = 1 - 0.693\left[\frac{D_{tot}}{D_{50,1}}\right]^{\beta} \tag{17}$$

Where D_{tot} is equal to the sum of the external dose delivered to the organ during the emergency phase by cloudshine or groundshine D_{ext} and the effective dose from materials that were inhaled $D_{inh,t}$ [Sv] and $D_{50.1}$ is the dose to the organ which would induce a given health effect in one half of the population receiving this dose [Sv].

In terms of early fatalities, early stage deaths are caused by the dose received by red marrow, lungs and gastrointestinal tracts (not considered here), so the total hazard for fatality is the sum of the hazards from those three sources.

$$H_{EF} = H_R + H_L + H_{GI} \tag{18}$$

When the cumulative hazard is calculated from equation (19).

$$H = (ln2)\, X^{\beta} \tag{19}$$

Where

$$X = \frac{D_{ext}}{LD_{50}} + \sum_{t=1}^{n} \frac{D_{inh,\,t}}{LD_{50}} \tag{20}$$

Where LD_{50} is a median lethal dose, the dose causing fatality in one half of the population affected by a specific dose.

For cancer risk, the following three equations are used for modeling:

$$r_i = aD_i\,(b + cD_i) \quad \text{if} \quad D_i < 1.5\ Sv \tag{21}$$

$$r_i = aD_i \quad \text{if} \quad D_i \geq 1.5\ Sv \tag{22}$$

$$r_i = abD_i \quad \text{if} \quad D_i \ \text{is a chronic dose} \tag{23}$$

The coefficients a, b and c depend on the organ and their exemplary values may be found in [3].

Table 5: Containment release categories and associated frequencies [6]

Containment release category	Frequency	% of Core Damage Frequency (CDF)	% of Large Release Frequency (LRF)
BP	1.1E-8	4.4	54
CFL	3.5E-13	<0.1	<0.1

2.9. Accident categories

The scope of this paper embraces the two most dangerous accidents defined in the Westinghouse documentation [6]. The main difference between them from a simulator's point of view is the release fraction of each nuclide group, but other differentiating factors involved are duration and release heat rate. Short descriptions of the accidents follow, which are then subject to further considerations and Table 5 presents their frequencies:

BP—Containment bypass—Large release
Fission products are released directly from the RCS to the environment via the secondary system or other interfacing system bypass. Containment failure occurs prior to onset of core damage.

CFL—Late containment failure—Large release
Late containment failure is defined as containment failure postulated to occur later than 24 hours after the onset of core damage. This failure mode occurs only from the loss of containment heat removal via failure of the passive containment cooling system. The fission products that are airborne at the time of containment failure will be discharged at high pressure to the environment, as the containment blows down. Subsequent release of fission products can then pass directly to the environment.

The release to the environment is expressed as a fraction of the total amount of nuclides available in the reactor. The crucial data associated with release category, including release fractions for each nuclide group, timeframe and release heat rate are presented below. For simplification purposes, the Westinghouse four plumes have been collapsed into two plumes. Table (6). presents the data regarding the accidents which is key to performing the simulations.

The accidents are obviously associated with release of radioactive materials to the environment. The isotopes were assigned to groups in accordance with Table (4). The fractions of specific groups are presented in Table (7).

3. Results

The ATMOS module results present the mean centerline air and ground level concentrations of the four most significant radionuclides: iodine isotope I-131, strontium Sr-90 and two isotopes of cesium Cs-134 and Cs-137. In general terms, the results from EARLY module present data about the number of different health symptom cases and doses received, also regarding the total effective 50-year dose.

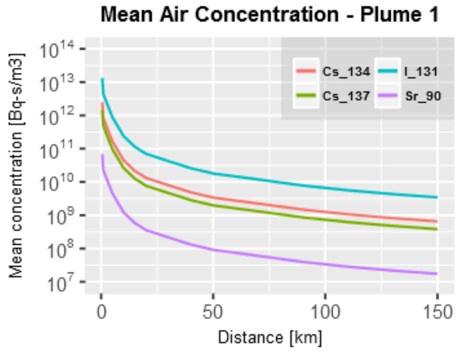

Figure 3: Mean air concentrations of radionuclides for first plume

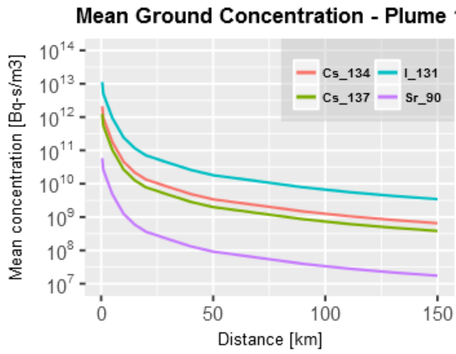

Figure 4: Mean ground concentrations of radionuclides for first plume

3.1. BP

Figures 3 to 6 present the semi-logarithmic functions of four isotopes concentration against the distance from the source. The isotopes chosen were I-131, Cs-134, Cs-137 and Sr-90 as the ones having a major health impact on people affected by radiation.

