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Predicting the cost of the consequences of a large nuclear accident in the UK

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ABSTRACT

Nuclear accidents have the potential to lead to significant off-site effects that require actions to minimise the radiological impacts on people. Such countermeasures may include sheltering, evacuation, restrictions on the sale of locally-grown food, and long-term relocation of the population amongst others. Countries with nuclear facilities draw up emergency preparedness plans, and put in place such provisions as distributing instructions and iodine prophylaxis to the local population. Their plans are applied in simulated exercises on a regular basis. The costs associated with emergency preparedness and the safety provisions to reduce the likelihood of an accident, and/or mitigate the consequences, are justified on the basis of the health risks and accident costs averted. There is, of course, only limited actual experience to indicate the likely costs so that much of the costing of accidents is based on calculations. This paper reviews the methodologies used, in particular the approach that has been developed in the UK, to appraise the costs of a hypothetical nuclear accident. Results of analysing a hypothetical nuclear accident at a fictitious reactor site within the United Kingdom are discussed in relation to the accidents at Three Mile Island 2, Chernobyl and Fukushima Dai-ichi.

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1. Introduction

The accident at Fukushima Dai-ichi on March 11 2011 has once again brought to the foreground the potential costs of large nuclear accidents. As of January 30 2015, TEPCO has paid out ¥4.64 trillion (US$38.9 billion) in compensation (TEPCO, 2015) and recent estimates suggest that decontamination and renovation of the affected areas will total ¥7.81 trillion (US$65.9 billion) (The Reconstruction Agency, 2015). This compares with the smaller accident at Three Mile Island 2, where US$71 million was paid in compensation with additional clean-up costs totalling US$975 million (Strawon, 2013), and the larger accident at Chernobyl where losses have been estimated in the region of hundreds of billions of dollars (IAEA, 2002).

Multi-billion dollar accidents away from the nuclear sector are, of course, not unknown. For example, the 2010 accident at BP’s Macondo well in the Gulf of Mexico caused 11 immediate fatalities and the resulting pollution incident is expected to cost the company ~US$55 billion on current estimates (Heffron et al., 2015 and references therein). Moreover it is worth bearing in mind, for comparison purposes, that the Great East Japan Earthquake killed over 19,000 people and its cost, excluding nuclear damage, has so far totalled ¥25.6 trillion (US$215 billion) (Ministry of Finance Japan, 2015). Nevertheless, the high cost of a large-scale nuclear accident

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1 It is noted that these costs have not been adjusted to present-day monetary values.
raises the question of the adequacy of current nuclear liability regimes and whether these can provide sufficient recompense for the people and businesses affected (Heffron et al., 2016). The research presented here examines the cost of a severe nuclear reactor accident, which is assumed to take place at a hypothetical site in southern England.

Methods have been established that, when coupled to a probabilistic safety assessment (PSA), can provide an insight into the cost of a nuclear accident, as discussed further in Section 2. Whilst these methods are generally useful for determining direct costs, indirect and intangible costs have typically been much harder to ascertain. At present, a significant amount of research is being undertaken to understand these further, most notably the OECD’s Expert Group on Costs of Nuclear Accidents, Liability Issues and their Impact on Electricity Costs (EG-COSTNA). See OECD-NEA (2014).

The work described in this paper aims to provide further insight into the direct and indirect costs of a nuclear accident, by using the latest Level-3 Probabilistic Safety Assessment code “PACE” coupled to an economic costing model “COCO-2” to appraise the costs of a hypothetical nuclear accident within the United Kingdom. Section 2 provides a brief overview of Probabilistic Safety Assessments and associated Cost Methodologies. Section 3 outlines a hypothetical nuclear accident at a fictitious reactor site within the United Kingdom that is assessed using PACE, with the results of these simulations provided in Section 4. The results are discussed in Section 5 in terms of the accidents at Three Mile Island 2, Chernobyl and Fukushima Dai-ichi; comparable accidents from a modern Gen III+ reactor and a brief consideration of future calculations which could be performed by PACE to assess countermeasure interventions, and corresponding economic costs, across Europe.

