Modeling of a Hypothetical Major Nuclear Accident in Poland from 1096 Meteorological Situations and Analysis of Transboundary Environmental Impacts for European Countries and Their Inhabitants

Piguet Frédéric-Paul[1][i], Eckert Pierre[ii], Knüsli Claudio[iii], Hélder Peixoto[iv], Giuliani Gregory[iv]

First Version: 2021.01.11

[i] *Institut Biosphère*, Geneva; [ii] Geneva; [iii] IPPNW (Suisse), Luzern; [iv] Institute for environmental sciences, University of Geneva.

Commissioning Organization: Grünen Bundestagfraktion, Berlin[2]

---

[1] Corresponding author: Frédéric-Paul Piguet, Institut Biosphère, CH-1226 Geneva, fppiguet@institutbiosphere.ch

[2] Grünen Bundestagfraktion, Fraktionsgeschäftsführung, Dorotheenstrasse 101, DE-10117 Berlin, Deutschland

Executive Summary

The purpose of this analysis is to study the transboundary radioactivity that would be linked – in the event of a hypothetical major accident – to the nuclear power plant projected by the Polish government in the region of Zarnowiec-Kopalino, some 70 kilometers from Gdansk, close to the front of the Baltic sea. The transport of radioactive material across borders can impact the population's health, pollute soils and trigger long-lasting evacuation of populations – among other hazards. The question is whether and, if so, to which extent a major nuclear accident from the Zarnowiec-Kopalino area could trigger important transboundary damages to the inhabitants of neighboring countries.

Through meteorological simulations of the transport of radioactive materials from an hypothetical damaged nuclear reactor, the study focuses on a first circle of four regions around Poland: Germany (West), Denmark and Sweden (north), Kalinigrad-Oblast, Lithuania and Latvia (east), Czechia, Slovaquia, Ukraine and Belarus (south and southeast); It also looks at more than 30 European countries with the purpose to provide a full picture of the potential environmental damage on health. The study models a major nuclear accident using 1096 meteorological files from year 2017 to year 2020, with help of the trajectory and dispersion model *Hysplit*. The total release amounts to 2.72E+18 Becquerels. The 22 nuclides of the source term of the simulated accident were analyzed together with the 23 radioactive nuclides produced by the source nuclides of the source term produce all along their decay process (and during the lapse of time of the simulation). Conversion of radiation from Becquerel to Sievert was established according to the literature, from the perspective of the yearly dose limits set by Council Directive 2013/59/Euratom to protect the public and the professionals in occupational or emergency activity (1 mSv, 6 mSv, 20 mSv, 50 mSv, 100 mSv and 500 mSv). This procedure was carried out so as to clarify the scientific results through a deeper understanding of the norms in use. To assess the impact on population, demographic data were treated by a geographical information system GIS software called *ArcGIS* as well as with the help of C-programs. Health effects of ionizing radiation were estimated from the collective committed effective dose (CCED) impacting the population exposed to the 72h of simulation of each radioactive cloud as well as ground surface deposition during the course of one year. The global health effects were used in connection with three risk models for different issues: cancer, cardiovascular and other non-cancer diseases, genetic and other detriments.

The main results are as follows: a large part of the collective committed effective dose that increases the occurrence of severe diseases among the population could greatly adversely impact the inhabitants of Poland and beyond. On average, we found that, in case of a major nuclear accident, 3/5 of the radio-induced severe diseases (cancer, cardiovascular diseases and the related radio-induced deaths) would occur outside Poland. More specifically, in 756 out of 1096 meteorological situations (69%), at least one of the four regions around the still in project Zarnowiec-Kopalino NPP would receive a higher collective committed dose than Poland, while in 76% of the meteorological situations 30 countries together would receive a higher CCED than Poland. From the perspective of limits on public exposure, figures show that more than 7 million people located in 31 European countries (including Poland) would receive an ionizing radiation dose ≥ 1 mSv. To compare with the limit that is set at 6 mSv for students or apprentices aged ≥ 16 and ≤ 18 years in the course of their studies if obliged to work with radiation sources, one of our results is that an ionizing dose ≥ 6 mSv could impact, on average, more that 860 000 Europeans (of all ages), of whom 400 000 in Poland, 112 000 in Germany, 127 000 in Kaliningrad, Lithuania and Estonia, 113 000 in Denmark and Sweden and 53 000 in Czechia, Slovaquia Ukraine and Belarus. With regard to the legal limit fixed at 20 mSv in any single year for adults in professional exposure as well as for emergency occupational whose exposure should remain, whenever possible, below 20 mSv, it is interesting to take note that 150 000 individuals (including children and teenagers) could be impacted by the radioactive cloud, on average, at the European scale, above this limit. In addition, from the perspective of the need to preserve people from the risk of radioactive ground deposition and relocate them outside contaminated areas for a period of time ranging from several months to more than one year, at the scale of the 31 countries and on average, figures were above 125 000 and 40 000 persons, for a limit set respectively at 20 mSv and 50 mSv. As a consequence, in taking into account the relocation of inhabitants living in areas where the individual dose would exceed 20 mSv per year, the number of radio-induced cancers and cardiovascular diseases would amount, on average, to 28 000, while the number of deaths would exceed 13 000.

It seems clear, from these figures and the related simulations, that if the Zarnowiec-Kopalino NPP project would finally be realized, it would constitute a potential source of radioactive transboundary pollution for many European inhabitants.

I Context

1.1 Scope of the study

The purpose of the analysis is to study the transboundary radioactivity that would be linked – in the event of a hypothetical major accident – to the nuclear power plant projected in the region of Zarnowiec-Kopalino, Poland, some 70 kilometers from Gdansk. Several studies have already looked at the health impact of a nuclear accident from this region (Seibert, Hofman & Philipp 2014; Mazur 2019), but they did not specifically address the risks of contamination beyond the Polish borders. Our intention is to fill this gap. The transport of radioactive material across borders following a major nuclear accident can be considered from the perspective of different types of impacts. These include the health impact on the population, the pollution of soils, aquifers and the long-lasting displacement of populations, as well as the economic consequences on agriculture, tourism and other activities, etc. The following study will focus more particularly on the health impact on populations as well as on soil pollution.

Table 1.1. Transport of radioactive material within and outside the borders of Poland: geographical area of reference for this study

No	Country (or region)	Grouping
1	Poland	POL
2	Germany	DEU
3	Kaliningrad-Oblast (Russia)	KLL
4	Lithuania	
5	Latvia	
6	Sweden	SDE
7	Denmark	
8	Czechia	CSUB
9	Slovakia	
10	Ukraine	
11	Belarus	

Germany is on Poland's western border, KLL in the east, SDE in the northwest and CSUB in the south and southeast.

In order to limit the number of results to be published and to issue a readable report, we have selected eleven countries whose territory is less than 400 kilometers from the site of the first Polish nuclear power plant, or whose territory is adjacent to the Polish border. Table 1.1 shows the list of countries and the criteria that were followed when establishing that list. In addition to this table, 31 European countries were gathered together in order to grasp the transboundary dimension of the transport of radioactive nuclides caused by such a major accident.

1.2 Ionising radiation – health hazards – Importance of epidemiology, linear no threshold model (LNT) and beyond

Health risks (HR) of ionizing radiation (IR) have first been described in the 19th century (Edison 1896) (Doll 1995, 1339-1349). Studies on genetic effects by IR followed (Muller 1928, 714). HR in humans due to IR have been analyzed in radio-diagnostics (Giles 1956, 447; Stewart 1958, 1495-1508; Pearce 2012, 499-505; Mathews 2013, f2360), in in Japanese nuclear bomb survivors (Ozasa et al. 2012, 229-243), in nuclear workers (Richardson et al. 2015, h5359; Leuraud 2015, e276-e281; Gillies 2017, 276-290), in people exposed to radon gases (Darby 2005, 223) and in children with respect to background radiation (Kendall 2013, 3-9; Spycher 2015, 622-628).

Collective dose calculations have been proven useful in IR risk estimations for exposed populations. Extensive epidemiological studies (National Cancer Institute 2020; Linet et al. 2020; Schubauer-Berigan et al. 2020; Berrington de Gonzalez et al. 2020; Hauptmann et al. 2020; Daniels et al. 2020) on HR induced by IR have confirmed the LNT (Linear No Threshold) model (BEIR VII 2006a; BEIR VII 2006b, 1-4; Shore 2018, 1217) in the low dose range (below 100 millisieverts, mSv). According to LNT even very small doses of 1 mSv and below result in elevated HR (cancer, non-cancer diseases and detrimental effects on the reproductive process).

The internationally legally binding limit of exposure to artificial sources is 1 millisievert/year (mSv/a) per person (infra 1.5(ii), 2.6(iii)). However, NPP accidents (Chernobyl 1986, Fukushima 2011) led to individual IR exposures of mainly below 100 mSv or above this level for many millions of residents (Cardis 1996, 241-271; WHO 2013; IPPNW 2016).

1.3 Calculation from the perspective of a European directive and provisions

It is important for any study on environmental risk and ionizing radiation to adopt an interdisciplinary approach and to look at norms and regulations before structuring the data. Legal information helps to determine what is the real issue and to shape the categories that are of interest for decision-makers and civil servants in charge of the protection of the population.

Table 1.2 shows clearly the structure of the limits on the effective dose related to ionising radiation that shall be respected and adapted to different circumstances. If the limit protecting the public is set at 1 mSv for any single year, it is established between 20 and 100 mSv in an emergency situation due to a severe nuclear accident (Art. 53.2(a)), while it could exceed 100 mSv in case of a major nuclear accident deemed to be very unlikely.

Table 1.2. Limits on the effective dose according to Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation (European Union 2013)

(mSv)	Yearly public exposure and yearly professional exposure	Professional exposure in special circumstances	Emergency occupational exposure for the public	Emergency occupational exposure for emergency workers
≤ 500				In order to save life in exceptional situations, the reference level for emergency workers shall not exceed 500 mSv (Art. 53.2(b))
≤ 100			Reference levels for emergency occupational exposure shall be set, in general below an effective dose of 100 mSv (Art 53.2(a))	
≤ 50		The limit shall be 50 mSv for professionals in special circumstances if the average annual dose over any five consecutive years, including the years for which the limit has been exceeded, does not exceed 20 mSv (Art. 9.2)		
≤ 20	The limit shall be 20 mSv in any single year for adults in professional exposure (Art. 9.2)		Emergency occupational exposures shall remain, whenever possible, below 20 mSv (Art 53.1 → Art. 9.2)	
≤ 6	The limit shall be 6 mSv for Students or apprentices aged ≥ 16 and ≤ 18 years in the course of their studies if obliged to work with radiation sources (Art 11.2)			
≤ 1	The limit shall be 1 mSv for any single year (Art. 12)			

Annex 1 of the Council Directive 2013/59/EURATOM states that, 1) for existing exposure situations, reference levels expressed in effective doses shall be set in the range of 1 to 20 mSv per year; (…); 3) For the transition from an emergency exposure situation to an existing exposure situation, appropriate reference levels shall be set, in particular upon the termination of long-term countermeasures such as relocation. 4) The reference levels set shall take account of the features of prevailing situations as well as societal criteria, which may include the following: (…); (b) in the range up to or equal to 20 mSv per year, specific information to enable individuals to manage their own exposure, if possible; (c) in the range up to or equal to 100 mSv per year, assessment of individual doses and specific information on radiation risks and on available actions to reduce exposures.

Similarly, as stated in Annex 1 of the Council Directive, relocation after an emergency exposure can be set from a yearly exposure of 20 mSv, or till 100 mSv with a specific accompaniment.

Despite the need for adaptation to circumstances and despite the fact that limits set between 1 and 6 mSv have no legal significance in case of a major nuclear accident, all the limits specified by Council Directive 2013/59/EURATOM show that doses above 1 mSv should not impact the public and that, more generally, thresholds in the two left columns are also of symbolic, scientific and moral significance: they are the gate keeper to protecting individual and public goods: > 6 mSv breaches students and apprentices interests (and the public good); > 20 mSv breaches professional's interest (and the public good); etc. All in all, legal provisions on emergency situations are somewhat completed by the provisions on yearly public exposure. Therefore, almost all reference thresholds of the present study come directly from the Directive on ionizing radiation, so that the public, decision maker and the media can understand the results of the simulation from the legal and moral perspectives besides the scientific one[3].

---

[3] This is interdisciplinarity in an interconnected world.

