Modeling of a Hypothetical Major Nuclear Accident at Tricastin Nuclear Power Plant under 1 096 Meteorological Simulations and Analysis of its Health Impact

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Executive Summary

Introduction

The objective of this interdisciplinary analysis is to study the distribution of the radioactivity that would be released in the event of a major accident at the Tricastin nuclear power plant in France. The release of radioactive material can impact the health of the population, pollute the soil and trigger the long-term evacuation of inhabitants. The purpose of measuring the impact of an INES scale level 7 accident is to provide data to assist the authorities responsible for protecting the population.

Methodology

The term "major nuclear accident" refers to a breach of containment, whether its origin is technical, geological or human (negligence and malfeasance). The release is calculated from the core inventory of a 2785 MWth reactor established by *Électricité de France* (EDF) and the orders of magnitude of a type S1 accident as described by the Institute for Radiation Protection and Nuclear Safety (IRSN).

To give an idea of the release, we compared it to that of Chernobyl. There are only 19 nuclides from Chernobyl for which there is information and which correspond to the list of nuclides selected for Tricastin. Taking into account the limitation of the available data, the Tricastin release would represent 67% of the Chernobyl release. If weighted by inhalation dose factors, it would be 64% of the Chernobyl release.

In terms of the dispersion of radioactive material in the environment, 1096 meteorological simulations were carried out for the years 2017, 2018 and 2020 using the American NOAA Hysplit dispersion study software at a resolution of 0.25° latitude and longitude[2]. The impact on soil was analysed using Corine maps (published by the European Copernicus programme and covering 39 European countries) at a resolution of 100 metres. The impact on different types of soil cover (herbaceous, crops and others) are expressed in Becquerels.

The evaluation of the impact on the population has been conducted using maps at 1 km resolution from WorldPop. We considered 51 European or neighbouring countries (from Southern Mediterranean countries to Moscow in the East). The impact on the population is evaluated from two complementary angles: 1. Inhalation during the passage of the radioactive cloud according to a 72-hour simulation; 2. Irradiation of radioactive ground deposits (the irradiation is measured over one year taking into account the half-life of radioactive elements and an indoor factor of 0.4). The analysis of the number of exposed persons is structured by the annual dose limits expressed in Sieverts for different categories of population as set by Council Directive 2013/59/Euratom. The assessment of the impact on populations relies on simplified assumptions about the behaviour of populations during the passage of the cloud.

The health impact of deterministic effects on tissues is not evaluated. However, the stochastic effects of ionizing radiation on health have been estimated according to the collective committed effective dose (CCED). Artificial radioactivity combined with natural radioactivity increases the risk of micro-injuries at the cellular level, and thus increases the number of radiation-induced diseases that the study seeks to quantify.

Results

Number of persons impacted by the cloud and state of emergency

With respect to the passage of the cloud, more than 13,000,000 persons, on average, would receive a dose greater than 1 mSv, which is the limit for civilians. More than 590,000 persons, on average, would receive a dose greater than 20 mSv, which is the limit for radiologists and nuclear personnel. For so-called emergency situations, on average, more than 137,000 people would be exposed to a dose above 100 mSv - the threshold at which the dilemma of 'preventive evacuation' for some and 'absolute confinement' for others would arise and for which a decision would need to be implemented within hours; the figure would be even higher than 275,000 persons in 10% of the meteorological situations, while at the other end of the spectrum it would amount to less than 35,000 persons in 10% of the cases. This being the case, the inhabitants of several cities could face, under certain extreme weather conditions, individual doses of more than 0.5 Sieverts - which corresponds to the intervention limit for rescue workers - up to a distance of 70 km from Tricastin on the North-South axis (the details of individual doses for 55 French and foreign cities are publicly available online).

Number of persons to be evacuated permanently due to soil deposition

With respect to ground deposition and the long-term relocation of populations, on average, more than 300,000 persons would have to be relocated if the public authorities retained the 20 mSv threshold during the

[2] NOAA's collection of meteorological files is incomplete in 2019. However, we thank NOAA for making many data available.

first year, 139,000 persons if the threshold was set at 50 mSv, and 79,000 persons if the threshold was set at 100 mSv. Concerning the latter threshold, in 10% of the most severe cases, more than 164,000 people would have to be relocated, a figure that would, however, be below 16,000 in 10% of the least severe cases.

Estimates of health impact

According to the stochastic health impact, calculated from individual doses in the range of 1¬2,000 mSv to obtain the committed collective effective dose of the cloud, and in the range 1-20 mSv for deposition, the results are as follows. According to the calculation model (based on epidemiological studies), on average, the number of radiation-induced cancers would be about 58,000, the number of radiation-induced cardiovascular diseases would be about 22,000, resulting in a total of 80,000 cases of severe radiation-induced diseases in the decades following the release of radioactive material from one of the four Tricastin reactors. The number of radiation-induced deaths would total 36,000 in the decades following such a major nuclear accident.

Concerning the distribution of the 1096 meteorological simulations, according to the criterion of global stochastic health impact, Italy would be more affected than France in 32 simulations (2.9%), and Spain in 10 simulations (0.9%). At the European scale, the 50 selected countries would be more affected than France in 122 meteorological situations (11.1%). In other words, France's neighbours may consider the Tricastin plant to be a potential threat to their populations (if they have not already done so).

