Uncertainty Handling during Nuclear Accidents

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ABSTRACT

In the years following Chernobyl, many reports and projects reflected on how to improve emergency management processes in dealing with an accidental offsite release of radiation at a nuclear facility. A common observation was the need to address the inevitable uncertainties. Various suggestions were made and some of these were researched in some depth. The Fukushima Daiichi Disaster has led to further reflections. However, many of the uncertainties inherent in responding to a threatened or actual release remain unaddressed in the analyses and model runs that are conducted to support the emergency managers in their decision making. They are often left to factor in allowances for the uncertainty through informal discussion and unsupported judgement, and the full range of sources of uncertainty may not be addressed. In this paper, we summarise the issues and report on a project which has investigated the handling of uncertainty in the UK's national crisis cell. We suggest the R&D programmes needed to provide emergency managers with better guidance on uncertainty and how it may affect the consequences of taking different countermeasures.

Keywords

Deep uncertainty, displaying spatial uncertainty, nuclear emergency management, scenario-focused analysis.

INTRODUCTION

Emergencies inevitably involve significant uncertainties, and threatened or actual offsite releases of radiation from nuclear facilities are no exceptions. In the initial threat or early release phase the source term, its strength, time profile and composition are hugely uncertain. How the released radionuclides will be transported by winds and washed out by rain depends on the current weather and that too can be very uncertain. The uncertainty on weather and uncertainty on release content and duration also need to be treated in combination in consideration of the range of possible outcomes as they are not independent. Thus in deciding between countermeasures such as advising on the uptake of stable iodine, sheltering and evacuation, emergency managers need to be aware of and take account of these uncertainties. This has long been realised and was given some prominence in the post-Chernobyl period during which emergency management processes were reviewed and revised, a number of decision support systems were designed (French 1997, 1997, French et al. 1998). Theoretical frameworks were developed which used probability to represent the uncertainties and updated these as data became available through the use of Bayesian statistics (Caminada et al. 2000), but to date these have not been fully implemented in many systems such as RODOS (Raskob et al. 2010) and ARGOS (Hoe et al. 2002). Some of the reasons for this relate to the computational tractability of the methods and the timely availability of data; but the major obstacle is that some of the uncertainties are *deep*. Deep uncertainty may be defined in many ways (French 2015). Our view is that an uncertainty is deep when the range of plausible probabilities that one might use in an analysis is so large that few issues can be resolved by a simple quantitative analysis and that the decision making will also need to be based on judgements relating to the significance of the uncertainties. But this is not to say that the judgemental processes cannot and should not be supported by relevant quantitative analyses. To leave the process to informal discussion and intuition is to risk unsound, biased and ill-considered choices (French et al. 2009, Argyris and French 2016).

Twenty five years on from the Chernobyl Accident, the Fukushima Daiichi Disaster in 2011 has given impetus to further consideration of nuclear emergency management processes. We believe that we can no longer avoid formal approaches to the consideration of uncertainty though, as we shall argue, these may not be fully quantitative. They will, however, need to challenge and catalyse the thinking of the emergency managers so that they consider fully the possibilities given the range of the uncertainties. We shall look to the developing field of scenario-focused decision analysis to provide the structures for this. Several authors have already noted the potential of this approach to structure analyses for nuclear emergency management (Carter and French 2003, Haywood 2010, Comes et al. 2013, Comes et al. 2015).

Below we report on an exercise-based project in the UK designed to investigate the handling of uncertainty, particularly *spatial* or *geographical* uncertainty. Its results emphasise further the need for better approaches conveying the inherent uncertainties to decision makers and, indeed, scientific experts from different domains in the early stages of a radiation accident. In the next section, we describe the sources of uncertainty that arise in the threat and release phases of an accident. We then briefly describe the exercises which investigated current approaches. Reflecting on the results, we develop a scenario-focused approach to presenting the uncertainty. We also reflect on the limits of quantification, and hence modelling and simulation, during the early phase. We close with a discussion of future directions for research. Fuller details of our work may be found in French et al. (2016).