2. Probabilistic safety assessments and cost methodologies

Probabilistic safety assessments (PSAs) are used throughout the nuclear industry to assess the risks of an accident occurring at a nuclear facility. These assessments are typically split into three ‘levels’ when considering nuclear reactors. Level-1 PSAs aim to determine the various fault modes that can occur within a nuclear power plant and then assign a probability to each of these events happening. Level-2 PSAs builds on the results of Level-1 PSAs to look at the release modes of materials from the site (i.e. to assess how containment and other mitigating systems operate) and as a result estimate the activities of materials potentially released. Level-3 PSAs build on the results of Level-2 PSAs to look at off-site consequences, such as the risk to the public. It should be noted that this simple connection between levels may not be sufficient; at some facilities Level-2 initiators may not require a Level-1 event to have occurred (e.g. fuelling machine failures in on-load refuelling scenarios in some reactor systems) and there may be bypass routes that mean releases occur without invoking containment behaviour. Level-3 PSA should cover all events on a site, including those due to other sources of hazard associated with each facility, such as spent fuel ponds at a reactor facility and, for multi-facility sites, those due to other facilities having knock-on effects or a single event affecting several facilities by, for example, the manifestation of a large external hazard. The terminology of three levels has little relevance to other types of nuclear facility, but the concept of developing off-site consequences from faults leading to releases of activity still holds.

As this work is specifically geared to the consequences of off-site exposure and contamination, only Level-3 PSAs will be detailed further in this section. For further information on Level-1 and Level-2 PSAs, the reader is referred to IAEA (2010a, 2010b).

The history of the development of Level-3 PSAs is summarised in OECD-NEA (2000). Bexon (2008) concluded that there had been no significant developments in Level-3 PSAs since the 1990s, with the majority of codes using a Gaussian plume representation of atmospheric dispersion processes to model the transport of radionuclides. Typically, various modules that simulate the implementation of countermeasures to reduce the radiological consequences to people and the environment are built into these models.

By 2000, four main costing models were in operation around the world that were either embedded within, or otherwise coupled to, these Level-3 PSA codes. These are: ARANO developed by VTT in Finland; MACCS developed by Sandia National Laboratory in the United States; COCO-1 that was coupled to either CONDOR or COSYMA and developed by the National Radiological Protection Board (now Public Health England) in the UK; and MECA that was coupled to COSYMA and developed at Universidade Politécnica de Madrid. Further details on the differences between ARANO, MACCS, COCO-1, and MECA; and their application in assessing the external costs of electricity are provided in OECD-NEA (2000).

An updated version of MACCS, “MACS2” (current version 3.10) has been released (US Department of Energy, 2004) and is the standard US Level-3 PSA code (Sandia National Laboratory, 2012). MACCS uses a Gaussian plume model to calculate the atmospheric transport and deposition of radionuclides following an accidental release, with those results used in turn as an input to the calculation of doses to people from multiple pathways. MACCS allows various doses to be calculated with and without protective actions including, for example, the use of a network representation of how particular groups in the population might evacuate the area near to the accident site. MACCS is used in cost-benefit analyses that form part of the U.S. licensing processes using a simple cost based economic model however, a new “Input-Output” economic model for MACCS is currently under development.

Within the UK COCO-1 was superseded by COCO-2 in 2008 (Higgins et al., 2008). COCO-1 estimated costs based on the regionalised GDP per head lost due to movement restrictions on, or displacement of, the local population. COCO-2 uses an “Input-Output” model to determine the direct and indirect (Type I) national production loss from curtailed activities in the affected region together with capital losses in the affected region and a willingness to pay valuation of health effect costs (indicative Type II regional tourism loss estimates are also provided).

Public Health England is completing the development of a new Level-3 PSA application called PACE (Probabilistic Accident Consequence Evaluation) (Charnock et al., 2013). The developers of PACE have taken advantage of advances in computing technology, such as increased processing power and the greater availability of spatial datasets, to produce a Level-3 PSA application that works seamlessly as part of the Geo-
graphic Information System, ArcGIS™. PACE provides many new features including the use of NAME III (Jones et al., 2007a) a Lagrangian dispersion model that utilises numerical weather data to model radionuclide dispersion. In addition, PACE calculations can also be performed with a much simpler Gaussian dispersion model. A discussion of the practical differences between these dispersion models can be found in Haywood (2011). PACE estimates the size, number, or extent of the accident consequences stemming from the release of radioactivity into the environment such as the number of people evacuated or sheltered, the number affected by immediate and latent health effects, and the amount of agricultural production restricted. Many of these PACE results are also inputs to the COCO-2 model implemented within PACE that estimates the economic costs of the predicted consequences.

3. Using PACE to model a hypothetical large accident in the UK

A set of calculations were performed to investigate the use of PACE and in particular to estimate the economic cost of a hypothetical large accident occurring in the UK using the COCO-2 model. The following sections highlight the pertinent details that were required to set-up the calculations, including: the location of the reactor, the size and timing of the released source term, the sampled weather conditions, and the countermeasure options adopted in the calculations. Further details of the parameters and options selected are discussed in Higgins and Sherwood (2017).

