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APPLICATION OF DISPERSION MODELS OF ESTE FOR MODELLING OF THE RADIOLOGICAL IMPACT OF RELEASED Cs-137 IN A SPECIFIC URBAN ENVIRONMENT

Jozef Sabol[1*], Ľudovít Lipták[2], Jan Bajura[1], Eva Fojcíková[2], Peter Čarný[2]

[1]Police Academy of the Czech Republic in Prague, Prague, Czech Republic
[2]ABmerit, s.r.o., Trnava, Slovakia

Abstract. *The software ESTE was used to assess the spread of contaminated air in terms of parameters that calculate radiation exposure to affected individuals. The computer simulation proved to be a reliable tool for obtaining relevant radiation protection quantities and their dependence on parameters such as the initial source activity, its position, wind direction, and wind velocity. An essential condition for accurate dispersion modelling in urban areas is the evaluation of urban wind fields specific to various environments and atmospheric conditions. The location, structure, and layout of buildings are reflected in the simulation of the behaviour and movement of radioactive air. The modelling considers external exposures, expressed in ambient dose equivalent, and internal exposures, leading to committed effective dose. The ESTE dispersion models have proven extremely useful in obtaining essential parameters for predicting the impact of dispersed radioactivity on individuals in the investigated areas. These data can help implement effective protection measures for people in such areas, where exposure also depends on the configuration of the building structures, which can be taken into account when adopting measures to minimise the exposure of individuals present or moving around. The ESTE code was applied to model the dispersion of Cs-137 in a specific urban environment.*

Keywords: *CBRN, Cs-137 release, dispersion model, ESTE software, radiation protection, radiological impact*

1. Introduction

CBRN material is used as an umbrella term for chemical, biological, radiological and nuclear agents in any physical or chemical form, which can cause hazards to populations, contaminate the territory and thus harm persons affected.

There is a substantial difference between the chemical (C) and biological (B) components on one side and radiological (R) and nuclear (N) agents on the other side. While the first dangerous substances (C and B) present health effects to persons due to their ingestion, inhalation or the contamination of the surface of the body, the R and N components can cause biological effects by not only entering the body but also from outside the body through external ionising radiation (IR) exposure. In addition, nuclear agents can cause life-threatening illness as a result of severe radioactive contamination caused by accidents involving nuclear facilities and explosions of nuclear weapons, which additionally result in thermal or blast effects.

The severity of CBRN impacts will depend on the incident itself – the amount of substances released, characteristics of the hazard, the environment, and the conditions in which it occurs – as well as the efficiency of the response. Urban CBRN incidents have great potential to cause long-lasting and devastating impacts on people, places, and economies.

Short-term effects include the direct influences on people's health and the economic losses and assets to be spent on response and clean-up. Special attention must be paid to long-term consequences, which can appear after some time and last many years.

Protecting public health is the first and most important aim when a CBRN incident occurs. Emergency services, first responders, authorities, and other government or private organisations must respond to these events and minimise the impact on the surrounding population.

In order to assess the danger of CBRN, it is essential to evaluate the actual situation in the place where CBRN components are moving, including their concentration and the effect on the surrounding area. It is obvious that the release of CBRN agents in a flat area will be very different from that in urban areas, where buildings will substantially disturb the dispersal of these dangerous substances. The most commonly used solutions are simulations and models that predict the next steps of an incident, such as how it will spread or scatter through an environment.

All urban dispersion models for mapping the movement of airborne hazardous material within an urban environment should consider how the buildings will affect their movements. These tools are designed to work accurately and quickly so users can understand how a contaminant might travel and spread and in what direction to see what areas might be impacted.

In principle, the dispersion of each CBRN agent can be modelled. For obvious reasons, simulation is often used to predict the behaviour of radioactive materials. The paper presents some results of simulation of the

* sabol@polac.cz

movement of these materials in urban areas, showing some results related to the spread of Cs-137 and its consequences, where the latest version of the software ESTE (Emergency Source Term Evaluation) developed by Abmerit was used for this purpose [1,2]. The need for such an estimation of the spreading of radioactive materials was prompted by some accidents at the NPPs, especially the one that occurred in Fukushima in 2011 [3], where mapping of radioactive contamination proved crucial in assessing the population's exposure at various distances from the NPP.