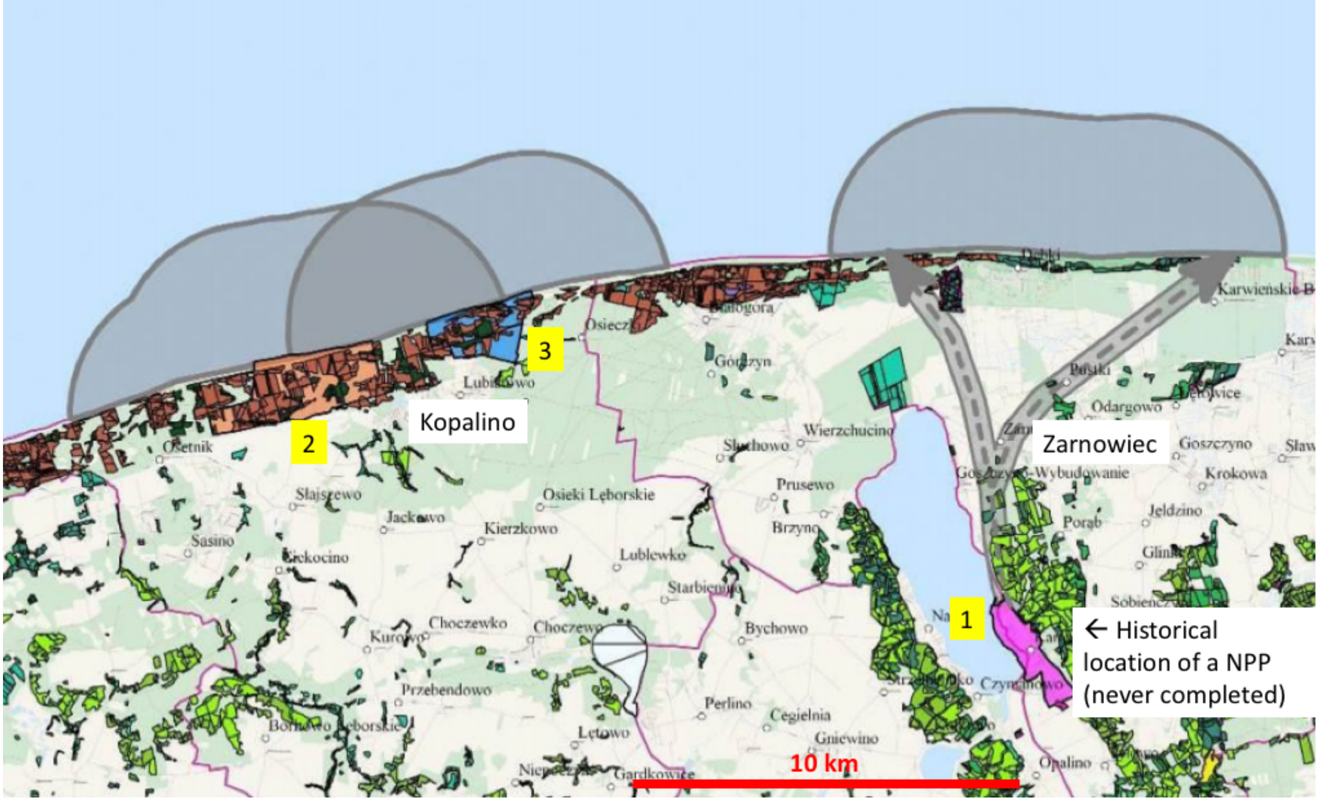
1.4 *The Current Project of a Polish NPP*

(i) Nuclear ambition

The Polish Government has confirmed several times his intention to plan and build several nuclear reactors, the first unit being scheduled for grid connection in 2033, and the next five, every two years till 2043 (Ministry of Energy 2018, 4). It also confirmed that the first NPP location is to be the Zarnowiec or Lubiatowo-Kopalino (Monitor Polski 2020, 15, 16).

(ii) Zarnowiec-Kopalino location of the projected plant

Historically, the first attempt to build a nuclear power plant in Poland was set up in Zarnowiec, near a small lake, 70 kilometers far from Gdansk. The decision on the location was taken in 1972 and the project was finally abandoned by the Council of Ministers (Wikipedia 2020) after the advice of the Minister of Industry, Tadeusz Syryjczyk (1999, 115). As the three possible sites of the new facility are very close, and due to the historical attempt to build a NPP in Poland, we will name the site Zarnowiec-Kopalino. In the 1096 simulations of the present study it is located near Kopalino (lat. 54.8026; long. 17.8437), which seems to be a better location than Zarnowiec to get sea water necessary for cooling the reactors.



Map 1 (PGE Group 2015), with some adaption of our own. The historical site of Zarnowiec (1) is still envisaged as a possibility to be the location of a nuclear power plant. Two other variants (2) and (3), closer to the sea, therefore easier to cool could attract the government's final choice. In this study, we ran our simulations from the Kopalino variant. Due to the historical precedent of the construction of a NPP in this area – even if never completed – we keep the name and specify the variant we study as such: Zarnowiec-Kopalino.

(iii) The Reactor model that could be built at Zarnowiec-Kopalino

It is stated by officials that the Polish nuclear reactor should amount between 1000-1600 MWe (Monitor Polski 2020, 13). October 19th 2020, the Polish government concluded a cooperation agreement on nuclear energy with the government of the United States, which stated that Westinghouse will participate in an engineering study for the planned nuclear power plants on the nuclear programme (NEI 2020). The reactor is not yet chosen, there is nonetheless ample evidence that AP1000 model, by Westinghouse, is the one most likely to be chosen by nuclear authorities at the end of the evaluation process. AP1000 has already mentioned in several documents both official and unofficial, pertaining to this nuclear ambition for many years (Sholly et al. 2014, 11; PGE Group 2015, 64; Monitor Polski 2020, 13).

The Westinghouse AP1000 2 Loops, is a PWR of third generation (III+) with a thermal power of 3400 MWth and a net capacity of 1100 MWe (U.S.NRC 2007). In the present study, it is the reference reactor in the selection process of a relevant source term to assess the possible consequences of a major nuclear accident by a NPP that would be located at Zarnowiec-Kopalino.

(iv) Source term of a major nuclear accident

This study takes into account the AP1000 source term detailed by Sholly et al. (2014, 31-32) since it matches the severity of a major nuclear accident. We explain below how the nuclides were aggregated in the simulation and how we accounted for the progeny of parent's nuclides (infra 2.2).

The list of 22 nuclides is the following: I-131[4], Cs-134, Cs-136, Cs-137, Rb-86, Sb-127, Te-127M, Te-129M, Te-132, Ba-140, Sr-89, Sr-90, Mo-99, Ru-103, Ru-106, Ce-141, Ce-144, Np-239, Pu-238, Pu-239, Pu-240, Pu-241.

The total release amounts to 2.72E+18 Becquerels (Bq). See Table A.1 in Annex A for the amounts and half-lives of each nuclide.

II Methodology

2.1 Outline of the methodology questions

A few methodological points are discussed below: the quantities of Becquerels used in the simulations (source term study) (infra 2.2); the physical coefficients of the dispersion of rare gases and aerosols in the atmosphere (deposition velocity, in-and below-cloud removals) (2.3); the consideration of meteorological data and their influence on the results (2.4); the assessment of impacted people, soils and countries using a Geographic Information System (2.5); the calculation that allows to use Becquerels to calculate the collective committed effective dose (CCED) received by the populations and the calculation performed to compare individual CED to the legal limits in mSv (2.6); the health impact and the related number of radio-induced diseases (2.7). Only an interdisciplinary approach can carry out such a questioning.

2.2 Source term

(i) Aggregation of the source term

The total release amounts to 2.72E+18 Becquerels (Bq) (*supra* I.4(iii)). This section aims to define how nuclides released from the reactor pressure vessel into the environment have been aggregated by keeping coherent and correct figures, without any significant bias. This question is of utmost importance for determining the clouds that were simulated over 72 h (2.59E+05 s) through 1096 meteorological situations. The list of nuclides was limited to nuclides with a half-life ≥ 2.04E+05 (s), which implies the shorter half-life nuclide to be included in the list is Np-239.

As the addition of two or more logarithmic curves never yields a logarithmic curve, we had to verify a first criterion: that the deviation of the decreasing curve of the total Becquerel does not deviate more than 3% from a reference logarithmic curve (whose half-life was found to be 7.35E+05 s for the present source term).

This criterion being satisfied, it became possible to approach the radioactive nuclides resulting from the decay of the elements listed in the source term. All radioactive elements decay into other nuclides (which are not always radioactive themselves). The relationship between the 'parent nuclide' and its 'progeny' is known and described (EPA 2019a). In the present case, 17 out of the 22 nuclides of the source term trigger 23 radioactive nuclides: Xe-131m, Ba-137m, Te-127, Te-127m, Te-127, Te-129, I-129, I-132, La-140, Y-90, Tc-99, Tc-99m, Rh-103m, Rh-106, Pr-144, Pr-144m, Pu-239, U-234, U-235m, U-235, U-236, Am-241, U-237 (see additional details in Table A.2 in Appendix A.

Given a simulation over 72 hours, we estimated briefly the change in the composition of the cloud during this lapse of time.

(ii) Verification of a possible bias to be eliminated

More specifically, the evolution of the radioactive cloud, modelized as a curve expressed in Bq over 72h, should be compared to the millisieverts a 'fictitious individual' would receive from the source term

---

[4] Nuclide I-131 is only considered as an aerosol in our calculation.

transported by the cloud, and the decay of the source term into new radioactive elements every two hours (for control).

As it appears, the curve of the nuclides of the source term considered with the curve of the 'progeny' and summed in millisieverts decreases a bit less than the curve of the source term modelized in Becquerels. The value in millisieverts of the last two hours of the simulation represents 83% of the value in millisieverts of the first two hours, while the curve of the source term expressed in Becquerels ends at 78% of its initial value.

(iii) Accuracy or inaccuracy of the present method

On the one hand, a model lowering by 5% the amount of mSv at the end of the cloud trajectory should be avoided. On the other hand, that approach makes it possible to run the simulations with more nuclides, while the source term appears finally more accurate than it would be if limited to one or only three nuclides. Consequently, the approach described above was selected for this study.

2.3 Deposition velocity in- and below-cloud wet removal of different nuclides[5]

(i) Framework

The user of *Hysplit* has to specify the deposition velocity of rare gas, aerosols, and particles that are rejected by a source and dispersed by winds. Furthermore, *Hysplit* requires the in- and below-cloud wet removal/scavenging parameters (Draxler et al., 2018). As these parameters are partly dependent from weather condition, the numbers to be found are indicative and managed by *Hysplit* accordingly.

(ii) Review of the literature

We give below a short review of the literature on the subject in order to specify below the adequate values.

- Cesium: The dry deposition velocity of ^{137}cesium is given by the *Hysplit* dispersion program at 0.001 (m/s) (Stein et al. 2015). However, Guglielmelli et al. (2016) set 0.002 (m/s). Direct observation on the Fukushima accident leads to consider the figure of 0.001 (m/s) is robust for ^{137}Cs, ^{136}Cs and ^{134}Cs (Takeyasu & Sumiya 2014). Wet removal/scavenging in- and below-cloud is set at 8.0E-05 (1/s) by *Hysplit* for ^{137}Cs. For this same isotope, wet in- and below-cloud removal is estimated at 3.5E-05 (1/s) (Guglielmelli et al. 2016), or even at 3.36E-04 and 8.4E-05 respectively (Leadbetter et al. 2015).
- Iodine can be released as gas, aerosol, or both. Considering the uncertainty for the fraction of each form, the Flexrisk report subsumed all iodine under the aerosol species (Seibert et al. 2013). We adopt the same approach and look at the deposition velocity and wet removal accordingly. For the aerosol form of iodine, *Hysplit* puts deposition velocity at 0.001 (m/s) and sets wet removal/scavenging in- and below-cloud at 4.0E-05 (1/s) (Stein et al. 2015).

ENSI admits nonetheless, that the deposition velocity can be given for all aerosols (ENSI 2009, 64). For all aerosols: the deposition velocity is set at 0.0015 (m/s) (ENSI 2009, 64) and the in- and below-cloud removal/scavenging is set at 7.0E-05 (1/s) (ENSI 2009, 65). The latter figures are close to the abovementioned ones on cesium and iodine.

(iii) Parameters of deposition velocity and in- and below-cloud wet removal for aerosols

The selection of the different coefficients affecting the atmospheric dispersion and the deposition of the 32 isotopes of this study is given in Table 2.8. The selected parameters will be used to simulate a major nuclear accident. The selection is made according to the literature, mainly Sander (2015), ENSI (2009), Draxler & Rolph (2012) and Baklanov et al. (2001) (*supra*).

Table 2.8. Parameters of deposition velocity; in- and below-cloud wet removal/scavenging for aerosols

Material	Deposition velocity (m/s)	in- and below-cloud wet removal (1/s)
Aerosols	0.0015	7.0E-05

Together with the release and the duration of the release, the above figures are used by *Hysplit*.

---

[5] That section is an excerpt of the one published in EUNUPRI_2019.