Agricultural soil pollution

Concerning the Cesium-137 radioactive pollution of soils a deposition equal to or greater than 37,600 Bq/m^2 of Cs-137 would affect, on average, 1,100 km^2 of vineyards, 5,700 km^2 of crops, and 5,000 km^2 of herbaceous land, to the detriment of agricultural activities.

More worryingly, a deposition of more than 226,000 Bq/m^2 of Cs-137 would permanently affect more than 370 km^2 of vineyards, 1,100 km^2 of crops and 500 km^2 of herbaceous land. Still, at this level of contamination and with all surfaces combined, in 5% of meteorological situations the deposition of radioactive materials would cover an area of more than 13,900 km^2, while in the lower end of the spectrum the impacted surfaces would be less than 1,290 km^2, the average being 4,950 km^2.

Conclusion

Although the French Institute for Radiation Protection and Nuclear Safety is making efforts to prevent S1-type accidents, dismissing the possibility of such an accident could lead to unpreparedness on the part of the public authorities. which would further aggravate the extent of damage in the event of such a disaster. Given the potential magnitude of such a disaster if it were to occur, there should be a public discussion of the plans and means that should be implemented to protect the population as effectively as possible.

I Context

1.1 Scope of the study

The objective of this interdisciplinary analysis is to study the distribution of radioactivity that would be released in the event of a major accident at the Tricastin nuclear power plant in France. The release of radioactive materials can impact the health of the population, pollute the soil and trigger the long-term evacuation of the inhabitants. The purpose of measuring the impact of an INES scale level 7 accident is to provide data to assist the authorities responsible for protecting the population.

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.

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.

Table 1.1. 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.

1.4 The Tricastin NPP

(i) Tricastin location and main characteristics of the four reactors

The Tricastin nuclear power plant is located along the Rhône River, 100 km north of the Mediterranean coast. The region is densely populated, with many small and medium-sized towns. It is almost halfway between Avignon in the south and Valence in the north. The most important cities within a 200 km radius are Marseille, Montpellier, Lyon et Nice.

Map 1: Location of Tricastin nuclear power plant, 100 km north of the Mediterranean coast.

The more populated the area surrounding a nuclear power plant, the more difficult it is to manage the consequences of a major nuclear accident.

Table 1.2. Tricastin nuclear power plant

NPP Name	Reactors No	Latitude decimal	Longitude decimal	Type	Power MWth	Net Pow. MWe	Type	First Grid. conn. year
Tricastin	4	44.3310	4.7318	PWR	2785	915	Framatome 3-loop CP1-Type	1980

The Tricastin nuclear power plant consists of 4 reactors of 2785 MWth (915 MWe). Construction of the first reactor began in 1974. The first reactor was put into operation and connected to the grid in 1980 and the last one in 1981 [4].

(ii) Source term of a major nuclear accident

The term "major nuclear accident" refers to a breach of containment, whether its origin is technical, geological or human (negligence and malfeasance). The question of the dimensioning of the source term is important because the size of the radioactive release is one of the determining factors of the impact on the population.

The question is to simulate the impact of a level 7 accident according to the INES scale in order to provide useful data to those responsible for protecting the population. Although the French Institute for Radiation Protection and Nuclear Safety is working to avoid such kind of accidents (IRSN 2013, 77), dismissing the hypothesis of such an accident at the Tricastin plant too quickly could lead to a disaster that the unpreparedness of the public authorities would make even worse.

In this study, the release is calculated from the core inventory of a 2785 MWth reactor, established by *Electricité de France* (EDF), a document that we were able to consult despite the fact that it has not been published to date (EDF 2004, 16). We also used the fractions of a type S1 accident described by the *Institut de radioprotection et de sureté nucléaire* (IRSN 2013, 77).

The term source used here comprehend a first list of 59 nuclides, whose half-life is equal or superior to 78h (see below additional explanations). From this first list of 59 nuclides, we have inferred a second list of progeny nuclides, numbering 45 items (*infra* 2.2).

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 2.853E+18 Becquerels (Bq) (*supra* I.4(ii)). 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 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 ≥ 2.82E+05 seconds (≈78 hours), which implies the shorter half-life nuclide to be included in the list is Te-132.

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[4] IAEA, Power Reactor Information System, https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=170 (consulted June 2021)

See Table A.1 in Appendix A for the amounts and half-lives of each nuclide.

The first list of 59 nuclides:

Group 2: I-129, I-131
Group 3: Cs-134, Cs-135, Cs-136, Cs-137, Rb-86,
Group 4: Sb-124, Sb-125, Sb-126, Sb-127, Te-125m, Te-127m, Te-129m, Te-132,
Group 5: Ba-140, Sr-89, Sr-90,
Group 6: Ag-108m, Ag-110m, Ag-111, Ru-103, Ru-106, Tc-99,
Group 7: Am-241, Am-243, Cm-242, Cm-243, Cm-244, Eu-152, Eu-154, Eu-155, Eu-156, Nb-93m, Nb-94, Nb-95, Nb-95m, Nd-147, Pm-147, Pm-148, Pm-148m, Pr-143, Sm-147, Sm-151, Y-91, Zr-93, Zr-95,
Group 8: Ce-141, Ce-144, Np-237, Pu-236, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, U-234, U-235, U-238
Additional details are available in Table A.1 of Appendix A.

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 7.7E+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; IAEA 2003, 6).

