Nuclear refugees after large early radioactive releases

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Abstract: However improbable, large early radioactive releases from a nuclear power plant would entail major consequences for the surrounding population. In Fukushima, 80,000 people had to evacuate the most contaminated areas around the NPP for a prolonged period of time. Had they remained where they lived, they would have received doses dangerous for their health in the long run. These people have been called “nuclear refugees”.
The paper first argues that the number of nuclear refugees is a better measure of the severity of radiological consequences than the number of fatalities, although the latter is widely used to assess other catastrophic events such as earthquakes or tsunami. It is a valuable partial indicator in the context of comprehensive studies of overall consequences.
Section 2 makes a clear distinction between long-term relocation and emergency evacuation and proposes a method to estimate the number of refugees.
Section 3 examines the distribution of nuclear refugees with respect to weather and release site. The distribution is asymmetric and fat-tailed: unfavorable weather can lead to the contamination of large areas of land; large cities have in turn a higher chance of being contaminated. Variability with respect to site is quite intuitive; however, results show that simulations are far superior to an approach based on population living within 20 or 30 km around the site.

Keywords: PSA, accident consequences, nuclear refugees.

1. INTRODUCTION

1.1. Fatalities

In the literature on disasters and emergency situations, different disasters are often compared on the basis of prompt fatalities. Car accidents or plane crashes can thus be compared with earthquakes or tsunamis on this basis. Nuclear accidents are sometimes included in such comparisons although the number of prompt fatalities in nuclear accidents is quite low: none are attributed to the Fukushima accident whereas about 30 are registered for the Chernobyl accident.

Nuclear accidents entail a large number of other damaging consequences; their total cost may reach hundreds of billions of dollars [1]. It has therefore been pinpointed that prompt fatalities are a poor indicator of overall accident severity as far as the nuclear sector is concerned. Total cancer fatalities consecutive to exposition to ionizing radiations have therefore been proposed as a more comprehensive and apt indicator. It was argued that considering only prompt fatalities is a way to minimize the total number of casualties.

From an economic point of view, this argument is not entirely valid. When attempting to quantify the loss involved in a prompt fatality, economists consider that, from the point of view of the nation, it is the loss of a “statistical life” i.e. the loss of a number of years equal to half the average lifespan, say between 40 and 45 years. In comparison, cancer fatalities induced by ionizing radiation typically take place 20 years after the event and thus entail a loss of life closer to half a statistical life.

In addition, fatalities due to cancer are profoundly different from prompt fatalities: they cannot be counted. They are estimated on the basis of a complex calculation of doses followed by a simple application of the “ICRP coefficients”. Relying in this way on the no threshold linear relationship is officially not recommended by ICRP. And in most cases, even 20 years after the disaster, observers will be unable to provide any evidence: the bulk of radiological cancers cannot be distinguished from other cancers and statistics will be inconclusive. Indeed the most severe accident scenarios should "only" cause tens of thousands of cancer fatalities spread out over some thirty years in the worst cases while total deaths attributed to cancers in a country like France are about 150,000 per year. Cancer fatalities due to a nuclear accident should therefore only represent of minor percentage of total cancer deaths each year. It will generally be impossible to detect them.

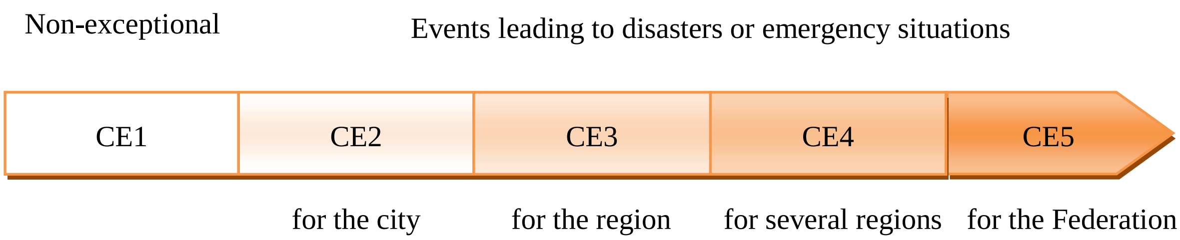
In brief, fatality statistics are not helpful to gauge nuclear accidents.