3.1 Hypothetical reactor location and geography

The siting of a nuclear reactor requires a number of factors to be considered including the proximity of rural and urban settlements, accessibility of cooling water and access to grid connections, as detailed further in Grimston et al. (2014). The location of the notional nuclear reactor used in this study was deliberately chosen not to be the position of a currently operating reactor, or a site that would be plausible for a future reactor, as the intention was to explore general effects rather than those associated with a particular site. Hence a
hypothetical site was chosen on the South Downs, at Ordnance Survey grid coordinates SU85202360 (Lat: 51.005, Lon: -0.786), placing it approximately 4 km from the centre of Midhurst. The selection of an inland site means there is a greater opportunity for people and businesses to be affected than at a site on the coast where, at least under some meteorological conditions, a release may initially head out to sea. The population density near the nuclear power station is presented in Fig. 1. Although the siting follows the normal conventions of having relatively few people living nearby, its position in the south east of the UK means that it is relatively close to large conurbations. This is likely to magnify the consequences of a major accident over that anticipated for more remote locations.

The PACE runs that were undertaken in this work relied on a nested grid comprising an inner grid of 1 km per side, followed by grids of 4 km, 16 km and 48 km per side. The inner grid extends over an area of 24 km east–west by 20 km north–south while the next largest grid extends 128 km east–west and 112 km north–south. The grid size was determined by the assessment required in each area. Thus, finer resolution grids, centred round the hypothetical nuclear power plant, were used in areas where emergency countermeasures such as sheltering and evacuation are more likely, with progressively lower resolution grids adopted for long and short term agricultural restrictions, and far-field collective dose effects.

### 3.2. Source term

In this work, a representative source term for a severe "Beyond Design Basis Accident" for a generic water-cooled reactor technology with a low likelihood of occurring is considered and is presented in Table 1. This particular source term does not represent any specific accident sequence from either an actual accident or any other Level-2 PSA calculation. Comparisons of the source term in Table 1 to the source terms associated with the accidents at Chernobyl and Fukushima Dai-ichi and also to probabilistic accident sequences associated with AREVA’s European Pressurised Reactor (EPR) are discussed in Section 5.3. The radionuclides considered when calculating the consequences of a release from the plant are shown in Table 1. The pre-release duration is assumed to be two hours, with the release then occurring over a period of four hours. The release phase is assumed to split into four one-hour periods, forming a flat-topped triangular distribution, with the peak emission occurring midway through the release.

A limited number of radionuclides are used in this particular scoping assessment to minimise (a) the time required to run the NAME III dispersion model (as described in Section 3.3); (b) the time required to run the corresponding PACE calculations; and (c) limit the complexity and specificity of the results provided. In addition, to keep the discharge as simple as possible, the release was assumed to occur from a single point source with a single effective release height of 40 m.

**Table 1 – Source term considered for this hypothetical large accident. Time intervals are labelled “Phases” for ease of subsequent reference.**

| Cumulative duration (h) | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 | Total |
|-------------------------|---------|---------|---------|---------|---------|-------|
| 2                       | 3       | 4       | 5       | 6       |         |       |
| Noble gases             |         |         |         |         |         |       |
| $^{133}$Xe              | $1.50 \times 10^{18}$ | $4.50 \times 10^{18}$ | $4.50 \times 10^{18}$ | $1.50 \times 10^{18}$ | $1.2 \times 10^{19}$ |
| $^{85}$I                | $1.25 \times 10^{18}$ | $3.75 \times 10^{16}$ | $3.75 \times 10^{16}$ | $1.25 \times 10^{16}$ | $1.0 \times 10^{17}$ |
| Alkali metals           | $1.88 \times 10^{18}$ | $5.63 \times 10^{16}$ | $5.63 \times 10^{16}$ | $1.88 \times 10^{16}$ | $1.5 \times 10^{17}$ |
| $^{131}$Cs              | $1.88 \times 10^{18}$ | $5.63 \times 10^{14}$ | $5.63 \times 10^{14}$ | $1.88 \times 10^{14}$ | $1.5 \times 10^{15}$ |
| $^{137}$Cs              | $1.25 \times 10^{14}$ | $3.75 \times 10^{14}$ | $3.75 \times 10^{14}$ | $1.25 \times 10^{14}$ | $1.0 \times 10^{15}$ |
| Alkali earths           | $1.25 \times 10^{15}$ | $3.75 \times 10^{13}$ | $3.75 \times 10^{13}$ | $1.25 \times 10^{13}$ | $1.0 \times 10^{14}$ |
| Chalcogens              | $1.25 \times 10^{15}$ | $3.75 \times 10^{15}$ | $3.75 \times 10^{15}$ | $1.25 \times 10^{15}$ | $1.0 \times 10^{16}$ |

[4] As described further in Section 5.3, the model release is not the result of a known fault sequence of a particular reactor design, but is similar to a release with an estimated frequency between $10^{-4}$ and $10^{-6}$ per reactor year from AREVA’s EPR, based on a full-scale Level-2 PSA (AREVA and EDF Energy, 2012).

