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A flexible tool for calculating the consequences of a hypothetical nuclear accident

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Summary. The paper presents a parametric model, implemented on a personal computer, for calculating contamination and doses following a hypothetical nuclear accident. The model is embedded in the high level environment of *Mathematica* and uses the Gaussian solution for the plume structure at short and medium distances and a wedge-like behaviour for long distances calculation. Along with the usual effects, like the influence of a local wet ground deposition or the corrections due to build-up, the model deals also with other aspects, such as the long distance behaviour of the plume, by taking into account random wind direction variations. A rather sophisticated approach is used, in particular, when evaluating food contamination and doses, allowing also for consideration of a possible ban of food consumption. Several tens of functions are on hand of the user who can take full advantage of the very flexible tools introduced in the recent version 7 of *Mathematica*. Some examples of the power of the tool are shown with reference to the radiological consequences of an hypothetical accidental release in a EPR reactor.

Key words: Mathematica, nuclear, reactor, accident, dose.

Riassunto *(Uno strumento flessibile per calcolare le conseguenze di un eventuale incidente nucleare)*. Il lavoro illustra un modello parametrico, implementato su personal computer, per il calcolo della contaminazione e delle dosi conseguenti ad un ipotetico incidente nucleare. Il modello si avvale del linguaggio di alto livello di *Mathematica* ed utilizza la soluzione gaussiana per la propagazione della nube sulla scala breve e media delle distanze, avvalendosi invece della soluzione a "wedge" per il comportamento a grandi distanze. Accanto agli effetti usuali, come l'influenza di una deposizione umida al suolo o quello del build-up, il modello tiene conto anche di altri aspetti, come quello del comportamento della nube sulle grandi distanze, prendendo in considerazione il carattere erratico della direzione del vento. In particolare, l'approccio al calcolo delle contaminazione degli alimenti e delle dosi a questi associate è effettuato in modo molto elaborato, permettendo anche di calcolare l'effetto di un eventuale blocco di consumi alimentari. Diverse decine di funzioni sono a disposizione degli utenti, che possono avvalersi degli strumenti molto flessibili introdotti nella recente versione 7 di *Mathematica*. Le potenzialità dello strumento di calcolo sono esplicitate mostrando alcuni esempi relativi alla valutazione delle conseguenze radiologiche di un ipotetico rilascio accidentale in un reattore EPR.

Parole chiave: Mathematica, nucleare, reattore, incidente, dose.

INTRODUCTION

In the two past decades several tools for calculating the consequences of a nuclear accident have been developed, particularly under the influence of the 1986 Chernobyl event. The spectrum of the available programs includes rather complex codes, some of which aim at a real time forecast of the contamination dynamics of the propagating cloud. They generally require an extensive use of timely meteorological data and, in most cases, the availability of powerful computing devices.

The algorithm presented in this paper (*RANA*, Radiological Assessment of Nuclear Accidents) was conceived since the beginning as a code to be run on a personal computer: it is a modular and flexible tool for the evaluation of contamination and doses resulting from a nuclear accident in Europe.

It uses simplified physical assumptions concerning the diffusion of the cloud, the deposition of the radioactive contamination on the ground and the transfer of the contamination to the food chain. This allows the algorithm to run within a reasonable amount of computing time, for most of the relevant calculations.

In the present context the word "accident" refers to both an event occurring at a nuclear plant and a radioactive release deliberately provoked by an offensive device.

RANA is implemented on *Mathematica* (Wolfram Research, Inc., USA, *Mathematica* version 7 (2008)),

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so it can benefit of the full power of that environment; supplementary functions can be added and some of those included in *RANA* can be modified in a relatively straightforward way, by taking advantage of the high level language of *Mathematica*.

Calculations can be performed from either a chosen source term or data on air and ground contamination. The first option makes use of a data bank[1] of nuclear reactors where the relevant data (*e.g.* geographical coordinates, type, power) of the selected nuclear plant are stored. *RANA* also includes the relevant parameters (such as the release fractions for the different nuclides groups, the accidental release duration and the released thermal energy) for the accident categories usually considered in the safety analysis of nuclear reactors accidents. This enables calculations to be performed directly if the release category to be associated with the given event is known. Otherwise, the program may request additional data, such as the release fractions; this will be the case, for instance, for events at reprocessing plants or offensive devices.

