LESSONS LEARNED FROM FORMER RADIATION ACCIDENTS ON DEVELOPMENT OF SOFTWARE TOOLS FOR EFFECTIVE DECISION MAKING SUPPORT

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Presenting Authors' biography

Petr Pecha: Senior researcher. Experience in modelling of radioactivity propagation into the living environment, probabilistic analysis of radiation accident consequences, assimilation of model predictions with observations from terrain. Participation on customization of the RODOS system for the Czech territory.

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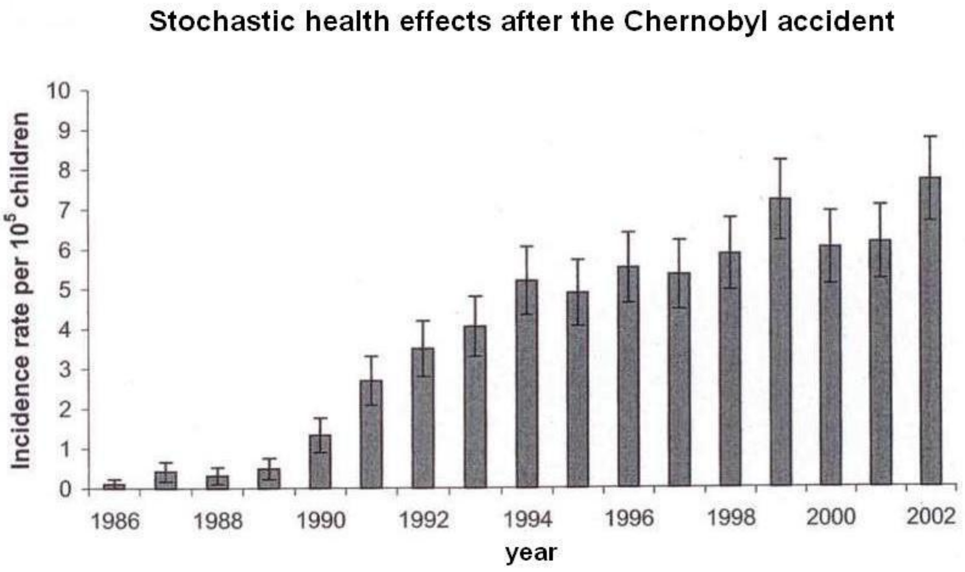
Natural and human-made hazards

Catastrophic flooding events, devastating earthquakes or pandemic proliferation of infectious diseases set an example of natural threats on population. Besides that, a large-scale hazard can result from man-made processes, caused by irresponsible individual behaviour and neglect or unintentional human errors usually connected with damages of obsolete devices on one hand or launching of immature industrial technologies on the other side. But not only industrial and transportation accidents are coming into question. The events from September 11, 2001 sparked dramatically terroristic actions aimed against civilian population. Public is now more aware of the potential threats from releases of chemical, biological and radiological materials initiated by deliberate actions with hostile intent. Terrorism spans its traditional methods to weapons of mass destruction. Anticipation and assessment of the dispersal of harmful agents will play decisive role in counter-terrorism preparedness and response.

World's worst ever-chemical disaster in Bhopal took place on December 3, 1984. A Union Carbide chemical plant's holding tank leaked out toxic gas which travelled along many residential streets. Around 500,000 people were exposed to the dangerous gas, and nearly 20,000 were killed. Around 120,000 people suffer the effects of that terrible accident and some have died today. Union Carbide denied allegations against the tragedy. The later investigations found the lack of effective warning systems and complete absence of community information and emergency procedures. The corporation believed that the accident was a result of sabotage, but finally the UC paid for the hazardous and deadly technology.

Accidents on nuclear facilities can lead to radioactivity release into the living environment. Radioactive releases preceding the Chernobyl disaster had consequences limited to the local scale. It comprises serious incidents at radioactive waste storage Kyshtym and plutonium separation plant Tomsk-7 (USSR, 1957) or fire at the Windscale nuclear reactor (1957). The worst reactor accident in United States history happened in the Three Mile Island NPP on March 29, 1979, when TMI-2 reactor suffered a partial fuel meltdown. The accident did not result in significant contamination and irradiation of people, but the incident was widely reported in press media and had far-reaching adverse effects on public opinion. Detrimental effect of nuclear weapons explosions came primarily from radiation during explosion and long term contamination was not so significant in global.