UNCERTAINTIES ABOUT THE SPREAD OF CONTAMINATION AND ITS IMPACTS

Here we limit ourselves to atmospheric transportation of radioactive contamination. Hydrological transport is also important, as the Fukushima Disaster showed, and adds to the complexity of the issues that we are addressing, but for this paper we ignore those. There are many factors contributing to the uncertainty in the predictions of the atmospheric dispersion of the radionuclides (French 2002, Haywood et al. 2010, Havskov Sørensen et al. 2014). Figure 1 and Figure 2 indicate some of these and how they influence the final uncertainty in the plume and the ultimate health impacts. Note that these figures simply represent how uncertainties and errors enter the modelling and then propagate through the modelling chain. They are conceptual and should not be read in a chronological manner from left to right. The modelling itself is iterative and complexly so. For example: there are the temporal iterations necessary to make predictions of the effects at a sequence of times to show their spread; there are computational iterations needed to 'solve' the mathematics; and there are iterations in the Monte Carlo simulations used in some of the modules along the model chain.

Imagine then that a reactor has 'tripped' in the sense that 'warning lights are flashing' and it is not working normally. In this situation, a release may be possible or may have already begun.

Uncertainties about factors that affect the physical process of atmospheric dispersion and deposition

- Will the aberrant conditions in the reactor lead to an off-site release? Or will the reactor be brought back under control?
- If there is a release, will it be into a sound containment building from which the gaseous radionuclides can be vented in a controlled way and particulate radionuclides filtered out of any release?
- If the release is uncontrolled, when will it occur?
- What will be the composition of the release in terms of radionuclides?
- How big will the release be?
- What will be the time profile of the release, including variation in its composition?
- What is the energy of the source term and its effective release height? If there is substantial wind shear, this will affect the direction that the plume takes.
- What will be the weather conditions at the time of the release and during the passage of the plume?
- What monitoring data do we have both on-site and off-site and how accurate are these?
- How much of the particulate release will be deposited at each stage of the passage of the plume? This will be affected by the ground topography and surface roughness and increased by any precipitation.

Uncertainties about factors that relate to the modelling used to forecast dispersion, deposition and consequent impacts

- What models are used to predict the source term? What are the assumptions underlying these?
- What atmospheric dispersion and deposition models are to be used? What are the assumptions

underlying these?

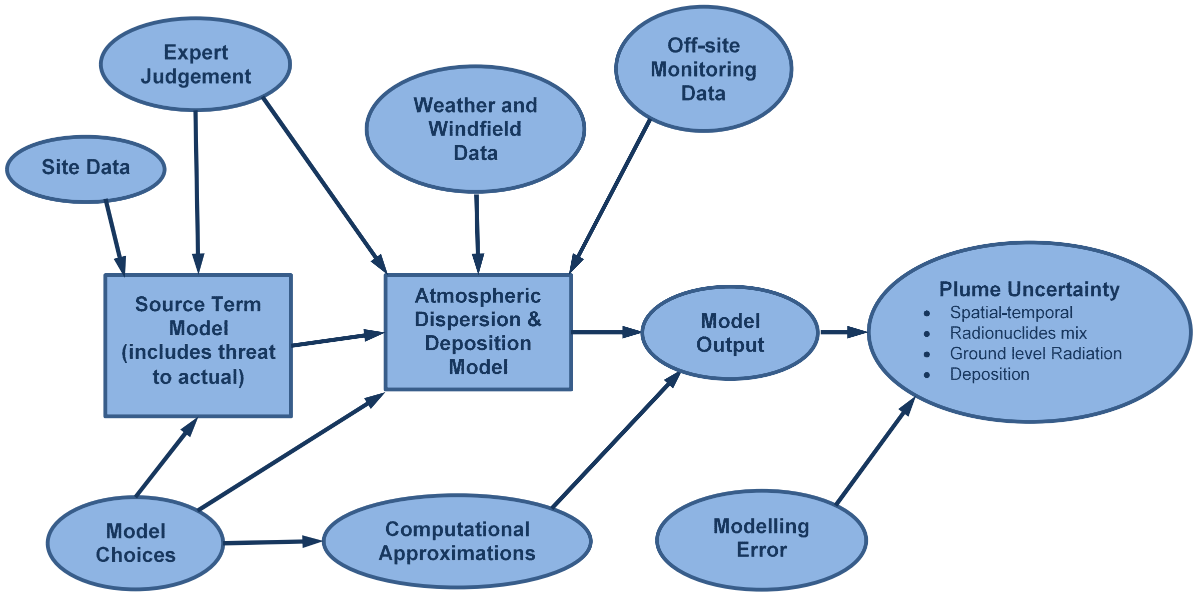

Figure 1: Factors contributing to the uncertainty in the spread of atmospheric dispersion

- What statistical analysis is used to assimilate monitoring data into the models?
- Where is expert judgement used to set model parameters or similar? How uncertain are these judgements? How well calibrated are the experts?
- What numerical methods are used to approximate the solution of the dispersion and deposition models?
- How good is our GIS data in terms of topography, geology, land use, agricultural production, position of dwellings and local populations?
- What models are used to assess potential agricultural impacts and the potential need for immediate food bans?
- How good is our knowledge of the demography, diet and behaviour in the areas potentially affected?
- What assumptions and models are used to predict any health effects?