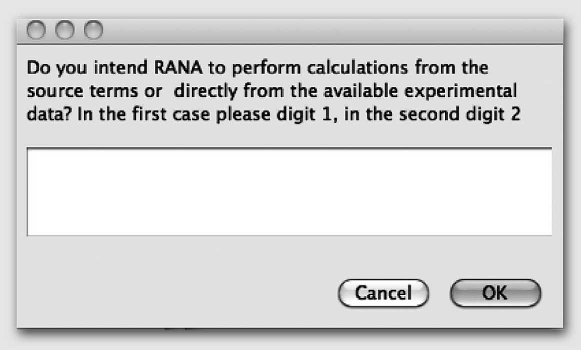
Should a particular source term be required (as it may be necessary for an accident in a special nuclear facility or for calculations for a new power plant, such as the 1650 MWe European Pressurized Reactor[2] considered later), *RANA* includes a "jolly reactor" whose parameters can be fixed according to user needs.

Although one can select several atmospheric conditions when running *RANA*, the algorithm cannot be used for real time evaluations in the event of an accident: its outcomes will rather give a parametric description of the event itself.

The basics of RANA

RANA is a cluster of 20 interconnected *Mathematica* packages, each of which deals with one of the modules in the consequences calculation chain, *e.g.* the basic equations, the data and the formulas for atmospheric diffusion, the dose factors, the nuclear parameters, the tools for the graphic interface for the different functions. This modular structure allows one to follow closely the assumptions of the model and, eventually, to easily introduce updates to the parameters and/or the standard functions of *RANA*.

The user can benefit from a palette of all the packages as well as a palette of the basic data used by *RANA* for the calculation of its end-points. *RANA* also provides an extensive set of error messages to help the user recover from syntax errors. An on-line help is available following *Mathematica* Help → FunctionNavigator → Add-Ons & Packages → Add-Ons → *RANA*.



Do you intend RANA to perform calculations from the source terms or directly from the available experimental data? In the first case please digit 1, in the second digit 2

Fig. 1 | *Mathematica prompt asking to choose between two alternative calculation paths.*

At the beginning the user is asked whether calculations should be performed from a source term or the program should run from available experimental data [to be supplied by the user, of course] *(Figure 1)*.

If the first alternative is selected, a series of prompts then requires a further choice between a reactor, a conventional nuclear plant or an offensive device. In fact, different kinds of radioactive sources require different sets of nuclides (11 are taken into account for an offensive device, 36 for a reactor and 44 for a reprocessing plant). Suppose a reactor calculation is needed: then a series of prompts may request a few input data. These include the reactor's name, the release category or release fractions, the interval between the reactor's shutdown and the beginning of the release and whether the calculation has to take into account rain along the path of the cloud rather than the default dry deposition.

The more the accident can be reduced to a "canonical" one, the less input data will be required.

Generally speaking, the calculated functions are presented either as a table of numbers or as graphics, with the required quantity being calculated as a function of the chosen distance from the source or as a function of the time at which the observation is made or as both. The user can ask for many different variants of a given function, such as, for instance, the atmospheric category (according to Pasquill-Gifford), a particular exposed group (*e.g.* children), one or more nuclides (selected among the radionuclides taken to be the most relevant for assessing the consequences of the accident) or, finally, selected ways of presentation (*e.g.* a 1D curve or contour lines graphics).

If, on the other hand, the calculation input has to come from air and ground contamination data, the prompt will only ask for the accident date (of course the same request is made in the first case). This figure is used for food contamination and ingestion dose calculations, as *RANA* compares the accident data with a rather detailed seasonal profile of the agriculture in the relevant region (see below). The agriculture and food consumption data are tailored to the Italian profile but may very easily changed so as to fit one's regional needs.

RANA also provides a *snapshot* tool, which, with a sin-

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[1] *Among the several data banks available, please refer to the Vienna International Atomic Energy Agency (IAEA) site, where continuously updated information is stored in the Power Reactor Information System (PRIS) data system*

[2] *For instance, for information on the European Pressurized Reactor (EPR), built by Areva, see its UK site. At this date (2011) two EPR units are in construction, both in Europe.*