3.3. Weather data and the NAME III model

The NAME III model (Jones et al., 2007a) used by PACE to model atmospheric dispersion uses numerical weather prediction (NWP) data from the UK MET Office. In particular, the mesoscale NWP data used in the study has a ground resolution of 12 km by 12 km, extends beyond the boundaries of the UK and is divided into 31 vertical levels with a maximum height of 19 km. Higher resolution data are available but were not thought appropriate for use in this scoping assessment.

PACE ran the NAME III model 400 times, sampling two years of hourly numerical weather data every 65 h, within a temporal domain of 48 h (i.e. dispersion was modelled for a further 42 h after the release finished to ensure that the whole release was allowed to disperse fully over the UK) to establish the likely distribution of consequences. Each run tracked the trajectories of 2000 particles per hour, to fit with the temporal resolution of the meteorological data. The use of only 400 runs may have slightly reduced the accuracy of the results generated at high percentiles as very infrequent events may not have been included.

3.4. Countermeasures and intervention levels

Various countermeasures can be employed in the various phases of an accident to ensure optimal protection of the population under the prevailing accident circumstances. In this work, we consider short-term countermeasures that are instigated at the start of the pre-release phase (i.e. after “time zero” in this assessment), and long-term countermeasures instigated once the release has finished and has been fully dispersed (i.e. 42 h after the release in this assessment).

As presented in the upper part of Table 2, short-term countermeasures include: sheltering, iodine prophylaxis, and evacuation. In the United Kingdom, guidance on the use of countermeasures is based on the principle of ‘averted dose’, i.e. the dose prevented by the application of a countermeasure or set of countermeasures. These are embodied in Emergency
Table 2 – Intervention levels used in this work to mimic UK ERLs (and their efficacy) within PACE. Throughout the work, bold text denotes the lower intervention level (LIL) and italicised text denotes the upper intervention level (UIL).

| Countermeasure       | Dose criteria                  | Comment                                                                 |
|----------------------|--------------------------------|-------------------------------------------------------------------------|
| Sheltering           | 6 mSv (effective), 60 mSv thyroid | This assumes sheltering to be approximately 50% effective at reducing the inhalation hazard. The actual ERLs seek to avert 3 mSv or 30 mSv of effective dose respectively. |
| Evacuation           | 30 mSv (effective), 300 mSv thyroid | There is a short warning period (see Table 1) and it is assumed that as a result evacuation can be 100% effective. |
| Stable iodine (inhalation) | 30 mSv thyroid   | Assumed to be 100% effective if taken 0.25 h before the plume arrives. Distributed to 50 km and taken 2.5 h after start of event. |
| Relocation           | 10 mSv y⁻¹       | Single criterion for both trials. The current calculations assume that permanent relocation applies to the group of people who would not be able to return to the affected area within three months of the release (i.e. after 90 days, the projected dose annual rate would still be above 10 mSv per year) while those temporarily relocated would be able to return. |

Reference Levels (ERLs) which represent lower and upper bounds of averted dose for enacting various countermeasures. Below the lower bound, the countermeasure is unlikely to be justified (it may do more harm than good); at the upper bound, the countermeasure would almost always be justified. Between the lower and upper bounds, countermeasures may be applied which take account of the difficulties imposed by external factors such as extreme weather to adjust the balance of benefits toward slightly higher trigger doses.

PACE utilises user-defined single-value (projected dose or activity concentrations when considering food) intervention levels to trigger the use of countermeasures. This differs from the ERLs, where a range of values may be used for each countermeasure. In this work, two separate calculations have been performed: one considers a lower intervention level (LIL) which is analogous to the lower ERL bound, the other considers an upper intervention level (UIL) which is analogous to the upper ERL bound.

The values for LILs and UILs for sheltering and evacuation are taken from the current ERLs, which are described further in NR PB (1990). It should be noted that whilst sheltering inside a building reduces the dose received from cloud and ground shine, the additional population level benefit of instructing people to shelter is likely to be relatively small for these exposure pathways, as most people already spend most of their time indoors. The dominant population level effect of actively sheltering (closing windows and trying as much as possible to reduce the ventilation rate) is therefore to reduce the dose received via the inhalation pathway. However, for those individuals who are outside when sheltering is initiated the greatest relative benefits are likely to be the protection from ground shine and, for the period of plume passage, cloud shine. In summary, sheltering is assumed to be 50% effective (i.e. the trigger projected dose used by PACE is set at 6 mSv in the expectation of averting 3 mSv the advised LIL, and similarly the advised upper bound projected dose intervention is set to 60 mSv to avert the 30 mSv UIL), whereas evacuation is assumed to be 100% effective (30 mSv for LIL and 300 mSv for UIL) and the advised averted values can be applied directly.