(iv) Deposition velocities on different types of grounds

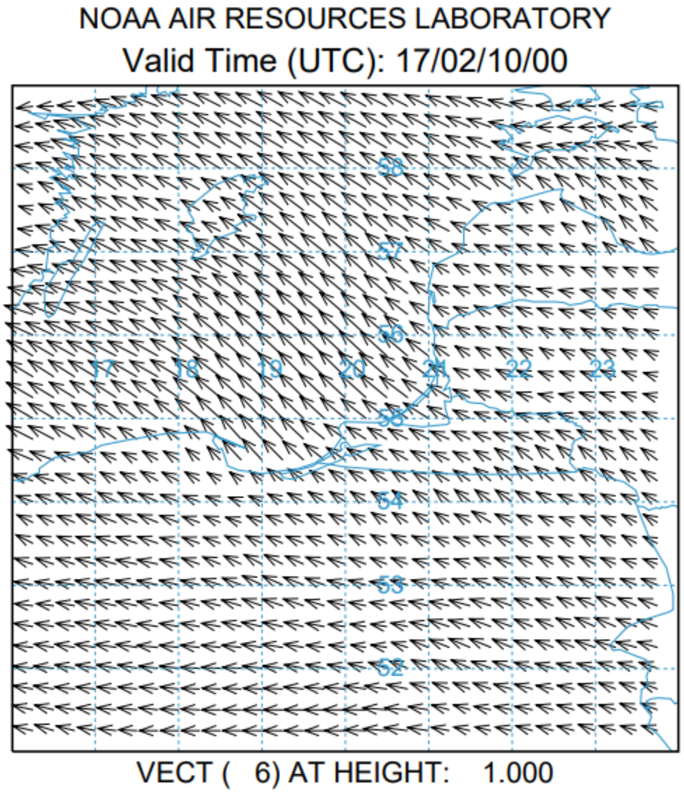
The different kinds of land cover have different abilities to capture radioactive particles. For instance, Sehmel quoted by Takeyasu & Sumiya (2014) give the deposition velocity for ^{137}Cs: 0.0003 – 0.0015 m/s for water, 0.0001 – 0.0009 m/s on 'soil', and 0.002 – 0.005 m/s on grass. These figures nonetheless cannot be generalized. Müller & Pröhl quoted by Baklanov & Sørensen (2001, 789) gave – for aerosol bound radionuclides – a deposition velocity at 0.0005 m/s in case of deposition on 'soil', at 0.0105 m/s for deposition on grass and at 0.0005 m/s on trees, knowing that such figures depend on the size of the deposited particles as well as on the size and development of the foliage of trees. Due to the high complexity and the lack of a systematic data collection on this specific issue, we do not detail the deposition process. Therefore, we publish detailed results concerning land cover in additional files for further analysis.

2.4 Meteorological aspects[6]

(i) What are atmospheric dispersion models?

Atmospheric dispersion models have been developed in the 1980s to study the effects of chemical and nuclear incidents. The aim was not only to predict the evolution of the pollutant cloud, but also to trace back the origin of a pollution in case a signal was observed at an observation point. One of the main triggers to develop this kind of models was the Chernobyl accident in 1986. Simple trajectory models existed at the time which allowed qualitative estimates, but it took a few more years until dispersion models were able to assess the event in a quantitative way (Piedelievre et al. 1990: 1205–1220).

Map 2. Example of wind field on the 17th February April 2017.



There are many different types of dispersion models; for a review see Leelössy et al. (2014, 257-278). Generally, the dispersion models must be characterized firstly by the content (type and mass of the components) and the emission (rate, duration, height). The transport, diffusion and deposition are then driven by the meteorological fields, mainly winds and precipitation (Map 2.A.).

---

[6] Section 2.4 is an excerpt of the one published in EUNUPRI_2019, as sections 2.6 and 2.7.

(ii) Considerations on the resolution of the meteorological fields

Wind fields are rather continuous over flat terrain and water surfaces but can become very complex over mountainous landscapes. On the region under consideration, the terrain is rather flat so that it is unnecessary to use a very high resolution for the wind representation.

We have chosen to use the winds provided by the NOAA at a resolution of 0.25° latitude and longitude (NOAA 2016). Wind forecasts per one hour time sequences are available up to +24 hours by a simple FTP request (NOAA 2018a). In order to reach dispersion patterns over 72 hours, we concatenated 3 consecutive 24-hour forecasts. Wind forecasts over 24 hours can be considered accurate and close enough to the observation. Although less accurate, the same can be assumed for precipitation.

(iii) The Hysplit dispersion model

Hysplit is a trajectory and dispersion model developed by the US National Oceanic and Atmospheric Administration (NOAA). *Hysplit* has been used in a variety of simulations describing the atmospheric transport, dispersion, and deposition of pollutants and hazardous materials. Some examples of the applications include tracking and forecasting the release of radioactive material, wildfire smoke, windblown dust, pollutants from various stationary and mobile emission sources, allergens and volcanic ash.

The dispersion of a pollutant is calculated by assuming either puff or particle dispersion. A collection of particles can be gathered in so called puffs, which are small clouds emitted by the pollution source. They are transported by the wind field and expand due to the atmospheric diffusion. The mean trajectory of the cloud defined by its centroid is computed and the growth is modelled by a Gaussian distribution. In this puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the pollutant mass (NOAA 2018b). In the particle model, a fixed number of particles are calculated in relation to the model domain "by the mean wind field and spread by a turbulent component. The model's default configuration assumes a 3-dimensional particle distribution (horizontal and vertical)" (NOAA 2018b). A full description of the model is given by Stein et al. (2015) (*infra* iv).

(iv) The Hysplit dispersion model evaluated by WMO in the case of Fukushima

The Fukushima accident in 2011 gave an opportunity to assess the various dispersion models. Unlike the Chernobyl case the models have been used in real time in order to protect or evacuate threatened populations. A comparison between dispersion models computed *a posteriori* – using deposition data and meteorological data to calculate atmospheric dispersion back to the source of the release – was carried out for the World Meteorological Organization (WMO) (Draxler et al. 2015). There was not a single ATDM-meteorology combination that provided the best results for both deposition and air concentration predictions. Generally, the *Hysplit* model driven by NOAA meteorological data performed correctly with respect to the other models. It was found that the use of high-resolution mesoscale analyses improved the dispersion model performance; however, high resolution precipitation analyses did not improve the predictions. The Fukushima study showed that the use of meteorological fields with a resolution of 20-50 km is suitable for our purpose.

(v) Production of the immission fields

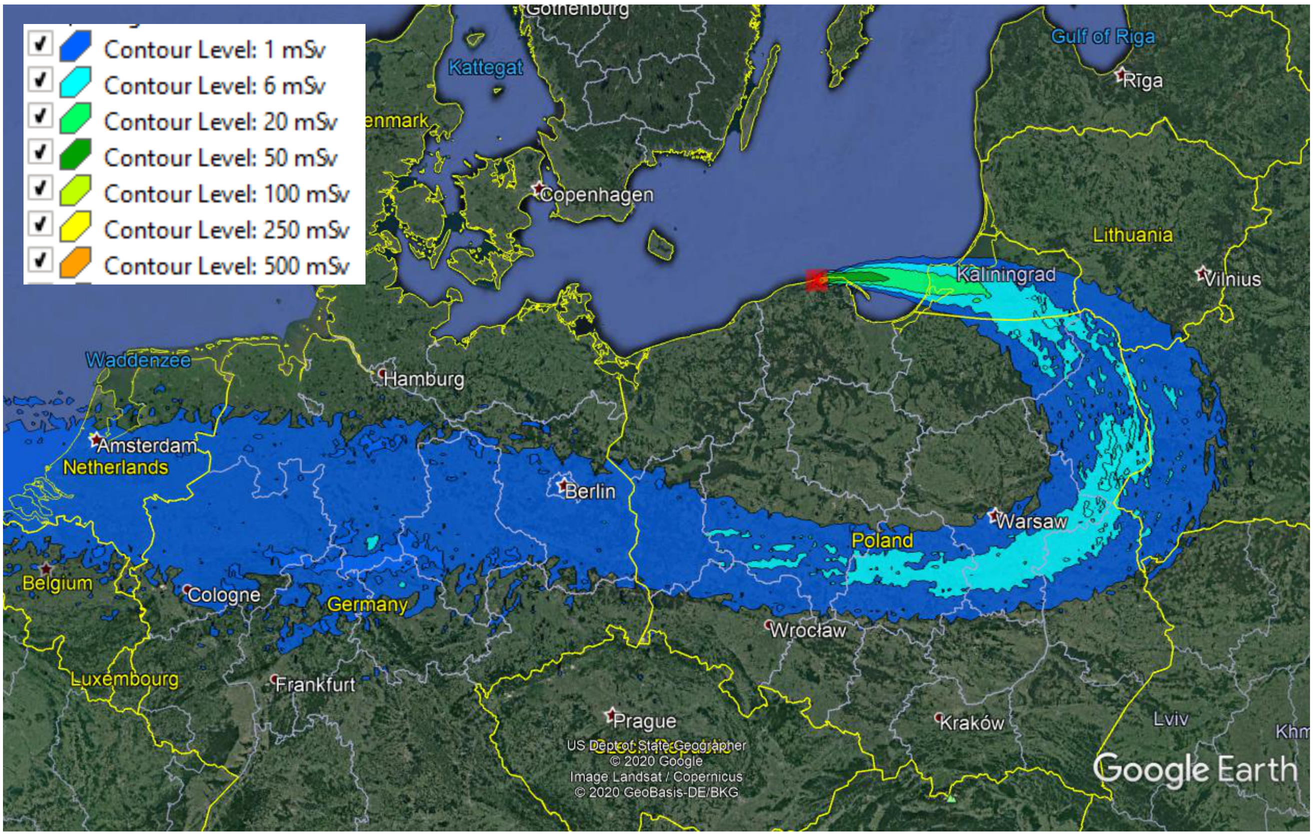
Technically, we have taken the radionuclide characterization of one nuclear plant. The geographical field of analysis was defined as 50° west longitude and 50° east longitude from the NPP and as 50° south latitude and 50° north latitude from the same NPP respectively. The resolution of the result is 0.05° in longitude and latitude.

We computed the dispersion only for aerosols. As a result, we computed the amounts of radioactive particles in the bottom 100 m of the atmosphere (Bq/m^3). This layer is representative of the radioactivity to which the population is exposed by inhalation and external exposition. For solid particles (aerosols), it is also possible to compute the amount of radioactivity (in Bq/m^2) deposited on the ground and we carried it on for aerosols.

As a result of *Hysplit* these quantities are stored into so called binary 'cdump' files. The computations have been carried out for all days of 2017 and 2018 together with the period 1.12.2019 – 30.11.2020 resulting in 3 years of simulations or 1096 days. The cdump files have been stored and can be used for further analysis.

In order to assess the amount of population or the geographical areas potentially touched by the radioactivity we carried out two different methods, the isoline-kml method and the ASCII method. These are two different methods to interpolate from the 0.05° grid onto the more detailed population grid. In both cases we first converted the amount of radioactive particles (given in Bq) into exposition doses (given in mSv) as explained below (*infra* 2.6).

First *Hysplit* allows to produce contourings out of the cdump files resulting into shapes for various dose thresholds. These are included in vector format as kml files[7]. Using a Geographic Information System (GIS), it is the possible to compute the area and population size enclosed inside the isolines. Kml files are also handy to represent the dispersion patterns superimposed on a geographical background by using for instance Google Earth.



Map 3. Example of dispersion pattern from a release on the 22nd March 2017

The second method consists to extract from the cdump files the exposition in ASCII format with the original resolution computed by *Hysplit* (0.05°). A bilinear interpolation is then applied in order to evaluate the doses on the detailed population grid. This approach is also used in order to assess the radioactivity on various towns. This is done by using the 9 *Hysplit* points surrounding the center of the town and by taking the maximum of these.

2.5 Analysis of the impact through the Geographic Information System (GIS)

The impact of radioactivity on the population and soil cover was calculated using GIS tools of ArcGIS Pro software, by Environmental Systems Research Institute (ESRI). The kml files generated by HYSPLIT software were converted to ESRI-shapefiles with the “KMLToLayer_conversion” tool, so that they could be used in statistical analysis. The shapefiles contain several polygons with different radiation concentration levels. Each shapefile was overlaid with a raster layer using the “ZonalStatisticsAsTable” tool which yielded a table with the affected number of population and land cover types.

The raster layers containing the population counts, for individual countries and for the year 2020, were obtained from the worldPop website, which includes datasets with a resolution of 30 arc (approximately 1km at the equator) created with the “top-down unconstrained” method. The land cover raster was obtained from

---

[7] KML means Keyhole Markup Language and the related files are employed for geographic mapping.

the Copernicus website which makes the Corine Land Cover products available for download. The raster used is the CLC2018 dataset produced within the frame of the Copernicus Land Monitoring Service referring to land cover / land use status of the year 2018. The dataset includes the classification of satellite images produced by teams from all the 39 countries members of the European Environmental Agency (EEA39). The land cover is represented in 44 different classes with a 100m resolution, which have been grouped in 4 classes for the present study. The projection used for the analysis is the Geographic Coordinate System, WGS84. The analysis were performed using ArcGIS integrated Python Window, which made possible the geoprocessing of large amounts of data.

In the present study, the 4 selected classes of land cover are: vineyards, herbaceous, cultivated, others. For the original classes of CLC2018, see the Appendix (Table A.3.)

2.6 From Becquerels to the collective committed effective dose received by the impacted population

(i) From Becquerels to mSv

The different sources of radioactivity are calculated by *Hysplit* in Becquerels (Bq). To evaluate the health impact of all persons affected implies to estimate the population dose in millisieverts (mSv). The calculation from Bq to mSv is carried out through well-known dose factors for inhalation (ICRP 2012), ground surface (EPA 2019b) and air submersion (or external exposition) (EPA 2019c). The related equations have to consider the specific unit account of each dose factors, the time integrated concentration expressed in (Bq·s/m^3) or (Bq·s/m^2).