Fig. 7 presents the distribution of the maximum equivalent 50-year dose ICRP60ED in the elements of the spatial grid for BP.

Table 8 presents the health effects and the mean number of people affected in the whole computational domain for BP.

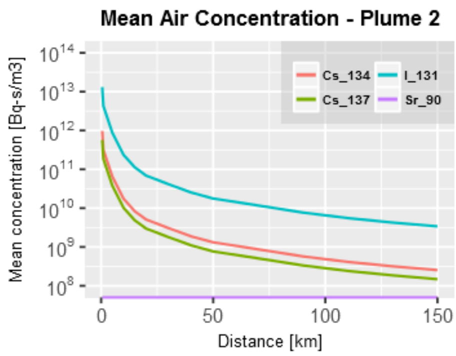

Figure 5: Mean air concentrations of radionuclides for second plume

Table 6: Data regarding the release categories [1]

Release category	Release start time of first plume, s	Duration time of first plume, s	Release heat rate of first plume, W	Release start time of second plume, s	Duration time of second plume, s	Release heat rate of second plume, W
BP	31890	40050	3.00E+06	46440	86400	2.00E+06
CFL	2922	81640	3.00E+06	26360	86400	2.00E+06

Table 7: Fractions of released groups of isotopes [1]

	BP	CFL	BP	CFL
	First Plume Segment		Second Plume Segment	
Noble Gases	1.00E+00	1.53E-03	0.00E+00	9.79E-01
Cs Group	1.96E-01	1.15E-05	7.60E-02	1.19E-05
Sr Ba Group	1.25E-02	3.35E-05	0.00E+00	5.43E-03
Iodines	2.15E-01	1.21E-05	2.34E-01	2.13E-05
Te Group	9.39E-03	1.02E-06	6.89E-03	3.67E-05
Noble Metals	4.48E-02	1.71E-05	0.00E+00	1.42E-03
Ce Group	3.19E-06	4.79E-08	1.00E-06	5.34E-04
La Group	1.30E-04	1.17E-05	0.00E+00	1.41E-01
Total	1.48E+00	1.61E-03	3.17E-01	1.13E+00

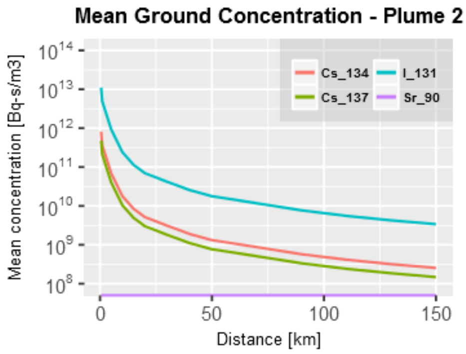

Figure 6: Mean ground concentrations of radionuclides for second plume

3.2. CFL

Analogical calculations were performed for CFL release category (Figures 8–12 and Table 9).

4. Discussion

Accidents at nuclear power stations may impact human health. Releases of radioative material may range in impact from almost imperceptible to severe widespread damage. The results presented above form the basis for evaluating the considered release categories in terms of their impact on the environment. Almost all of the presented release categories entail serious health consequences.

The order of isotopes concentration is preserved in almost all release categories. Isotope of iodine I-131 has the highest concentration for all investigated cases except the second plume segment of late containment failure. Strontium Sr-90 is the second most concentrated isotope in most cases, then cesium Cs-134 and Cs-137. For the second plume segment, the concentration in air and at ground-level is equal to 0. Both types of concentration are proportional to the fraction of released nuclides.

