COMPARISON OF APPROXIMATE RESPONSE FUNCTIONS TO ASSESS THE EXTENT OF RADIOLOGICAL CONSEQUENCES AFTER A NUCLEAR ACCIDENT

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Level 3 PSA involves a comprehensive evaluation of the consequences of a hypothetical nuclear accident. This often relies on the repeated use of computationally expensive simulation models. To ease the computational burden, surrogate models may be built to provide quick approximations of more accurate models

The paper proposes approximate response functions for two types of impacts directly associated with the radioactive contamination of the territory: the extent of contaminated areas, and the number of people living in contaminated territories. Linear and power functions are used to describe the relationship between the severity of the release - expressed in terms of quantity of aerosols released - and the magnitude of the impacts. The values of their parameters are site-specific, weather-specific and impact-specific; however, results show that power functions best fit true response functions in all cases.

Power functions derived from a limited number of points judiciously chosen on level 2 PSA risk-frequency curve and for which complete simulations are performed provide a correct approximation of radiological consequences of hypothetical nuclear accidents. This approach could be used to better assess the overall uncertainty associated with each accident sequence identified in level 2 PSA, by including the ensuing data sets as additional input variables in Monte-Carlo analysis.

The paper first argues that surrogate models are a good alternative to more expensive models, for comparison purposes between different sites and different source terms. Section 2 examines the mathematical formulation of possible surrogates for three French NPP sites and for two types of radiological consequences. Section 3 examines sample selection and construction of the surrogates and gives an appraisal of their accuracy. Section 4 concludes and provides perspectives for future.

I. INTRODUCTION

I.A. Why is it important to study the consequences of a nuclear accident?

Nuclear power plant accidents can lead to the emission of radioactive elements that disperse in the atmosphere and then deposit to the ground. Long-lived radionuclides may contaminate the environment for a prolonged period of time. The severity of the releases and the weather conditions prevailing at the time of the release and during the transport of radioactive elements in the atmosphere determine the size and extent of contaminated areas, the number of people directly affected by the accident and, more generally, the cost of the accident.

Studies of the consequences of hypothetical nuclear accidents can help: 1) understand the major issues of the crisis, and thus better prepare for the management of the crisis should an accident occur; this preparation should include those elements that contribute most to the cost of the accident; [1] 2) gauge the relative importance of the various types of consequences incurred; 3) compare the risk a nuclear accident imposes on society with the cost of the preventive measures helping reduce that risk; studies of accident consequences thus enable better inform safety. [2 and 3]

Accident consequences depend crucially on the nature and severity of radioactive releases, as well as on the weather conditions prevailing at the time of the release and during the transport of radioactive elements until their deposition to the ground. Focusing on the most extreme (and least probable) release and on its most severe expression (due to exceptionally unfavorable weather conditions), would misguide the decision-maker, promote suboptimal decisions, cause public funds to be wasted and therefore mean unnecessary costs for the national economy as a whole.

On the contrary, a probabilistic assessment of the consequences associated with a large number of accidents and for a large number of weather data provides the decision-maker with a realistic estimate, nor too pessimistic nor overly optimistic, of the consequences of nuclear accidents.

This type of evaluation is part of a broader study aiming at drawing a risk curve.[4] The risk curve, also called “probability – consequence” curve, provides the probability (y-axis) of each unwanted event and the level of consequences (x-axis) such an event could entail, for example their level of socio-economic consequences.

I.B. Estimates of consequences of nuclear accidents are based on complex models

The evaluation of the consequences of nuclear accidents involves combining deposits with land-use data (population data, agricultural production, etc.). Deposits are estimated at each grid point of a predefined grid using atmospheric dispersion models. This requires: 1) A source term which details the quantity, nature and kinetics of radioactive releases; 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.

I.B.1. Estimating the source term

Source terms are derived from level 2 probabilistic safety assessments (Level 2 PSAs). The first PSA was conducted in the United States from 1972 to 1975 and led to the WASH 1400 report known as “*Rasmussen Report*” after its author, Norman Rasmussen, then head of the Nuclear Engineering Department Massachusetts Institute of Technology.[5]

There are three levels of PSAs. Level 1 PSAs study the different failure modes leading to the core meltdown and result in core damage frequencies. Level 2 PSAs aim at describing the complex phenomena taking place within the containment building after a core melt and leading to a release; they result in estimates of the frequencies of radioactive releases to the environment. Level 3 PSAs go beyond probabilities and aim at quantifying the consequences in terms of damage to the public and to the environment, and more generally overall socio-economic consequences of nuclear accidents.