The world's worst nuclear power plant disaster, the Chernobyl accident, happened on April 26, 1986 and dominates the list of fatal reactor accidents. Due to flagrant gross operator negligence many mistakes during the unauthorized test were done. The test was prepared carelessly, a number of operating rules were broken and faults in reactor safety design were subsequently revealed. During criticality excursion the reactor power increased about 100 times in one second. This produced a steam explosion blowing the top off the reactor (the blast was not nuclear explosion). The core was explosively destroyed and the uncovered graphite started to burn intensively. Radioactive material was flung far into the atmosphere and lighter components were drifted by wind into nearby countries and parts of Europe.



Stochastic health effects after the Chernobyl accident

Figure 1: Increase in thyroid cancer in children (aged 0-18 years at the time of the Chernobil accident) in Belarus during the period 1986-2002 [1].

The initial causalities included 2 workers and more than thirty fire fighters who had been sent to fight with the burning inferno. Deterministic health effects inducing an acute radiation syndrome (acute radiation sickness) were confirmed for 134 patients. Beyond all dispute, the stochastic health effects in late stage of the accident are expected to be serious, as millions people in different countries were subjected to increased level of radiation exposures. There are many reports on an increase in the incidence of some diseases as a result of the disaster[1]. It could last several decades until the long term consequences become clear. In fact, according to present knowledge, the accident has given rise in the incidence of thyroid cancer in children[2] (see above Figure 1). WHO reports in 2005 about 50 deaths that are directly attributed to radiation from the disaster, and about 4000 cases of thyroid cancer were diagnosed, mainly in children and adolescent. At least nine children died, however the survival rate among the cancer victims has been estimated to 99 %. Acute radiation sickness, thyroid carcinoma and psychological consequences belong to the firmly established health consequences. As concerned other diseases, as yet the scientific community has not been able to relate those to the effect of ionising irradiation [3]. However, large research projects are launched for profound and continuous study of the unanswered issues of the health effects involving leukaemia, health of children irradiated before birth, genetic consequences and corporal defects.

Psychological consequences arise from an understandable fear of exposure of unknown dangerous agent, fear for exposed children, mistrust of reassurance from the authorities and fear and stress from forced evacuation from home and land. Some people can then suffer from psychological illness, others relieve the stress by increased consumption of alcohol and cigarettes. Dietary changes have to be introduced in order to avoid perceived contamination. As indirect consequences, some death from suicide, cirrhosis or lung cancer can be expected. Psychological consequences are absolutely real and their investigation deserves greater attention in emergency preparedness plans.

Learning lessons from disasters

The review of selected accidents, which resulted in severe consequences, shows that most of them could have been avoided. Lack of regulations, contempt for rules, human failures and insufficient training have been identified as a frequent initiating parameters. Faults in the inherent reactor design led to the weakening of intrinsic safety features[3]. During the evolution of the former accidents, the situation was usually worsened by inadequate emergency management because of possible information confusion and noise, unpreparedness, insufficient planning, unproved resources, and underestimation of psychosociological aspects. The responsible decision-making team has to be provided by the proper software support tool, which enables to estimate the true scale of the accident and to predict its consequences.

Correct public information should suppress a panic among citizens and put the record on current situation. The space should be delimited for "yellow journalism" with sensation-loving stories and dilettante pseudo-experts possessed by miscellaneous subjective visions. In some information resources the Chernobil disaster was either trivialised[4] or exaggerated[5]. The consequences were misinterpreted (intentionally or unqualifiedly). The rivals persist on their own attitudes, which can be verified only by time. Such an example we can read in [2], that "

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[1] Presumptions of the Commission of the European Communities after the visit of Ukraine in 1993 reported an increase of about 1% in incidence of all cancers over the normal life time in the contaminated regions.

[2] The doses of internal irradiation to the thyroid gland from ^{131}I intake with milk and green leafy vegetables were the most significant. It could comprise from 90-98% of the total dose to the thyroid.