For iodine prophylaxis, the short two-hour period between the triggering event and the release may compromise the ability to supply potassium iodate tablets to all those that would benefit. Furthermore, it was assumed that if stable iodine was consumed at least 15 min before the plume arrived, then the prophylactic was 100% effective. However, PACE assumes an exponential decline in the effectiveness of tablets if administration is delayed beyond this time. The population within the detailed emergency planning zone (DEPZ) surrounding the hypothetical site of the release is assumed to have immediate access to potassium iodate tablets, which have been pre-distributed, as part of the site emergency plan. However, as PACE does not currently support the triggering of prophylaxis at multiple times, a compromise assumption is required to accommodate the time taken to make tablets available to those requiring them beyond the DEPZ which inevitably underestimates the potential protection afforded to those within the DEPZ. In summary, to account for the variation in the likely delay before stable iodine is available to all those that may require it, potassium iodate was assumed to be pre-distributed to a radius of 50 km from the site, but with the condition that the prophylactic is then only consumed 2.5 h after the start of the event.

Long-term countermeasures in this work consist of temporary relocation and permanent relocation triggered by a single intervention level of 10 mSv per year, applied for both LIL and UIL at the end of the emergency phase. The current calculations assume that permanent relocation applies to the group of people who would not be able to return to the affected area within three months of the release (i.e. after 90 days, the projected dose annual rate would still be above 10 mSv per year) while those temporarily relocated would be able to return. PACE allows longer periods of temporary accommodation to be selected, before assuming permanent relocation and the writing off of assets. A longer period of temporary relocation period before declaring assets lost is likely to reduce costs.

In terms of agricultural countermeasures, intervention levels based on the EU’s Community Food Intervention Level (European Commission, 1998) were adopted. Furthermore, two decontamination options available within PACE were con-
sidered (Higgins and Sherwood, 2017). As mentioned in the UK Recovery Handbook for Radiation Incidents (Public Health England, 2015) there are many potential decontamination options that could be considered following an accident and this choice is likely to have a large effect on decontamination costs.

3.5. Data used within the PACE calculation

The default input information that PACE uses has a resolution of 1 km² for all data types except agriculture which has a resolution of 4 km².

Population data is based from the 2001 Census (Office for National Statistics, 2003), and economic data is provided from the results of the 2008 COCO-2 model. Depending on the site of the reactor, the data is recast as appropriate to constrain the number of required calculations. The main sources of economic data used by COCO-2 are detailed in Table 20 of Higgins et al. (2008).

Not all cost contributions can be fully captured with the analysis performed by PACE and the integral economic assessment model, COCO-2. The analysis results presented in Section 4 illustrate various direct and indirect component costs that are available from PACE. It also highlights what additional factors might be considered to provide a broader cost perspective and the likely effect that might have on the overall cost of an accident. The COCO-2 cost baseline is currently 2004 and this baseline has been used in this work. Ideally, a more current baseline would be desirable. However, with the inevitable delay before the required data becomes available, it is unlikely that the primary calculations carried out at the end of 2014 could have applied data newer than 2012. The change in real terms in GDP between 2004 and 2012 is less than 6% (Office for National Statistics, 2013) which is very small both historically and on the basis of the likely level of uncertainty in the calculations undertaken. Thus, the relative impact of an accident can be gauged either on the basis of the 2004 baseline economy or, if desired, by applying a simple GDP deflator, such as the one published by the UK Treasury (HM Government, 2015) to the estimated costs to provide an approximate result with respect to a new baseline.

4. Results

Results of the PACE calculations undertaken, as outlined in Table 1, and modelled under the two countermeasure regimes (upper and lower ERLs) detailed in Table 2 are reported in this section. The results demonstrate the physical consequences in terms of the disruption to the local population and environment most directly affected by the accident and the countermeasures imposed. The results also include an assessment of the health consequences and the economic effects of the disruption. Section 4.1 outlines the number of people that would be subjected to various countermeasures and their associated costs. Section 4.2 looks at the expected radiological effects in the population under various assumptions and conditions (and their corresponding costs). Section 4.3 looks at the agricultural losses both in terms of the quantity of lost produce and the corresponding economic cost. Section 4.4 provides an overall summary of the results.