(ii) First part of the calculation of the health impact

Radioactivity impacting people has been calculated through three clouds (rare gas, aerosols and refractories). The calculation is completed by the integration of the deposition of aerosols and refractories. As a result, it gives the five sources of radioactivity below:

When calculating committed effective doses from deposition we only considered external exposition. Inhalation of radioactive aerosols from resuspension in the atmosphere is far from negligible. However, we did not calculate it.

Hysplit ran the five sources of radioactivity in Becquerels (Bq). Besides this, we estimated the committed effective doses (CED) in millisieverts (mSv) through well-known equation. The purpose is to prepare the evaluation of the health damages to all affected persons.

As a next step, the individual committed effective doses (CED) can be used to estimate the collective committed effective dose (CCED) received by the population:

$$\text{CCED} = \text{CED} \cdot \text{number of affected persons}$$

The CCED is expressed in person-Sieverts (persSv) and it is determined together by the radioactivity level as well by the number of persons exposed to radioactivity. For high doses ≥ 1000 mSv, we calculated the dose by multiplying the value of the isoline by the number of affected persons (isoline approach), while for doses <1000 mSv, we used data having the specific dose of each pixel (pixel-dose approach).

(iii) Indoor factor for radioactive deposition.

We took into accounts the indoor factor at 0.4 when calculating radioactive deposition and we ignored low doses below 1 mSv. Additionally, it is assumed that persons in areas with doses above 20 mSv during the first year would be evacuated (according to EU directive), which makes only people living in areas where doses from deposition are below 20 mSv would receive a committed effective dose from deposition.

2.7 Methodology of the health question

(i) Context

Ionizing radiation (IR) is ubiquitary. IR from natural sources leads to an annual world population collective committed effective dose (CCED) of 18 000 000 person-Sievert (2.4 Sv/1000 · 7.5E+09 persons) (Bennet 1995, 3-12). IR acts either internally by incorporation of radionuclides (ingestion or inhalation), or externally by skin penetration of beta-, gamma-rays and neutrons (by immersion from cloudshine and groundshine) or direct skin contact with radionuclides. The energy of IR provokes mutations of the genome and other critical cellular processes such as bystander effect leading to genomic instability (Sipyagina et al. 2015, 18-22). In this way radiation induces cancer, congenital malformations, and genetic diseases which are passed from generation to generation.

(ii) Estimating the numbers of victims in a major NPP-Accident – retrospectively and prospectively

The estimated number of human victims due to the Chernobyl disaster varies between 4,000 cancer deaths (IAEA 2006, 118-120), and more than 1,000,000 victims due to cancer and non-cancer pathologies (Yablokov et al. 2009, 58-160). This discrepancy of more than two orders of magnitude is attributable to some degree, to the stochastic nature of health detriments by IR, as well as to long latency periods between exposure and manifestation of radio-induced pathologies. More important, however, are diverging estimates of the source term, populations studied, varying exposure periods and different risk-factors chosen by published scientific studies with diverging commitments (Fairlie & Sumner 2006, Claussen & Rosen 2016, Lenoir 2016). Considering the abovementioned divergence in determining *retrospectively* the number of victims due to the Chernobyl NPP accident, we use the following three calculation models (A, B, C) to estimate *prospectively* the number of victims of a future potential major European NPP accident. The calculation is based on the Collective committed effective dose expressed in person-Sievert (persSv) (supra i).

(iii) Model A

Model A: Cancer-based model - estimations according to UNSCEAR / WHO

This model places emphasis on victims with radio-induced cancer and is originally based on the ICRP-Document 103 (ICRP 2007). The latter uses an EAR (Excess Absolute Risk) factor of 5.5%/Sv (0.055/Sv) for cancer mortality which is applied to collective committed effective dose (CCED) of IR. However, calculations by ICRP also include a “reduction factor” (“dose and dose rate effectiveness factor”, DDREF) of 2 which is outdated nowadays according to UNSCEAR/WHO (WHO 2013, 31-32) and also to the German SSK (2014, 5-16).

Summary Methodology Model A

Model A contains numeric estimates of radio-induced cancer using a risk factor of 0.2/Sv for incidence and 0.1/Sv for mortality. Results are presented with confidence intervals according to BEIR VII (2006a).

(iv) Model B

Model B: Updated cancer and cardiovascular risk estimates

Model B refers to more recent studies on radio-induced cancer risks. Additionally, cardiovascular risks due to a major nuclear accident are included in Model B.

B1. Cancer risks

With respect to radio-induced cancer risk, there is new epidemiological evidence in favor of higher risk factors (Cardis et al. 2005, 77-80; Körblein & Hoffmann 2006, 109-114; IPPNW 2014, 3; Richardson et al. 2015, h5359; Hoffmann et al. 2017, 6-8) than used in Model A (Appendix, Table A.4). These EAR-factors are about 4.5 times higher than the EAR of 0.055 for radio-induced cancer mortality used by ICRP 103 (2007). In Model B this would translate into a doubling of the estimated cancer cases in comparison to Model A (which has already allowed for a DDREF of 1).

B2. Cardiovascular risks

According to ICRP elevated risks for nonmalignant diseases are known after IR exposure (Ozasa et al. 2012, 229- 243). However, the suggestion of the ICRP (ICRP 2012, 1-2) for a threshold of 500 mSv for radio-induced diseases other than cancer is outdated (Appendix, Table A.5. *Methodology Model B2*). Cardio-vascular excess risks have been described in children and adults due to IR exposure after Chernobyl (Nyagu 1994, Prysyazhnyuk et al. 2002, 188-287, Lazyuk et al. 2005, 24-25). Studies on low level exposure to IR found an elevated risk for arterial hypertension in nuclear workers (Azizova et al. 2019) as well as a significant excess mortality from cardiovascular diseases Gillies 2017) at a similar level as excess cancer mortality after IR exposure (Little et al. 2012, 1503-1511). Generally – as for cancer – incidence rates are higher than mortality rates also for cardiovascular diseases. In Europe the ratio of mortality to incidence for cardio-vascular diseases is about 1 to 3 (European Heart Network 2017).

Summary Methodology Model B

Model B contains numeric estimates of cancer incidence using a risk factor of 0.4/Sv (and 0.2/Sv for cancer mortality) and using a risk factor of 0.15/Sv for cardiovascular disease (CVD) incidence (and 0.05/Sv for mortality).

Severe diseases (cancer and CVD combined) therefore make 0.55/Sv for incidence and 0.25/Sv for mortality. Results are presented both for average and variable meteorological situations without confidence intervals (*infra 3.2*).

(v) Model C

Model C: Broadened Radiation Health Risk Assessment

Acknowledging that cancer and cardiovascular diseases reflect only the "tip of the iceberg" of radio-induced health effects observed after the Chernobyl NPP accident (Tereshchenko et al. 2003, 283-287), estimates of both Model A and Model B seriously underestimate the true burden of radio-induced pathologies. Model C therefore includes cancer and cardiovascular cases as mentioned in Model B and, in addition, covers the risks for other radio-induced diseases as well as reproductive and developmental hazards by ionizing radiation. For these conditions no EAR-risk factors are systematically established, although for some conditions ERRs (excess relative risks) > 1/Sv are documented (Appendix, Table A.6.).

C1. Non-cancer diseases other than cardiovascular diseases

Apart from cardio-vascular diseases, many other nonmalignant diseases (of the respiratory, gastrointestinal, neurological, central nervous, endocrine, immune- and musculo-skeletal system, infections, skin diseases, non-neoplastic hematological disorders and diseases of the lymphatic system) are associated with exposure to IR (Appendix, Table A.6.). Many of these diseases, especially of the endocrine, neurologic, and musculo–skeleton system, cause chronic debilitation and eventual death. They are huge burden for individuals, families and society.

These non-malignant diseases far exceeded the number of malignant diseases and frequently evolved rapidly during the first decade after the Chernobyl NPP accident (Yablokov 2016, 294). This is clearly different from radio-induced cancer cases which are typically diagnosed in later decades. Thus, increased risks for radio-induced non-cancer diseases were observed shortly after just a few single yearly doses, which correspond to total doses from the low-dose range.

Of particular concern is the significant excess of many of these conditions in children living in contaminated regions. In the Ukraine this has been observed especially concerning the respiratory, cardiovascular and digestive system, thyroid and other endocrine diseases, and immunodeficiency disorders, with more than 70% of children being chronically ill 10 years after the Chernobyl NPP accident (Prysyazhnyuk et al. 2002, 188-276). According to data from the Belarussian Ministry of Public Health, in 1985 – just before the 1986 catastrophe – 90% of children were considered "practically healthy". By 2000, fewer than 20% were considered healthy, and in the most contaminated Gomel Province, fewer than 10% of children were well (Yablokov et al. 2009, 58-160).

Significant excess mortality to respiratory, digestive diseases and nonmalignant diseases of the blood is also documented from Japanese atomic bomb survivors (Ozasa et al. 2012, 229-243). A recent study on nuclear workers' external exposure to low dose of IR demonstrated an elevated mortality associated with mental disorders (significant) and respiratory and digestive diseases (not significant) (Gillies et al. 2017, 276-290) (Appendix, Table A.7.).

C2. Reproductive and developmental hazards by ionizing radiation

All along the complex human reproductive process, elevated risks by ionizing radiation at many levels are well known. Their medical and societal relevance is evident considering the extensive radiobiological and epidemiological research over decades on the consequences of the Chernobyl disaster. IR health effects encompass pre-conceptual aspects such as female endocrine dysfunction leading to infertility as well as preexisting parental irradiation associated with consecutive severe development detriments and diseases in the offspring (Hoffmann et al. 2017, 12). Exposure to IR during pregnancy causes chromosomal aberrations leading – among others – to elevated incidence of Down's syndrome (Sperling 1987, 1991, 1994a, 1994b) and changes of the sex odds ratio (Scherb et al. 2016, 104-111). In utero irradiation furthermore leads to adverse effects on the embryo or fetus inducing spontaneous abortions and congenital malformations, radio-induced excess risks for low birth weight, perinatal and infant mortality as well as elevated risks for childhood malignancies (Hoffmann et al. 2017) (Appendix, Table A.7). In-depth details about non-cancer health effects are given elsewhere (Claussen & Rosen 2016; Hoffmann et al. 2017, 10-3).

Summary Methodology Model C

To conclude on Model C, quantitative estimates for cancer and cardiovascular diseases are performed according to Model B. In addition, Model C developed semi quantitative estimates of other non-malignant radio-induced health effects according to Yablokov who suggests that these cases outnumber cancer cases by a significant margin (Yablokov et al. 2009, 58-160).

III Results

3.1 Distribution of the collective committed effective doses (CCED)

(i) Reminder of the main hypothesis

As already stated (supra 2.2(ii)), we tempered the pixel-dose approach by the 'isoline' approach. We took into account the indoor factor at 0.4 when calculating radioactive deposition and we ignored low doses below 1 mSv. Additionally, it is assumed that persons in areas with doses above 20 mSv during the first year would be evacuated (according to EU directive), which makes only people living in areas where doses from deposition are below 20 mSv would receive a committed effective dose from deposition (supra). The meteorological situations proceed from a simulation of radioactive releases on 1096 meteorological situations (from 1096 days strictly representative of the four seasons – including a bissextile year of 366 days.

(ii) Distribution of the average CCED

Table 3.1 shows that the CCED of deposition amounts to only 20 911 persSv (i.e. 2/5 of the cloud CCED (52 0142 persSv). The latter would be somewhat higher if evacuation was finally set up over 50 mSv/(1st year) or 100 mSv/(1st year). In the present configuration (evacuation with persons located in area above 20 mSv/(first year), Poland would receive 20 995 persSv, less than the half CCED of EUR31, while DEU, KLL, SDE and CSUB would receive, respectively 1/7 (6 323 persSv), 1/8 (5 140 persSv), 1/10 (4 274) and 1/7 (6 303 persSv) of the average EUR11 CCED (52 142 persSv). In other terms, on average and for 1 096 meteorological simulations, Poland despite being the most impacted country would receive 2/5 of the total CCED in case of a major nuclear accident. The other 3/5 would radio-contaminate, on average, the surrounding countries. However, the average amount of CCED does not tell the whole picture.

Table 3.1. Collective committed effective dose – through the 'pixel-dose' approach tempered by the 'isoline' approach – with three population evacuation thresholds for deposition, during the first year, over 20, 50 and 100 mSv respectively (over 1096 simulations equally representative of the seasons)

NPP: Zarnowiec-Kopal.	Impacted area	EUR31 (persSv)	POL (persSv)	DEU (persSv)	KLL (persSv)	SDE (persSv)	CSUB (persSv)
Deposition [1, 20[	average	20 911	7 030	2 845	2 298	1 933	2 802
c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 20[	average	52 142	20 995	6 323	5 140	4 274	6 303
c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 50[	average	53 927	22 698	6 326	5 198	4 290	6 303
c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 100[	average	55 612	24 372	6 326	5 204	4 295	6 303

Notation: c = cloud; d = deposition

POL (Poland), DEU (Germany), KLL (Kaliningr.-Obl. & Latvia & Lithuania), SDE (Sweden & Denmark), CSUB (Czechia & Slovakia & Ukraine & Belarus). EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN)

(iii) Transboundary distribution of the radioactive load

The severity of the radioactive load expressed through the person-Sievert approach varies depending on meteorological situations. As the Zarnowiec-Kopal. NPP is projected beside the sea front, meteorological circumstances could spread the radioactive load into sea water. If we look at table 3.2 and refer at the 31 countries together (EUR31), the median (30 316 persSv) represents 1/10 of the highest centile (Q99: 308 796 persSv), while the lowest centile (Q1: 456 persSv) represents 1/66 of the median[8]. The contrast between the highest and lowest parts of the distribution is considerable.