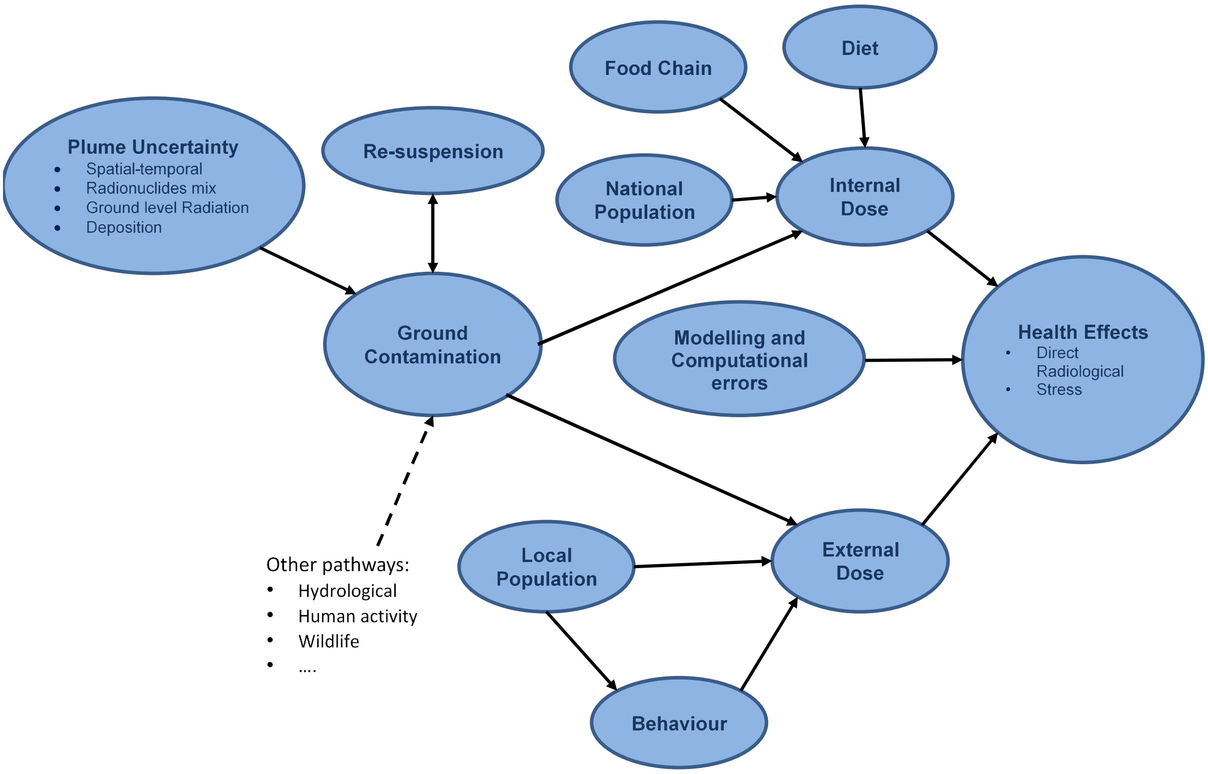

Figure 2: Factors contributing to the uncertainty in the predictions of dose and human health effects

- If several models are used in parallel to predict broadly the same effects, how are any conflicts between their predictions resolved?
- If we could calculate perfectly and had perfect data, how accurate would the models be in predicting the impacts in this situation?

In the first hours, the uncertainty in modelling public health impact assessments is generally dominated by source term uncertainties such as the release height, timing and scale and, secondly, to meteorological uncertainties, particularly the arrival of any front and precipitation patterns (Haywood et al. 2010).

The modelling of the processes that lead to health and other impacts involves much simplistic averaging across many sub-groups. Moreover, the *linear hypothesis*, which is used to estimate the health risk to populations exposed to very low levels of radiation over long time periods, is precisely what its name suggests: a hypothesis justified by linear extrapolation from observed effects at much higher doses (Argyris and French 2016, Blandford and Sagan 2016). When combined with many conservative assumptions on the average exposure of members of the population, the linear hypothesis may lead to overestimation of the public dose.