[3] Unlike WWER reactors cooled and moderated by light water (NPPs EDU, ETE), the Chernobyl reactor RBMK was cooled by light water and moderated by graphite. As a consequence of this configuration, the RBMK reactor possesses a positive void coefficient inducing positive temperature coefficient of reactivity. With increased steam production in the cooling channels the absorption of neutrons decreases and power steeply increases.

[4] The article "Chernobyl – the Biggest BLUFF of the 20th Century" in the prominent Polish newsmagazine WPROST, no. 2, Jan. 2001.

[5] "Chernobyl death toll grossly underestimated" – a new Greenpeace report foretells quarter of a million cancer cases and nearly 100 000 fatal cancers.

... a large number of death of the recovery workers (known as liquidators) were reported by Reuters but these are due to natural causes. There were similar reports of farm animals born with deformities but this neglected the fact that the normal rate of congenital birth defects in some farm animals is nearly 10%.... “.

The accidents have to be timely and adequately reported. Deterrent situation happened in the same beginning of the Chernobil accident when despite the enormity of the radioactivity release no report was made about it until 2 days later when the Swedes detected a dramatic increase in wind-borne radiation. The need was recognized for improved operator training and setting the clear criteria for calling an emergency. The operators cannot be overloaded by too many tasks[6]. Frankly speaking, the lapses in quality assurance and maintenance, inadequate operator training, lack of communication of important safety information, poor management, and complacency are the main reasons of an accident initiation.

Despite suffering from horrible experience, evidently positive effect of rigorous assessment of nuclear and chemical safety and its ongoing improvement has been initiated.

Software tool for emergency management support

The activities are focused on the analysis and evaluation of safety risks, planning, organizing, implementing and monitoring rescue activities during the crisis situations. Effective management relies on thorough integration and cooperation of all government executive organs with aim to protect the civilian population, primarily in the events of natural and human-made disasters. In broad sense the effort is concentrated on phases of mitigation, preparedness, response and recovery[7]. In the following text we shall focus our considerations namely on development of software tool for decision support during nuclear emergency.

Prospective intervention actions have to be managed with regard to type of accidental release scenario and evolution of a failure at its all phases. Each phase is characterised by its own time scale, predominated irradiation pathways and specific countermeasures introduced for protection of persons. It is necessary to develop the software tool specifically for each accident phase, namely:

- **Pre-release phase:** Abnormal behaviour of some components was indicated, hazardous emission is threatened but has not yet happened. Simulation software is activated and necessary inputs are collected for dispersion calculations. Successive preliminary estimation of irradiation doses is periodically simulated. Time scale of pre-release phase can be several hours/days.
- **Release phase:** It covers interval of so called “plume phase” starting from the same beginning of release up to the moment when cloud leaves the observed area. Time scale of the release phase is several hours to a few days. The phase is the most important from view of fast response of urgent emergency actions. Evacuation or sheltering of inhabitants and iodine prophylaxis should come on force in the areas, where highest contamination is predicted. Due to complexity of the problem and uncertainties involved we could never succeed with as sophisticated as possible computer codes. The

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[6] For example during the Three Mile Island event, the mechanical failures were compounded by the initial failure of the plant and operators recognized the situation as loss of coolant accident. Due to inadequate training and ambiguous control room indicators, a series of incorrect operators’ actions occurred and finally they lost control of the reactor state. False messages went out on the local radio and together with discredited and untrue reports of infant death caused a great deal of mental stress of nearby population.

[7] In the period 1997 – 2005 the customization of the European system RODOS (Real-time On-line Decision Support system) for the Czech Republic was carried out and set of reports is available from archive.

solution insists in assimilation of both mathematical modelling and measuring in terrain. Consequently, the actual values of important random parameters can be estimated, as are the release source strength, dispersion parameters, dry and wet fallout of radioactivity on terrain or components of wind field. Our contribution in the field is development and application of advance statistical method of Bayesian filtration [4].

- **Latter phase of accident:** Sometimes is called as post-emergency phase and covers latter stages of accident consequence evolution until environmental radiation levels resume to acceptable levels. It may extend over a prolonged period of several weeks or many years. In light of the program support constructed for assessment of long term evolution of contamination on terrain, the assimilation techniques based on extended Kalman filters (EKF) come into question [5]. A priori estimation of the initial conditions for EKF recursion follows from the previous plume phase analysis.

