11th International Symposium on Fusion Nuclear Technology
16-20 September 2013 · Barcelona, Spain

Università di Roma Tor Vergata

Università di Roma Tor Vergata INTERNATIONAL CBRNe MASTER COURSES Chemical, Biological, Radiological, Nuclear and explosive Department of Industrial Engineering and Faculty of Medicine and Surgery

Using free license codes to simulate the diffusion of contaminants in case of radiological release

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A — Introduction

- The **radiological risk** is inherent to a wide range of activities: medical, military, industrial and research including **nuclear fusion**.

An explosion in a nuclear fusion plant could result from a LOVA (LOss of Vacuum Accident) or from a LOCA (LOss of Coolant Accident) which lead to air ingress: the dust, which is normally produced during the life of the reactor and accumulates into the Vacuum Vessels (VV) can be mobilized and form an explosive dust-air cloud which can be ignited by the energy of hydrogen combustion following hydrogen ignition by a weak spark [2].

- A valid tool to predict the consequences of accidents and reduce their risk consists in **computing systems** that allow **modeling** the evolution of a possible release of radioactive materials in different kind of scenario.
- Being able to **predict** the consequences of a radiological or nuclear accident for the **population** and the environment is essential to:
  - **EMERGENCY PLANNING**
  - **EMERGENCY MANAGEMENT**

the first action needs a great number of data to create sufficiently detailed scenarios to implement the **planning proces**; the second action requires a fast, field portable tool which can be used to predict the immediate consequences of an accident to support the **decision making** process.

- Free license codes, such as the **HotSpot code**, can be used with this aim, contributing collecting useful **preliminary data**.

B — Aim of the work

The aim of this work is to demonstrate the capability of free license codes to model the radiological diffusion in case of real or hypothetical accidents to collect data which are useful to guarantee the safety of people and operators, and the security of **nuclear power plants**.

Both these aspects are critical issues for the development of <u>nuclear fusion plants</u> like ITER

(International Thermonuclear Experimental Reactor)

Workflow

1. **Benchmark of the code:** with data from a real accident involving the explosion and subsequent release of radioactive material from a spent nuclear fuel reprocessing facility [3] to evaluate the confidence of the results.
2. **Validation of the model:** results from the simulation and experimental data were compared to evaluate the best model and settings of the code to simulate an explosion at the ITER facility.
3. **Simulation of an explosion at the ITER facility:** simulation of a worst case scenario for the explosion of the plant and the release of 100% of the radioactive dust and Hydrogen was simulated. Results have been discussed and presented here.

C — The HotSpot code

HotSpot evaluates the radiation effects associated with the atmospheric release of radioactive materials basing on a **<u>Gaussian dispersion model</u>**. The models in HotSpot estimate the short-range (the best confindence is within a downwind distance of 10 km), and perform short-term (few hours) predictions for downwind radiological impact of the release of radioactive material in the atmosphere [4]. Outputs are available both as **Ground Deposition (GD)**, expressed in $kBq \cdot m^{-2}$, or as **total effective dose equivalent (TEDE)** [5] expressed in Sievert (Sv).

$$C\,(x,y,z,H) = \frac{Q}{2\pi\sigma_y\sigma_z u}\, exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} exp\left[-\frac{\lambda x}{u}\right] DF(x)$$

C = Time-integrated atmospheric concentration (Ci-s)/(m3).
Q = Source term (Ci).
H = Effective release height (m).
λ = Radioactive decay constant (s–1).
x = Downwind distance (m).
y = Crosswind distance (m).
z = Vertical axis distance (m).
σ_y = Standard deviation of the integrated concentration distribution in the crosswind direction (m).
σ_z = Standard deviation of the integrated concentration distribution in the vertical direction (m).
u = Average wind speed at the effective release height (m/s).
L = Inversion layer height (m).
DF(x) = Plume Depletion factor

The model was developed for general releases of radionuclides and for nuclear events, and allows the user to simulate the release of any radionuclide which is included in the ICRP 30 and in the ICRP 60+ thanks to the "General" models:

- general explosion,
- general plume,
- general fire,
- general resuspension.