Is there a way to provide a better indicator than fatalities? An indicator that would be easily understandable by each and every one? Which could be readily observed and would describe the extent of human suffering involved?

1.2. Damage indicators in Katarisk

KATARISK is a Swiss tool aimed at understanding all possible sources of disaster [2]. It distinguishes five broad categories of events (CE) of increasing severity (disasters manageable at a local, regional, federal or European scale).

Figure 1: Classification of events in KATARISK



KATARISK uses a number of damage indicators applicable to a large spectrum of events, ranging from railway accidents to a nuclear accident, including earthquakes, droughts, floods, dam overflows, hurricanes, and epidemics. Indicators are not limited to fatalities:

Table 2: Example of damage indicators proposed by KATARISK

Fatalities, injuries during events causing serious damage over a wide area (number of people)
Fatalities, injuries, illnesses during epidemics (number of people)
Number of persons evacuated
Persons in need (refugees, homeless, people requiring care)
Impairment of vital resources: damage to agricultural land, water and forest (number of km^2)

For each indicator, limit values are suggested for each event category irrespective of the nature of the emergency (see Table 3).

For nuclear accidents, fatalities are not tremendously descriptive as argued in the introduction. The number of persons evacuated is a short term emergency indicator which does not address long term effects. Thus the number of refugees and the "impairment of vital resources" both appear the most relevant in this list. There is a clear difference between these two indicators, however: the number of contaminated km^2 depends on the considered level of contamination — a map of contamination will display several colors — and the resulting figures are more complex and open to interpretation than a single figure. They are more difficult to assess whereas radiological refugees can readily be counted. Therefore, the number of refugees appears as the preferred candidate indicator.

In the nuclear industry, the number of nuclear refugees is a valuable indicator. Its meaning is easy to understand for everyone. The reality it describes is directly observed; it conspicuously exposes the suffering of victims and is necessarily the focus of the media. It is important, however, to keep in mind that these remarkable assets cannot transform it into a comprehensive measure of accident losses: it is a very useful indicator in the context of comprehensive studies of overall consequences.

Table 3: Values for damage indicators proposed by KATARISK for comparison of disasters

CE1	CE2	CE3	CE4	CE5	
Fatalities, injuries during events causing serious damage over a wide area (number of people)					
1	100	1,000	10,000	100,000	1,000,000
Fatalities, injuries, illnesses during epidemics (number of people)					
1	10,000	50,000	100,000	1,000,000	7,000,000
Number of persons evacuated					
1	1,000	10,000	100,000	1,000,000	10,000,000
Persons in need (refugees, homeless, people requiring care)					
1	10,000	100,000	1,000,000	10,000,000	
Impairment of vital resources: damage to agricultural land, water and forest (number of km^2)					
0.1	5	50	500	5,000	50,000

2. NUCLEAR REFUGEES: DEFINITION AND ESTIMATION METHOD

2.1. Definition

After Chernobyl, the criterion for relocation was: ground activity concentration above 555 kBq/m^2 of Cs-137. After the Fukushima accident, Japanese authorities enforced a threshold of 500 kBq/m^2 of Cs-137, although the criterion was expressed in terms of doses. This was broadly consistent with the feedback from Chernobyl.

In general, refugees are those people who have to leave their home for many years due to excessive contamination. This refers to a threshold level declared by the authorities; it can be expressed in terms of doses but it is equivalent and simpler to refer to levels of ground contamination. The present study uses the figure of 555 kBq/m^2 of Cs-137. The precise level chosen does not affect the calculation method or the nature of results.