Quantifying all of these uncertainties coherently without time constraints would be a challenge. Given the urgency in the early phase of a radiation accident and given that some uncertainties, particularly those relating to the source term, are deep, the challenge is enormous.

Note also that the decision makers are interested in what action to take *where* and *when*. So many uncertainties that are of concern to them have spatial-temporal aspects and these are particularly difficult to communicate (French et al. 2016)

THE ADMLC PROJECT AND CURRENT UK PRACTICE

The work reported here was part of a project funded by the UK Atmospheric Dispersion Liaison Committee (ADMLC). The project's focus was on how information would be presented to the scientific advisors to the UK's national crisis response group. It did not consider the many similar issues which arise in the co-ordination of the local response. The project involved a range of activities, including a substantial literature review; however, its key elements related to three workshops, all using hypothetical scenarios to focus their discussions and illustrate the many uncertainties that arise in responding to a radiation accident. During each workshop an accident scenario was presented, stepping through the first few hours and explaining what would be known at each time, what would not be known, what seemed most likely to happen, and what the radiological and health impacts might be. The first workshop sought to understand the current processes of information presentation and discussion. It involved members of Government departments and agencies, who might well be involved in advising on the handling of an actual radiological emergency. Discussion focused on how to advise senior ministers and officials on the significance of the uncertainties involved in predicting the course of the plume, the impact of this on health and the likely need to prepare resources to support recovery. Building on this experience, the project developed proposals for presenting information on the potential geographical spread and impact of a radiation plume. The second workshop involved many world experts on the presentation of scientific and expert advice in high risk contexts, and aimed to challenge and criticise these proposals. The third workshop had similar attendance to the first, but this time focusing on the presentation of information using plots, graphs, and other display techniques proposed by the project to convey the uncertainty, and then to reflect on how useful the different approaches were.

At present, no or very few uncertainties are quantified in the information that the agencies, responders and plant operators provide to the advisors or emergency managers. In the discussion at the first workshop we observed that the group focused on a *reasonable worst case* (RWC). It is not an easy concept to define. Essentially, the idea is to think about how bad things might get so that appropriate resources can be put in place, which is why consideration of RWC is common in emergency planning. In that context it is defined as being designed to exclude theoretically possible scenarios which have so little probability of occurring that planning for them would lead to a disproportionate use of resources. The concept has been taken over from emergency planning into emergency response without apparent recognition that the contexts of these two activities is significantly different. The former considers the possibility, remote or otherwise, of some disaster. The latter relates to something that has most definitely happened. It is far from clear that emergency response should focus almost entirely on a single reasonable worst case. There may be many different negative impacts (health, agricultural, economic, etc.) that could arise and some may not be visible in a single RWC. Moreover, while it sounds sensible to prepare for the reasonable worst, it is important to realise that an actual event may not evolve into such a negative extreme. Framing issues so negatively has long be recognised in psychological studies as increasing risk taking in decision making (Kuhberger 1998, French et al. 2016): not a characteristic one might wish to encourage in emergency management. Also the advice and assessments to be presented to the emergency management team is sought to support decision making. It is not clear that describing a reasonable worst case is the most helpful form of information for this. The focus of a reasonable worst case is simply on what might happen. It does not offer an analysis of what might happen were different actions taken.

A way to avoid focusing on a single reasonable worst case may be to build on the ideas of scenario analysis and offer crisis managers several potential scenarios. Scenario analysis is used throughout business and government to develop strategic thinking (Schoemaker 1995, van der Heijden 1996). More closely to our context, it is used in volcanic emergency response. Currently there is a growing interest in using scenarios to tackle problems with deep uncertainty (French 2015). The most basic forms of scenario analysis develop a series of maybe 4 or 5 scenarios that are 'interesting' in some sense and may be used as backdrops for strategic conversations. How ‘interesting’ is defined is moot, with many possibilities. Perhaps:

- reasonable best and worst cases of some form – useful for bounding possibilities;
- a likely case – useful for maintaining a balanced perspective;
- an assumption that a particular event happens or does not – useful if a significant event such as structural damage to a containment building is unpredictable and shrouded in deep uncertainty.