2. Main characteristics and the potential of ESTE code

The ESTE system is capable of performing an assessment of an accidental source term based on characteristics and conditions of the release of radioactivity due to an accident or intentional terrorist attack involving strong radioactive sources or nuclear reactors.

The main principles and the forms in which the results can be interpreted are illustrated in Fig. 1.

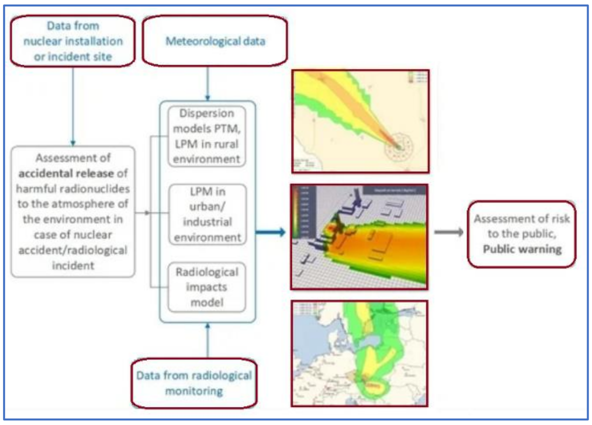

Figure 1. Basic graphical arrangements of main elements and functions of ESTE code

The calculated ensemble of radiological parameters considered in ESTE are dose rates, doses by external irradiation from radionuclides in the atmosphere, doses by external irradiation from radionuclides deposited on terrain, doses by inhalation of airborne radionuclides, and doses by ingestion of contaminated foodstuffs. An implemented geographical information system and a population database support the evaluation of impacts on the population and recommendation of protective measures. Thus, the proposed measures are improved by the number of affected inhabitants and their age structures, for example. The ESTE system is used for real-time response to accidents at nuclear installations, and that fact determines the features of the implemented transport and dispersion models.

The urban-oriented particle model, which performs an evaluation of the situation in close vicinity to the event, is applicable either:

a) in case of a malicious act, with the application of a radiological dispersion device (RDD) or dirty bomb in an urban environment or
b) in industrial accidents.

As mentioned, the ESTE software was developed mainly to assess the spreading radioactivity from accidents involving NPPs. An example of results for the release of radioactivity and its impact on the level of contamination of the surrounding area of the NPP Mochovce (Slovak Republic) is presented in Fig. 2 (based on [1]).

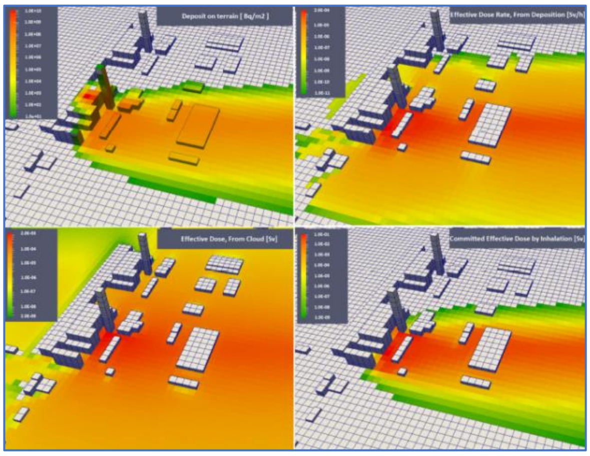

Figure 2. Example of impact calculation for an urban environment: A release from the reactor building of the Mochovce NPP is simulated. The figure shows deposition on surfaces (top left), effective dose rate from deposition (top right), dose rate from the cloud (bottom left), and dose rate by inhalation (bottom right).