The time at which the activity of the first decay product is at a maximum is derived as follows:

If the activity of the progeny as a function of time is designated as $A_2(t)$, then,

$$A_2(t) = A_1(0)\lambda_2 \frac{(e^{-\lambda_1 t} - e^{-\lambda_2 t})B_2}{\lambda_2 - \lambda_1}$$

$A_2(t)$	= activity of daughter at time t
$A_1(0)$	= initial activity of parent
λ_1	= decay constant of parent
λ_2	= Radioactive decay constant
B_2	= branching ratio of daughter

Equation 1: (IAEA 2003, 6)

$$t_{max} = \frac{1}{\lambda_2 - \lambda_1} \ln \frac{\lambda_2}{\lambda_1}$$

λ_1 = decay constant of parent
λ_2 = Radioactive decay constant of 'daughter'

Equation 2: (IAEA 2!!!, 85)

Equations 1 and 2 allow to calculate the amounts of progeny nuclides.

When looking at a table of reference on half-life, decay products, decay mode and fractional yield (EPA 2019a), it appears that 37 out of the 59 nuclides of the first list of the source term trigger 45 radioactive nuclides. The list of progeny nuclides comes as follows:
Xe-131m, Ba-137m, Te-125m, Te-127, Te-127m, Te-127, Te-129, I-129, I-132, La-140, Y-90, Ag-108, Ag-110, Rh-103m, Rh-106, Np-237, Np-239, Pu-238, Pu-239, Am-243, Pu-240, Gd-152, Nb-95, Pm-147, Sm-147, Sm-148, Sm-148, Pm-148, Nb-93m, Nb-95, Nb-95m, Pr-144, Pr-144m, Pa-233, U-232, U-234, U-235m, U-235, U-236, Am-241, U-237, U-238, Th-230, Th-231, Th-234.
Additional details can be found in Tables A.2 in Appendix A.

(ii) Aggregation of the cloud: verification of a possible bias
The evolution of the radioactive cloud, modelized as a curve expressed in Becquerels over 72h, should be compared to the millisieverts a 'fictitious individual' would receive from the source term 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 85% of the value in millisieverts of the first two hours, which makes we finally underestimated the impact measured in mSv at the end of the simulation of the aggregated cloud by around 5%. Additional details can be found elsewhere (*infra* 2.6).

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 59 nuclides 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*.

(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.

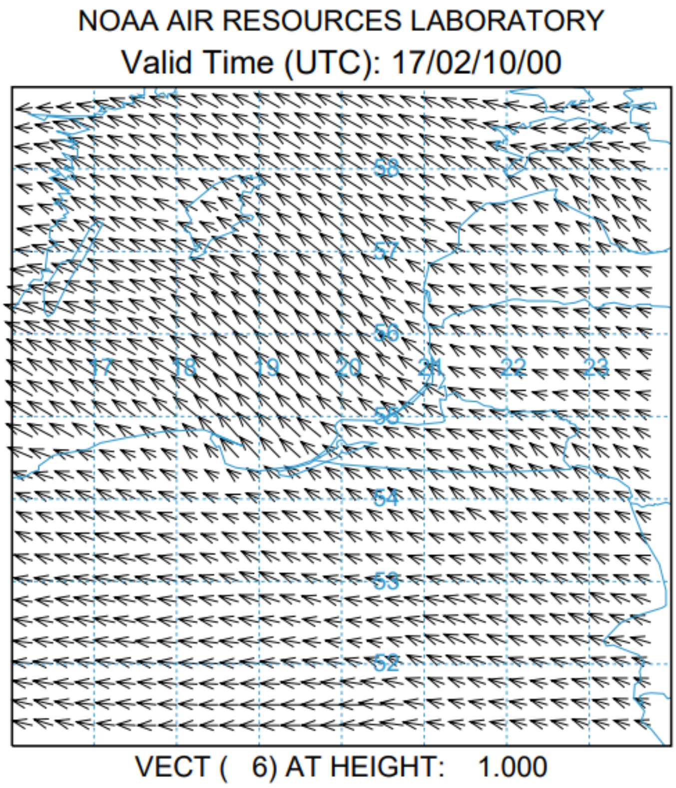
[5] That section is an excerpt of the one published in EUNUPRI_2019.

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.).

(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.

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

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).