Data assimilation – true way from model to realistic prediction

Recent trends in risk assessment methodology insist in transition from deterministic procedures to probabilistic approach which enables generate more informative probabilistic answers on assessment questions. Corresponding analysis should involve uncertainties due to stochastic character of input data, insufficient description of real physical processes by parametrization, incomplete knowledge of submodel parameters, uncertain release scenario, simplifications in computational procedure etc. Simulation of uncertainties propagation through the model brings data not only for the probabilistic assessment, but also for another main task of the analysis called data assimilation (DA) of the model predictions with real measurements incoming from terrain. The most advanced environmental software incorporates assimilation subsystem which brings together both model predictions and monitoring from terrain.

There are several important sources of information which can improve predictions of the system state. Basic physical knowledge is included in the prior background fields (e.g. time and space evolution of radioactivity concentration in the air, activity deposited on the ground etc.) predicted by the model. Assumptions related to the random characteristics of the model inputs or assessment criteria can be supported by some kind of expert judgements. Substantial benefit can result from accessibility of data incoming from terrain. Each such resource can be known on a certain degree of details (e.g. a level of sophistication of the environmental model, dense or rare measurements in space and time, cases with indirect observations, complete or only partial knowledge of model error covariance structure). Merging of all these contending resources for purposes of improvement of predictions is a principle of assimilation and had shown to be very promising in many branches of contemporary Earth sciences.

Our experience and results in the field have confirmed a common opinion that combination of modelling and monitoring in the late stage of an accident [5] is less difficult than in the early phase [4]. In the early phase, relatively few observations from terrain are available and model predictions are thus burdened with large uncertainties. Quickly changing situation can be assessed so far under substantial simplifications. In the late phase the monitoring becomes more and more important and radiological situation changes at much longer timescales.

Development and application of advanced statistical methods have been accomplished in the institute ÚTIA AV ČR within the grant project supported by GAČR (2007-2009) with aim to improve the reliability of the model predictions on basis of assimilation with measured data incoming from terrain. Specifically, the processing of online radiation measurements from the Early Warning radiation Network of the Czech Republic (administrated in SÚRO) is tested in close cooperation with SÚRO in Prague. Demonstration of our own contribution to DA methodology based on the particle filtering (PF) follows.

Illustration of application of advanced statistical DA technique of Bayesian filtering in the early stage of a hypothetical accident

Experience and knowledge accumulated in the Institute of Information Theory and Automation in the field of Bayesian filtering are further developed. The particle filtering (PF) came into question because of its significant attribute which meets our SGPM trajectory model: The state trajectories (particles) remains unchanged during the data (observations) update step and only their weights are updated. Thus, the history of each path is not lost and the next time update is straightforward. The PF originating from the sequential Monte Carlo method is applied here for simulation of the posterior distribution of the system state. The 3-D trajectories represent the "particles" and during the resampling, those particles having small weights with regard to the measurements are eliminated.

The robustness of the PF method outlined above is illustrated for case of a certain circumstance when in the same beginning of an accident the decision maker is not provided by fully clear and unambiguous information. Experience from former radiation accidents pointed out the side effects leading to an information shock with possible temporal paralysis of communication lines. In this sense we have adjusted a hypothetical accident scenario. Real meteorological situation from March 31, 2009 is taken into consideration and the moment of hypothetical radioactivity release is set to 10.00 UTC. Available real meteorological observations measured at the point of nuclear power plant (NPP) and short term meteorological forecast are somewhat inconsistent (see Table 1).

Table 1: A hypothetical accidental release scenario of ^{131}I . Short-term meteorological forecast and real meteorological measurements (in brackets) for "point" of NPP Temelin (49°10'48.53"N × 14°22'30.93"E), time stamp 20090331-1000 UTC.