The results from the PACE and COCO-2 calculations are presented within the general constraints of the COCO-2 model. COCO-2 assumes economic recovery at a national level happens quite quickly following an accident with affected businesses resuming activities in the area, relocating to elsewhere in the country or having their output replaced by other UK businesses; although it is noted that local effects may persist for much longer.

4.1. Population affected

Table 3 illustrates the highly variable consequences of an accidental release depending on weather conditions, with potentially large numbers affected at very high percentiles. Whilst very large numbers are required to shelter at very high percentiles, with the numbers expected to evacuate possibly exceeding the practical capacity of the authorities to organise and manage effectively in the short time available, the numbers requiring permanent relocation are more manageable. Permanent relocation in this calculation is defined as those living in areas where the dose over a year will continue to exceed the dose criterion for relocation after more than 90 days; although those scheduled to relocate permanently are assumed to stay in temporary accommodation for two years. As outlined in Table 2, the criterion for relocation is 10 mSv per year for both the lower and the upper intervention levels. The corresponding economic costs associated with sheltering, evacuation and relocation of people that directly impacts the economy are presented in Table 4.

Fig. 2 is a probability map that shows the likelihood of the population having to shelter assuming the application of either the lower or the upper intervention levels. The difference between the geographical areas affected by the implementation of the lower intervention level on the one hand and the upper intervention level on the other is rather striking, especially in the number of people affected.

Fig. 3 shows a probability map of the areas where evacuation would be advised for both the lower intervention level and upper intervention level. From Fig. 3, the large extent of the area potentially affected has a significant effect on the likely cost of evacuation (as observed in the range of short-term accommodation costs in Table 4). It is important to note that, at least for short duration releases, a countermeasure may be advised at locations particular to a given meteorological sequence. Thus it is possible that some low probability grid squares will be identified for evacuation, while others are not, depending on the sequence.

Fig. 4 shows a percentile map of the areas where temporary evacuation would be advised. While evacuation for 90 days or less might affect a large area, the figure indicates that only a small area would require long-term relocation.

In summary, for the lower intervention level, the mean numbers of those who would be advised to shelter, take prophylactic iodine tablets (PITs) and evacuate are 410,000, 360,000, and 44,000 respectively. For the upper intervention level, the mean numbers of those affected is generally an order of magnitude lower; i.e. 13,000 would be advised to shelter, 42,000 would be advised to take PITs, and 1500 would be advised to evacuate. The mean numbers of people who would be advised to either temporarily relocate or permanently relocate are 12,000 and 620 respectively, under the single relocation criteria considered. To put these numbers in context 3.5 million people live within 50 km of the hypothetical reactor site. The difference in the mean economic costs to the people and businesses between the lower and upper intervention levels is ~£50 million.
4.2 Health effects

Table 5 summarises the health effects arising from this hypothetical accident, with Table 6 summarising the health costs (associated with both mortality and morbidity). It is noted from Table 2 that, when invoked, evacuation is 100% effective. This assumption idealises this aspect of the response to the accident. Further details on the specific aspects of the cost methodology used in this study for health costs, such as discount rates, are contained in Higgins et al. (2008) and Higgins and Sherwood (2017). The results presented do not employ a cut-off or threshold dose below which the individual risk of developing a long-term health effect is deemed insignificant. This is in accord with the IAEA’s Basic Safety Standards where “it is assumed that the probability of the eventual occurrence of a stochastic effect is proportional to the dose received, with no threshold” (IAEA, 2014).

It should be stressed that the estimated fatalities in Table 5 are statistical deaths predicted and valued for prevention, planning and optimising the response to potential accidents.

As indicated in Section 4.1, the use of upper intervention levels to trigger the countermeasure response greatly reduces the numbers of people required to shelter and, more importantly from a practical perspective, evacuate. The difference may amount to a change from the impractical to the practicable. Clearly, the reduction in the practical difficulties and potential health consequences that stem from moving fewer people coupled with the lower cost of organising the transport and services required to move and then reunite the local community, for example children and parents, should be weighed against the increase in radiation related health.
Fig. 2 – Probability maps of where sheltering is advised for (a) lower intervention levels; and (b) upper intervention levels. Intervention levels are detailed in Table 2.

Fig. 3 – Probability maps of where evacuation is advised for (a) lower intervention levels; and (b) upper intervention levels. Intervention levels are detailed in Table 2.

effects and their associated costs (Murakami et al., 2015). Implementing the upper intervention level rather than the lower intervention level does not lead to a dramatic rise in health effects. For example, the mean number of radiation-induced cancer incidences over all ages and all time is 1500 for the lower intervention level and 2000 for the upper intervention level. However, the corresponding difference in the mean total health cost between the upper and lower intervention levels is £60 million which more than cancels out the difference in the mean economic costs to people and busi-
Fig. 4 – 95th percentile map of the spatial and temporal extent of the zone within which the population would be advised to relocate. As noted in Table 2, permanent relocation applies to the group of people who would not be able to return to the affected area within three months of the release (i.e. after 90 days, the projected dose annual rate would still be above 10 mSv per year) while those temporarily relocated would be able to return.