Following on our remarks that there may be no single reasonable worst case which illustrates all potential negative impacts, this might be extended to cover two or three reasonable worst cases. Note that only a handful of scenarios are developed. Part of this is because in qualitative scenario analysis, each scenario is carefully explored and there is not time to do more; certainly not within the context of emergency management. But there is also the issue of cognitive capacity in that decision makers often cannot absorb and balance out the implications of many scenarios (Miller 1956).

In the scenario analyses undertaken within strategic management, the scenarios are developed in discussion between the decision makers and their advisors. In the context of emergency management this would be too time consuming. The scenarios need to be developed by the ‘backroom analysts’ and presented to the emergency management team. We suggest that the scenarios might be developed by focusing on the key uncertainties (Schoemaker 1993, Mahmoud et al. 2009). In our case, the key uncertainties relate to:

- the source term including release profile, release composition, and release height;
- weather including windfield, precipitation, and the arrival of any sudden changes such as that caused by a front.

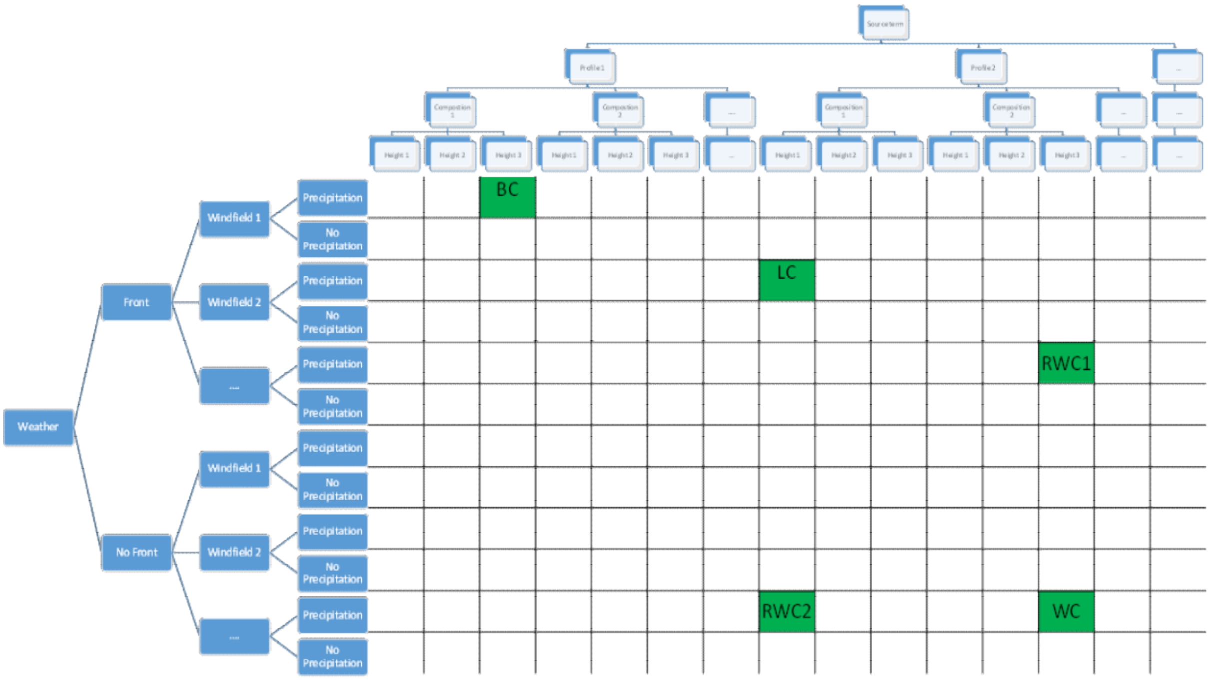

Figure 3: Generating scenarios to consider during a radiation accident
BC – best case; LC – likely case; RWC – reasonable worst case; WC – worst case

The first step is to discretise the possibilities: see Figure 3. The tree on the left suggests how different possible weather systems might be generated: will or will not a front arrive; how might the windfield evolve; will or will it not rain? Obviously, one might consider not whether a front will arrive, but at what time it will arrive, generating more than two possibilities. Other eventualities may be split into more or less possibilities. What matters is that developing such a tree helps set up a set of different weather systems that are candidates for consideration in the analysis. Similarly, the possibilities for the source term (the tree at the top of the figure) are partitioned according to its time profile, its composition and its effective release height. However, we do emphasise that this is indicative at least conceptually of how the various possibilities might be developed. The leaf nodes of the weather and source term trees label the rows and columns. Each element in the table defines a scenario. Even with the simplest set of possibilities on the components of the source term and weather, there would be too many scenarios to generate, much less discuss with the advisors and emergency managers. Thus we suggest that judgement is used to select 4 or 5 scenarios which span the range of possibilities to help those making the decisions appreciate the range of possible impacts. But note that these 4 or 5 scenarios are not meant to form a partition of the future. Figure 3 contains many unsampled possibilities. Thus the scenarios cannot be connected by a decision tree or similar model.