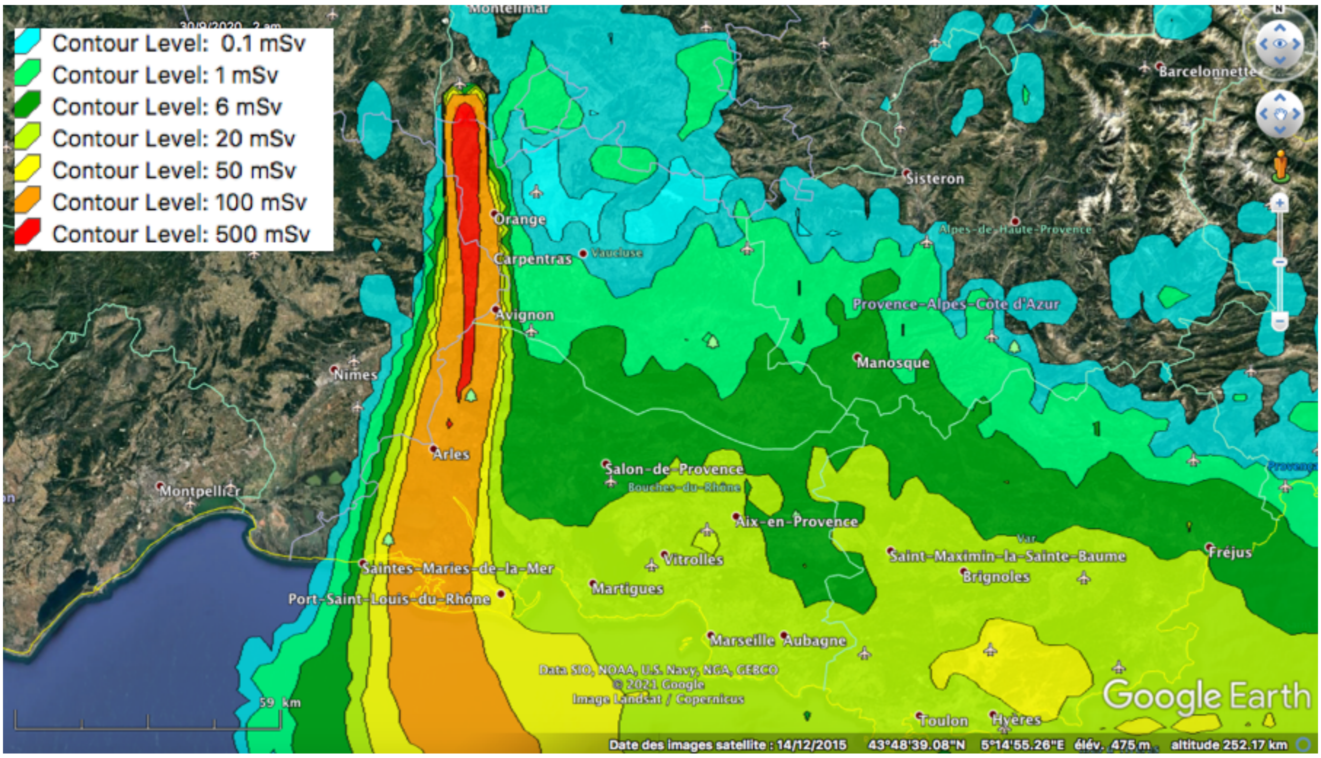
(iv) The Hysplit dispersion model evaluated by WMO in the case of Fukushima

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



Map 3. Example of dispersion pattern from a release on the 30th of September 2020.

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 1.01.2020 – 31.12.2020 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.

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 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 100 m 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 analyses 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.10.)

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 ($Bq \cdot s/m^3$) or ($Bq \cdot s/m^2$).

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

(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 (ENSI 2009, 67) 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 Council Directive 2013/59/EURATOM), which makes only people living in areas where doses from deposition are below 20 mSv would receive a committed effective dose from deposition.
Additional details can be found in Tables A.3 (cloud) and A.4. (one-year deposition) of Appendix A.

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 Radioactive cloud: number of persons above legal thresholds

The number of people who would be impacted by the passage of the cloud can be read in Table 3.1. Among the legal limits to protect people, we can point out the limits for the public (≥ 1 mSv), for young professionals (≥ 6 mSv), for professionals (≥ 20 mSv), for the public in emergency situations (≥ 100 mSv), for rescuers in life-saving situations (≥ 500 mSv) (supra 1.3). Each of these intuitively communicates a certain level of danger.

The average impacted person approach in the first row of Table 3.1 indicates that many people could be affected. Below this row, the quantile distribution shows a large variability.

Table 3.1. Distribution of the number of persons impacted by the radioactive cloud at different levels
(Results obtained from 1096 meteorological simulations over years 2017, 2018, 2020)
Tricastin

Cloud	'Europe-51' ≥ 1 mSv (persons)	'Europe-51' ≥ 6 mSv (persons)	'Europe-51' ≥ 20 mSv (persons)	'Europe-51' ≥ 50 mSv (persons)	'Europe-51' ≥ 100 mSv (persons)	'Europe-51' ≥ 500 mSv (persons)	'Europe-51' ≥ 1000 mSv (persons)	'Europe-51' ≥ 2000 mSv (persons)
Average	13 251 141	2 089 318	595 657	252 697	137 946	35 977	18 307	8 455
Max	76 184 983	16 212 516	4 040 718	2 355 654	789 682	275 930	169 944	58 823
Q99	51 022 007	8 967 932	2 497 467	1 280 350	496 224	157 921	69 697	39 262
Q95	34 277 330	5 766 651	1 736 338	605 208	337 556	96 085	55 030	32 591
Q90	27 644 642	4 421 165	1 327 868	463 848	275 911	76 087	46 935	28 808
Q85	22 012 018	3 660 042	1 034 861	389 058	240 089	66 551	40 916	25 608
Q75	17 265 023	2 746 969	731 158	313 983	183 616	52 341	33 345	17 637
Q50	10 411 515	1 645 436	423 832	192 146	110 447	29 220	12 381	0
Q25	5 849 885	777 147	234 037	120 442	62 329	9 445	0	0
Q15	4 234 870	504 650	178 803	92 884	45 859	3 177	0	0
Q10	3 565 396	370 110	159 948	78 940	35 103	1 187	0	0
Q5	2 657 519	268 298	138 646	55 631	25 404	0	0	0
Q1	1 203 749	186 722	79 186	28 978	9 584	0	0	0
Min	443 508	60 434	18 211	3 294	3 031	0	0	0

3.2 Radioactive deposition: number of persons above legal thresholds

For deposition, the relation between Becquerels and Sieverts is calculated in the first year after the accident. In Table 3.2, Becquerels are given at the beginning of the calculation and millisieverts are calculated taking into account the half-life and decay products of each radioelement over one year (*supra* 2.6).