UTC hour	10.00	11.00	12.00	13.00	....
activity release of ^{131}I Bq/h	5.68 × e+14	7.92 × e+14	0	0	....
wind direction $^{1),2)}$	95.0 (69.0)	101.0 (65.0)	84.0 (80.0)	80.0 (64.0)	....
wind speed$^{(1)}$	2.0 (3.0)	2.1 (3.3)	1.9 (3.8)	2.2 (4.0)	....
Pasquill class of atm. stabil.	A	A	B	B	....

$^{1)}$ *... at 10 m heigh;* $^{2)}$ *... blowing "from" (degrees measured clockwise from North)*

Following ex post analysis can give a retrospective view on such atypical situations (their occurrence rate is surprisingly not negligible). The evolution of emergency situation from the same beginning of accident is usually so far varied and complicated that specific ad hoc solutions have to be introduced.

Let empathize the initial decision-maker situation. He is responsible for generation of as reliable as possible prediction of time and space evolution of the contamination. According to these prognoses the urgent emergency actions have to be planned and launched in the most impacted areas. He has not much time for decision actions, the toxic plume will reach the borders of our republic during a few tens of hours or less. The first reasonable predictions in regional or national scale should be available as soon as possible. Unfortunately, the accidental release scenario is burdened with large uncertainties (release source term, initial plume buoyancy, variability of geographic characteristics etc.). Moreover, for the time of release fixed to March 31, 2009 at 10.00 UTC, the short-term meteorological forecast is somewhat different as compared to the meteorological measurement (see Table 1).

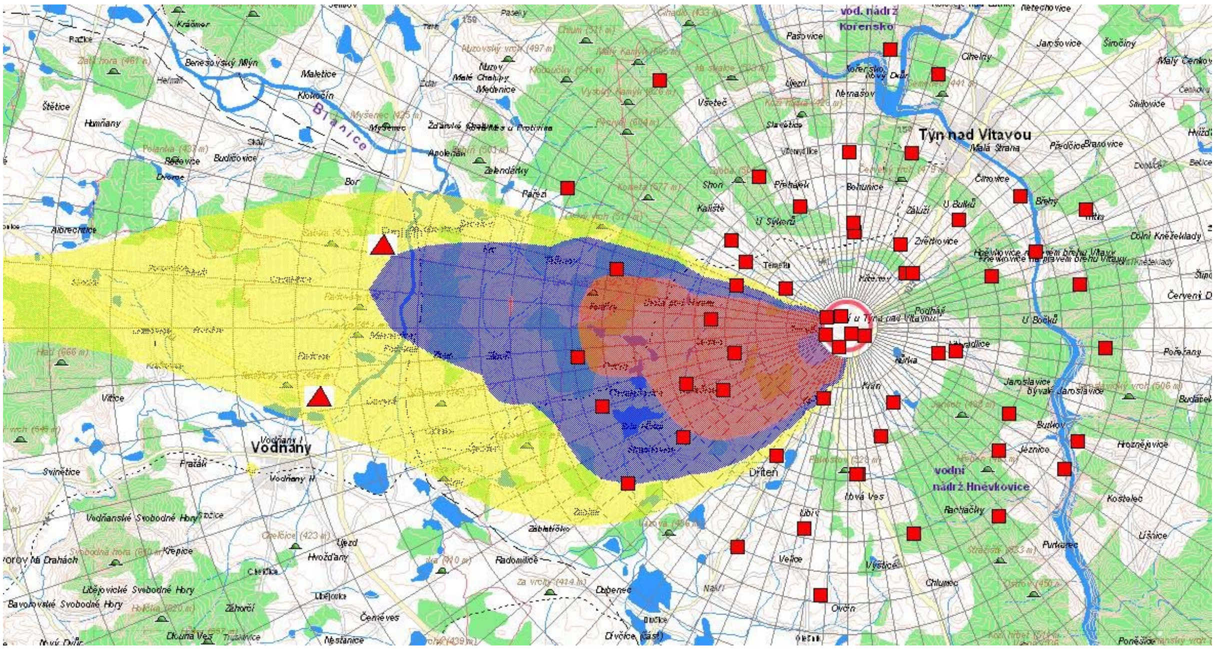

Figure 2: Prediction of ^{131}I contamination on terrain just after three hours from the release start. Short-term meteorological forecast from Table 1 is used. Red squares are real positions of the Czech Radiation Monitoring Network measurement stations (TDS sensor on fence of NPP areal, II. circuit stations). Two red triangles: random placements of 2 potential mobile stations.