Poland is the country that would receive the highest CCED of the five regions we considered in this study. For different reasons, Kaliningrad-Oblast and Latvia together with Lithuania as well as Czechia, Slovakia and Ukraine together with Belarus would be hurt by a CCED in a bit less than 3/5 of the simulations; Sweden and Denmark would receive such a radioactive load in 2/5 of the meteorological configurations, while Germany would be impacted in 1/5 of the 1096 situations simulated in this study. However, in disadvantageous meteorological situation, Germany could be affected by a very high CCED, despite having its border more than 250 km from Zarnowiec-Kopal.. In a hundredth of the cases, the CCED received by Germany (149 342 persSv) would be as high as 6/7 of the corresponding CCED received by Poland (176 257 persSv), while it would exceed by three times the corresponding CCED that would hurt KKL (47 755 persSv) and by roughly two times the CCED that could impact SDE (60 481 persSv) and CSUB (57 792 persSv). In a twentieth of the meteorological situations, the CCED incurred by Germany (41 241 persSv), KKL (24 685 persSv), SDE (26 532 persSv) and CSUB (33 222 persSv) would represent, respectively, 2/5, 1/4, 1/4 and 1/3 of the corresponding CCED for Poland (104 186 persSv).

Table 3.2. CCED from the cloud and deposition < 20 mSv during the first year distributed by quantiles (and average)

Cloud + deposition < 20 mSv (1st year)
Collective committed effective doses
NPP: Zarnowiec-Kopal.

Impac. area	EUR31 (persSv)	POL (persSv)	DEU (persSv)	KLL (persSv)	SDE (persSv)	CSUB (persSv)
Average	52 142	20 995	6 323	5 140	4 274	6 303
Max	430 368	364 289	318 682	91 933	145 083	166 223
Q99	308 796	176 257	149 342	47 755	60 481	57 792
Q95	177 646	104 186	41 241	24 685	26 532	33 222
Q85	102 369	53 277	482	12 100	7 546	15 203
Q75	70 113	23 963	0	6 396	1 023	6 988
Q50	30 316	1 730	0	79	0	16
Q25	11 089	186	0	0	0	0
Q15	6 044	94	0	0	0	0
Q5	2 060	52	0	0	0	0
Q1	456	3	0	0	0	0
Min	137	0	0	0	0	0

Results over 1096 meteorological simulations (2017-20) without low dose <1 mSv. POL (Poland), DEU (Germany), KLL (Kaliningr.-Obl. & Latvia & Lithuania), SDE (Sweden & Denmark), CSUB (Czechia & Slovakia & Ukraine & Belarus). EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN)

Furthermore, we organized the data so as to evaluate them through temporal synchronicity (which is not the case in Table 3.2). Table 3.3 shows that the four regions together – DEU & KLL & SDE & CSUB could be impacted by a higher collective committed effective dose than Poland on 756 out of 1096 simulations (69%). Moreover, Germany, KLL, SDE and CSUB could also get impaired by a higher CCED than Poland in, respectively, 96, 374, 265, 184 meteorological configurations. 732 meteorological situations out of 1096 simulations (67%) have been identified whereupon one, two and even three countries/regions – considered individually – could be simultaneously hampered by a CCED higher than the one received by Poland during the same meteorological situation. From the latter figure, one can deduce Poland would be affected by the highest CCED among the four countries/regions in 'only' 364 weather situations (33%), while it would weigh down under a highest CCED than EUR31 in ‘only’ 24% of the meteorological situations.

Table 3.3. Occurrence of meteorological situations where the health impact would be higher beyond Poland's borders (over 1096 simulations equally representative of the seasons)

NPP: Zarnowiec-Kopal.

Impacted regions:	(EUR31 - Pol) > Pol	(4 regions) > POL	DEU > POL	KLL > POL	SDE > POL	CSUB > POL
Situations (No)	835	756	96	374	265	184
Situations/(1096 simulat.) (%)	76%	69%	9%	34%	24%	17%

Poland (POL); four regions: (Germany (DEU), Kaliningr.-Obl.+ Latvia + Lithuania (KLL), Sweden + Denmark (SDE), Czechia, Slovakia, Ukraine, Belarus (CSUB))EUR31: POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN

All in all, we found 732 meteorological situations where one, two and even three countries would be simultaneously hampered by a CCED higher

---

[8] In Table 3.2, the dates of the events are not coordinated from one column to the other; to this extent, each column is independent of the other ones.

than the CCED Poland would receive as a consequence of the same simulation of a major nuclear accident in Zarnowiec-Kopalino.

In other terms, a higher CCED outside Poland's borders is more probable than the opposite.

3.2 Distribution of the health impact

CCED is an important step in the accounting of the health impact of a major nuclear accident. As stated earlier, this study is based on the no-threshold approach (supra 1.2) that estimates the health impact from the CCED and EAR factors expressed as a fraction of a Sievert (x/Sv). In other words, the distribution of quantiles in below Tables 3.4 & 3.5 is calculated using different EARs and CCEDs as displayed in the first column of Table 3.2 (supra).

(i) Table 3.4. Model A, radio-induced cancer cases

The first three columns of Table 3.4-3.5 display model A being dispatched through the confidence interval (low, medium, high). They give the estimate of radio-induced cancer cases according to Model A issued by WHO/UNSCEAR. Based on the CCEDs (the first column of Table 3.2) and a medium risk factor (EAR) of 0.2/Sv for cancer incidence and (according to UNSCEAR 2013), we have estimated radio-induced cancer cases for EUR31, on average and by quantiles (and confidence intervals according to BEIR VII (2006a).

Table 3.4 shows that the figure of Model A(medium), on average, with 10 428 cases, represents a bit more than 1/3 of the result given by Model B (28 678 cases). It is worth highlighting that Model B includes radio-induced cardio-vascular diseases while Model A does not (*supra and infra*).

(ii) Table 3.4. Model B, radio-induced cancer cases and radio-induced severe cardiovascular diseases

The fourth column of Table 3.4 estimates the number of radio-induced cancer cases as well as radio-induced cardiovascular diseases according to Model B. Model B is more recent and seems preferable to Model A due to new epidemiological data (Cardis 2005, 77-80; Körblein & Küchenhoff 2006, 109-114; IPPNW 2014; Richardson et al. 2015, h5359; Hoffmann et al. 2017, 6-8). With respect to cancer cases and cardio-vascular diseases, Model B implies a risk factor (EAR) set at 0.55/Sv (*supra* 2.4(iv)). The low level of cases for the first part of the distribution is due to the location of the plant near the sea front. The highest part of the distribution shows that, for Model B, the number of cases is above 16 600, while it exceeds 97 700 cases above Q95) and could even hit 236 702 cases of radio-induced severe diseases.

Table 3.4. Radio-induced severe diseases (cancer cases for Model A, and, cardio & cancer cases for Model B)

Cloud + (deposition < 20 mSv (1st year))

NPP: Zarnowiec(Kopal.)

Impac. area	EUR31 Model A(lo) *Pers. (No)*	EUR31 Model A(me) *Pers. (No)*	EUR31 Model A(hi) *Pers. (No)*	EUR31 Model B *Pers. (No)*
Average	4 693	10 428	18 250	28 678
Max	38 733	86 074	150 629	236 702
Q99	27 792	61 759	108 079	169 838
Q95	15 988	35 529	62 176	97 705
Q90	11 392	25 317	44 304	69 621
Q85	9 213	20 474	35 829	56 303
Q75	6 310	14 023	24 539	38 562
Q50	2 728	6 063	10 611	16 674
Q25	998	2 218	3 881	6 099
Q15	544	1 209	2 115	3 324
Q10	339	754	1 319	2 072
Q5	185	412	721	1 133
Q1	41	91	160	251
Min	12	27	48	75

Results over 1096 meteo. simulat. (2017-20) without low dose <1 mSv.

EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN)

Table 3.5. Radio-induced deaths (from cancer for Model A, and from cancer & cardiovasc. diseases for Model B)

Cloud + (deposition < 20 mSv (1st year))

NPP: Zarnowiec(Kopal.)

Impac. area	EUR31 Model A(lo) Deaths (No)	EUR31 Model A(me) Deaths (No)	EUR31 Model A(hi) Deaths (No)	EUR31 Model B Deaths (No)
Average	2 607	5 214	9 907	13 035
Max	21 518	43 037	81 770	107 592
Q99	15 440	30 880	58 671	77 199
Q95	8 882	17 765	33 753	44 412
Q90	6 329	12 658	24 051	31 646
Q85	5 118	10 237	19 450	25 592
Q75	3 506	7 011	13 321	17 528
Q50	1 516	3 032	5 760	7 579
Q25	554	1 109	2 107	2 772
Q15	302	604	1 148	1 511
Q10	188	377	716	942
Q5	103	206	391	515
Q1	23	46	87	114
Min	7	14	26	34

Results over 1096 meteo. simulat. (2017-20) without low dose <1 mSv.

EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN)

(iii) Table 3.5. Model A, radio-induced deaths from cancer

The first three columns of Table 3.5 estimates (mean and confidence interval) the number of radio-induced deaths from cancer cases according to Model A issued by WHO/UNSCEAR (for the number of estimated radio-induced cancer deaths divide cancer cases by 2).

(iv) Table 3.5. Model B, radio-induced deaths from cancer cases *and* severe cardiovascular diseases

The fourth column of Table 3.5 shows the number of deaths from added cancer cases *and* added severe cardiovascular diseases as a consequence of a major nuclear accident. For the estimates of the number of deaths, the number of cases of the preceding table has to be divided by 2.2. The average number of deaths would reach around 13 035, while the median numbers 7 579 deaths and the highest hundredth could exceed 77 100 deaths. The 'low' number of cases below the median is explained elsewhere (*supra* ii).

3.3 Distribution of the health impact among countries according to Model B

Table 3.6. Radio-induced severe diseases (cardio & cancer) Model B among different countries and regions

u

Cloud + deposition < 20 mSv (1st year)

NPP: Zarnowiec-Kopal.

Impac. area	EUR31	POL	DEU	KLL	SDE	CSUB
	Model B	Model B	Model B	Model B	Model B	Model B
	Pers. (No)	Pers. (No)	Pers. (No)	Pers. (No)	Pers. (No)	Pers. (No)
Average	28 678	11 547	3 478	2 827	2 351	3 467
Max	236 702	200 359	175 275	50 563	79 796	91 423
Q99	169 838	96 941	82 138	26 265	33 264	31 786
Q95	97 705	57 302	22 683	13 577	14 593	18 272
Q85	69 621	29 303	265	6 655	4 150	8 362
Q75	56 303	13 180	0	3 518	563	3 844
Q50	38 562	952	0	44	0	9
Q25	16 674	103	0	0	0	0
Q15	6 099	52	0	0	0	0
Q5	1 133	28	0	0	0	0
Q1	251	2	0	0	0	0
Min	75	0	0	0	0	0

Results over 1096 meteo. simulation (2017-20) without low dose <1 mSv.

POL (Poland), DEU (Germany), KLL (Kaliningr.-Obl. & Latvia & Lithuania), SDE (Sweden & Denmark), CSUB (Czechia & Slovakia & Ukraine & Belarus). EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN)

Table 3.7. Radio-induced deaths according to Model B among different countries and regions

Cloud + deposition < 20 mSv (1st year)

NPP: Zarnowiec-Kopal.

Impac. area	EUR31	POL	DEU	KLL	SDE	CSUB
	Model B	Model B	Model B	Model B	Model B	Model B
	Deaths (No)	Deaths (No)	Deaths (No)	Deaths (No)	Deaths (No)	Deaths (No)
Average	13 035	5 249	1 581	1 285	1 069	1 576
Max	107 592	91 072	79 671	22 983	36 271	41 556
Q99	77 199	44 064	37 335	11 939	15 120	14 448
Q95	44 412	26 046	10 310	6 171	6 633	8 306
Q85	25 592	13 319	120	3 025	1 887	3 801
Q75	17 528	5 991	0	1 599	256	1 747
Q50	7 579	433	0	20	0	4
Q25	2 772	47	0	0	0	0
Q15	1 511	23	0	0	0	0
Q5	515	13	0	0	0	0
Q1	114	1	0	0	0	0
Min	34	0	0	0	0	0

Results over 1096 meteo. simulat. (2017-20) without low dose <1 mSv.

EUR11: POL (Poland), DEU (Germany), KLL (Kaliningr.-Obl. & Latvia & Lithuania), SDE (Sweden & Denmark), CSUB (Czechia & Slovakia & Ukraine & Belarus)

3.4 Distribution of individual doses to persons

According to European Directive (supra), some legal threshold for individual doses are set up – over one year – at 1 mSv, 6 mSv, 20 mSv, 50 mSv, 100 mSv.