Emergency evacuations are generally performed to protect the population living in the immediate vicinity of the NPP from the radioactive plume. Evacuees may come back home fairly rapidly once the emergency is over provided contamination levels allow. Conversely, all refugees may not have been evacuated. Thus refugees and evacuees do not refer to identical populations.

Estimating the number of nuclear refugees involves combining deposits with population data. Since contamination heavily depends on climatic conditions, so does the number of refugees. It is probabilistic in nature.

2.2. Estimation of deposits

Deposits are estimated at each grid point of a predefined grid using atmospheric dispersion models. These require:

1) **A source term** which details the quantity, nature and discharges of radioactive elements into the environment. As far as accident costs and nuclear refugees are concerned, the most important element is Cesium-137 as it contaminates the environment for a prolonged period of time. For this study, this is the only required radioelement (see above definition).

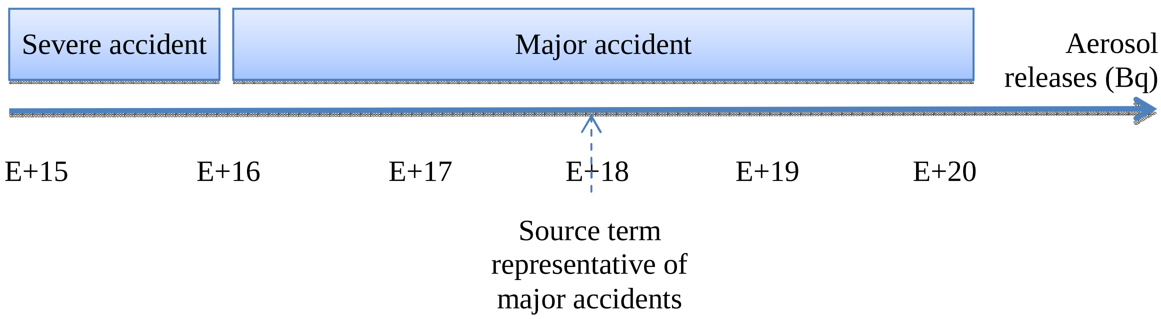
2) **Meteorological data:** the wind direction and its possible changes during the course of the plume determine the areas affected by the fallout. Rain leaches the plume and causes greater deposition of radioactive particles in some places.

In this study, source terms are based on the IRSN level 2 PSA for the French 900 MWe reactors. Activity of released aerosols is the physical indicator used to assess the severity releases. It varies between less than 1E+15 Bq to more than 1E+19 Bq. Two categories of nuclear accidents with large off-site impacts have been distinguished:

1) Severe accidents, with controlled and filtered releases of radionuclides into the environment, for which the activity of released aerosols varies between 1E+15 Bq and 1E+16 Bq; and

2) Major accidents with massive radioactive releases to the environment, comparable in severity to Fukushima or Chernobyl. The activity of released aerosols ranges from 1E+16 Bq to 1E+19 Bq and above.

Figure 3: Broad categories of accidents and release of aerosols in the case of a 900 MWe French reactor



This paper addresses major accidents with large early releases. To give a realistic picture and avoid focusing on extreme cases, a median source term was considered which corresponds to the release of 1E+18 Bq of aerosols.

To address meteorological variability, 6,000 runs have been calculated spanning 10 years (2002 to 2011) of actual 3D weather data. Two consecutive runs are 12.5 hours apart and each run lasts up to several days.

2.3. Order of magnitude of radiological refugees for a major accident in France

With these definitions, a major accident in France would involve the relocation of about 100,000 nuclear refugees. This figure is subject to large variations due to weather conditions. It also varies significantly from site to site (there are 19 NPP sites in France).