3. Application of ESTE in modelling and assessing Cs-137 impact

Cesium (Cs) is a soft, flexible, silvery-white metal that becomes liquid near room temperature but easily bonds with chlorides to create a crystalline powder. The most common radioactive form of cesium is Cs-137. Cesium-137 is produced by nuclear fission reaction, one of the byproducts, and is also released from nuclear weapons testing [3].

In general, cesium moves easily through the air. Cesium dissolves easily in water. This element binds strongly to soil and concrete but does not travel far below the surface. Plants and vegetation growing in or near contaminated soil may take up small amounts of Cs-137 from the soil.

External exposure to large amounts of Cs-137 can cause burns, acute radiation sickness, and even death. Exposure to Cs-137 can increase the risk of cancer because of exposure to high-energy gamma radiation.

Exposure to radioactive cesium occurs from ingesting contaminated food, drinking water or breathing polluted air. High levels of radioactive cesium in or near an individual's body can cause nausea, vomiting, diarrhoea, bleeding, coma, and even death.

The software ESTE was initially intended to be used primarily for mapping releases of radioactive materials following accidents involving NPPs where the release of Cs-137 plays an important role.

Atmospheric dispersion and deposition of radioactive materials, including Cs-137, began to be intensively studied especially after the Chernobyl and then the Fukushima NPP accidents.

Through an atmospheric dispersion code and publicly available meteorological data, the atmospheric dispersion of such radionuclides as ^{137}Cs has been simulated globally using different codes. The simulation has been validated by comparison to publicly available measurements collected in several locations worldwide. Sensitivity analysis shows that the release height of the radionuclides, wet deposition velocity, and source term are the parameters with the most impact on the simulation results. For example, in the case of the Fukushima nuclear accident, the simulation showed that the radioactive plume, consisting of ^{137}Cs, has been transported over the entire northern hemisphere, depositing up to 1.2 MBq m^{-2} near the NPPs to less than 20 Bq m^{-2} in Europe. The consequent effective dose to the population over 50 years, calculated by considering both external and internal exposure pathways, is found to be about 40 mSv in the surroundings of Fukushima Dai-ichi. At the same time, other countries in the northern hemisphere experienced doses that were several orders of magnitude lower, suggesting a negligible impact on population health elsewhere [4].

Many software developments have addressed the dispersion of dangerous substances during the last ten years or so. One of the most advanced approaches is considered to be applied by ABmerit, which has recently become very active in this area. Their code ESTE has been widely used for modelling the spread of specific radionuclides, including Cs-137. The ABmerit software is based on a Lagrangian particle model (LPM) for computing atmospheric dispersion. The model is implemented in the nuclear decision support system ESTE CBRN, and a software tool was developed to calculate the atmospheric dispersion of airborne hazardous materials and radiological impacts in the built-up area [5].

Under the framework of the project CHIMERA, in which PACR is participating [6], some modelling has been carried out to map the spread of Cs-137 in the vicinity of the compound of the Police Academy of the Czech Republic in Prague (PACR) [7].

Another modelling was aimed at the assessment of spreading radioactivity in the frequently visited populated centre of Warsaw near the prominent building Palace of Culture and Science [7].

As mentioned above, the ESTE is a software tool for modelling the spread of radioactive or chemical pollutants in urban or industrial buildings after applying a dirty bomb or any other release of dangerous substances, including a terrorist attack. The ESTE models, algorithms, and the entire SW tool are subject to continuous development. The task of the system is computational modelling of the spread of radioactive substances and calculation of the radiation situation in the affected area, where the following factors are taken into account:

- Contamination of street and building surfaces,
- Concentration in the air,
- Dose and dose rate in the affected area.

The system is particularly suitable for preparing exercises and simulations for rescue unit exercises.

The modelling of the contamination caused by the release of Cs-137 was performed at the place just opposite of the PACR (position 14.4313° long and 50.0159° lat). The activity of the source was considered to be 10^{12} Bq. The wind speed was presumed to be 2.7 m/s at 6 m above the ground.