Table 5 – The cumulative distribution of people predicted to suffer radiologically-induced health effects due to the hypothetical nuclear accident and corresponding countermeasures. The table includes results for the lower intervention level (shown in bold text) and the upper intervention level (shown in italicised text) as described in Table 2.

| Sample percentile | Early fatalities | Non-fatal reactions a | Hereditary effects | Leukaemia fatalities | Solid cancer fatalities | Cancer fatalities b | Leukaemia incidence c | Solid cancer incidence | Cancer incidence b |
|-------------------|-----------------|-----------------------|-------------------|---------------------|-----------------------|---------------------|-----------------------|--------------------|-------------------|
| 5th (UIL/LIL)     | –               | –                     | 4.2               | 4.7                 | 47                    | 52                  | 4.7                   | 260                | 270               |
| 25th (UIL/LIL)    | –               | –                     | 4.1               | 4.6                 | 33                    | 39                  | 4.6                   | 100                | 110               |
| 50th (UIL/LIL)    | –               | –                     | 25                | 27                  | 290                   | 320                 | 27                    | 1500               | 1500              |
| 75th (UIL/LIL)    | –               | –                     | 56                | 62                  | 640                   | 710                 | 62                    | 2700               | 2800              |
| 95th (UIL/LIL)    | –               | –                     | 55                | 61                  | 590                   | 650                 | 61                    | 2200               | 2300              |
| Mean (UIL/LIL)    | –               | –                     | 150               | 190                 | 1600                  | 1800                | 190                   | 5700               | 5800              |
| Max. (UIL/LIL)    | –               | –                     | 480               | 320                 | 2600                  | 3000                | 320                   | 9000               | 9200              |

a The number of non-fatal reactions are estimated to be zero in all cases except for the maximum. For the maximum case, the expected number of fatalities is not zero but is very much below 1 and has hence not been shown.

b The percentile results of this column are derived independently and without reference to other percentile columns (See Section 4).

c PACE assumes a lethality fraction of 1; this conservative assumption is currently under review.

nesses, mentioned in Section 4.1, although the two types of cost accrue over very different timescales.5

4.3 Agricultural costs

The material and economic losses following the imposition of agricultural restrictions are shown in Table 7. The material losses represent the current and estimated future lost production due to restrictions placed on the sale of food assuming the land continued to be farmed in the same way. As mentioned in Section 6, all restrictions are assumed imposed at the current activity levels for restricting the sale of food specified by the EU (European Commission, 1998). Table 7 shows the total time integrated loss of production from the areas affected after the accident. It provides a measure of the food supply that must be replaced following an accident either through the development of alternative resources within the UK or by the purchase of food on world markets. Further details on how PACE accounts for agricultural costs in these calculations are provided in Higgins and Sherwood (2017). The costs shown in Table 7 account for the value of lost production over at most two years; at which point production elsewhere is assumed to have replaced the lost supply, at least in value to the economy if not in kind.

The mean total cost to the agricultural sector is £130 million, but without assuming a particular deployment of

5 That is the economic costs to people and businesses are typically accrued in the subsequent weeks and months following an accident, whereas health costs are typically accrued over the years and decades following an accident.
selected agricultural countermeasures that would need to be separately costed but are likely to reduce the cost of waste disposal and restore some lands to agricultural production earlier (Public Health England, 2015).

4.4. Summary

Table 8 summarises the range of costs likely to accrue from triggering countermeasure actions based on either the lower or upper intervention levels. Three observations can immediately be drawn. First, there appears to be only a small difference between lower and upper ERLs over both the economic costs to businesses and people and also the health costs. Second, health costs typically dominate over costs to businesses and people. Third, between the 5th percentile and 95th percentile, the total cost increases by roughly two orders of magnitude, with a further factor of two cost increase, between 95th percentile and the maximum value recorded.