Level 2 PSAs identify and quantify systematically and comprehensively the complete range of events leading to radioactive releases to the environment. All accident sequences leading to “undesired” consequences can be represented graphically on an event tree with a frequency assigned to each of the branches of the tree. A huge number of accident sequences may occur on a nuclear reactor. Therefore, different accident sequences are grouped by release categories with sequences grouped in the same category having similar characteristics regarding the severity and the kinetics of the releases. Level 2 PSAs generally produce thousands of release categories.

I.B.2. Estimating the dispersion of radioactive releases to the environment

For each release category, the next step in the evaluation process consists in modeling the atmospheric dispersion of releases and their fallout in the form of surface deposits. This is precisely the purpose of IRSN C3X platform. IRSN C3X platform is based on two separate atmospheric dispersion models: a Gaussian model named pX is used to calculate the dispersion of radioactive releases within a short distance from the nuclear power plant, up to tens of kilometers from the NPP; a Eulerian model named ldX is used to estimate the dispersion of radioactive releases over a very long distance, up to thousands of kilometers from the NPP.

Like all Gaussian models, pX is based on the analytic solution of the advection-diffusion equation obtained under simplifying hypotheses.[6] This Gaussian solution features standard deviations which model the spread of the plume as a function of time. Classically, their time-evolution is modeled by empirical laws derived from experiments carried in situ. Several such laws exist and are, essentially, taken into account by pX. Such models have the advantage of being fast and able to operate with limited input data. Breaking down the plume into independent puffs makes it possible to provide a fine rendering of the complex kinetics of a release and, more importantly, of a flow which is not homogeneous in space and time. IRSN considers that pX used with a tridimensional wind field is valid up to 80 km from the site, an empirical appreciation.

Eulerian model ldX resolves the advection-diffusion equation on a grid.[7] Such models are frequently used to represent atmospheric pollution, for example relative to road traffic. Contrary to Gaussian models, ldX is capable of simulating the dispersion of a pollutant over long distances, up to the entire globe. However, by its very principle, this type of model provides an average concentration per elemental cell of the grid, which limits its utilization to areas removed from the site of the accident by more than 5 to 10 times the size of a grid cell.

These calculations require complete software suites modeling the complex phenomena governing atmospheric dispersion and deposition, but also the transfer of radioactive elements in the food chain and their effect on human health. They require a very substantial amount of input data and produce a significant amount of output data. They are very time-consuming and require high performance computers with high storage capacity.

I.B.3. Results are weather-specific, site-specific and consequence-specific

Impact studies are weather-specific and site-specific.[8] They are also consequence-specific: frequency-consequence curves will depend heavily on the type of consequences one is interested in, for example the size of contaminated areas or the number of people affected.

It also varies depending on the level of contamination: contaminated areas are usually grouped in two categories depending on the extent of cesium 137 contamination taking as a reference the decisions taken after the Chernobyl accident in Ukraine, Russia and Belarus.[9] Exclusion zones, also called "highly contaminated areas", are those areas from which populations must leave for many years. In reference to the Chernobyl accident, they correspond to cesium 137 deposits above 555 kBq/m². After the Fukushima accident, Japanese authorities based their decisions on dose limits which refer to very similar levels of activity. Other contaminated areas, also called "moderately contaminated areas", are those areas where cesium 137 deposits are comprised between 37 and 555 kBq/km².

Each type of consequence (size of moderately contaminated areas, size of highly contaminated areas, number of nuclear refugees, number people living in moderately contaminated areas, etc.) provides a partial figure of the consequences of a nuclear accident. Ideally, these consequences should be grouped together and represented by a global figure. This global figure of the overall consequences of a nuclear accident is for example the cost of the accident.

I.B.4. Need for approximate response models

Arguably, the time to complete calculation for a single source term can be very long. Therefore, performing comprehensive estimates of the various types of consequences associated with each of the many PSA Level 2 release categories would be particularly tedious, and may not provide information that would significantly differ from an approach based on the use of approximated response models.[10 and 11]

In this approach, comprehensive estimates are performed for a limited number of release categories carefully chosen along the risk curve. Their results enable to build approximate response models. In turn, these approximate response models can provide estimates of the consequences of nuclear accidents for all other possible releases categories.