Table 3.2. Relation between millisieverts and Becquerels in calculation on radioactive deposition

NPP and MWth:	Fra 2785 MWth								
ALL nuclides (mSv (1st yr)$^{-1}$)	0.01	0.10	1.00	6	20	50	100	1000	2000
Parents' Becquerels(t1) (Bq m^{-2})	1.22E+04	1.22E+05	1.22E+06	7.32E+06	2.44E+07	6.10E+07	1.22E+08	1.22E+09	2.44E+09
Cs-137(t1) (Bq m^{-2})	3.76E+02	3.76E+03	3.76E+04	2.26E+05	7.52E+05	1.88E+06	3.76E+06	3.76E+07	7.52E+07
Cs-137 + Ba-137 (mSv (1st yr)$^{-1}$)	0.0018	0.0176	0.176	1.06	3.53	8.82	17.64	176.36	352.71

Note: From Bq to mSv –> through specific half-lives & dose factors; and through indoor factor at 0.4 (*supra* 2.6)

Table 3.3. Distribution of the number of persons impacted by deposition at different levels
(Results obtained from 1096 meteorological simulations over years 2017, 2018, 2020)
Tricastin, 1st year deposition on ground surfaces

	'Europe-51' ≥ 1 mSv (persons)	'Europe-51' ≥ 6 mSv (persons)	'Europe-51' ≥ 20 mSv (persons)	'Europe-51' ≥ 50 mSv (persons)	'Europe-51' ≥ 100 mSv (persons)	'Europe-51' ≥ 500 mSv (persons)	'Europe-51' ≥ 1000 mSv (persons)	'Europe-51' ≥ 2000 mSv (persons)
Average	7 169 096	1 016 563	311 913	139 484	79 126	18 616	8 768	3 373
Max	44 000 113	5 992 772	2 911 429	1 333 761	460 803	171 496	70 840	32 399
Q99	28 166 517	4 029 977	1 546 504	517 501	308 844	70 993	40 824	25 072
Q95	18 332 251	2 858 507	822 443	340 683	211 772	56 609	33 155	19 714
Q90	14 406 474	2 238 657	577 470	278 750	164 491	47 061	29 494	15 737
Q85	12 273 972	1 823 852	471 126	239 661	138 134	41 307	26 414	11 413
Q75	9 562 735	1 424 328	376 039	183 683	106 793	33 903	18 576	1 166
Q50	5 570 882	716 007	227 880	111 005	61 995	12 474	0	0
Q25	3 013 588	363 152	144 620	62 152	31 898	0	0	0
Q15	2 081 971	260 003	112 486	45 846	23 409	0	0	0
Q10	1 646 288	219 631	95 081	36 012	16 338	0	0	0
Q5	1 081 028	182 196	71 607	25 075	8 505	0	0	0
Q1	478 001	133 875	37 296	9 109	2 665	0	0	0
Min	208 335	23 526	11 381	1 496	0	0	0	0

Table 3.3 is structured like Table 3.1, but it concerns radioactive deposits during the first year after a major accident. The variability of the deposition figures raises a number of questions. Legislators and public authorities may need to adjust the dose levels at which they plan to evacuate people (20 mSv, 50 mSv or

100 mSv?), taking into account the capacity of official agencies to manage a long-term evacuation of tens of thousands of inhabitants.

3.3 Health impact

(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 the strictest threshold of Council Directive 2013/59/EURATOM), which makes only people living in areas where doses from deposition are below 20 mSv would receive a committed effective dose from deposition (*supra* 1.3). 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. The EAR factors were defined according to the epidemiological literature; Model A was analysed as less relevant than Model B which is based on more recent literature. (*supra* 2.7).

(ii) Average CCED and average health impact according to model A and Model B

Table 3.4 shows the effects of the EAR factors of Model A and Model B when it comes to evaluate the health impact from the collective committed effective dose (CCED). The health impact of deposition over one year would be less impacting than the health impact of the cloud. The severe radiation-induced diseases quantified here would develop over several decades, as would the deaths in Table 3.5. These figures are only as good as the assumptions on which they are based.

Table 3.4. Radio-induced severe diseases (cancer & cardiovascular cases) on average, according to Model A and Model B

Results obtained from 1096 meteorological simulations		Factors EAR:	0.2	0.4	0.15	0.55
			Model A	Model B	Model B	Model B (cancer & cardiovascular diseases)
NPP name	Type of impact	CCED Average personSv person-sieverts	People with radio-induced cancer (No)	People with radio-induced cancer (No)	People with severe cardiovascular disease	People with severe radio-induced diseases (No)
Tricastin	Cloud + deposition	146 321	29 264	58 528	21 948	80 476
Tricastin	Cloud	120 919	24 184	48 368	18 138	66 506
Tricastin	Deposition	25 401	5 080	10 161	3 810	13 971

Table 3.5. Average radio-induced deaths (cancer & cardiovascular diseases) according to Model A and Model B