That the presentation of each scenario would include maps or sequences of maps showing the evolution of events under the assumptions implicit in its definition. Figure 4 gives an example of dose bands integrated over 2 days. Note that much simulation and modelling are used to develop each scenario. Indeed, uncertainty calculations may be made within a scenario, e.g. in generating meteorological ensembles. Our approach quantifies *within* scenarios, but leaves comparisons *between* scenarios unquantified (Stewart et al, 2013, French, 2015). Since the assignment of probabilities given the paucity of data and the urgency, the key idea in presenting several scenarios is to stretch the emergency management team's thinking and make them consider a wide range of possibilities. It should also encourage them to recognise variation and that impacts will differ in reality from the models, leading to greater flexibility in their response. We also note that presenting scenarios via maps as in Figure 4, helps in appreciating some of the spatial temporal uncertainty.

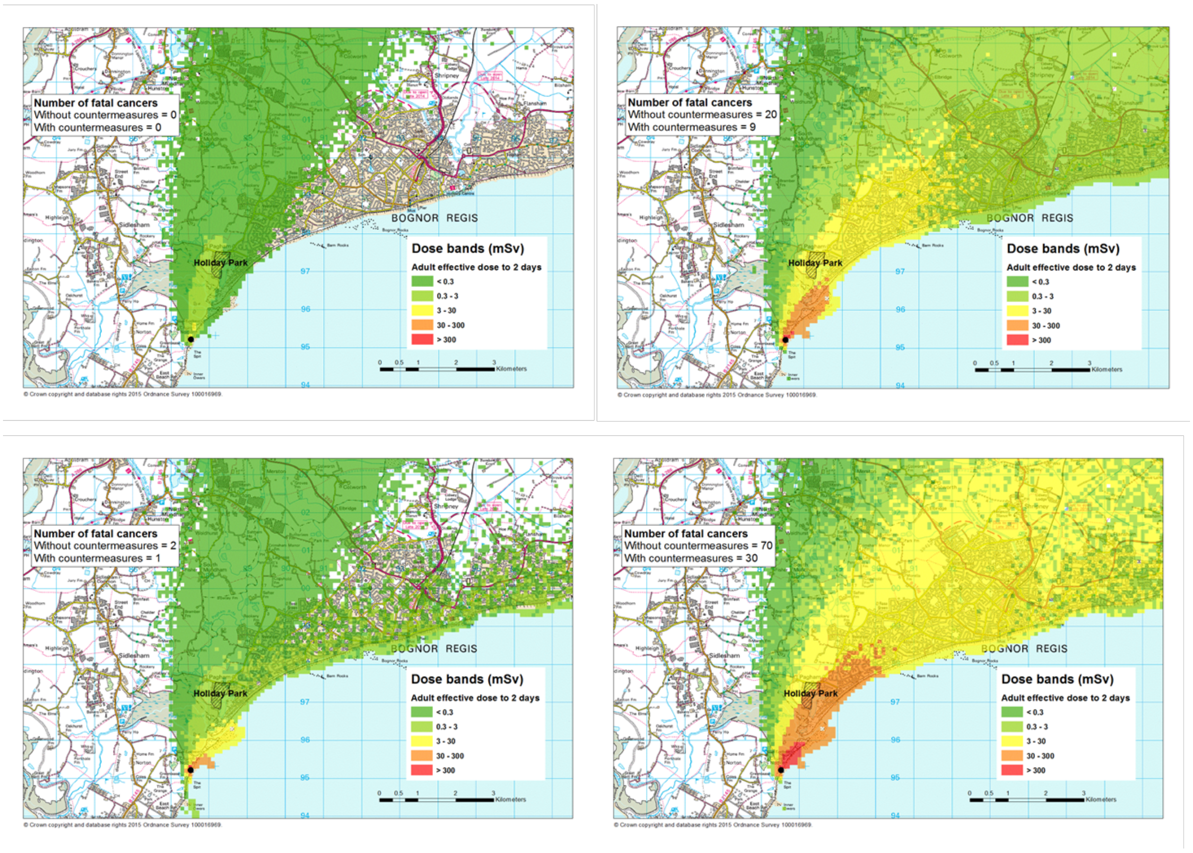

Figure 4: Plots of dose bands from four scenarios used in the exercise
Note 1: These are entirely hypothetical scenarios based on a hypothetical site.
Note 2: The plots are not probability distributions, but rather are predicted dose given the different scenarios' assumptions on source term and meteorology.