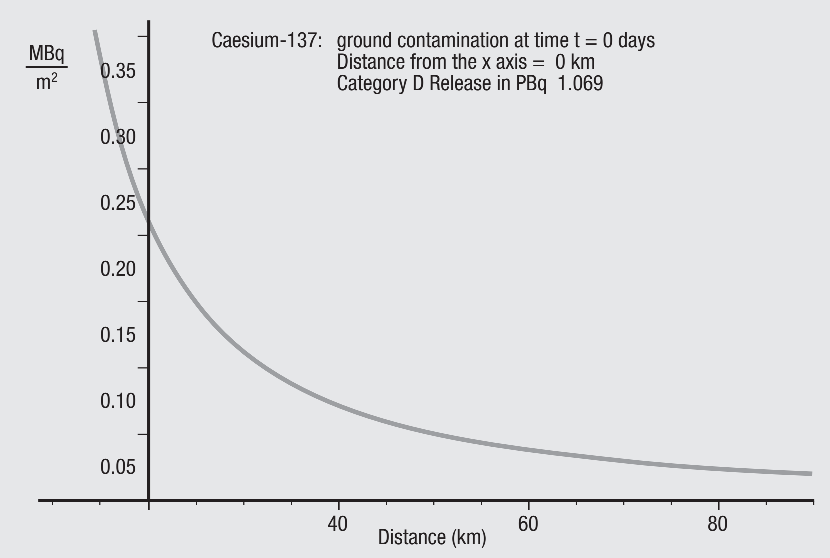


Fig. 2 | *The downwind ground contamination profile for Caesium-137 as a function of the distance from the source, as generated after a release of 1.069 PBq (Peta Becquerel) of this nuclide.*

gle command, enables the user to get a quick basic picture of the most relevant indicators of the radiological consequences of the accident, including iodine and caesium air contamination, effective and thyroid iodine doses, milk contamination (these quantities being given as a function of time and of distance within a selected range).

The user is presented with two choices for the calculations: the requested function can be explicitly written with its appropriate arguments or, alternatively, a *Mathematica* button can be used and some prompts take care of specifying the arguments. In some cases the button can start a Manipulate function, simplifying the whole calculation.

If, for example, the profile of the ground contamination for a given event is needed, one has to provide the following input

`Contamination1D[Ground,{Cs137,4},{30, 90}]`

(with the graphic result shown in *Figure 2*).

The result shown in *Figure 2* can also be achieved by clicking the button:

`Contamination1D`

that has been automatically generated at the beginning of Mathematica session and is associated with the following code (see below). Indeed at the beginning of the RANA session, once the alternatives have been fixed, four tools are generated:

1 - *a Nuclear Data sheet (see below);*
2 - *a Panel of functional buttons* (an example of which was given above);
3 - *an Accident consequences window*, where the calculations from the panel are reported;
4 - *an Early Accident consequences window* with the same appearance as the Nuclear Data sheet but conceived in such a way as to get, through the *Mathematica* function Manipulate, a full harvest of data on hypothetical early radiological effects occurring in the vicinity of the nuclear plant, as will be shown in an example.

Table 1 shows the nuclear data panel together with the outcome of one of its buttons.

The diffusion equations

As we have already mentioned, weather conditions are classified according to the Pasquill-Gifford scheme. *RANA* diffusion equations make use of the Gaussian solution of the diffusion equation for short and medium distances:

$$Q_i(x,y,z) = Q_0 \frac{e^{-\frac{y^2}{2\sigma_y(i,x)^2}}\{e^{-\frac{(z-h)^2}{2\sigma_z(i,x)^2}} - e^{-\frac{(z+h)^2}{2\sigma_z(i,x)^2}}\}e^{-l_g(i,x)}}{2\pi\sigma_y(i,x)\sigma_z(i,x)u(i)}$$

```
If[ <<Come == 2, ButtonBox[StyleBox["\"Contamination1D \"",
ShowStringCharacters→False, FontColor→RGBColor[0,.3,1],FontFamily→"Courier-Bold",FontSize→18],
ButtonFunction→Module[{a,b,c,d,e,g},
SelectionMove[ nb,After,Notebook];SetOptions[ nb,DefaultNewCellStyle →"Print";
Label[ a];ToUpperCase[ToString[Input["Matrix ( Air or Ground)?"]]]>>mezzo; If[ FreeQ[{"AIR","GROUND"}],<<mezzo],Goto[a][;
Label[ b];nuc=Input["Nuclide? (e.g.:Iodine-131 or Caesium-137)"];If[FreeQ[radionuclidi,nuc],Goto[ b]];
Label[ c] ;cat=Input["Category?"];If[ FreeQ[Range[8],cat],Goto[ c]];Label[ d];dist=
Input["Initial and final distances and from the x axis in km (2 or 3 numbers list)?"];
If[ ListQ[dist] && Length[dist] ≤ 3 && Length[ dist]≥2, Goto[ e],Goto[ d];Label[ e];temp=
Input["Time since deposition (days)?"];SetOptions[ nb,Visible→True];
NotebookWrite[ nb,"Contamination1D[ <<mezzo,{nuc,cat},dist,temp}",All];
SelectionEvaluate[ nb];] &),Evaluator→Automatic, Active→True ]] // DisplayForm
```