Comprehensive estimates may be better in absolute terms; but this paper argues that approximate response models may be particularly relevant when seeking to compare various results, for example for different sites or for different source terms.

II. METHODOLOGY

II.A. Sampling of observations and model building

First, comprehensive estimates were performed for seven source terms, one for each decade from 1E+14 Bq to 1E+20 Bq of aerosols released, for three nuclear power plants and for two types of consequences, namely the size of contaminated areas and the number of people affected by the accident. This is the result of a pragmatic choice, which will be analyzed and compared to other possible sampling methods in Section 3.

The calculations are performed for a large number of sequences of weather data, each sequence covering all the period from the beginning of the release until the end of the deposition of all radioactive elements on the ground. The sample of weather data consists of thousands of sequences of weather data spread over several years of weather data provided by Meteo France. The result is a probability distribution function of the consequences of the accident with respect to the weather. This distribution can be represented by a limited number of values, for example its percentiles 5, 25, 50, 75 and 95.

For each of the above-mentioned percentiles, one can always draw a curve that represents the increase in the magnitude of the consequences with respect to the severity of the releases. An example to illustrate this point is shown on Figure 1, which represents the increase in the size of moderately contaminated areas depending on the severity of the releases that may occur on a French 900 MWe PWR. In Figure 1, each dot corresponds to the median value of the distribution of results calculated for all data sequences from the sample of weather data.

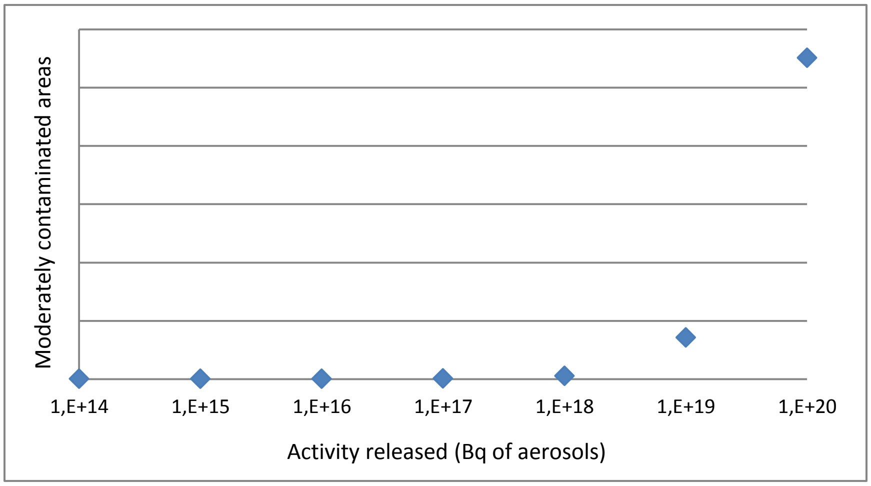

Fig. 1. Graphical representation of the results depending on the severity of the releases

Two types of mathematical functions seem appropriate: a linear function and a power function, as shown on Figure 2 and Figure 3 below. Both Figures represent the results computed for seven source terms, one for each decade from 1E+14 to 1E+20 Bq of aerosols released. For each source term, 5 dots represent 5 percentiles chosen to be representative of the distribution of the results according to the weather: respectively the percentiles 5, 25, 50, 75 and 95 of the distribution. The lines represent respectively the results of a linear regression on Figure 2, and the results of a power regression on Figure 3. The yellow area between the lines obtained for percentiles 5 and 95 represent the range of variation of the results depending on the weather prevailing at the time of the releases.