The project discussed this proposal at the second of its workshops and then ran an exercise in the third workshop with the same range of participants from across government and its agencies as the first. We created a hypothetical accident in which there was a possibility that a small early release might be capped, but if not it could develop into a second very significant release. The meteorology included the arrival of a front with an associated change of wind direction which could take the plume out to sea, so the timing of any second release was important, but very uncertain. If it went over land, the plume could reach a sizeable town and also would have considerable agricultural impact with extensive food bans. Our team developed several scenarios with different combinations of source terms, release times and meteorology. Recognising that only a handful could be presented to the emergency managers in a reasonable time, we selected four to present at the exercise, which spanned the possibilities.

The exercise was not an unqualified success. Presenting the scenarios did open up the discussion, but the participants relatively quickly chose one as a RWC and concentrated on that. Moreover they really only considered immediate health concerns and ignored, for example, potential agricultural issues. They did discuss uncertainty more than in the first workshop, considering the probability of a significant second release. However, there was a confusion between the unconditional probability of a very significant second release and its conditional probability *if* a second release occurred, the former being much smaller than the latter. This meant that their discussion was based on much higher chance of serious impacts than the evidence presented to them was meant to suggest. This observation emphasises that experts are as prone to error as anyone else (Kahneman and Klein, 2009; French et al, 2016), and that procedures to ensure continual challenge and hence reflection and checking of their thinking should be adopted in their discussions.

DISCUSSION AND NEXT STEPS

The lack of full discussion of the range of scenarios in the context of this exercise is disappointing, but has not discouraged us. We are, if ever, more convinced of the need to develop current emergency management practices to recognise the issue of uncertainty explicitly in their deliberations and decision making. We ran a fourth exercise followed by a discussion with scientists and researchers attending *Radiation Protection Week* held in Oxford in September 2016. They too agreed with our conclusion that too little attention is paid to uncertainty in current practices and this needs to be addressed.

There are simple things we might do that could make emergency management teams consider more carefully a range of scenarios. Most simply we could have prepared tabulations and graphical displays that compared the different potential impacts of the scenarios. Our presentations stepped through the four scenarios a little too separately and might well have compared across them rather more. Another tactic would be to develop key points for a press release. In previous work (Bennett et al. 1999, Bennett et al. 2010), it was noted that focusing on what to tell the public would widen the discussion so that the public were prepared for different possibilities, while still reassuring them that the authorities were taking appropriate steps to mitigate the potential outcomes. In this context, we would be concerned that the focus on immediate health issues could lead to ministerial statements which ignored other significant issues such as potential food bans and agricultural impacts. Failing to forewarn the public about the potential scale of these could lead, if they were needed, to subsequent increases in stress levels with the concomitant health impacts that have been found after Chernobyl and Fukushima (Havenaar et al. 2003, IAEA 2006, 2015). Thus we would consider catalysing wider discussion in a future exercise by asking for ‘bullet-points for a press release’.

A more significant development would be to bring an explicit discussion of probabilities into the process. But this is non-trivial. Firstly, as we have noted some aspects of the accident may be deeply uncertain; secondly, even when the deep uncertainties have been resolved – or sidestepped by fixing deeply uncertain entities within a scenario – there may be insufficient data or computational time to conduct an adequate probabilistic analysis. Nonetheless, after the first few hours as the cause and likely progress of the release becomes clearer, it may be possible to use expert judgement to assess rough probabilities. Even if this is not possible in a real accident, exploring such ideas in training exercises may help emergency managers develop an awareness of the value in deliberating on the uncertainties and the full implications of *not* considering these.