Table 3.8 Number of meteorological situations where a region is impacted by the cloud and number of persons affected by different levels of individual doses

NPP: Zarnowiec-Kopal.

Region	Levels of contamination by the cloud –>	≥ 1 mSv	≥ 6 mSv	≥ 20 mSv	≥ 50 mSv	≥ 100 mSv
POL	Number of situations with impact (No)	1 096	1 096	1 095	1 091	1 082
POL	No of situations with impact/1096 situati. (%)	100%	100%	100%	100%	99%
POL	Average No of pers. in these specific situati. (No)	1 605 797	398 144	114 928	46 904	18 875
DEU	Number of situations with impact (No)	218	143	38	2	0
DEU	No of situations with impact/1096 situati. (%)	20%	13%	3%	0.2%	0%
DEU	Average No of pers. in these specific situati. (No)	5 479 163	862 357	284 942	48 165	(…)
KLL	Number of situations with impact (No)	648	507	240	57	8
KLL	No of situations with impact/1096 situati. (%)	59%	46%	22%	5%	1%
KLL	Average No of pers. in these specific situati. (No)	916 562	276 280	95 539	37 505	14 561
SDE	Number of situations with impact (No)	444	310	173	58	7
SDE	No of situations with impact/1096 situati. (%)	41%	28%	16%	5%	1%
SDE	Average No of pers. in these specific situati. (No)	1 255 801	400 524	64 352	8 958	10 388
CSUB	Number of situations with impact (No)	631	329	35	2	0
CSUB	No of situations with impact/1096 situati. (%)	58%	30%	3%	0.2%	0%
CSUB	Average No of pers. in these specific situati. (No)	2 600 644	184 297	50 285	6 978	(…)

Poland (POL); four regions: (Germany (DEU), Kaliningr.-Obl.+ Latvia + Lithuania (KLL), Sweden + Denmark (SDE), Czechia, Slovakia, Ukraine, Belarus (CSUB))

Table 3.9. Number of meteorological situations where a region would be impacted by the deposition and number of persons affected by different levels of individual doses

NPP: Zarnowiec-Kopal.

Region	Levels of contamination by deposition (1st year)	≥ 1 mSv	≥ 6 mSv	≥ 20 mSv	≥ 50 mSv	≥ 100 mSv
POL	Number of situations with impact (No)	1 096	1 096	1 095	1 091	1 078
POL	No of situations with impact/1096 situati. (%)	100%	100%	100%	100%	98%
POL	Average No of pers. in these specific situati. (No)	1 464 349	332 220	96 553	38 810	14 483
DEU	Number of situations with impact (No)	221	139	30	1	0
DEU	No of situations with impact/1096 situati. (%)	20%	13%	3%	0.1%	0%
DEU	Average No of pers. in these specific situati. (No)	4 721 104	672 427	194 643	56 077	(…)
KLL	Number of situations with impact (No)	652	492	215	48	7
KLL	No of situations with impact/1096 situati. (%)	59%	45%	20%	4%	1%
KLL	Average No of pers. in these specific situati. (No)	837 606	233 322	75 088	22 994	8 100
SDE	Number of situations with impact (No)	447	308	157	39	6
SDE	No of situations with impact/1096 situati. (%)	41%	28%	14%	4%	1%
SDE	Average No of pers. in these specific situati. (No)	1 142 218	319 424	46 877	8 160	8 155
CSUB	Number of situations with impact (No)	635	324	33	3	0
CSUB	No of situations with impact/1096 situati. (%)	58%	30%	3%	0.3%	0%
CSUB	Average No of pers. in these specific situati. (No)	2 189 922	125 367	37 320	431	(…)

Poland (POL); four regions: (Germany (DEU), Kaliningr.-Obl.+ Latvia + Lithuania (KLL), Sweden + Denmark (SDE), Czechia, Slovakia, Ukraine, Belarus (CSUB))

3.5 Impacts on cities and towns

The question of the impact measured in millisiverts on the inhabitants of towns and cities of different sizes continues the exploration of the concept of transboundary radioactive pollution in a preventive perspective. The examination of the results nevertheless begins with the cities of Poland.

The following table shows that the Polish city most likely to be affected is Gdynia, which is affected 224 times for 1,096 simulations (1/5) and would also record the highest level of contamination. Next come the cities of Gdansk and Olsztyn, the latter with lower levels of contamination.

Table 3.10. Possible impacts on cities from the cloud: number of occurrences over 1096 simulations, average mSv for these occurrences, and higher mSv impacts

NPP: Zarnowiec-Kopalino	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland
	Bialystok	Bydgosz.	Gdansk	Gdynia	Gorz.-W.	Koszalin	Lodz	Olsztyn	Poznan	Szczecin	Warsaw
No of impacts with a dose such as (mSv > 0) (No)	199	125	199	224	96	122	116	199	109	92	149
Average mSv of the above 92 to 224 impacts (mSv)	3.5	3.8	23.1	43.3	3.0	12.1	3.0	5.9	3.3	3.3	2.8
Higher impact identified (mSv)	47.7	33.2	227.5	339.6	19.4	99.5	35.5	58.2	21.1	20.0	27.6
Third higher impact identified (mSv)	23.2	19.0	193.4	295.8	15.8	75.8	12.5	46.4	14.0	16.3	15.7

If we look at the next table, it appears that several cities outside Poland's East border (Kaliningrad, Kaunas and Klaipeda) would have a higher probability to be hit than Polish cities mentioned in the above table. Danish and Swedish cities like Kalmar seem also to be exposed.

Table 3.11. Possible impacts on cities or towns from the cloud: number of occurrences over 1096 simulations, average mSv for these occurrences, and higher mSv impacts

NPP: Zarnowiec-Kopalino	DNK	DNK	SWE	SWE	SWE	SWE	SWE	Kali. Ob.	LTU	LTU
	Copenha	Bornhol.	Kalmar	Malmö	Växsjö	Gotland	Stockho.	Kaliningr.	Kaunas	Klaipeda
No of impacts with a dose such as (mSv > 0) (No)	102	117	117	107	111	147	104	294	251	239
Avera. mSv of the above 102 to 294 impacts (mSv)	4.5	10.0	7.0	5.1	4.2	5.2	2.9	8.9	2.9	6.2
Higher impact identified (mSv)	38.7	75.9	73.3	37.7	40.3	39.8	26.0	90.4	26.0	60.4
Third higher impact identified (mSv)	18.0	66.4	40.7	24.0	29.5	27.7	15.2	66.4	16.0	42.0

Outside the Western border, the probability to be impacted seems a bit lower than outside the northern and eastern border. It is nonetheless comparable to several Polish cities. The weight of the potential impact can be rather high in some meteorological conditions (93.1 mSv in Neubrandenburg, an amount whose addition to the figure of deposition would exceed 100 mSv and exceed the highest limit considered in emergency situations that the Council Directive aims at protecting as a public good and whose breach leads to totally insufferable consequences (European Commission 2017, Art. 53.2(a)).

Table 3.12. Possible impacts on cities or towns from the cloud: number of occurrences over 1096 simulations, average mSv for these occurrences, and higher mSv impacts

NPP: Zarnowiec-Kopalino	DEU	DEU	DEU	DEU	DEU	DEU	DEU	DEU	DEU
	Anklam	Berg. Rü.	Berlin	Francf O.	Greifswld	Hambur.	Neubran.	Rostock	Schwedt
No of impacts with a dose such as (mSv > 0) (No)	96	100	80	88	100	75	79	97	88
Avera. mSv of the above 75 to 100 impacts (mSv)	4.0	4.9	3.1	3.0	4.7	3.7	3.8	3.7	3.0
Higher impact identified (mSv)	38.3	43.9	32.1	25.3	45.8	32.1	93.1	24.9	19.3
Third higher impact identified (mSv)	26.5	27.0	15.6	13.9	21.3	20.3	9.7	21.1	12.8

To conclude this point, on the one hand, the probability of impacting this or that city (or town) mentioned in the above tables ranges between 7% and 27% and it would even be lower if we considered only substantial impacts; this is not surprising since the surface in square kilometers of cities is much smaller than that of countries.

On the other hands, it is clear that, all in all, the probability that no city will be affected in the event of a major nuclear accident is not very high. Locating a nuclear power plant in the area of Zarnowiec-Kopalino, on the shores of the Baltic Sea, does not extinguish the risk of a massive radioactive pollution, which would occurred at the expense of one, or two, Polish or foreign cities.

3.6 Deposition on ground surface

Table 3.13. Correspondence between millisieverts and Becquerels in calculation on radioactive deposition

NPP: ZA2 3415 MWth

Parents' Becquerels(t1) (Bq m-2)	2.50E+06	1.66E+07	4.16E+07	8.32E+07	2.08E+08	4.16E+08	8.32E+08	1.25E+09	1.66E+09
ALL nuclides (mSv (1st yr)-1)	3	20	50	100	250	500	1 000	1 500	2 000
Cs-137(t1) (Bq m-2)	1.04E+05	6.95E+05	1.74E+06	3.47E+06	8.69E+06	1.74E+07	3.47E+07	5.21E+07	6.95E+07
Cs-137 + Ba-137 (mSv (1st yr)-1)	0.5	3.3	8.1	16.3	40.7	81.5	162.9	244.4	325.9

Note: From Bq to mSv –> through specific half-lives & dose factors; and through indoor factor at 0.4

Table 3.14. Average number of radioactive square kilometers, for different levels of individual dose, over 1096 meteorological simulations

NPP: ZA2 3415 MWth

Area: EUR39

ALL nuclides (mSv (1st yr)-1)	≥3	≥20	≥50	≥100	≥250	≥500	≥1000	≥1500	≥2000
All surfaces (km2)	17 949	763	212	106	41	14	3	1	1
Excerpt: Cultivated + herbaceous (km2)	2 862	122	35	17	6	2	0	0	0

Note: From Bq to mSv –> through specific half-lives & dose factors; and through indoor factor at 0.4

EUR39: ALB, AUT, BEL, BIH, BGR, HRV, CYP, CZE, DNK, EST, FIN, FRA, DEU, GRC, HUN, ISL, IRL, ITA, (kos), LVA, LIE, LTU, LUX, MLT, MNE, NLD, MKD, NOR, POL, PRT, ROU, SRB, SVK, SVN, ESP, SWE, CHE, TUR, GBR

IV Conclusion

This study modelling a major nuclear accident of the planned nuclear power plant Zarnowiec-Kopalino from the data of 1096 realistic meteorological situations reveals a highly significant potential for transboundary radio-contamination both of the 11 surrounding countries but also a in wider circle of 31 European states. Victims outside Poland – mainly hit by radioinduced cancer and non-cancer diseases – would exceed the number of cases in Poland itself. Meteorological extremes could carry the radionuclides thousands of kilometers away from the original source.

BIBLIOGRAPHY

Azizova, T., Briks, K., Bannikova, M., Grigoryeva, E. 2019. Hypertension Incidence Risk in a Cohort of Russian Workers Exposed to Radiation at the Mayak Production Association Over Prolonged Periods. Hypertension (2019;73: 1174–1184)
https://www.ahajournals.org/doi/10.1161/HYPERTENSIONAHA.118.11719

Baklanov, A. Sørensen, J.H. 2001. Parameterisation of Radionuclide Deposition in Atmospheric Long-Range Transport Modelling. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere 26 (10): 787–799.
https://www.sciencedirect.com/science/article/pii/S1464190901000879

BEIR VII, National Research Council. 2006a. Health Risks from Exposure to Low Levels of Ionizing Radiation: Phase 2. The National Academies Press. ISBN 978-0-309-09156-5.
http://www.philrutherford.com/Radiation_Risk/BEIR/BEIR_VII.pdf

BEIR VII. National Research Council 2006b. Health Risks from Exposure to Low Levels of Ionizing Radiation, BEIR VII Phase 2. Report in brief, p. 1-4.
http://dels.nas.edu/resources/static-assets/materials-based-on-reports/reports-in-brief/beir_vii_final.pdf

Bennett, B.G. 1995. Exposures from Worldwide Releases of Radionuclides. [In:] Proceedings of an International Atomic Energy Agency Symposium on the Environmental Impact of Radioactive Releases. Vienna, May 1995. IAEA-SM-339/185: 117–126.
https://inis.iaea.org/collection/NCLCollectionStore/_Public/27/035/27035333.pdf

Bennett, B.G. 1996. Assessment by Unscear of worldwide doses from the Chernobyl accident. [In:] One decade after Chernobyl: Summing up the Consequences of the accident. European Commission, IAEA, WHO, p. 3-12.
https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1001_web.pdf

Berrington de Gonzalez, A., Daniels, R. D., et al. 2020. Epidemiological Studies of Low-Dose Ionizing Radiation and Cancer: Rationale and Framework for the Monograph and Overview of Eligible Studies. JNCI Monographs, Volume 2020, Issue 56, Oxford, July 2020, Pages 97–113, https://academic.oup.com/jncimono/article/2020/56/97/5869935?searchresult=1