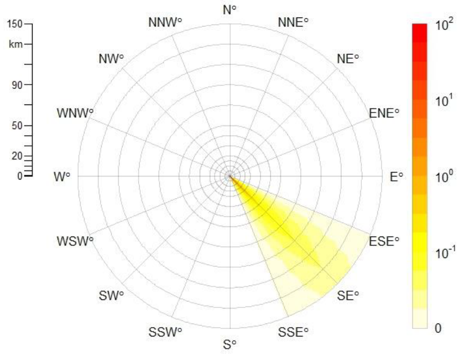

Figure 7: Distribution of maximum effective 50-year dose (ICRP60ED) in [Sv] for BP

Table 8: Number of people affected by ailments in the range of whole domain for BP

Type of ailment		Range, km	Average no. of cases
CAN	FAT/LEUKEMIA	0–150	42.14
CAN	FAT/BONE	0–150	4.086
CAN	FAT/BREAST	0–150	36.72
CAN	FAT/LUNG	0–150	2138
CAN	FAT/THYROID	0–150	173.9
CAN	FAT/COLON	0–150	84.18
CAN	FAT/LIVER	0–150	4.201
CAN	FAT/PANCREAS	0–150	47.01
CAN	FAT/STOMACH	0–150	33.79
CAN	FAT/OTHER	0–150	497.8
CAN	FAT/TOTAL	0–150	3062
CAN	INJ/BREAST	0–150	67.86
CAN	INJ/THYROID	0–150	1988
CAN	INJ/TOTAL	0–150	2056

Assumed weather conditions cause all plume segments to move towards large population agglomerations: Gdansk, Gdynia and Sopot. This urban conglomeration lies at a distance of around 70 km from the nuclear facility. The relatively small distance results in high concentrations over these areas. The mean air concentration of specific isotopes decreased by about 900 times over that distance and mean ground-level concentration decreased by about 750 times. Nevertheless, the health risk remains high, as is clearly shown in the EARLY results section.

Of the cases investigated CFL demonstrably has the highest dose (about 563 mSv). In another accident, BP—87.2 mSv. The striking difference between CFL and BP is associated with the great fraction of isotopes from the La Group, for example the daughters of Nd-147 such as Pm-147 and Sm-147. Observed doses are not negligible and can cause very serious diseases, as is presented in the tables showing health-effect cases.

CFL causes the greatest magnitude of death toll, as expected. Furthermore, BP and CFL cause much more cancer

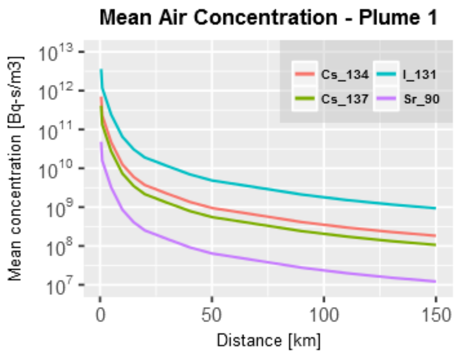

Figure 8: Mean air concentrations of radionuclides for first plume

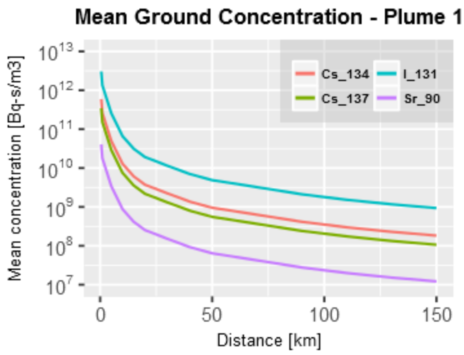

Figure 9: Mean ground concentrations of radionuclides for first plume

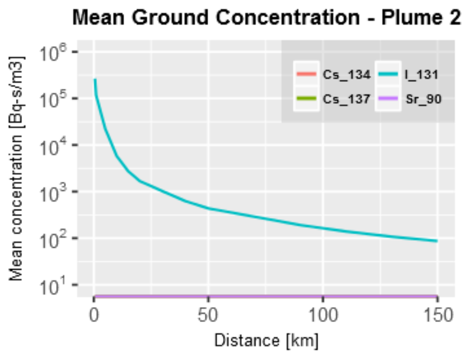

Figure 11: Mean ground concentrations of radionuclides for second plume

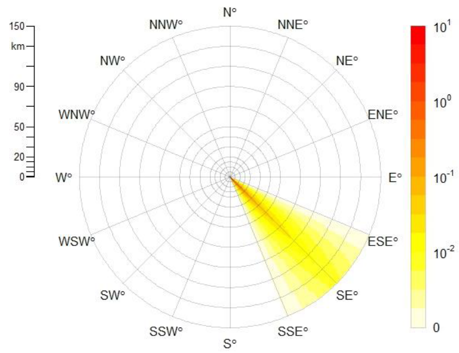

Figure 12: Distribution of maximum effective 50-year dose (ICRP60ED) in [Sv] for CFL

injuries. It is worth noting that fatal health consequences in such conditions are much more sensitive to the La Group fraction than others, whereas early cancer injuries correspond to the amount of Noble Gases, Iodines and Cs Group nuclides released.