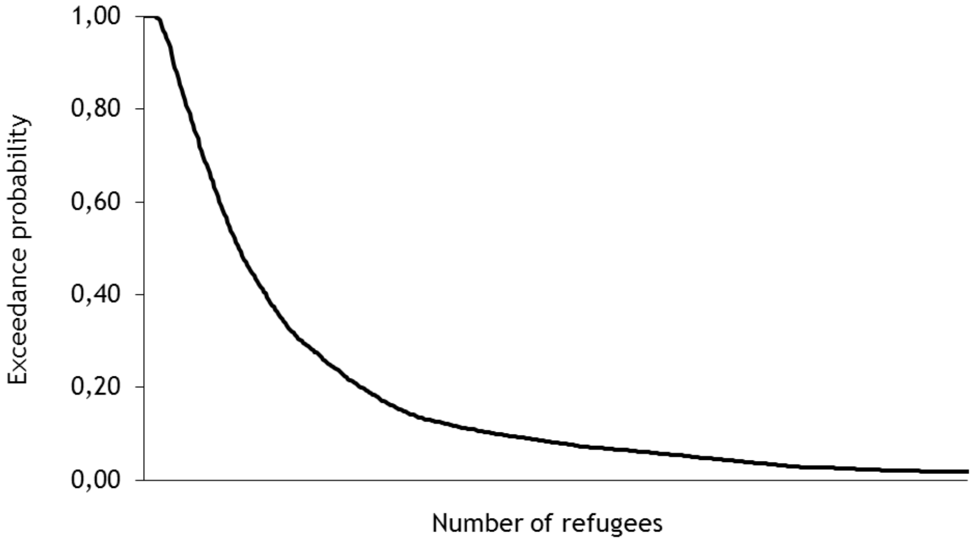
3. THE NUMBER OF NUCLEAR REFUGEES HEAVILY DEPENDS ON WEATHER

3.1. Asymmetric and fat-tailed

The 6,000 runs calculated as described provide a distribution of radiological refugees with respect to weather. Very high numbers can then be observed; these extreme values are unlikely but they point to potentially disastrous situations. In other words, the distribution is extreme: asymmetric and fat-tailed. More and more unfavorable weather conditions lead to larger and larger areas of land being contaminated and higher and higher probabilities for a large city to be contaminated. Each time this happens, the number of nuclear refugees jumps up, the so-called "fall off the cliff effect".

The geographical distribution of population is extreme which implies an extreme distribution of refugees. Zajdenweber (2001) [3] argues that it is the reason behind a number of extreme distributions, for instance the distribution of wealth.
Results computed for a typical French nuclear site are shown Figure 4 below.

Figure 4: Exceedance probability curve



The median value can be multiplied several times when particularly adverse weather prevails at the time of the accident. For example, 400,000 refugees is by no means an inconceivable figure. Conversely, favorable weather considerably reduces the number of nuclear refugees.

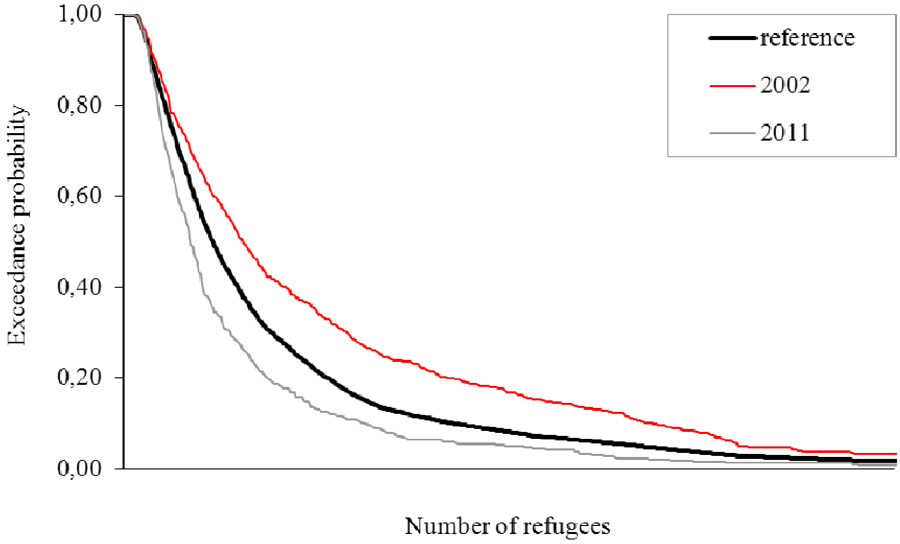
3.2. A representative met-sample needs to be fairly large

Extreme distributions are only poorly identified with limited samples. This is the case with radiological refugees, as shown on Figure 5.