Results obtained from 1096 meteorological simulations		Factors EAR:	0.1	0.2	0.05	0.25
NPP name	Type of impact	CCED Average personSv person-sieverts	Model A (cancer) Radio-induced Deaths (No)	Model B (cancer) Radio-induced Deaths (No)	Model B (cardio-vascular diseases) Radio-induced Deaths (No)	Model B (cancer & cardiovascular diseases) Radio-induced Deaths (No)
Tricastin	Cloud + deposition	146 321	14 632	29 264	7 316	36 580
Tricastin	Cloud	120 919	12 092	24 184	6 046	30 230
Tricastin	Deposition	25 401	2 540	5 080	1 270	6 350

The distribution of the health impact in five territories is edited in the Appendix (Tables A.8, A.9)

(iii) Transboundary distribution of individual doses for more than 50 towns and cities

All in all, we calculated individual doses for more than 50 towns and cities, located in France, Italy, Germany, Switzerland, Spain, Belgium, United-Kingdom and Luxembourg. In some towns, close to the Tricastin nuclear power plant, individual doses could exceed 7 Sv. About 40 km south of Tricastin, the maximum individual dose peaks at around 1,500 mSv in some rare simulations. At greater distances, it can be higher than 10 mSv, as in Germany and Austria. In order to present the complete data to officials interested in the field, the data are available online at the following URL: https://nrisk.institutbiosphere.ch/in-fr.html. The database contains the individual doses that could impact the inhabitants of the following cities:

Alès (FRA), Arles (FRA), Avignon (FRA), Bordeaux (FRA), Besançon (FRA), Béziers (FRA), Cannes (FRA), Carpentras (FRA), Clermont-Ferrand (FRA), Cournon-d'Auvergne (FRA), Dijon (FRA), Gap (FRA), Grenoble

(FRA), Lyon (FRA), Marseille (FRA), Montélimar (FRA), Montpellier (FRA), Muhlouse (FRA), Nancy (FRA), Nimes (FRA), Orange (FRA), Paris (FRA), Perpignan (FRA), Rodez (FRA), St-Etienne (FRA), Strasbourg (FRA), Toulon (FRA), Toulouse (FRA), Valence (FRA), Valréas (FRA), Alba (ITA), Alessandria (ITA), Bologna (ITA), Firenze/Florence (ITA), Genoa/Gênes (ITA), Milano (ITA), San Remo (ITA), Torino/Turin (ITA), Freiburg im Breisgau (DEU), Koblenz (DEU), Köln (DEU), Mannheim (DEU), München/Munich (DEU), Stuttgart (DEU), Bern (CHE), Genève (CHE), Lausanne (CHE), Barcelona (ESP), Figueras (ESP), Bregenz (AUT), Innsbruck (AUT), Villach (AUT), Bruxelles/Brussel (BEL), London (GBR), Luxembourg (LUX).

(iv) Transboundary distribution of the health impact

The severity of the health impact would also vary between countries. In some weather situations, Italy would be more affected than France, but this only represents 2.9% of the 1096 simulations. Spain would be more affected in 0.9% of the simulations. In contrast, France is more affected than the rest of Europe in 88.9% of simulations.

The severity of the health impact expressed in person-sieverts varies according to the meteorological situations as well as the population density that the radioactive cloud would encounter.

Table 3.6. Model B: Radio-induced severe diseases (cardio & cancer) that would occur in 5 territories

Cloud + (deposition ≤ 20 mSv (1st year)) — Results obtained from 1096 meteorological simulations

NPP: Tricastin

Impacted:	'Europe-51' Model B Pers. (No)		France Model B Pers. (No)		Italy Model B Pers. (No)		Switzerland Model B Pers. (No)		Spain Model B Pers. (No)
Average	80 476	Average	62 536	Average	6 800	Average	1 685	Average	1 051
Max	342 398	Max	332 077	Max	144 781	Max	78 937	Max	67 606
Q99	244 338	Q99	197 483	Q99	66 185	Q99	30 236	Q99	28 728
Q95	169 578	Q95	134 876	Q95	32 841	Q95	10 501	Q95	3 924
Q90	140 846	Q90	117 179	Q90	21 778	Q90	4 213	Q90	591
Q85	127 890	Q85	106 045	Q85	15 604	Q85	1 484	Q85	135
Q75	111 473	Q75	88 937	Q75	7 463	Q75	178	Q75	0
Q50	73 353	Q50	56 752	Q50	741	Q50	0	Q50	0
Q25	41 753	Q25	26 926	Q25	0	Q25	0	Q25	0
Q15	30 134	Q15	17 964	Q15	0	Q15	0	Q15	0
Q10	22 824	Q10	14 417	Q10	0	Q10	0	Q10	0
Q5	16 716	Q5	10 148	Q5	0	Q5	0	Q5	0
Q1	10 484	Q1	6 182	Q1	0	Q1	0	Q1	0
Min	4 340	Min	3 441	Min	0	Min	0	Min	0

Results over 1096 meteorological simulations (overs years 2017, 2018, 2020) without low dose <1 mSv.

The results for radiation-induced deaths in the different countries and regions, according to Model B, are published in the Appendix (Table A.9).

(v) Deposition on ground surface and impacts on soils

For deposition, the relation between Becquerels and Sieverts is calculated in the first year after the accident (*supra* Table 3.2). With regards to deposition on different type of land cover, Table 3.7 gives an insight of the whole picture.