Cardis, E., Anspaugh, L., Ivanov, V.K., Likhtarev, K., Mabuchi, A.E., Okeanov, A.E., Prisyazjhniuk, K. 1996. One Decade after Chernobyl: Summing up the Consequences of the Accident. Proceedings of an International Conference Vienna. 8-12 April 1996, p.241-271.
https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1001_web.pdf

Cardis, E., Vrijheid, M., Blettner, M. et al. 2005. Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries. IARC Lyon, BMJ 9 July 2005: Vol. 331; p.77-80.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC558612/

Claussen, A., Rosen, A. 2016. Report of International Physicians for the Prevention of Nuclear War and Physicians for social responsibility: 30 years living with Chernobyl, 5 years living with Fukushima: Health effects of the nuclear disasters in Chernobyl and Fukushima.
https://ippnw.de/commonFiles/pdfs/Atomenergie/Tschernobyl/Report_TF_3005_en_17_screen.pdf

Copernicus. Corine Land Cover, CLC 2018.
https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download

Daniels, R. D., Kendall, G. M., Thierry-Chef, I. et al. Strengths and Weaknesses of Dosimetry Used in Studies of Low-Dose Radiation Exposure and Cancer. JNCI Monographs, Volume 2020, Issue 56, Oxford, July 2020, Pages 114–132.
https://academic.oup.com/jncimono/article/2020/56/114/5869933?searchresult=1

Darby, S., Hill, D. Auvinen, A. et al. 2005. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. Brit Med J. 2005 Jan 29, 330:223.
https://www.ncbi.nlm.nih.gov/pubmed/15613366

Doll, R. 1995. Hazards of ionising radiation: 100 years of observations on man. British Journal of Cancer. 1995 Dec, 72(6), p.1339–1349.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2034083/

Draxler, R., Rolph, G.D. 2012. Evaluation of the Transfer Coefficient Matrix (TCM) approach to model the atmospheric radionuclide air concentrations from Fukushima. Journal of Geophysical Research (Atmospheres). VOL. 117, D05107.
https://www.researchgate.net/publication/258662914_Evaluation_of_the_Transfer_Coefficient_Matrix_TCM_approach_to_model_the_atmospheric_radionuclide_air_concentrations_from_Fukushima

Draxler, R., Arnold, D., Chino, et al. 2015. World Meteorological Organization's Model Simulations of the Radionuclide Dispersion and Deposition from the Fukushima Daiichi Nuclear Power Plant Accident. Journal of Environmental Radioactivity 139 (January), p.172–184.
https://www.sciencedirect.com/science/article/pii/S0265931X13002142

Draxler, R., Stunder, B., Rolph, G., Stein, A. et al. 2018. HYSPLIT4 User's Guide. Air Resources Laboratory. https://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf

Edison, T. A., 1896. 'Effect of X-rays upon the eye', Nature Vol. 53, p. 421.

ENSI, Swiss Federal Nuclear Safety Inspectorate. 2009. G14 Calcul de l'exposition aux radiations ionisantes dans l'environnement due à l'émission de substances radioactives par les installations nucléaires. ENSI FR, Swiss Confederation. 21 December 2009, 21 december 2009.
https://www.ensi.ch/fr/documents/directive-ifsn-g14-francais/.

EPA, United States Environmental Protection Agency. 2019a. Table A-1. Nuclides of ICRP Publication 107 ordered by atomic number. Federal Guidance Report No. 15: External exposure to radionuclides in air, water, and soil. Bellamy, Dewji, Leggett, Hiller, Veinot, Manger, Eckerman, Ryman, Easterly, Hertel, Stewart.
https://www.epa.gov/radiation/federal-guidance-report-no-15-external-exposure-radionuclides-air-water-and-soil

EPA, United States Environmental Protection Agency. 2019b. Table 4-1. Reference person effective dose rate coefficients for ground surface. Federal Guidance Report No. 15: External exposure to radionuclides in air, water, and soil. Bellamy, Dewji, Leggett, Hiller, Veinot, Manger, Eckerman, Ryman, Easterly, Hertel, Stewart.
https://www.epa.gov/radiation/federal-guidance-report-no-15-external-exposure-radionuclides-air-water-and-soil

EPA, United States Environmental Protection Agency. 2019c. Table 4-6. Reference person effective dose rate coefficients for air submersion. Federal Guidance Report No. 15: External exposure to radionuclides in air, water, and soil. Bellamy, Dewji, Leggett, Hiller, Veinot, Manger, Eckerman, Ryman, Easterly, Hertel, Stewart.
https://www.epa.gov/radiation/federal-guidance-report-no-15-external-exposure-radionuclides-air-water-and-soil

European Heart Network. European Cardiovascular Disease Statistics. 2017.
http://www.ehnheart.org/cvd-statistics/cvd-statistics-2017.html

European Union. 2013. Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom
https://eur-lex.europa.eu/eli/dir/2013/59/oj

Fairlie, I., Sumner, D. 2006. The Other Report On Chernobyl - an independent scientific evaluation of the health-related effects of the Chernobyl nuclear disaster with critical analyses of recent IAEA/WHO report. April 6, 2005, page 5.
http://cricket.biol.sc.edu/chernobyl/papers/torch.pdf

Giles, D., Hewitt, D., Stewart, A. et al. 1956. Malignant disease in childhood and diagnostic irradiation in Utero. Preliminary Communication, Volume 268, ISSUE 6940, P447, September 01, 1956.
https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(56)91923-7/fulltext

Gillies, M., Richardson, D.B., Cardis, E. et al. 2017. Mortality from Circulatory Diseases and other Non-Cancer Outcomes among Nuclear Workers in France, the United Kingdom and the United States (INWORKS). Radiat Res. 2017; 188(3), p: 276–290.
https://www.ncbi.nlm.nih.gov/pubmed/28692406

Grant, E.J., Brenner, A. Sugiyama, et al. 2017. Solid Cancer Incidence among the Life Span Study of Atomic Bomb Survivors: 1958–2009.Radiation Research, 187(5), p.513-537.
https://bioone.org/journals/radiation-research/volume-187/issue-5/RR14492.1/Solid-Cancer-Incidence-among-the-Life-Span-Study-of-Atomic/10.1667/RR14492.1.full

Guglielmelli, A., Castelluccio, D.M., Rocchi, F. 2016. Methodological Aspects for the Evaluation of the Radiological Impact of Severe Nuclear Accidents: Codes, Numerical Examples and Countermeasures. September 2016.
https://www.researchgate.net/publication/309391537_Methodological_aspects_for_the_evaluation_of_the_radiological_impact_of_severe_nuclear_accidents_codes_numerical_examples_and_countermeasures

Hauptmann, M., Daniels, R. D., Cardis, E. et al. 2020. Epidemiological Studies of Low-Dose Ionizing Radiation and Cancer: Summary Bias Assessment and Meta-Analysis. JNCI Monographs, Volume 2020, Issue 56, Oxford, July 2020, Pages 188–200.
https://academic.oup.com/jncimono/article/2020/56/188/5869934?searchresult=1

Hoffmann W., Schmitz-Feuerhake, I., Hinrichsen K. et al. BUND-Stellungnahme zum Entwurf des Strahlenschutzgesetzes : Deutscher Bundestag, Ausschussdrucksache. March 24, 2017.
https://www.bund.net/fileadmin/user_upload_bund/publikationen/atomkraft/atomkraft_strahlenschutzgesetz_stellungnahme.pdf

IAEA, International Atomic Energy Agency. 2006. Environmental Consequences of the Chernobyl Accident and Their Remediation: Twenty Years of Experience. Report of the UN Chernobyl Forum Expert Group "Environment", 166 p.
https://www-pub.iaea.org/books/iaeabooks/7382/Environmental-Consequences-of-the-Chernobyl-Accident-and-their-Remediation-Twenty-Years-of-Experience

ICRP, International Commission on Radiological Protection. 2012. ICRP Publication 119, Compendium of Dose Coefficients based on ICRP Publication 60. ICRP Publication 119. Ann. ICRP 41
https://www.icrp.org/publication.asp?id=ICRP%20Publication%20119

ICRP, International Commission on Radiological Protection. 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37, p.2-4.
http://www.icrp.org/publication.asp?id=ICRP%20Publication%20103

ICRP, International Commission on Radiological Protection. 2012. CRP Statement on Tissue Reactions / Early and Late Effects of Radiation in Normal Tissues and Organs – Threshold Doses for Tissue Reactions in a Radiation Protection Context. ICRP Publication 118. Ann. ICRP 41, p.1-2.
http://www.icrp.org/publication.asp?id=ICRP%20Publication%20118

IPPNW, International Physicians for the Prevention of Nuclear War. 2014. Health effects of ionising radiation: Summary of expert meeting in Ulm, Germany, October 19th, 2013.
https://www.ippnw.de/commonFiles/pdfs/Atomenergie/Health_effects_of_ionising_radiation.pdf

IPPNW, International Physicians for the Prevention of Nuclear War. 2016. 30 years living with Chernobyl 5 years living with Fukushima Health effects of the nuclear disasters in Chernobyl and Fukushima. https://ippnw.de/commonFiles/pdfs/Atomenergie/Tschernobyl/Report_TF_3005_en_17_screen.pdf

IRSN, Institut de radioprotection et de sûreté nucléaire. 2007. Examen de la méthode d'analyse coût-bénéfice pour la sureté. Annexe du Rapport DSR N°157, Réunion du Groupe permanent chargé des réacteurs nucléaires du 5 juillet 2007.
https://inis.iaea.org/collection/NCLCollectionStore/_Public/44/089/44089309.pdf

Kendall, G.M., Little, M.P., Wakeford, R. et al. 2013. A record-based case-control study of natural background radiation and the incidence of childhood leukaemia and other cancers in Great Britain during 1980–2006. Leukemia. 2013; 27, p. 3–9.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3998763/

Körblein, A., Hoffmann, W. 2006. Background Radiation and Cancer Mortality in Bavaria: An Ecological Analysis May 2006 Archives of Environmental and Occupational Health 61(3), p.109-114.
https://www.ncbi.nlm.nih.gov/pubmed/17672352

Lazyuk, D., Gaiduk, V., Petrovskaya, F. et al. 2005. Cardiovascular diseases among liquidators and populations of Belarus. [In:] Health of Liquidators (Clean-up Workers), 20 years after the Chernobyl Explosion. PSR/IPPNW Switzerland. p. 24 -25.
https://www.ippnw.org/pdf/chernobyl-health-of-clean-up-workers.pdf

Leadbetter, S.J., Hort, M.C., Jones, A.R. et al. 2015. Sensitivity of the Modelled Deposition of Caesium-137 from the Fukushima Dai-Ichi Nuclear Power Plant to the Wet Deposition Parameterisation in NAME. Journal of Environmental Radioactivity, 2015 Jan; 139, p. 200-211.
https://www.ncbi.nlm.nih.gov/pubmed/24745690

Leelössy, A., Molnar, F., Izsák F., et al. 2014. Dispersion Modeling of Air Pollutants in the Atmosphere: A Review. 2014. Central European Journal of Geosciences, September 2014, Volume 6, Issue 3, p. 257–278.
https://link.springer.com/article/10.2478/s13533-012-0188-6

Lelieveld, J., Kunkel, D., Lawrence, M. G. 2012. Global Risk of Radioactive Fallout after Major Nuclear Reactor Accidents. Atmospheric Chemistry and Physics 12 (9), p. 4245.
https://www.atmos-chem-phys.net/12/4245/2012/acp-12-4245-2012.pdf

Lenoir, Y. 2016. La Comédie Atomique – l'histoire occultée des dangers des radiations. La Découverte, p. 26 - 30 (ISBN – 978-2-7071-8844-1).
https://editionsladecouverte.fr/catalogue/index-La_com__die_atomique-9782707188441.html

Leuraud, K., Richardson, D.B., Cardis, E. et al. 2015. Ionising radiation and risk of death from leukaemia and lymphoma in radiation-monitored workers (INWORKS): an international cohort study. Lancet Haematol 2015; 2, p. 276–281
http://www.thelancet.com/pdfs/journals/lanhae/PIIS2352-3026(15)00094-0.pdf

Linet, M. S., Schubauer-Berigan, M. K., Berrington de González, A. 2020. Outcome Assessment in Epidemiological Studies of Low-Dose Radiation Exposure and Cancer Risks: Sources, Level of Ascertainment, and Misclassification. JNCI Monographs, Volume 2020, Issue 56, Oxford, July 2020, Pages 154–175. https://academic.oup.com/jncimono/article/2020/56/154/5869937?searchresult=1

Little, M.P., Azizova, T.V., Bazyka, D., et al. 2012. Systematic Review and Meta-analysis of Circulatory Disease from Exposure to Low-Level Ionizing Radiation and Estimates of Potential Population Mortality Risks. Environ Health Perspectives. 2012; 120: p.1503–1511.
https://ehp.niehs.nih.gov/1204982/

Mathews, J.D. Forsythe, A.V., Brady, Z. et al. 2013. Risk in 680 000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. Brit Med J. 2013; 346: f2360.
http://www.bmj.com/content/346/bmj.f2360