Figure 5 shows the effect of limiting the met-sample to one year of (actual) data i.e. 600 runs over 1 year of weather data. The worse year within the full 10 years of data is 2002 with significantly higher numbers of refugees. In contrast, the best year is 2011. Overall, up to ± 30 % deviations from the reference distribution are observed.

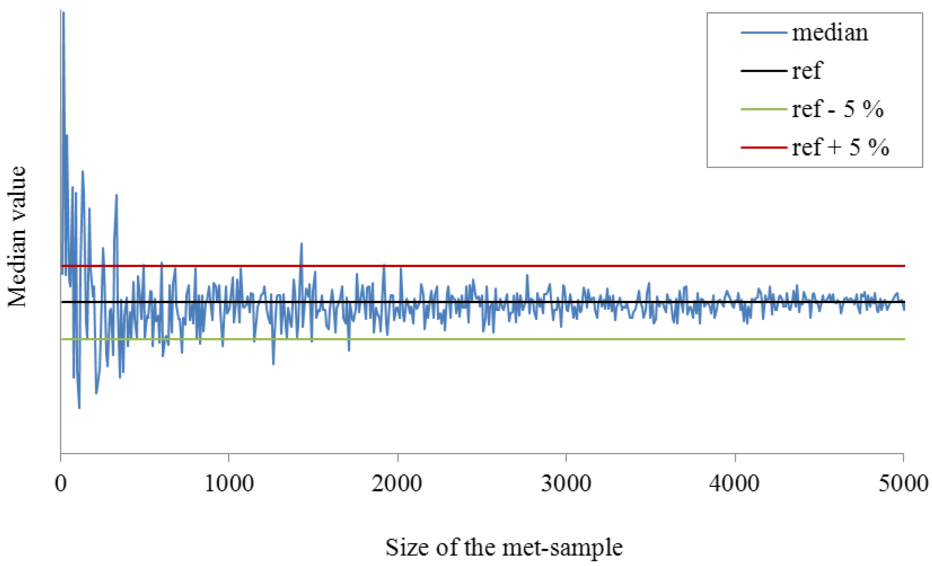
One year of meteorological data cannot correctly "represent" long-term weather trends. The met-sample needs to span several years of data; this is particularly true when focusing on extreme values of the probability distribution function, for example the 5% to 95% percentiles. How many years are required?

**Figure 5: Met-sampling and nuclear refugees
(exceedance probability curves)**



An optimal met-sample should be sufficiently large to be "representative" and sufficiently small to guarantee acceptable execution times. An experiment was carried out by running computations for increasing sizes of the met-sample. These ranged from 10 to 6,000 runs of weather data randomly drawn from the total 6,000 calculated at the outset. The distribution of nuclear refugees was computed for each of these draws; it tends toward the reference distribution which appears in Figures 4 and 5. For instance, Figure 6 represents median values for increasing sizes of the met-sample in this experiment.