The highest doses are absorbed by the organs exposed to radiation due to external exposure and inhalation. Skin, lungs and thyroid are the most exposed organs, assuming no food and water ingestion. Doses absorbed by the thyroid correspond to the released fraction of Iodines. Skin and lung doses are a combination of many factors, hence the direct influence of specific nuclide group cannot be indicated.

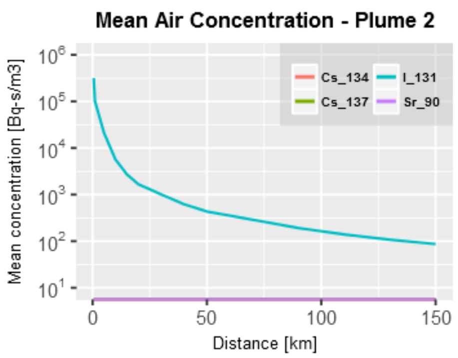

Figure 10: Mean air concentrations of radionuclides for second plume

The mortality results in each accident case were compared with natural mortality. The doses are specified for various organs or the whole-body 50-year effective dose (ICRP60ED). Natural current mortality caused by cancers from regions of Poland [7] was chosen as reference data. The number of cancer cases is estimated for a 50-year period post-accident at three distance ranges: before (0–40 km), in (40–90 km) and beyond (90–150 km) the Gdansk, Gdynia, Sopot conglomeration. The comparison of relative number of deaths with natural cancer mortality is shown in Table 10. In BP case, there is expected mortality

Table 9: Number of people affected by ailments in the range of whole domain for CFL

Type of ailment		Range, km	Average no of cases
CAN	FAT/LEUKEMIA	0-150	1435.8
CAN	FAT/BONE	0-150	1530.8
CAN	FAT/BREAST	0-150	51.4
CAN	FAT/LUNG	0-150	30309.0
CAN	FAT/THYROID	0-150	2.9
CAN	FAT/COLON	0-150	155.3
CAN	FAT/LIVER	0-150	347.1
CAN	FAT/PANCREAS	0-150	479.0
CAN	FAT/STOMACH	0-150	61.7
CAN	FAT/OTHER	0-150	6049.0
CAN	FAT/TOTAL	0-150	40356.0
CAN	INJ/BREAST	0-150	94.9
CAN	INJ/THYROID	0-150	33.6
CAN	INJ/TOTAL	0-150	128.5

Table 10: Comparative mortality by cancers per 100,000 people in Poland against simulation results

Type of cancer	Deaths per 100,000 currently (50 year)	Deaths per 100,000 in case CFL	Deaths per 100,000 in case BP
Breast	1110	3.792	2.710
Lung	2580	2236.886	157.785
Colon	1095	11.461	6.213
Stomach	545	4.556	2.494
Total	10075	2977.840	225.976

of about 226 per 100,000 people in radiation danger; in CFL case, this figure is almost 2980 per 100,000, which is about 30% of natural current mortality caused by cancers.

5. Conclusions and Summary

The aim of this study was to construct a model and perform simulations of release of radioactive materials from an assumed nuclear power plant located in Lubiatowo, Poland, one of two considered locations of an actual future facility. The Westinghouse AP1000 reactor at issue is not yet operational, but there are a few units under construction in China. The AP1000 documentation described 6 possible accidents with frequencies of occurring and crucial data required to perform simulations.

The simulations included complex calculations of isotope concentration distribution, doses absorbed by specific organs, the effective 50-year dose and associated health consequences occurring up to 50 years after the accident. The results presented in this paper are considered at a distance of 150 km from the power plant, assuming adverse steady weather conditions in the direction where the largest agglomerations of population are located. Additionally, an evacuation procedure was implemented for two scenarios, enabling a comparison of the results obtained.