So consider Figure 3 further. Note that the five scenarios clearly only allocate a small fraction of the probability mass: i.e. it is much more probable that something else will happen. If probabilities are to be used sensibly we need to look at all possible scenarios. What we might do is ask the advisors with suitable expertise to assign rough probabilities to broad events whose outcomes are similar to the five modelled scenarios. By ‘outcome’, we mean the health, agricultural and other consequences that arise from the contamination. By ‘similar to’ we mean the overall impact of these consequences is roughly the same. Thus we might ask the advisors to discuss the likelihood of four events (see Figure 5):

- *Event 1*: the outcome is broadly similar to that shown in the BC scenario, though the details including the precise geographical area affected may be different (shaded yellow).
- *Event 2*: the outcome is broadly similar to that shown in the LC scenario, though the details including the precise geographical area affected may be different (shaded green).
- *Event 3*: the outcome is broadly similar to those shown in the RWC1 and RWC2 scenarios, though the details including the precise geographical area affected may be different (shaded blue).
- *Event 4*: the outcome is broadly similar to that shown in the WC scenario, though the details including the precise geographical area affected may be different (shaded red).

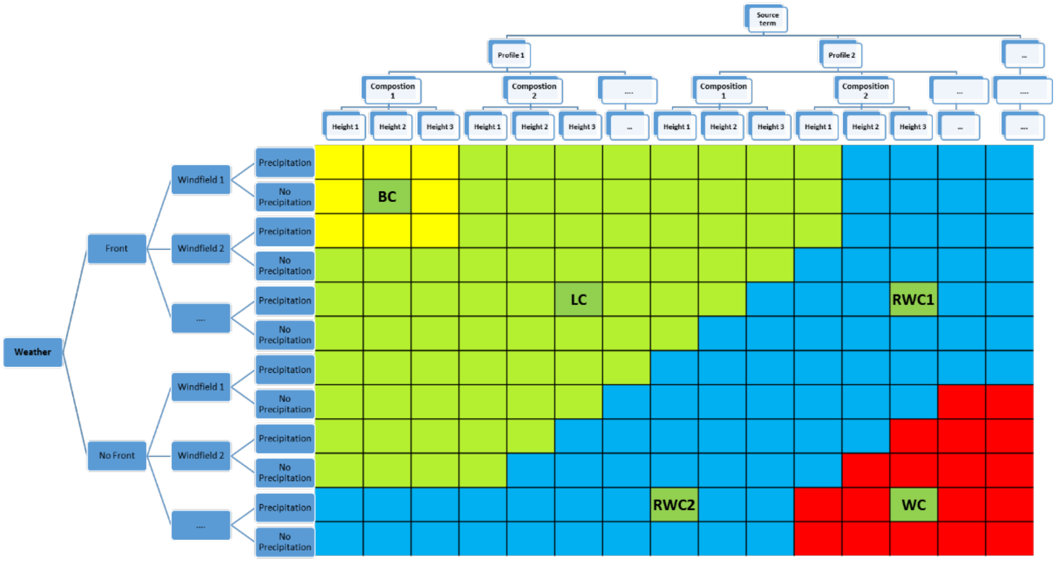

Figure 5: Possible way of reintroducing probabilities into the analysis

In simpler terms, in deliberating on the possible decisions to be taken we would ask the advisors to summarise the uncertainty in the form:

> "At the moment our informed judgement is that there is a probability of a% that the outcome could be as good or better than BC, a probability of b% that the outcome will be comparable with LC, a probability of c% that it could get as bad as RWC1 and RWC1 or something similar, and a probability of d% that it would get as bad as WC."

Clearly $a+b+c+d = 1$ in this case; and by the time that deep uncertainties have become resolved, one would expect ($c+d$) to be very much less than ($a+b$).

We hope to explore these ideas in future exercises. To be honest, we wonder whether the description of events 1 to 4 are too complex for experts to comprehend and thus assess probabilities, however approximately. However, we are convinced that more attention need be paid to the inherent uncertainties and to all the potential impacts in the early phase and that emergency managers need to be sensitized to such issues.

ACKNOWLEDGEMENTS

Our recent work has been funded by the UK Engineering and Physical Sciences Research Council under grant reference number EP/K007580/1 and by the UK Atmospheric Dispersion Modelling Liaison Committee, as well as by the organisations in which we work. Before that we have worked on many UK and European research and development projects relating to crisis management. We have had many useful discussions with colleagues on these projects and more generally across the community of emergency managers. We are grateful to all for their thoughts and input. However, we would emphasise that the views expressed here are ours and are not necessarily held by any of our funders or colleagues.

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