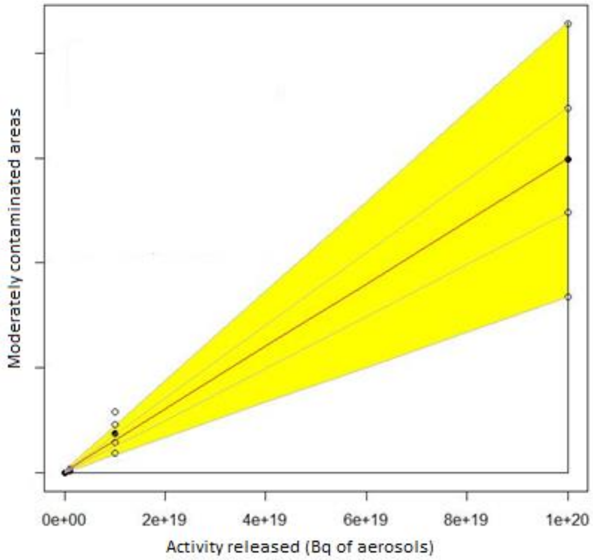

Fig. 2. Linear regression

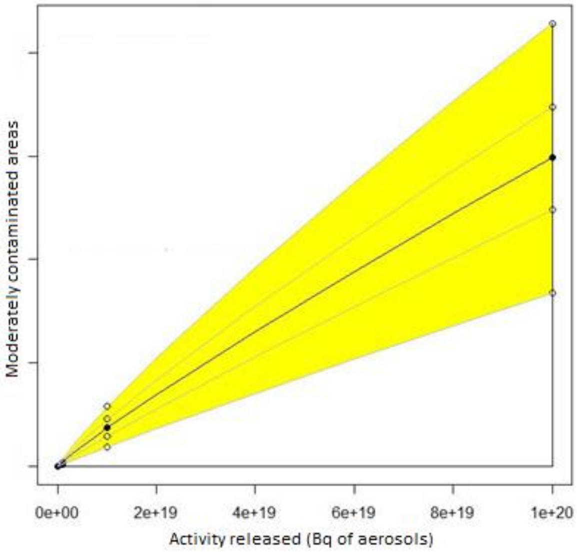

Fig. 3. Power regression

Section 3 compares both types of mathematical functions according to several error criteria, and determines which is best suited to experimental data. Other types of functions could be envisaged, for example a piecewise regression with cutoffs; this will be briefly explained in Section 4.

II.B. Choice of error criteria

Two approximate response models are derived from experimental data, one for each type of regression retained in this study: Model 1 is a linear regression, while Model 2 corresponds to a power regression. To measure the adequacy of both models to experimental data, several criteria can be evaluated and compared.

II.B.1. Some criteria are based on the measurement of squared residuals

The coefficient of determination, R^2, is probably the simplest and most used criterion. It measures the adequacy between the model and the observed data by means of a value ranging between 0 and 1. In the case of a simple linear regression, it is equal to the square of the correlation coefficient. More generally, the coefficient of determination is the proportion of the variance in the dependent variable that is explained by the model. Let's call RSS the residual sum of squares and TSS the total sum of squares; then:

$$R^2 = 1 - RSS/TSS$$

In our study, the values obtained for R^2 with the two models are very close to each other and very close to 1. Hence, the coefficient of determination does not seem to be here a satisfactory criterion for distinguishing the two models in a clear and unambiguous manner.

The residual sum of squares, SSR, is a value ranging between 0 and infinity: the lower is the value of SSR, the better is the model:

$$SSR = \sum_{i=1}^{n} (y_i - f(x_i))^2$$

with: *n, the number of observations;*
y_i*, the value observed at* x_i*;*
and $f(x_i)$*, the value predicted by the model at* x_i

By definition, the residual sum of squares puts more weight on large errors; in this study, it could therefore provide a biased picture of the phenomenon, since the magnitude of the consequences rapidly increases with the severity of the releases.

The mean square error, MSE, gives a measure of the variance between the observed values and the values predicted by the model; in case of an unbiased estimator:

$$MSE = \frac{1}{n} * \sum_{i=1}^{n} (y_i - f(x_i))^2 = 1/n * SSR$$

The root-mean-square error, RMSE, is the square root of the mean square deviation. This criterion allows for a direct comparison to the observed values, as it is expressed in the same unit as the observations, for example in km² for the size of contaminated areas. Thus, it is fairly easy to understand:

$$RMSE = \sqrt{MSE}$$

The method of weighted least squares, WLS, provides a measure of the residual error between the observed values and the values predicted by the model, taking into account the uncertainty associated with the observation:

$$WLS = \sum_{i=1}^{n} \frac{(y_i - f(x_i))^2}{\gamma_i}$$

where γ_i *is the uncertainty associated with the observation i*

The advantage of this method is that it allows taking into account the modeler's knowledge of the uncertainties associated with the calculation of observations. In our case, the size of the grid cells used for atmospheric dispersion modeling increases with the distance to the release site: it ranges from 1 km² in the direct vicinity of the damaged power plant, to around 80 km² for the rest of France, and finally to about 2 000 km² over an area covering the rest of Europe. Estimates of the size of the contaminated areas, but also of the size of the affected population, etc. are necessarily more imprecise the longer the distance from the release site.