Table 1 | *The nuclides buttons panel with one of its outputs*

Krypton-88	Strontium-89	Strontium-90	Strontium-91
Yttrium-91	Zirconium-95	Zirconium-97	Molybdenum-99
Ruthenium-103	Ruthenium-106	Tellurium-127m	Tellurium-129m
Tellurium-132	Antimony-127	Antimony-129	Iodine-131
Iodine-132	Iodine-133	Iodine-134	Iodine-135
Xenon-133	Xenon-135	Caesium-134	Caesium-136
Caesium-137	Barium-140	Lanthanum-140	Cerium-141
Cerium-144	Neptunium-239	Plutonium-238	Plutonium-239
Plutonium-240	Plutonium-241	Curium-242	Curium-244

{Iodine-131,{{1.00342 x 10^6, 0.0110769}, 1.934 x 10^1}}

(Here Q is the time integrated activity concentration following a release Q_0, x is the wind axis, i stands for one of the Pasquill-Gifford diffusion categories, σ_k is the plume width along the k axis, $u(i)$ is the wind speed, $h(i)$ is the maximum height of the cloud due to eventual thermal buoyancy and lg takes care of the ground deposition from the cloud along the x axis).

For longer distances the diffusion equation use the "wedge" model [1]: the transition from Gaussian to wedge occurs, for a given Pasquill category i (i = A, B, C, ...G), at a distance $x(i)$ downwind given by:

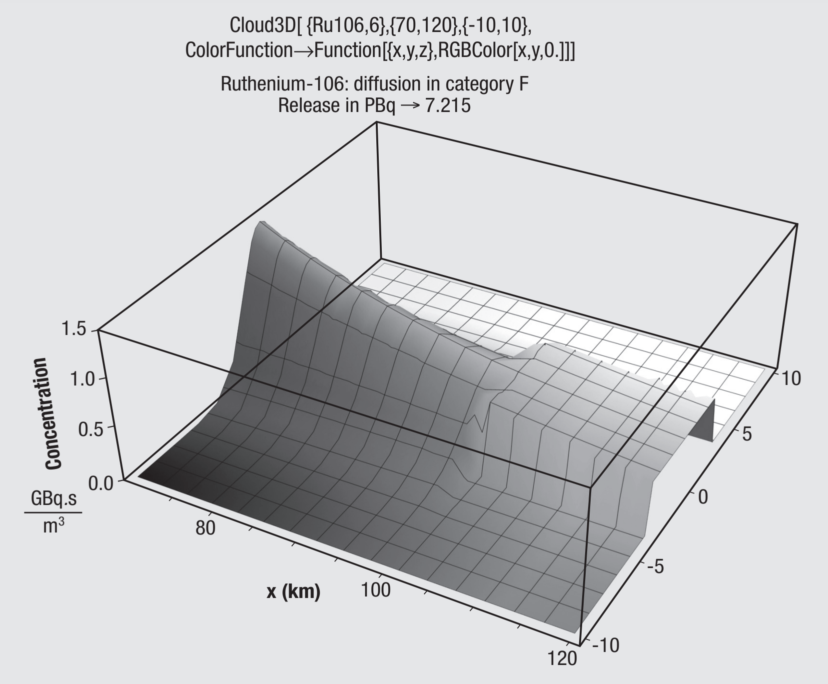
$$\sigma_z(i,x) = \sqrt{\frac{2}{\pi}}H(i)$$

where H(i) is the height of the mixing layer. For distances > $x(i)$ the cloud is uniformly distributed along the z vertical axis up to height H(i), and a step function lateral distribution is assumed, with a (constant) angular width $\varphi(i)$ given by :

$$\phi(i) = ArcTan\sqrt{\frac{2\pi\sigma_y(i,x)}{x(i)}}$$

Figure 3 shows (in gray, that is not according to the input function) the cloud transition from the Gaussian to the wedge model.