The following parameters have been calculated:

- The predicted the level of the effective dose from external radiation during the first 10 min following the release (Fig. 3),
- The committed effective dose by inhalation by adults (Fig. 4)
- The activity concentration after 10 min (Fig. 5).

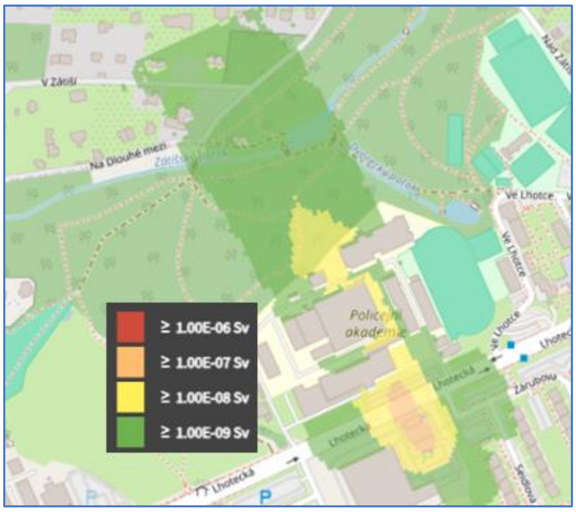

Figure 3. Effective dose from external radiation during the first 10 min from the spread of the source

Figure 4. Committed effective dose after 10 min of contaminated air inhalation

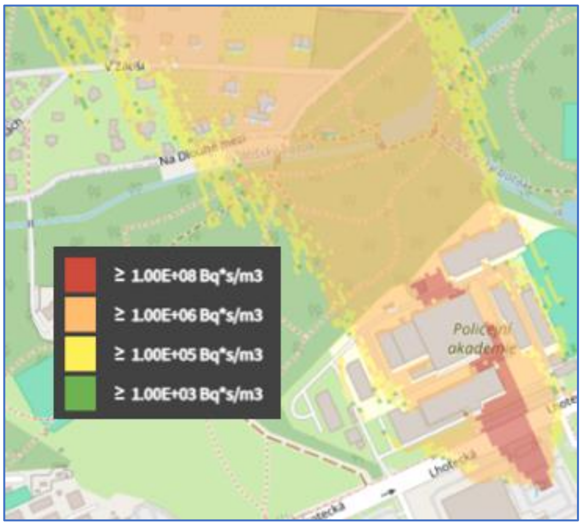

Figure 5. The ground layer time integral of air volume activity after 10 min from the beginning of the release

All results are related to the radioactivity at the release point, which was situated on the other side of the main road overlooking the compound of the PACR (Fig. 6).

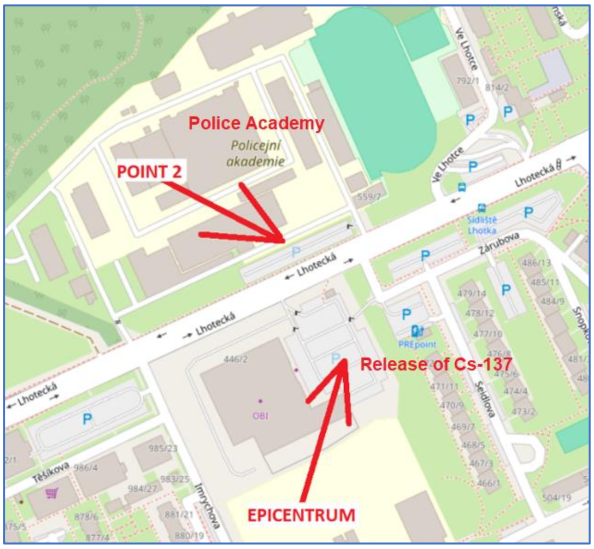

Figure 6. Position of the epicentre and PACR compound

Another simulation of spreading Cs-137 using ESTE code was carried out in Warsaw. In the case of Warsaw, the spread of radioactive materials was modelled from a radioactive source (e.g. a dirty bomb) in a defined location (21.0094° long, 52.2312° lat). In this situation, urban dispersion and dosimetric models have been applied.