II.B.2. Other criteria are instead based on direct measurement of the deviations

Criteria based on the direct measurement of deviations are less prone to overweight large errors; the main criteria of this category are the following ones.

The mean absolute error, MAE, is easily understandable because it is expressed in the same unit as the observed values:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - f(x_i)|$$

The mean absolute percentage error, MAPE, is by definition the mean absolute error MAE expressed as a percentage:

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - f(x_i)|}{y_i}$$

It cannot be used in this case because of the existence of observations y_i almost equal to zero, leading to aberrantly elevated results.

The symmetric mean absolute percentage error, SMAPE, will thus be preferred because it minimizes the risk of obtaining outliers when the observed values are very close to zero. Calculating the SMAPE provides a value ranging between 0 % and 200 %:

$$\text{SMAPE} = \frac{200}{n}\sum_{i=1}^{n}\left|\frac{y_i - f(x_i)}{y_i + f(x_i)}\right|$$

Four complementary error criteria were selected as part of this study: the root-mean-square error RMSE, the mean absolute error MAE, the symmetric mean absolute percentage error SMAPE, and finally the weighted least squares WLS, the weighing coefficient being the size of the grid cells. Both types of regressions, linear and power, are then compared according to these four criteria. The most suitable model is the one that minimizes the above-mentioned error criteria.

III. RESULTS

III.A. Results relative to the size of contaminated areas

Below are estimates for the four error criteria selected as part of this study, for three French 900 MWe nuclear power plants, and for two types of contaminated territories, namely the “highly contaminated areas” and the “moderately contaminated areas”.

Results for moderately contaminated areas are provided in Table I, while those for highly contaminated areas are provided in Table II. For illustration purposes, Figure 4 shows the graphical representation of both linear and power functions built upon experimental data regarding the size of moderately contaminated areas. In Figure 4, the dots correspond to the median values of the probability distribution functions established on the basis of complete calculations performed for all sequences of weather data and for seven source terms.

Regarding the size of the contaminated areas, the power regression (Model 2) minimizes all four error criteria; this conclusion holds for the three NPPs and for both types of contaminated territories.

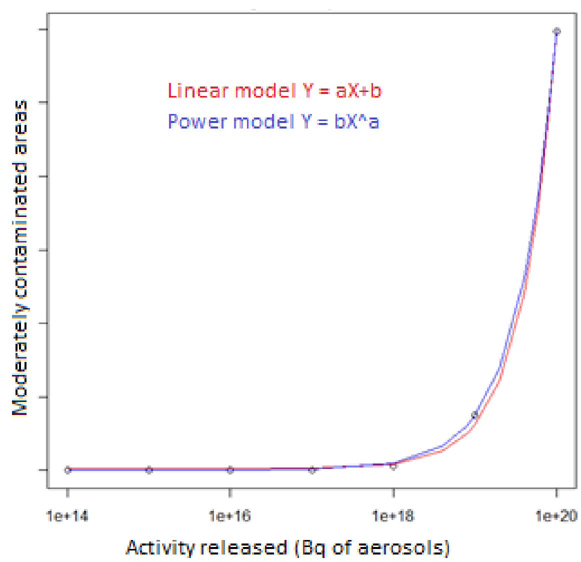

Fig. 4. Size of contaminated areas depending on the severity of the releases (median values - Site 1)

TABLE I. Estimates for four error criteria (moderately contaminated areas)

	Site 1		Site 2		Site 3	
Model	linear	power	linear	power	linear	power
RMSE	5,5E+03	1,4E+03	6,3E+03	5,5E+02	4,6E+03	4,0E+02
MAE	3,8E+03	7,3E+02	4,3E+03	3,1E+02	3,3E+03	1,8E+02
SMAPE	1,1E+02	5,9E+01	1,1E+02	5,7E+01	1,3E+02	2,9E+01
WLS	1,7E+07	2,5E+04	2,4E+07	2,7E+03	2,2E+07	4,4E+02

TABLE II. Estimates for four error criteria (highly contaminated areas)