The model can accomodate thermal buoyancy of the plume, by referring to the stored data for the standard release categories or by prompting for the thermal power of the release. A correction is made for prolonged releases by allowing for a release duration dependent increase of the plume lateral width. Corrections for long distance plume propagation (typically more than a few tens of kilometers) are introduced through a



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Cloud3D[ {Ru106,6},{70,120},{-10,10},
ColorFunction→Function[{x,y,z},RGBColor[x,y,0.]]]
```

Fig. 3 | *The transition of the cloud modelling from Gaussian to wedge profile, shown for Ruthenium-106 atmospheric diffusion in the selected Pasquill category.*

Table 2 | *Some of the functions used in RANA calculations*

FoodContamination	FoodContamination1D	InitialGroundContamination
Contamination1D	IsoContamination	Emergencies
Clouds1D	Cloud3D	EarlySomaticEffects

random walk type approach. For a given Pasquill category, wind direction persistence is assumed for a distance $x(i) = 3600\, u(i)$, where $u(i)$ is in m/s; $x(i)$ gives the step of the random walk, from which the effective distance covered by the cloud is then evaluated.

If required, wet deposition is taken into account by prompting for the distance interval within which rain has occurred. Plume depletion by ground deposition is calculated by integrating dQ/dx in the usual way, with a deposition velocity that may depend (if wet deposition is chosen) from the distance downwind. Finally, both finite plume corrections in cloud and ground doses, radionuclides decay and daughter build-up are evaluated in the algorithm.

Calculating contamination and doses

Contamination and dose calculations from contaminated food make reference to a national food basket including vegetables, milk, fruit, wheat and meat. Fresh leafy vegetables are supposed to be available in the market every day of the year, whereas more standard assumptions are made for other foods.

Once the accident date ta has been specified, *RANA* automatically selects those crops for which $tg < ta < th$ where tg and th are, respectively, the sprouting and the harvest times for the given crop. The selected crop will contribute to the direct deposition contamination pathway, with the root uptake path also taken into account for all the relevant crops.

There is a strong dependence of the food chain contamination on the accident date, due both to the variable interval between harvest time and the accident date, as well as to the time dependent crops interception factor that has been introduced in the algorithm.

More details about the food chain module and other aspects of *RANA* will be given in a subsequent paper (E. Tabet, in preparation).

In calculating individual and collective dose following a release of radioactive material *RANA* takes into consideration the following exposure routes:

- external γ irradiation from the cloud;
- internal irradiation from inhalation of contaminated air;
- external γ irradiation from material deposited on the ground;
- internal irradiation from the ingestion of contaminated food.

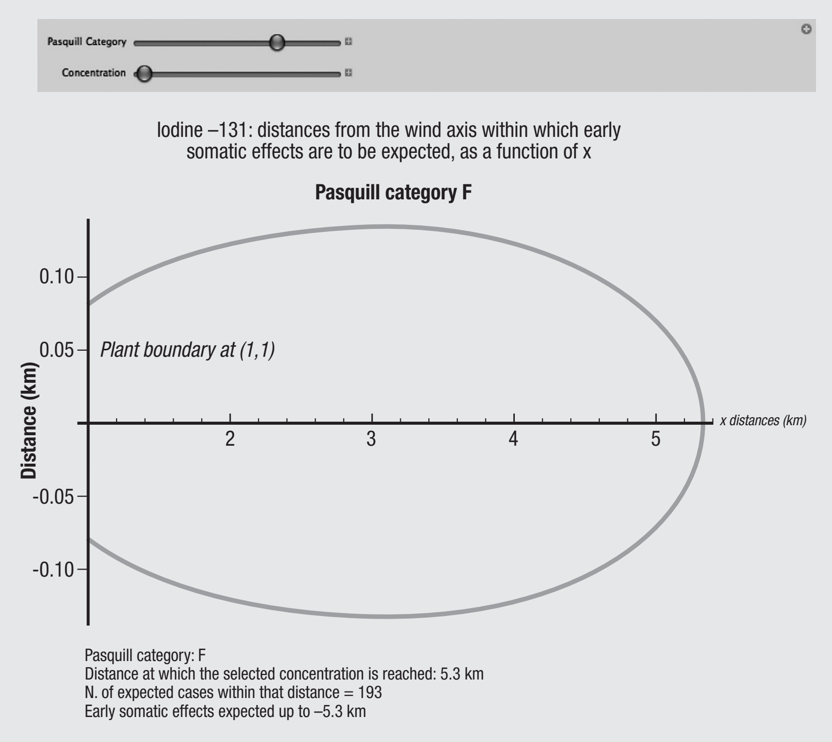
The algorithm gives, for the routes considered, the effective dose, the skin dose from external irradiation <only for some nuclides>, the skin dose from material deposited on the skin and the dose to the thyroid from inhalation.

Doses are calculated for infants (0-1 y), children (7-12 y) or adults making use of the European Basic Safety Standards dose factors [2] which are now being updated. External ground doses (for an

Table 3 | *A few examples of RANA functions and outputs for different areas*

Presentation/Area	N.	G.	Example
Contamination	*	*	3 D cloud, ground contamination table
Contamination[a]	*	*	Data distribution on provincial or regional scale
Athmosferic diffusion	*	No	Weather parameters, cloud lateral and vertical width, deposition speeds
Doses	*	*	Individual or collective doses as a function of time and of the distance from the source
Doses[a]	*	*	Doses on a local scale
Early Effects	*	*	Graphical profile of the early effects area, relevant distances and figures
Basic equations	*	No	Time and space dependent nuclides pattern for any diffusion category