Table 3.7. All surfaces, number of radioactive square kilometres distributed by quantiles (under 1096 simulations)

Fra 2785 MWth Parent + Progeny (mSv (1st yr)-1) Parents' Becquerels(t1) (Bq m-2) Impacted area: 'Europe39'	≥0.1 1.22E+05 km2	≥1 1.22E+06 km2	≥6 7.32E+06 km2	≥20 2.44E+07 km2	≥50 6.10E+07 km2	≥100 1.22E+08 km2	≥500 6.10E+08 km2	≥1000 1.22E+09 km2	≥2000 2.44E+09 km2
Q95	420 519	95 668	13 963	3 126	1 388	888	241	128	58
Q80	260 088	60 386	7 164	1 885	986	585	162	84	16
Q50	134 887	31 052	3 483	1 277	594	338	39	0	0
Q20	52 215	11 705	1 797	801	279	112	0	0	0
Q5	12 449	2 981	1 293	427	122	36	0	0	0
Addit. Informat.: Cs-137(t1) (Bq m^{-2})	3.76E+03	3.76E+04	2.26E+05	7.52E+05	1.88E+06	3.76E+06	1.88E+07	3.76E+07	7.52E+07

On average and for all surfaces combined, we found that 38,000 km^2 would, on average, receive 3.76E+04 Bq/m^2 of Cs-137, while 4,900 km^2 would, on average, receive 3.76E+04 Bq/m^2 of Cs-137.
It is worth noting that the three categories of land-cover more specifically analysed are vineyard, herbaceous, pasture, and a forth one that we call 'others'. The distribution of radioactive deposition on these four categories is given in the Appendix (Tables A.11 to A.14).

IV. Discussion

4.1 From five different releases to collective committed effective doses

(i) Release
The size of the radioactive release is based on the official literature. To give an idea of the release, we compared it to that of Chernobyl. There are only 19 nuclides from Chernobyl for which there is information and which correspond to the list of nuclides selected for Tricastin. Taking into account the limitation of the available data, the Tricastin release would represent 67% of the Chernobyl release. If weighted by inhalation dose factors, it would be 64% of the Chernobyl release.

(ii) Cloud meteorological behavior
We identified the deposition velocity and complementary parameters from the literature. It has been questioned as to why we decided not to take into account the characteristics of the land-cover which influences the deposition (supra 2.3).

(iii) From Bq to mSv
We used different lists of dose factors in order to cope with different situations, inhalation, external exposition from EPA.
For calculating the health impact, during the passage of the cloud, we followed official recommendation, that does not use an indoor factor, and assumes that adults are breathing in a stressed mood. Concerning the first-year of exposition to groundshine, the estimate of the committed effective doses from deposition was based on external exposition only. We followed the recommendation of ENSI, that recommends an indoor factor of 0.4 (*supra* 2.6). The calculation related to deposition was restricted to the first year, an option which limits the CCED.

4.2 Health Effects

(i) Estimated number of victims from a nuclear accident
Estimations of the numbers of victims are open to controversy, in already established major NPP accidents such as in Chernobyl (Claussen & Rosen 2016). Furthermore, this might hold true in hypothetical situations as described in the present study. Apart from the difficulties of characterizing the source term, varying meteorological and complex geographical conditions, large uncertainties come from diametrically opposed perceptions of radiation induced non-cancer health effects. Politicians and economists have different views on health issues than physicians do. However, population safety aspects should primarily rely on scientifically based medical knowledge. In the thirty years since the Chernobyl NPP accident – for more than one human generation – the WHO has failed to conduct an adequate broad systematic evaluation of the health of the millions of inhabitants of radio-contaminated regions. Therefore, the several thousands of reports given on community, district, or country levels and their comprehensive reviews (Yablokov et al. 2009: 58-160) are all the more important. If the WHO then takes a retrospective position on the countless non-cancer health effects after the Chernobyl catastrophe, this cannot satisfy scientific criteria (WHO 2006). Purported, improved reporting, cited as the reason for the obvious, in explicit terms, massively increasing health problems is not a sufficiently valid explanation, especially as many studies compare populations in regions with different radio-contamination levels.

A similar position is taken by UNSCEAR for radio-induced health effects in general and even for radio-induced cancers (where EARs are established), arguing that future excess cancers, due to radiation after the Fukushima NPP accident would not be statistically discernible (UNSCEAR 2013, 77-79)[8].

In contrast, our estimations predicated on the latest scientific evidence, reveal that there may be on average 80,000 cancer victims from a hypothetic major accident at Tricastin NPP. According to the perspective of the physicians' ethics code, it is unjust to discount a large number of victims based on the argument that their occurrence seems to be diluted at the large scale (when comparing the number of affected persons to the millions of radio-contaminated persons). Furthermore, 'dilution' is not an argument since persons close to the source of a major nuclear accident will have between a 10%, 20%, or even a higher risk percentage of contracting a malignant or cardiovascular disease.

It is well known that an individual cancer case cannot be linked to ionizing radiation as causative factor. However, this does not invalidate the statistical relevance at the scale of a radio-contaminated population. This is certainly the case for individual cancer patients in the cohort of nuclear bomb survivors (Ozasa et al. 2012, 229-243) in Japan, which represents the backbone of the actual radiation risk calculation concepts – according to recent observations even in the low dose range (Grant 2017, 515-537).