The simulations show that thousands of people could be directly affected by the consequences of radiation. The types and numbers of ailments depend on the specific scenarios. Some cause negligible effects, whereas others indicate very high mortality and numbers of injuries. Nevertheless, the relative number of deaths due to cancer is only slightly higher than natural. In most cases, the total number of deaths per 100,000 does not exceed 30% in comparison with natural current mortality caused by cancers. The worst CFL accident is very dangerous if no preventive actions are taken, but assuming simply relocation of people to safe areas CFL becomes much safer than others. Thus, to mitigate the consequences of any possible future accident, evacuation plans must be drawn up in advance and if needs be actioned with utmost urgency. Additional shielding and protective measures may reduce the number of victims to a minimum.

The performed simulations are merely a visualization of estimated possible effects of a real accident. The actual effect depends on too many different variables and is impossible to measure. The sources of uncertainty are as follows: many simplifying assumptions, especially weather conditions, imperfect knowledge of the release process, quality of the computational grid and corresponding data, e.g., population in each sector, as well as MACCS software limitations. However, MACCS2 is a great tool for assessing the impact of radioactive material release accident, forming a basis for further considerations. Analysis shows that the lethality and incidence of cancer caused by radioactive release is significantly lower than natural.

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Nomenclature

$\bar{u}$ — mean windspeed, m/s

$\chi(x, y, z)$ — time-integrated concentration at the downwind location, Bq s/m^3

Λ — washout function, s^{-1}

λ_e — effective decay constant, s^{-1}

σ_y — standard deviation in y direction, m

σ_z — standard deviation in z direction, m

$\triangle h$ — height of the plume rise, m

υ_d — dry deposition velocity, m/s

a — coefficient for standard deviation equations/coefficient for risk equation, -/-

AC_i^c — time-integrated air concentration of radionuclide i at the plume centerline, Bq s/m^3

b — coefficient for standard deviation equations/coefficient for risk equation, -/-

BR — user specified breathing rate, breaths/min

C — off-centerline correction factor or finite cloud dose correction factor, -

c coefficient for standard deviation equations/coefficient for risk equation, -/-

D absorber dose, Gy

d coefficient for standard deviation equations, -

$D2$ one week dose from groundshine to organ, Sv

$D_{50,1}$ dose to the organ which would induce certain health effect in half of population receiving this dose, Sv

D_{ext} external dose delivered to the organ during emergency phase by cloudshine or groundshine, Sv

$D_{inh,t}$ effective dose from materials that were inhaled, Sv

D_{tot} sum of external dose delivered to the organ during emergency phase by cloudshine or groundshine and the effective dose from materials that were inhaled, Sv

D_{TR} groundshine dose when the plume is passing, Sv

DC_k cloudshine dose, Sv

$DFC_{\infty ik}$ time-integrated air concentration of radionuclide i at the plume centerline, Bq s/m^3

DFI_{ik} inhalation dose conversion factor for either early or lifetime dose, Sv/Bq inhaled

DFS_i skin dose conversion factor, Sv .m^2/Bq

DG_1^k groundshine dose when the plume is passing, Sv

DG_k^2 groundshine dose to organ k when the plume has already passed for a period two time points, Sv

DI_k dose received from inhalation, Sv

DR_k resuspension inhalation dose to organ k, Sv

DS skin dose, Sv

E energy deposited in tissues/equivalent dose, J/Sv

F fraction of exposure duration during the plume passage, equal to ratio of time of exposure to the time in which the plume passes the specific spatial element, -

F height of the column from which the deposition is occurring, m

f_i a fraction of population susceptible to the risk, -

GC_i ground concentration of radionuclides at the time the plume leaves the spatial element, Bq/m^2

$GDR_k(t_o)$ groundshine dose rate to organ k in the specific spatial element in time t_o, Sv/s

H cumulative hazard/wplume release height, -/m

H_T quivalent dose received by tissue, Sv

I intensity of rainfall

J off-centerline correction factor, -

L is the height of the capping inversion layer, m

LD_{50} median lethal dose, the dose causing fatality in a half of population affected by a specific dose, Sv

m mass of medium in which energy is deposited, kg

N_i number of health effect cases, -

P total population exposed, -

Q radioactive material deposited, Bq

Q_0 radioactive material in the cloud, Bq

r_i risk of health effect, -

RF time-integrated resuspension factor, s/m

SFC cloudshine shielding factor, -

t time, s

$T2$ a one week time, s

t_1 tial time of people's presence in the specific area, s

t_2 final time of people's presence in the specific area, s

t_e time at which the plume segment enters this spatial element, s

t_o time when a plume leaves the spatial element, s

w_R radiation weighting factor, -

w_T tissue weighting factor, -