Figure 6: Median value of the distribution of refugees for increasing sizes of met-sample



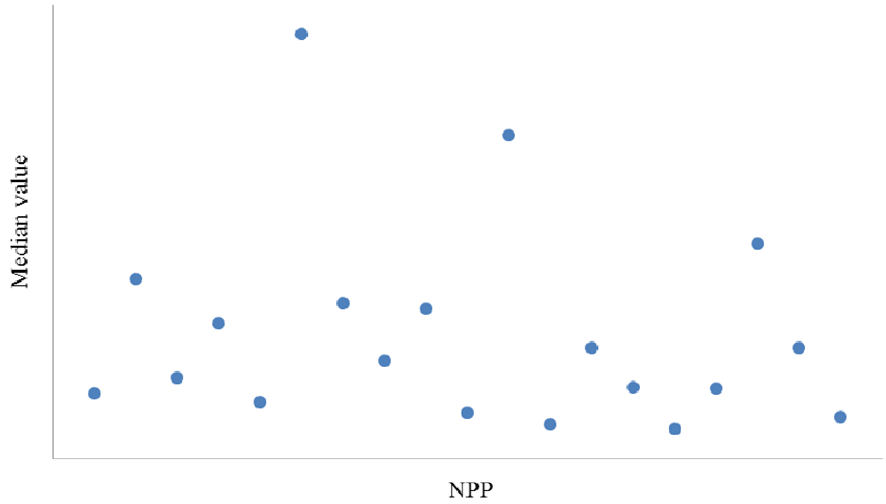
The Figure suggests that a 2,000 met-sample could be large enough, as the deviation from the reference value then falls within a ± 5% bracket. Similar calculations for the 5-percentile, mean and 95-percentile values suggest a 4,000 threshold above which all these figures remain within a ± 5% deviation from the reference value.

Such a result is source term-specific, site-specific and experiment-specific. It seems reasonable to recommend using a 10-year, 6000 runs sample and to check it is sufficiently representative by conducting the type of experiment mentioned above.

4. THE NUMBER OF NUCLEAR REFUGEES DEPENDS ON THE RELEASE SITE

The general result states that a major accident occurring on a French nuclear reactor leads to a median relocation in the order of 100,000 nuclear refugees. This median is subject to large variations with respect to the actual location of the accident because potentially affected populations greatly vary from one NPP to another. For example, accidents at seafront NPPs should imply less nuclear refugees, as winds can direct the plume to the sea — precisely what happened several times during the releases from the Fukushima Dai-ichi site. Figure 7 illustrates this variability in the case of France.

Figure 7: Nuclear refugees from various NPP sites (median values)



It has sometimes been suggested to measure the vulnerability of different sites with respect to population by drawing circles around NPP sites and counting the population within such circles [4]. This however, is unable to offer more than a rough preliminary idea. A good understanding of phenomena requires assessing the complex chain of phenomena which lead from the release to the contamination of land. Dominant wind directions and topography can significantly affect the dispersion of radionuclides in the atmosphere and their deposition onto the ground [5; 6].

A word of caution before concluding: one should avoid jumping to conclusions on the basis of such data as depicted in Figure 7. The risk attached to different NPPs cannot be compared on the sole basis of estimates of nuclear refugees. It depends on other factors such as the probabilities of radioactive releases; these in turn could depend on differences in reactor design; on safety enhancements carried out since they were commissioned; on the likelihood of external threats (earthquakes, floods…); etc.

4. CONCLUSION

The number of expected radiological refugees due to nuclear accidents is fairly simple to calculate. It is easy to understand and communicate. It could be quite useful to help perceive the consequences of major accidents. There are obvious limits, however, to the use of this indicator: it should not be as helpful for less severe accidents (with few refugees); it gives no indication as to image costs or possible modifications in the electricity production system resulting in higher prices for consumers.

For major nuclear accidents in France, the number of expected radiological refugees is high; highly depend on climatic conditions; and variable from site to site. Both size and variability depend on the presence of large cities within the relocation zone.

This raises the question of how best to manage the contamination of large cities. On the one hand relocating the entire population should reduce long-term health effects of exposition to residual ground shine. However, mass relocation can cause great suffering for displaced populations as exemplified by the Fukushima case. Since cities are easier to decontaminate than agricultural areas, they could perhaps benefit from a thorough decontamination effort with a view to allow city dwellers to return home as soon as possible and thus avoid the hardships of temporary sheltering and those of being transplanted.

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