Essential input values required by the model are:
- the **activity of the source** term involved in the scenario;
- the meteorological data: **the wind velocity and direction** and the solar insolation factor. These data are required to determine the proper Pasquill's stability class.

D — (1.) Benchmark and (2.) Validation

Characteristics of the accident

The accident involved the **explosion** of a stainless steel tank containing spent nuclear fuel, organic, and inorganic compounds used in the reprocessing process. The explosion was caused by an uncontrolled rise of the internal pressure due to a collateral exorgonic reaction of these compounds. The accident caused the **release either from the sidewalls of the building and from the roof or the 150m stack of the plant**, following **two different dispersion models.**

^{106}**Ru** is one of the components of the radionuclide mixture in the tank, and its ground concentration after the accident showed a peculiar "**two peaks**" distribution (**<u>Fig.1</u>**) due to:

- the different wind direction blowing at the sidewalls and roof/stack height;
- **the different amount of radionuclides released with this wind directions: about 65% with 190° true wind direction; and 35% with 210° true wind direction.**

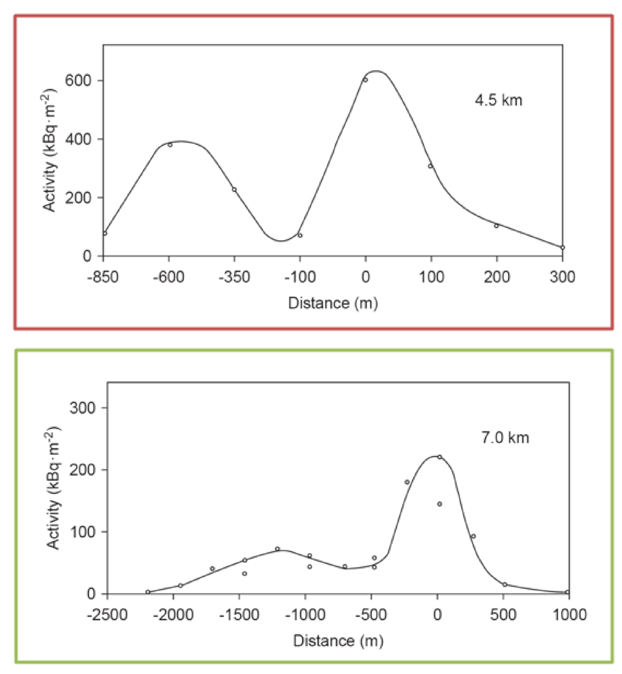

Figure 1 *experimental data for the ground contamination with ^{106}Ru across the path of the fallout, at a downwind distance of 4.5 km, and 7.0 km from the facility involved in the accident [3].*

Settings of the code for the benchmark

We associated all the simulated releases with different boundary conditions, using the information in the report[3] as guidelines for: the **model for the release**, the **source term**, the **wind speed and direction**, **Pasquill's stability class** [10], and other settings of the code such as the **sample time**, to find the combination that better fit with the experimental data.

In **<u>Table 1</u>** we give a more detailed description of the combination of boundary conditions and settings identified with the benchmark, resulting in the output values showing the best fit with experimental data.

<u>Table 2</u> *ground concentration values (kBq/m^2) with ^{106}Ru according to the report [3], for the downwind distances of 4,5 and 7 km, and for the best fitting simulation calculated at the same distances. The percentage differences between the values is also shown.*

Percentage difference between code output and experimental values for ground concentration of ^{106}Ru			
190° True wind direction			
Downwind distance (km)	190° Exp data	190° Code output	% DIFF
4,5	625	690	**10,40%**
7,0	225	240	**6,67%**
210° True wind direction			
Downwind distance (km)	210° Exp data	210° Code output	% DIFF
4,5	400	380	**5,00%**

<u>Table 1</u> *Options and values chosen for the simulation, unmodified HotSpot default values are not shown.*

Boundary conditions for simulations of ground contamination with ^{106}Ru	
Model	**General Explosion**
Source Term	
Radionuclide	Ru-106 W 368.2
Deposition velocity	20 cm/s
Meteorology	
10-meter-wind-speed	$5\ m \cdot s^{-1}$
Stability Class	D
Setup	
Sample time	1 min

Downwind receptors location coordinates		
	190°	
Km	**x (km)**	**y (km)**
4.5	0,718	4,432
7.0	1,216	6,894
	210°	
Km	**x (km)**	**y (km)**
4.5	2,250	3,897
7.0	3,500	6,062

Code output values are shown in **<u>Table 2</u>** together with the percentage difference from the experimental data.