	Site 1		Site 2		Site 3	
Model	linear	power	linear	power	linear	power
RMSE	2,1E+02	3,2E+01	4,4E+02	3,4E+01	3,3E+02	2,1E+01
MAE	1,4E+02	1,7E+01	3,0E+02	2,2E+01	2,3E+02	1,0E+01
SMAPE	2,4E+02	6,8E+01	1,1E+02	6,9E+01	1,4E+02	8,6E+01
MCP	2,7E+04	1,0E+01	1,1E+05	9,0E+00	8,1E+05	2,0E+00

III.B. Results relative to the affected population

Regarding the population affected by the accident, estimates for the four error criteria, for three NPPs and for two types of contaminated territories confirm that the power model is best suited. Results for the population living in moderately contaminated areas are provided in Table III, while those related to nuclear refugees are provided in Table IV.

TABLE III. Estimates for four error criteria (size of the population living in moderately contaminated areas)

	Site 1		Site 2		Site 3	
Model	linear	power	linear	power	linear	power
RMSE	9,1E+05	1,3E+05	4,4E+05	2,3E+05	2,3E+06	1,6E+06
MAE	6,8E+05	5,6E+04	3,2E+05	1,3E+05	1,6E+06	7,7E+05
SMAPE	1,3E+02	4,2E+01	1,0E+02	5,2E+01	1,3E+02	6,3E+01
WLS	6,4E+11	9,9E+07	1,4E+11	2,0E+08	2,4E+12	1,2E+10

TABLE IV. Estimates for four error criteria (size of displaced population)

	Site 1		Site 2		Site 3	
Model	linear	power	linear	power	linear	power
RMSE	6,2E+04	3,4E+03	4,3E+04	6,5E+03	2,1E+05	1,3E+04
MAE	4,3E+04	1,4E+03	3,0E+04	4,0E+03	1,5E+05	5,8E+03
SMAPE	1,4E+02	7,1E+01	1,1E+02	8,8E+01	1,6E+02	1,2E+02
WLS	3,0E+09	7,2E+04	8,8E+08	2,8E+05	3,4E+10	1,1E+06

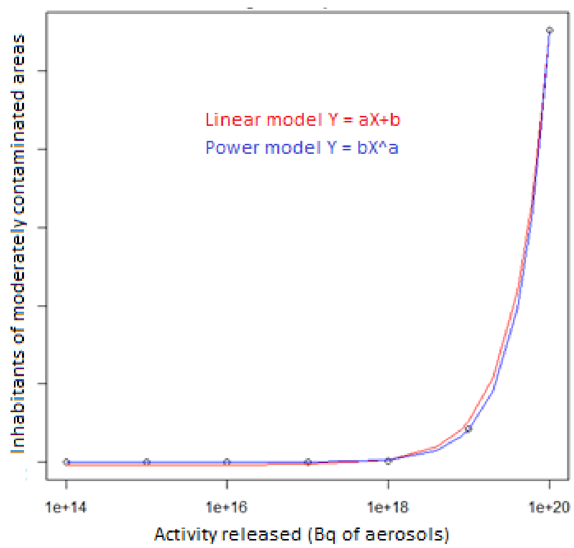

Fig. 5. Number of people living in moderately contaminated areas depending on the severity of the releases (median values - Site 1)

III.C. Results concerning percentiles other than the median

This conclusion holds for the other four selected percentiles (percentiles 5, 25, 75 and 95). The power model minimizes all four error criteria, for both types of consequences (size of the contaminated areas and size of the affected population), for both types of territories (moderately contaminated areas and highly contaminated areas), and for the three selected NPPs.

This conclusion remains valid when one removes the extreme values corresponding to a release of 1E+20 Bq of aerosols in the environment.

III.D. Model comparison and discussion

The four error criteria selected favor the power regression in all cases. However, it is interesting to note that the coefficient of determination R^2 calculated for both models, linear and power, are very close to each other and very close to 1. For example, regarding the size of the moderately contaminated areas, the R^2 coefficient is estimated at 0,99929 with the linear model and at 0,99995 with the power model (based on the median values of the probability distribution functions for site 1). The linear model performs less well than the power model to fit the data, but it cannot be deemed inadequate.

III.D.1. Influence of sample selection

As discussed in Section 2, observed data result from simulations conducted for seven source terms, one for each decade from 1E+14 Bq to 1E+20 Bq of aerosols released to the environment. This is a pragmatic choice whose relevance must be assessed. Thus, we must answer two questions: 1) The observations are distributed evenly on a logarithmic scale; is this choice appropriate? And 2) Is the number of observations large enough to build a model that predicts the results with enough accuracy?