Dose Factors	*	No	Effective, skin, ingestion and thyroid dose factors lists
Geodata[b]	*	No	Province coordinates
Nuclides	*	No	Basic nuclear data: decay times, γ ranges in air
Reactors	*	No	Plant data, time dependent radioactive release, plant distances from main towns
SnapShot	*	*	Iodine and Caesium air and ground contamination, doses, milk contamination as a function of time and distance

a: Calculations from the experimental data;
b: On a national basis;
N: numerical;
G. graphical.



Pasquill category: F
Distance at which the selected concentration is reached: 5.3 km
N. of expected cases within that distance = 193
Early somatic effects expected up to –5.3 km

Fig. 4 | *Early effects of the release of Iodine-131 in a hypothetical case (see text for details).*

arbitrary exposure time) are evaluated including the contributions of daughters after the deposition.

Collective doses can be calculated for any specified x interval downwind and for an arbitrary lateral distance from the plume axis. Now *RANA* includes, beside dose calculations for late *(stochastic)* effects, also dose evaluations for early harm induced by radiation *(immediate effects)*. This addition follows the new forecasts on nuclear energy exploitation in Italy. The present version of *RANA* also allows to take into account the effect of various emergency countermeasures (such as sheltering or food ban) on dose values.

The functions of RANA

RANA is started just by calling upon one of its over 100 functions or from its start-up icon.

As already remarked, at the end of the start-up process several button-like functions are generated in the "*RANA* evaluator".

More details on the tools used by the algorithm can be found in *Table 3*.

Finally, *Figure 4* shows an example of early consequences calculations, as generated from the consequences buttons panel.

As for the calculations shown in this paper, we have considered a severe accident chosen among those that could hypothetically occur in an EPR[3]. The chosen event gives rise to the release into the atmosphere of approximately a few thousandths of the reactor's radioactive inventory, as for the Iodine and Caesium isotopes. The results of *Figure 4*, however, should be taken as a case study, presented so to illustrate the power of the tools, since we have used *arbitrarily chosen dose limits for the onset of early effects*. Work is in progress to associate all the considered nuclides with their appropriate values for dose limits for this kind of effects.

CONCLUSIONS

RANA is a simplified tool for the parametric evaluation of the consequences of a radioactive release, where its approximations are, hopefully, balanced by some advantages in the algorithm. Among these are the transparency of all the physical assumptions at each step of the model, the full modularity of its implementation on *Mathematica*, the flexibility and adaptability of *RANA* with respect to future needs and improvements and the possibility of fully exploiting the powerful tools of *Mathematica* in creating new functions.

This is clearly seen in the last example, where the powerful tools introduced in the last version of *Mathematica* allow for a drastically simplified description of rather complex situations, as those encountered when trying to calculate the short distance impact of a nuclear accident. *RANA* is still undergoing several improvements and refinements, some of which have already been mentioned.

Finally, as already said, a more detailed presentation of the algorithm is in preparation and will be presented elsewhere (E. Tabet, in preparation)[4].

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[3] *For comments and estimates about EPR accidental releases, pleace also refer to the relevant documents of the US Nuclear Regulatory Commission.*

[4] *The paper will also deal with an assessment of the events recently occurred at the nuclear site of Fukushima, Japan. [Note by the Author, after proof reading].*

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Conflict of interest statement

There are no financial or personal relationships with other people or organizations that could inappropriately bias conduct and findings of this study.

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