<u>A good agreement of data is evident for distances under the 10 km from the point of the release of radionuclides</u>

E — (3.) Simulation of an explosion at the ITER facility

An explosion in a nuclear fusion plant such as ITER could cause the atmospheric dispersion of **radioactive isotopes of Tungsten, Beryllium and Hydrogen** (Tritium) [15-27].

To estimate the hypothetical distribution of radioactivity as a function of distance, and evaluate its impact on **health for workers** and on the **environment** we evaluate scenarios according to the boundary conditions (diffusion model, meteorology, sample time…) validated with the benchmark.

About 1000 kg of dust can be present in the VV, as result of the normal activity of the plant. According to the materials and characteristics of the process in the plant, the percentage composition of the dust would be:

- **50% Beryllium,**
- **30% Tungsten,**
- **20%Tritium.**

To evaluate the total contribution of the radionuclides, a **radionuclide mixture** is used as boundary condition for the simulations (peculiarities of the mixture are shown in **<u>Table 3</u>**.

<u>Table 3</u> *shows the specific (Bq) of the most active isotopes for the three elements*

Radionuclides mixture			
Radionuclide	**Grams**	**Specific activity Bq/g**	**Total activity Bq**
^{7}**Be**	5,00E+05	1,23E+16	6,125E+21
^{187}**W**	3,00E+05	2,45E+16	7,35E+21
^{3}**H**	2,00E+05	3,3775E+14	6,755E+19

Two different scenario have been simulated :

- **Explosion Model** for the release of the total amount of the dust as an explosion from ground level,
- **Combined Model** for the release of **65%** of the total amount of dust as an explosion from ground level and **35%** as a general plume released with an height of 24m from ground level .

Boundary conditions and settings of the code for the two simulations are shown in **<u>Table 4</u>** and **<u>Table 5</u>**

For the General explosion model, we plotted numerical results directly as TEDE or Ground deposition vs the downwind distance; for the Combined model we summed up numerical results from the simulations and then plotted as TEDE or Ground deposition vs the downwind distance, plots are shown (**<u>Fig. 2</u>**)

<u>Table 4</u> *Boundary conditions for the Explosion Model, unmodified default HotSpot values are not shown.*

EXPLOSION MODEL		
Model	**General Explosion**	
Source Term	**Activity (Bq)**	**Deposition velocity (cm/s)**
7-Be	6,125E+21	7,00E-02
187-W	7,35E+21	1,00E-01
3-H	6,755E+19	1,00E-03*
***the deposition velocity for 3H is estimated to be of the order of 1,00E-5, but the lowest value allowed by the code is 0,001 unless the value 0 is selected.**		
10-meter-wind-speed	$5\ m \cdot s^{-1}$	
Stability Class	D	
Wind direction	270°	
Sample time	1 min	

<u>Table 5</u>: *boundary conditions for the Combined Model, unmodified default HotSpot values are not shown*

COMBINED MODEL			
Model		**General Explosion**	**General Plume**
Source Term	**Deposition velocity (cm/s)**	**Activity (Bq)**	**Activity (Bq)**
7-Be	7,00E-02	3,98125E+21	2,1438E+21
187-W	1,00E-01	4,7775E+21	2,5725E+21
3-H	1,00E-03*	4,39075E+19	2,3643E+19
***the deposition velocity for 3H is estimated to be of the order of 1,00E-5, but the lowest value allowed by the code is 0,001 unless the value 0 is selected.**			
Height of the release		/	24m
10-meter-wind-speed	$5\ m \cdot s^{-1}$		
Stability Class	D		
Wind direction	270°		
Sample time	1 min		