The protocol chosen to test whether the even distribution of observations is satisfactory or not is the following one. From the initial sample, we first set to a fixed value the 3 observations that have the least influence on the model according to Cook's distance (the blue dots in Figure 6); the result is a mathematical four-point problem. We then set both extremes to a fixed value (the orange dots in Figure 6); this determines the range of possible values the two remaining observations (the green dots) can take between these two extremes. Then, we move the green dot with the largest Cook's distance between its immediately preceding observation and its immediately following observation, i.e. all along interval I of Figure 6. This new dot is successively attributed values interpolated for a large number of abscissas in the interval I. We then obtain a new sample of 7 observations, with one of the observations being interpolated; this provides a new model which is compared to the initial model.

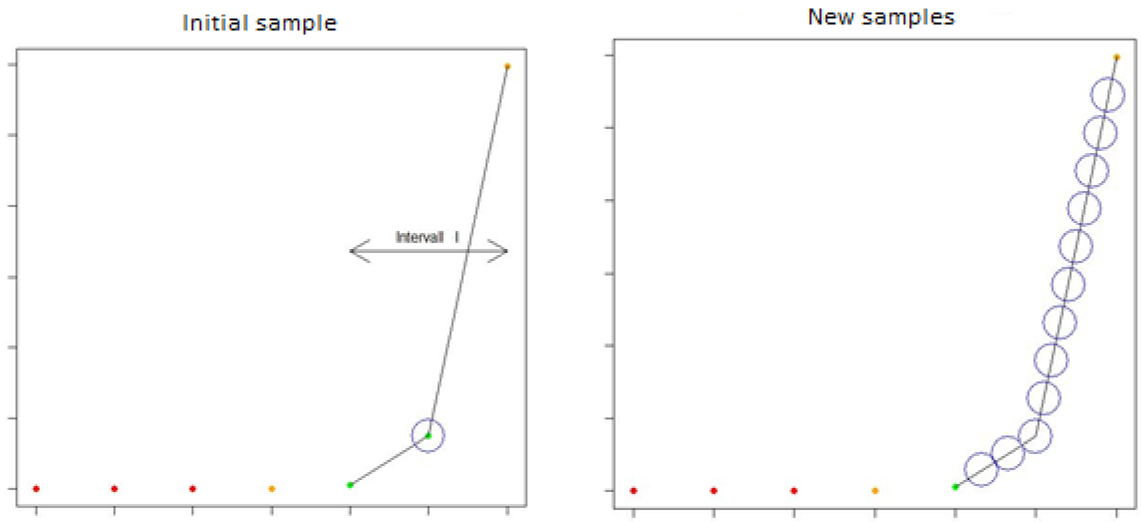

Fig. 6. Method used for the interpolation of new observations

If the new model is much better for a given abscissa, we set the green dot with the largest Cook's distance to the value interpolated for this abscissa. We then move the second green dot using the same method, i.e. using a linear interpolation between the previous observation and the following observation, until finding a better model. The root-mean-square error, RMSE, is the criterion used to assess the adequacy of the models, which we seek to minimize.

The results suggest that it is possible to improve the model, essentially by moving the observation located at 1E+18 Bq on the x-axis. However, this produces only a small gain in the model accuracy, around 1%. Moreover, the new abscissa varies depending on the site and on the type of consequences (areas, populations, etc.). Therefore, the choice of the initial sample - an observation for each decade of releases - is satisfactory.

Below is the protocol used to determine whether the number of observations is sufficient or not. We start by adding an eighth observation to the model; for that purpose, we interpolate successively 200,000 new observations, evenly distributed over the interval [1E+14 Bq; 1E+20 Bq] of aerosols released. Studentized residuals and Cook's distance are estimated for each new interpolated value. Studentized residuals help identify observations with a singular value along the y-axis, while Cook's distance measures the influence of a new observation on the model. Complete calculations with a complete software suite are then performed for those observations that appear singular while having a great influence on the model.

The results suggest that it might be interesting to add a new observation at 5E+19 Bq on the x-axis, regardless of the site and of the type of consequences. The same protocol was repeated for the addition of a ninth observation; the results show that adding a ninth observation does not improve significantly the model.