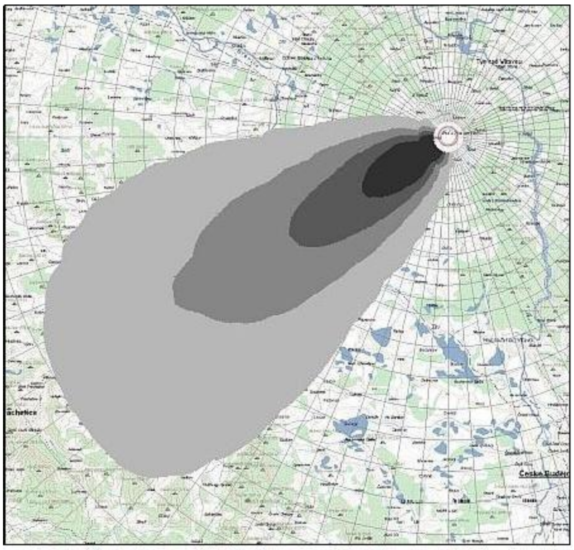

Figure. 3: Expectations of the posterior probability density function of the ^{131}I activity deposition, just 2 hours after the release start, when the first set of incoming measurements were assimilated with prior model predictions.

In this situation we should respect the fact that if something happens, the shape of the corresponding accidental trajectory very close to the source should correspond more likely with the measurements (values in brackets in Table 1) than to the simple deterministic predictions according to the Figure 1 when short-term meteorological forecast was used. The forecast is generated for the grid 9 × 9 km and sometimes needn't to catch the local changes properly.

For solution of this troublesome situation we have proposed the DA routine of recursive Bayesian tracking [4]. In the first step (time update) the prior field of the values of interest (in our case it is the deposited activity on terrain) is estimated. Just after the set of measurements comes out from terrain, the assimilation of the measurements with prior estimation is done. This second step is called data update and the posterior probability density is estimated numerically using a sequential Monte Carlo method of particle filtering. The numerical experiment from Figure 3 is conducted as a twin experiment, where the measurements are simulated via a twin model and perturbed. Specifically, the "artificial" measurements are generated just in the positions of the Czech Early Warning Network (see Figure 2) according to "measurement" trajectory. This 3-D trajectory is calculated by the same environmental model (deterministic version of our HARP code) using the real meteorological measurements at the point of NPP (see Table 1 – values in brackets).

Even on the basis of the previous fleeting glance (more detailed analysis e.g. in [4]) we can point out the significant role of the assimilation techniques when initial incomplete and ambiguous release scenario burdened with substantial uncertainties had to be analysed. The mathematical model predicts the development of contamination approximately according to the Figure 2. Taking into account the artificial measurements, the prediction is distinctly modified (see Figure 3). A tendency to lean to either model predictions or measurements are mapping by selection of covariance matrix of model and measurements errors. The case from Figure 3 stands for test with small measurement errors (low covariance matrix of measurement errors) when assimilated surface is strongly leaned towards measurements.

Conclusion

DA procedure described above ensures improved predictions of spatio-temporal distribution of the quantity of interest (here radioactivity of ^{131}I deposited on the ground). At the same time, the outstanding feature of the technique is joint estimation of uncertainties of the main random parameters of the dispersion model (wind field vector, radioactivity release strength, wet and dry deposition, dispersion parameters). From this point of view, the results from Figure 3 can be interpreted alternatively as a certain example of a probabilistic assessment approach.

Even the analysed task represents only tiny part of the overall emergency problem, we believe, that an extension of the presented Bayesian methodology in the recursive time steps can contribute to the improvement of consequences predictions up to medium distances. It will provide a proper basis for introduction of effective countermeasures on population protection. Many problems remain unresolved and more cooperation of modellers with measurement teams is inevitable. Presented software tool should be carefully tested without respect to our expectations, that we shall never keep at our disposal the measurements from a real accident and that all consideration will remain only on a hypothetical level of “artificially simulated” observations.

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