Fig. 7 shows the spread of Cs-137 radioactive materials assuming a wind speed of 2.7 m/s and its direction 149°. The original activity of the source was 10^{12} Bq. The distribution of the ground layer of the time integral of air volume activity after 10 min from the beginning of the release is predominantly affected by the direction of the wind and buildings of various heights.

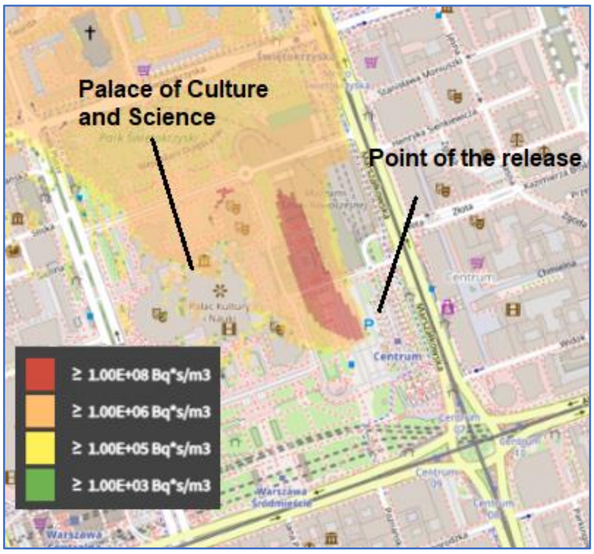

Figure 7. The integral volume of activity during the first 10 min following the release

Another characteristic of the contaminated area is presented by the distribution of the committed effective dose by inhalation of people who spent the first 10 min there following the release of radioactivity (Fig. 8).

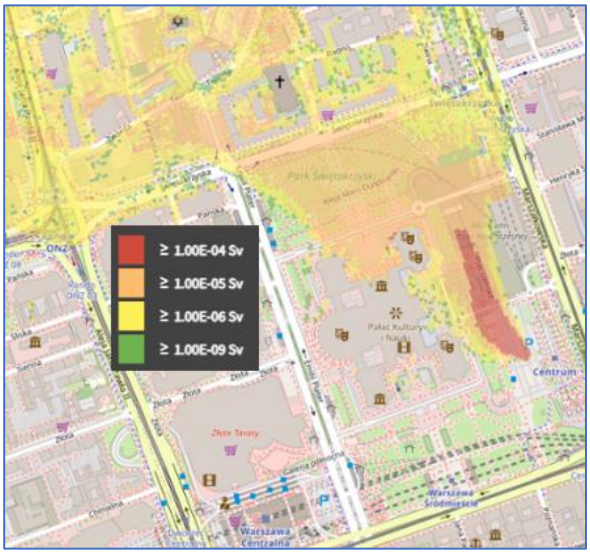

Figure 8. The distribution of the committed effective dose due to the inhalation of radioactive air within the contaminated cloud

Sometimes, comparing the results from various measurements, calculations, or modelling is difficult. This is mainly caused by the incorrect use of quantities and, in some cases, difficulties in their interpretations. There are many reasons behind these problems, but the following three seem to be the most relevant:

- There are too many quantities, and their definition is rather complicated,
- More quantities are still being introduced, which are supposed to remove some obstacles of previous quantities,
- Moreover, there is always quite a substantial period during which more than one quantity to quantify more or less the same process or properties are used simultaneously (one of the examples presents the use of R (roentgen), although this quantity and its unit are no longer supposed to be applied in radiation protection),
- Another difficulty is that because of precise and complex definitions of some quantities, their interpretations, even by those working with radiation sources, are not always correct,
- An enormous problem is also national laws, regulations, or other relevant materials, where errors or misinterpretations in the use of radiation protection quantities are quite common.