(ii) Strengths of the health impact assessment

- Presenting three different risk models on radio-induced health effects may achieve more understanding for differing views. However, estimates according to WHO/UNSCEAR focusing only on radio-induced cancer already show the devastating health effects for tens of thousands of affected people by a possible major accident in a Western Europe NPP. This could alert responsible authorities for a rapid revision of the highly insufficient radioprotection measures.
- The integration of cardiovascular diseases into risk assessment enables a somewhat broader assessment of the incidence of life-threatening radio-induced non-malignant health effects.
- Considering not only cancer, but also other non-cancer health effects such as reproductive hazards into risk estimations is mandatory from the medical view point even if only a semi-quantitative approach seems feasible. This is justified by the huge numbers of human body systems and functions affected by ionizing radiation. It seems rewarding to warn non-medical authorities and the general population about these radiation hazards that are well known to physicians since more than 60 years (Stewart et al. 1956, 447).

(iii) Shortcomings of the health impact assessment

- As the aim of this study was giving an estimate on the orders of magnitude of radio-induced victims due to a major nuclear accident, distinct entities like thyroid cancer or leukemia have not been dealt with.
- This study does not pay attention to gender aspects, nor does it specifically calculate risks for children who are much more radiosensitive than adults.
- Ingestion by nutrition and water intake as well as resuspension with inhalation and external irradiation has not been considered.
- This study didn't take into account an eventual "optimal" emergency management scenario which clearly would have an individual dose-reducing effect. However, a meaningful estimate of the number of victims with evacuation taken into account corresponds likely to a "chaotic" scenario in the event of a major nuclear accident in France. A French study on a possible accident at NPP Dampierre described "negligible" numbers of lethal cancer cases in an "optimal" scenario in contrast to 10,000 lethal cancer cases in a "realistic" scenario (IRSN 2007, 21).
- Furthermore, the health effects covered by the study are explained by direct ionizing radiation effects. Additional important health aspects such as radio-phobia, social effects, induced abortions, psychological adaptive difficulties to the huge economic and societal changes provoked by a major nuclear accident could not be assessed in this study since they are all an indirect consequence of the specific property of a nuclear accident: The extremely intrusive, temporally and spatially illimitable radio-contamination.

[8] *"A general radiation-related increase in the incidence of health effects among the exposed population would not be expected to be discernible over the baseline level"* UNSCEAR 2013, 77-79.

4.3 Preventive evacuation and long-term evacuation

(i) Preventive evacuation

Preventive evacuation aims at preventing people from receiving a CED ≥ 100 mSv. It is not a systematic measure. It should protect the most fragile people that would be unable to remain below that threshold by remaining in their home for instance. In other terms, it has to be selective. The problem is that a situation of alert for a potentially forthcoming major nuclear accident could degenerate in a vast traffic jam since different panic behaviors, for instance parents that will rush to their children's school to keep them safe, have the potential to create an indescribable chaos. According to our calculations, the number of people in areas with more than 100 mSv is 137,000 on average, and it would exceed 275,000 persons in 10% of the meteorological situations. These figures suggest that the situation could become unmanageable for civil protection as a result of the phenomena just described.

(ii) Long-term evacuation

To evaluate the number of people to be evacuated was based on the criterion of a deposition leading to three possible limits/scenario as set up in the of Council Directive 2013/59/EURATOM: 20 mSv, 50 mSv and 100 mSv per year. We found that, on average, between 300,000 persons to 79,000 persons would need to be housed outside the evacuation zone for at least one year. However, to better quantify the people to be relocated, additional research is needed to more accurately simulate the fate of radioactive deposition after an INES level 7 accident. The type of soil cover, leaching phenomena, the impact of leaching on aquifers and the inhabitants who depend on them, and the infiltration of radioactivity into homes and workplaces would have to be taken into account.

4.4 Radioactive deposition on land cover and more specifically crop and grazing lands

(i) Strengths and shortcomings

We found that 38,000 km^2 would, on average, receive 3.7E+04 Bq/m^2 of Cs-137, – on average for 1096 meteorological situations. By comparison, the average number for the deposition of Cs-137 at the same level of 3.7E+04 Bq/m^2 of Cs-137 from European NPPs is 165,000 km^2 in the study of Lelieveld et al. (2012, p. 4251). Understanding this gap requires further research.

V Conclusion

The study simulated a major nuclear accident at Tricastin NPP, in the South of France, by modelling the release of 59 radioactive nuclides as well as their atmospheric transport using 1,096 meteorological simulations. The objective was to assess the impacts on health, population relocation and land cover.

Following the background, methodology and results sections, the strengths and limitations of the results were discussed in a fourth section.

To summarize the main results, we found that, on average, 80,000 persons would develop severe radio-induced diseases and 36,000 would die from these diseases within a few decades. In addition, 38,000 km^2 of land surface would receive more than 3.7E+04 Bq per square metre, a concentration that corresponds to significant soil contamination. The impacts would nevertheless vary significantly, depending on the meteorological situations.

While France would on average experience the biggest impact, many meteorological situations would lead the radioactive cloud to Italy, Switzerland or Spain (among other countries). From a strategic point of view and according to the literature, the combined impacts could trigger serious, economic, institutional and political consequences for the most affected country, especially for France.

It is well known that human negligence and malfeasance have led to a number of disasters in this or the previous century. Therefore, it would be foolhardy to pretend that the probability of a major nuclear release from a Tricastin reactor is very unlikely.

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