III.D.2. Impact of the construction of the model

Approximate response models were built upon percentiles of the distribution of the results depending on the weather prevailing at the time of the release. Therefore, there is absolutely no reason why sequences of weather data should be identical from one observation to the other, for a given percentile.

This approach is necessary as a first step, as it is based on the study of a limited number of cases - 5 cases corresponding to the 5 percentiles chosen along the distribution -, which greatly simplifies the analysis. It provides useful information when seeking to compare the two models, linear and power, and helps understand the complex phenomena under consideration.

It must be completed by a more systematic approach as a second step, based on a systematic analysis of the results calculated for each sequence of weather data. This analysis was performed for one specific NPP site, and indeed provides interesting results as shown on Figure 7.

Figure 7 shows the increase in the size of moderately contaminated areas depending on the severity of the releases, for one specific sequence of weather data judiciously chosen within the entire sample of weather data. Interestingly, the size of the contaminated areas increases according to a power function until abscissa 1E+19 Bq of aerosols released, then the curve bends within the interval [1E+19; 1E+20] Bq of aerosols released. The power model is represented by the red line in Figure 7, while the “true values” are represented by the blue line. The red line diverges significantly from the blue line from 1E+19 Bq of aerosols released and higher.

The reason for this divergence is the following one: the NPP site is located sufficiently far away from the sea so that all radioactive elements are deposited inland when less than 1E+19 Bq of aerosols are released into the atmosphere; but it is also close enough to the sea so that much radioactivity is deposited offshore when more than 1E+19 Bq aerosols are released into the atmosphere.

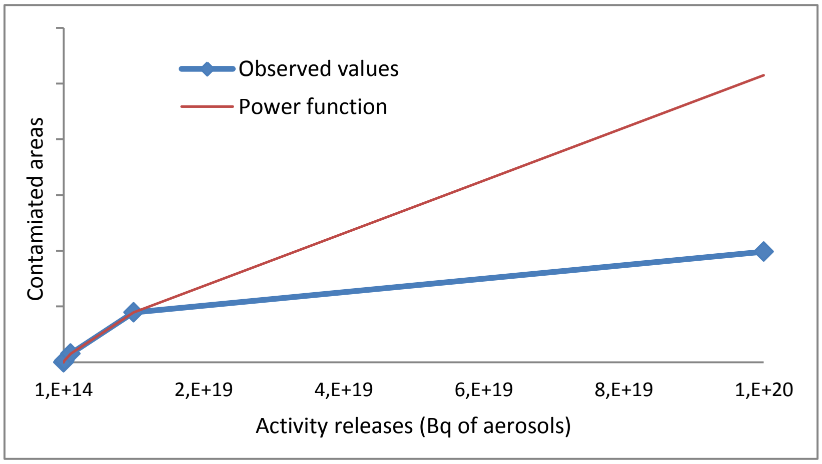

Fig. 7. Size of moderately contaminated areas depending on the severity of the releases
for a specific sequence of weather data

IV. CONCLUSIONS

The present paper showed that it is possible to develop simple mathematical models to come up with reasonable estimates of the potential consequences of hypothetical nuclear accidents. Such models can be built from a limited number of observations for which complete calculations are performed with complete software suites.

This approach is indeed necessary to combine, at a reasonable computational cost, estimates of the consequences of nuclear accidents with the associated frequencies estimated by Level 2 PSAs.

Two models were compared: a linear model and a model power. The power model is favored in all cases (different NPP sites, different types of consequences, different types of territories according to their level of contamination) by all error criteria used in this study. The power model is thus best suited; to improve it, it might be useful to add an eighth observation with abscissa 5E+ 19Bq of aerosols released.

However, specific weather conditions may entail radioactivity to be largely deposited offshore provided the release is large enough and/or the damaged NPP is close enough to the sea. Such cases can be graphically represented by a power function truncated beyond a certain release threshold.

Areas for future research should include extending the scope of the study to a higher number of cases (various NPP sites, a larger number of sequences of weather data, etc.). It should also include other types of models, whose relevance should be assessed using an approach similar to that implemented in this paper. One way of taking due account of the above-mentioned specific cases would be for example to use a piecewise regression model with one cutoff point. This regression could first follow a power function until a certain release threshold is reached, and then follow a linear function. Another possibility, perhaps more simple to implement in practice, would be to use a piecewise linear regression with one cutoff point for each decade of releases.

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