To illustrate this, a figure below (Fig. 9) showing the radiation level in mR/h (reproduced from [8]) can demonstrate the situation. Moreover, old units are sometimes automatically converted to new units, but this is not always correct. Here, we cannot convert mR (milirentgen) to mSv since unit R can only be used for a limited range of photon radiation based on the ionisation in the air. In contrast, Sv can be used for any radiation.

The frequent changes in the definition of some quantities and the introduction of new quantities with the same unit may complicate the sound communication of radiation threats with the public, which may confuse them and prevent them from recognising the level of danger following nuclear or radiation emergencies.

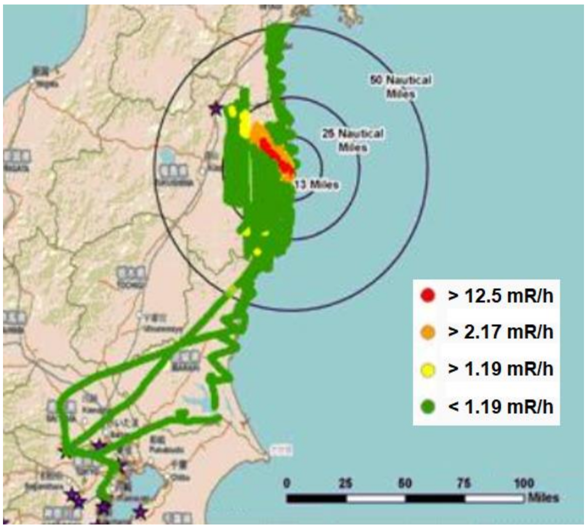

Figure 9. Results of monitoring radiation level related to the height of 1 m over the ground surface using drones, published by the US Department of Energy.

It is generally recognized that principal radiation protection objectives consist in reducing the probability of the risk of stochastic effects and preventing the occurrence of harmful deterministic effects. The approach was proposed to be applied for both external and internal exposures of persons expressed in the same quantities, which can then be summed to assess the total impact from each of these exposure components.

Although there have been attempts to include two main quantities for this purpose, namely effective dose and RBE-weighted dose, with the units of Sv and Gy-Eq, the current situation is still confusing and difficult to apply in practice. [9]. Since these radiation protection quantities are virtually unmeasurable directly, they have to be assessed through the monitoring of other quantities and then the results converted using a rather complicated process into the main relevant quantities.

The interpretation of monitoring results is sometimes so problematic that even those who are responsible for radiation protection at workplaces do not sometimes fully realize the role of all factors which have to be taken into account. The existing problems relevant to the use of radiation protection quantities are discussed in order to point out some inconsistencies in the current intricate state of presenting the results of external and internal exposures in a unified and comprehensive way. The authors believe that the current system of radiation protection is too complicated for routine applications where a simplified system should be elaborated based on a limited number of measurable quantities.

4. Conclusion

A brief characteristic application of the ESTE code in assessing radioactivity dispersion in two locations (one in Prague and another in Warsaw) illustrates its potential and usefulness in adopting appropriate steps for minimising the exposure of people present in the contaminated area.

The ESTE system is used in nuclear crisis centres at various emergency preparedness and response levels in Slovakia, the Czech Republic and some other countries. ESTE is also applicable as a decision-support system in case of a malicious act with a radioactive dispersal device in an urban or industrial environment.

The dispersion models implemented in ESTE are the Lagrangian particle model (LPM) and the Puff trajectory model (PTM). The PTM is applied in ESTE for the dispersion calculation near the point of release, up to 100 km from the location of a nuclear or radiological accident. The LPM for general atmospheric transport is applied for short-range, mesoscale and large-scale dispersion up to dispersion on the global scale. A specifically suited/adjusted version of LPM is implemented in ESTE to model dispersion in urban environment.

The paper also mentions some current problems in a unified and generally recommended use of radiation protection quantities and units. A consistent system of quantification of radioactive materials and the exposure of persons or contamination resulting from these materials is essential in achieving consistency in assessing the consequences of any uncontrollable release of radioactivity.

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