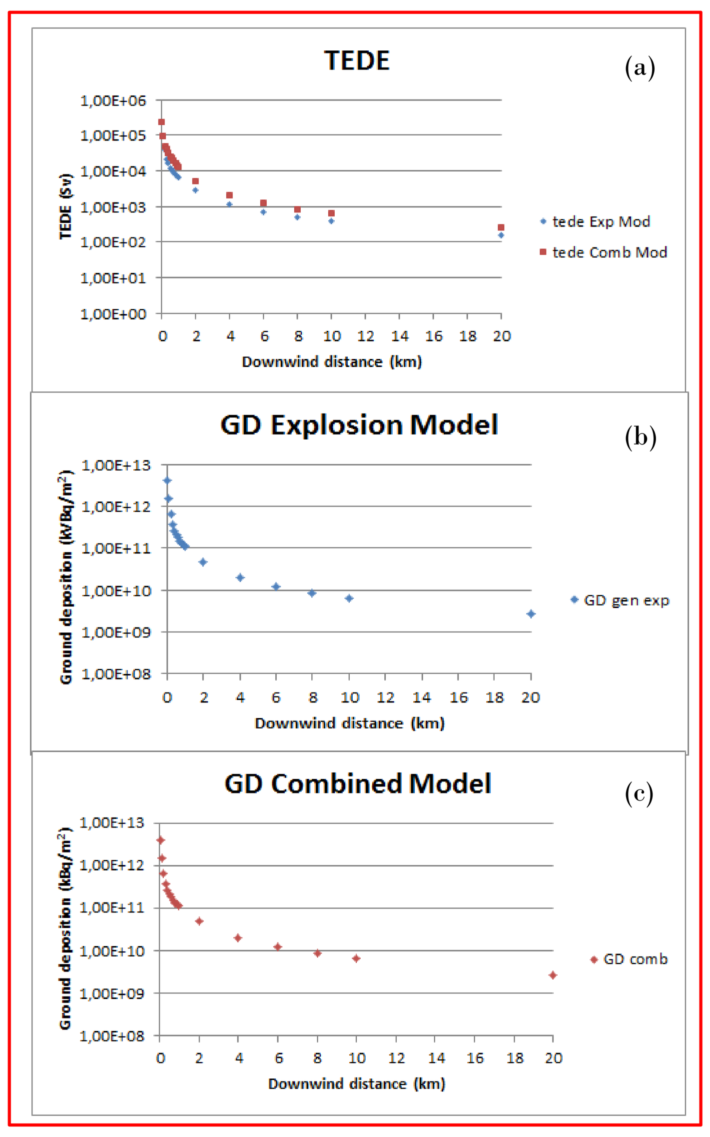

Figure 2: *TEDE and GD values as function of the downwind distance :*
(a) comparison between TEDE values for the Explosion (red squares) and Combined (blue rhombus) Model;
(b) comparison between Ground Deposition results for the Explosion Model and
(c) for the Combined Model.

F — Conclusions

- Numerical results from the simulations suggest that an accident in ITER facility with release of activated dusts would be significant.
- For the two simulation models, TEDE values of $1{,}0E^5$ Sv would be reached in the proximity of the plant; these values decrease with increasing of the distance of about two orders of magnitude at 4,5 km from the source, reaching the value of the order of $1{,}0E^2$ Sv for distances between 10 and 20 km. (an error of about 10% is associated to the values within a distance of 10 km).
- According to these results, external doses of 500 mSv (the lower threshold limit for evacuation) and 50 mSv (the upper threshold limit for sheltering) [14] would occur in the area surrounding the facility, representing an elevated hazard for workers and people by its proximity.
- Despite the code is conservative and estimate tend to be greater than real values, it has to be underlined that this code needs very **little time for calculations** (less than 1 minute) and **very few, and raw, input data** are required to obtain conservative mapping of the area surrounding the facility involved in the accident using the HotSpot code as **DSS** (Decision Support System) in the phase of **<u>emergency planning and management</u>** also for nuclear fusion facilities such as ITER.

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