Mazur A. 2019. Hypothetical Accident in Polish nuclear power plant. Worst case scenario for main polish cities. Sciendo. Ecol Chem ENG S. 2019; 26(1):9-28. DOI: 10.1515/eces-2019-0001.
https://content.sciendo.com/view/journals/eces/26/1/article-p9.xml?language=en

Ministry of Energy. 2018. Extract from draft: Energy policy of Poland until 2040 (EPP2040). 8 p. https://www.gov.pl/documents/33372/436746/EN_Extract_EPP2040.pdf

Monitor Polski. 2020. Dziennik urzedowy Rzeczypospolitej Polskiej (Polish Monitor. Official Journal of the Republic of Poland). Poz. 946. 2020-10-16. 68 p.
https://monitorpolski.gov.pl/MP/rok/2020

Muller, H.J. 1928. The Production of Mutations by X-rays. Proceedings of the National Academy of Sciences of the United States of America. 1928 Septembre, 14(9), p. 714–726.
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1085688/pdf/pnas01821-0038.pdf

National Cancer Institute. 2020. Epidemiological studies of low-dose ionizing radiation and cancer: Summary bias assessment and meta-analysis, JNCI Monographs, Volume 2020, Issue 56, Oxford, July 2020. https://dceg.cancer.gov/news-events/news/2020/low-dose-monograph?s=09

NEI. 2020. Nuclear Engineering International. “Poland signs nuclear deal with USA”. 2020-10-26.
https://www.neimagazine.com/news/newspoland-signs-nuclear-deal-with-usa-8201218

NOAA, National Oceanic and Atmospheric Administration. 2016. Archive of Concatenated Short-Term NCEP Global Forecast System.
Ftp://arlftp.arlhq.noaa.gov/pub/archives/gfs0p25/

NOAA, National Oceanic and Atmospheric Administration. 2018a. FTP Forecast Index. Ftp://arlftp.arlhq.noaa.gov/archives/gfs0p25 (consulted Autumn 2018a)

NOAA, National Oceanic and Atmospheric Administration. 2018b. Air Resources Laboratory, “Hysplit”. https://www.arl.noaa.gov/hysplit/hysplit/ (consulted June 2018b)

Nyagu, A.I. 1994. Medizinische Folgen der Tschernobyl-Havarie in der Ukraine, Chernobyl Ministry of Ukraine, Scientific Center for Radiation Medicine, Academy of Medical Sciences of Ukraine, Pripyat scientific-industrial association, Scientific-Technical Center, Kiev – Chernobyl (Russian).

Ozasa, K. Shimizu, Y., Suyama, A., et al. 2012. Studies of the mortality of atomic bomb survivors, Report 14, 1950-2003: an overview of cancer and noncancer diseases. Radiat Res. 2012, Mar; 177(3), p.229-243.
https://www.ncbi.nlm.nih.gov/pubmed/22171960

Pearce, M.S., Salotti, J.A., Little, M.P. et al. 2012. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. Lancet 2012; 380, p. 499–505.
http://www.thelancet.com/pdfs/journals/lancet/PIIS0140-6736(12)60815-0.pdf

PGE Group. 2015. The First Polish Nuclear Power Plant Environmental Scoping Report. (PGE_SCN_DES_0001_EN_2.0) PGE EJ 1 sp. z o.o: pp. 220. (Consulted December 2020)
https://www.envir.ee/sites/default/files/poola_tuumaelektrijaama_kmh_scoping_report_2015.pdf

Piedelievre, J.P., Musson-Genon, L., Bompay, F. 1990. MEDIA—An Eulerian Model of Atmospheric Dispersion: First Validation on the Chernobyl Release. Journal of Applied Meteorology 29 (12), p. 1205–1220.
https://www.jstor.org/stable/pdf/26185536.pdf?seq=1#page_scan_tab_contents

Prysyazhnyuk, A.Y., Grishtshenko, V.G., Fedorenko, Z.P. et al. 2002. Review of epidemiological finding in the study of medical consequences of the Chernobyl accident in Ukrainian population. [In:] Imanaka T (Ed.), Recent Research Activities on the Chernobyl NPP Accident in Belarus, Ukraine and Russia, KURRI-KR-79 (Kyoto University, Kyoto), p. 188–287.
https://pdfs.semanticscholar.org/04ba/3b7994ca15da3f9cce0eb83fe84832b31446.pdf

Python Software Foundation. Python Language Reference, version 3.8.
https://www.python.org

Richardson, D.B., Cardis, E., Daniels, R.D. et al. 2015. Risk of cancer from occupational exposure to ionising radiation: retrospective cohort study of workers in France, the United Kingdom, and the United States (INWORKS). BMJ 2015; 351:h5359.
http://www.bmj.com/content/351/bmj.h5359

Sailer, M., Küppers C., Rehm U., Schmidt G. 1990. Ausgewählte Sicherheitsprobleme und Auswirkungen von schweren Unfällen des Kernkraftwerks Mühleberg/Schweiz. Verein Mühleberg unter der Lupe.
https://1drv.ms/f/s!AlHpZwGF5Z4AiKVFFMe7cmzlsmLKLg

Sander, R. 2015. Compilation of Henry's Law Constants (Version 4.0) for Water as Solvent. Atmos. Chem. Phys., 15, p. 4399–4981.
https://www.atmos-chem-phys.net/15/4399/2015/

Scherb, H., Kusmierz, R., Voigt, K. 2016. Human sex ratio at birth and residential proximity to nuclear facilities in France. Reprod Toxicol, 2016 April, 60, p. 104-111.
https://www.ncbi.nlm.nih.gov/pubmed/26880420

Schubauer-Berigan, M. K., Berrington de González, A., Cardis, E. et al. 2020. Evaluation of Confounding and Selection Bias in Epidemiological Studies of Populations Exposed to Low-Dose, High-Energy Photon Radiation. JNCI Monographs, Volume 2020, Issue 56, Oxford, July 2020, Pages 133–153. https://academic.oup.com/jncimono/article/2020/56/133/5869936?searchresult=1

Seibert, P., Arnold, D., Arnold, N., Gufler, K. et al. 2013. Flexrisk-Flexible Tools for Assessment of Nuclear Risk in Europe: Final Report. BOKU-Met Report 23, p. 116.
https://meteo.boku.ac.at/report/BOKU-Met_Report_23_PRELIMv2_online.pdf

Seibert P., Hofman R., Philipp A. 2014. Possible Consequences of Severe Accidents at the Proposed Nuclear Power Plant Site Lubiatowo near Gdańsk, Poland. Final Report from March 4, 2014. 2nd edition, July 2014. University of Vienna, Department of Meteorologyand Geophysics, Vienna, Austria. 33 p.
http://www.univie.ac.at/theoret-met/flexrisk_pl/en/flexrisk_pl_report_v2.pdf

Sholly S., Müllner N., Arnold N., Gufler K. 2014. Source Terms for Potential NPPs at the Lubiatowo Site, Poland. University of Natural Resources and Life Sciences, Vienna. 34 p.

Shore, R.E, Beck, H.L., Boice, J.D. et al. 2018. Implications of recent epidemiologic studies for the linear nonthreshold model and radiation protection. Journal of Radiological Protection, Volume 38, Number 3. https://iopscience.iop.org/article/10.1088/1361-6498/aad348/meta

Sipyagina, A.E., Baleva, L.S., Karakhan, N.M. et al. 2015. Role of Postradiation Genome Instability in Evaluating the Development of Radiation-Determined Pathology in Children After the Chernobyl. AASCIT Journal of Medicine 2015; 1(2), p. 18-22.
https://pdfs.semanticscholar.org/1641/89f2913af6572c94e7e0647b10e1b1fea274.pdf

Sperling, K, et al. 1987. Gemeinschaftsstudie zur saisonalen und regionalen Häufigkeit pränatal diagnostizierter Chromosomenanomalien für die Bundesrepublik Deutschland einschl. Berlins im Jahre 1986. Ann. Univ. Sarah. Med. Suppl. 7 (1987) 307-313.

Sperling, K., J Pelz, J., Wegner, R.D. et al. 1991. Frequency of trisomy 21 in Germany before and after the Chernobyl accident. Biomedicine & Pharmacotherapy, Volume 45, Issue 6, 1991, p, 255-262.
https://www.sciencedirect.com/science/article/abs/pii/075333229190026P

Sperling, K., Pelz, J., Wegner, R.D., Dörries, A. et al. 1994a. Significant increase in trisomy 21 in Berlin nine months after the Chernobyl reactor accident: temporal correlation or causal relation relation? BMJ. 1994 Jul 16; 309(6948), p.158–162.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2540705/

Sperling, K., Pelz,J., Wegner, R.D., Dörries, A. et al. 1994b. Bewertung eines Trisomie 21 Clusters. Med. Genetik 6, p.378-385.

Spycher, B.D, Lupatsch, J.E., Zwahlen, M. et al. 2015. For the Swiss Pediatric Oncology Group and the Swiss National Cohort Study Group. Background Ionizing Radiation and the Risk of Childhood Cancer: A Census-Based Nationwide Cohort Study. Environ Health Perspect 123, p. 622–628.
https://ehp.niehs.nih.gov/1408548/

SSK, Strahlenschutzkommission. 2014. Dose and dose-rate effectiveness factor (DDREF): Recommendation by German Commission on Radiological Protection, with scientific grounds. p. 5 – 16.
https://www.ssk.de/SharedDocs/Beratungsergebnisse_PDF/2014/DDREF_e.pdf?__blob=publicationFile

Stein, A. F., Draxler, R.R., Rolph, G., D., et al. 2015. NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System. Bulletin of the American Meteorological Society 96 (12), p. 2059–2077.
https://journals.ametsoc.org/doi/full/10.1175/BAMS-D-14-00110.1

Stewart, A., Webb, J., Giles, B.D., Heitt, D. 1956. Preliminary communication: malignant disease in childhood and diagnostic irradiation in utero. Lancet. 1956 Septembre 1; 271(6940), p.447.
https://www.ncbi.nlm.nih.gov/pubmed/13358242

Stewart, A., Webb, J. Hewitt, D. 1958. A survey of childhood malignancies. Br Med J. 1958 Jun 28; 1(5086), p. 1495–1508.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2029590/

Swiss Federal Council. 2019. Radiological Protection Ordinance 814.501. (Status as of 1 February 2019).
https://www.admin.ch/opc/en/classified-compilation/20163016/201902010000/814.501.pdf

Syryjczyk T. 1999. Przesłanki decyzji w przedmiocie likwidacji Elektrowni Jądrowej Żarnowiec. (Consulted December 2020) http://www.syryjczyk.krakow.pl/Elektrownia%20Jadrowa_T.htm

Takeyasu, M., Sumiya, S. 2014. Estimation of Dry Deposition Velocities of Radionuclides Released by the Accident at the Fukushima Dai-Ichi Nuclear Power Plant. Progress in Nuclear Science and Technology Volume 4, p. 64-67.
http://www.aesj.or.jp/publication/pnst004/data/064_067.pdf

Tereshchenko, V.M., et al. 2003. Epidemiologic research on non-neo plastic morbidity in Chernobyl NPP accident liquidation participants in 1986-87. Hygiene of population aggregates. Issue 41, p. 283-287 (quoted from Greenpeace report 2006, p. 125
http://hps.org/documents/greenpeace_chernobyl_health_report.pdf)

UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation. 2013. Volume I, report to the General Assembly, Scientific Annex A: Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami. UNSCEAR Report 2013, p. 77 – 79.
http://www.unscear.org/docs/publications/2013/UNSCEAR_2013_Report_Vol.I.pdf

U.S.NRC. 2007. United States Nuclear Regulatory Commission. AP1000 Design Control Document, Revision 16. 42 p.
https://www.nrc.gov/docs/ML0715/ML071580898.pdf

WHO, World Health Organization. 2006. Health effects of the Chernobyl accident: an overview. April 2006. (accessed on 3rd May 2019)
https://www.who.int/ionizing_radiation/chernobyl/backgrounder/en/

WHO, World Health Organization. 2013. Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami based on a preliminary dose estimation. ISBN 978 92 4 150513 0.
https://apps.who.int/iris/bitstream/handle/10665/78218/9789241505130_eng.pdf?sequence=1

Wikipedia. Żarnowiec Nuclear Power Plant. (Consulted November 2020)
https://en.wikipedia.org/wiki/%C5%BBarnowiec_Nuclear_Power_Plant#cite_note-Syr-5

WorldPop, Unconstrained individual countries 2000-2020 UN adjusted (1km resolution), https://www.worldpop.org/geodata/listing?id=75

Yablokov, A.V., Nesterenko, V.B., Nesterenko, A.V. 2009. Chernobyl – Consequences of the Catastrophe for People and Environment, Annals of the New York Academy of Sciences, Vol. 1181, Boston, Massachusetts. 327 p.
http://www.foejapan.org/energy/evt/pdf/121214.pdf

Yablokov, A.V., Nesterenko, V.B., Nesterenko, A.V., Preobrashenskaya, N.E. 2016. Posledstviya Katastrofy dlya Cheloveka y prirody Tovarishchestvo nauchnykh izdaniy KMK. Moskva, 2016, ISBN 978-5-9908165-2-7.
https://www.yabloko.ru/files/chern_8_vsya_kniga_25_marta.pdf