It is worth stressing that the costs are derived on the basis of a “perfect” response to any implemented countermeasures (i.e. the doses that people receive are known and are acted upon appropriately, efficiently and with full compliance) albeit with slight modification in the instance of sheltering and iodine prophylaxis, as described in Table 2. As indicated by the

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### Table 6 – The cumulative distribution of the economic costs predicted for those who suffer radiologically-induced health effects due to the hypothetical nuclear accident and corresponding countermeasures. The table includes results for the lower intervention level (shown in bold text) and the upper intervention level (shown in italicised text) as described in Table 2.

| Sample percentile | Early fatalities (LM) | Non-fatal reactions$^a$ (LM) | Hereditary effects$^b$ (LM) | Additional cost for cancer fatalities$^c$ (LM) | Cost for cancer incidence (LM) | Total health cost$^d$ (LM) |
|-------------------|-----------------------|-------------------------------|-----------------------------|--------------------------------|-------------------------------|--------------------------|
|                   |                       |                               |                             | Leukaemia                      | Solid cancers                 | Total                     |
| 5th (UIL/LIL)     | –                     | –                             | –                           | –                              | –                             | 1.35                      |
| 25th (UIL/LIL)    | –                     | –                             | –                           | –                              | –                             | 1.35                      |
| 50th (UIL/LIL)    | –                     | –                             | –                           | –                              | –                             | 1.35                      |
| 75th (UIL/LIL)    | –                     | –                             | –                           | –                              | –                             | 1.35                      |
| 95th (UIL/LIL)    | –                     | –                             | –                           | –                              | –                             | 1.35                      |
| Mean (UIL/LIL)    | –                     | –                             | –                           | –                              | –                             | 1.35                      |
| Max. (UIL/LIL)    | –                     | –                             | –                           | –                              | –                             | 1.35                      |

$^a$ There are no early effect costs except the small cost (<£1 x 10^3) for the maximum number of non-fatal reactions which is not shown.

$^b$ PACE currently costs all hereditary effects as occurring in the first generation.

$^c$ The cost of cancer fatality is the sum of the incidence cost and the additional fatality cost.

$^d$ The percentile results of this column are derived independently and without reference to other percentile columns (See Section 4).

* The total health costs includes a very small contribution from a depreciated and excessively conservative estimate of early fatality and non-fatality reaction costs.

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### Table 7 – The potential quantities of lost agriculture (assuming un-attenuated loss) and the corresponding economic costs.

| Sample percentile | Cow milk | Green veg. | Potatoes | Grain | Cattle meat | Sheep meat | Total cost$^a$ |
|-------------------|----------|------------|----------|-------|-------------|------------|----------------|
| 5th               | (1.9 x 10^3) | (1.4 x 10^6) | –        | –     | (2.5 x 10^5) | (1.4 x 10^5) | £2.2M          |
| 25th              | (1.1 x 10^3) | (3.5 x 10^5) | –        | –     | (1.2 x 10^5) | (4.4 x 10^5) | £9.1M          |
| 50th              | (2.8 x 10^3) | (8.1 x 10^5) | (2.8 x 10^6) | (2.4 x 10^7) | (8.1 x 10^5) | (1.0 x 10^6) | £5.5M          |
| 75th              | (9.2 x 10^3) | (2.6 x 10^7) | (1.1 x 10^5) | (3.8 x 10^6) | (2.4 x 10^6) | (1.0 x 10^6) | £35M           |
| 95th              | (3.3 x 10^4) | (8.8 x 10^6) | (4.7 x 10^7) | (4.0 x 10^6) | (2.6 x 10^6) | (1.6 x 10^6) | £130M          |
| Mean              | (3.3 x 10^4) | (1.3 x 10^5) | (1.0 x 10^5) | (6.1 x 10^6) | (4.9 x 10^6) | (3.0 x 10^6) | £130M          |
| Max.              | (1.2 x 10^5) | (9.6 x 10^6) | (1.7 x 10^6) | (9.8 x 10^6) | (7.8 x 10^6) | (3.7 x 10^6) | £1200M         |

$^a$ The total agricultural costs include the value of lost production of dairy and beef cattle, sheep, cereals, potatoes, legumes, leafy green vegetables, root vegetables, sugar beet, soft fruit and hard fruit.
mean values shown in Table 8, the use of lower intervention levels are likely to cost less overall by incurring lower health costs although the immediate business costs will be higher. The difference in this case is small and the cost balance may change at sites with different distributions of population and business activity.

As further described in Higgins and Sherwood (2017), the 95% confidence interval for the 95th percentile total cost is within the approximate range of £2.5 billion to £3.4 billion for both the lower and upper intervention levels. Such confidence intervals are not an absolute measure of the total uncertainty in the prediction, which would require a full uncertainty analysis, but instead reflect the consequences of using a limited number of meteorological sequences together with the rate of change in the total cost with percentile at high percentiles.

5. Discussion

Whilst it is important to remember that the calculations have been performed for a hypothetical nuclear reactor accident (with a single, approximated source term) at a single, fictitious nuclear site, it is still possible to draw some inferences regarding consequences and costs relevant to the UK. To assess the implications of the results from the PACE and COCO-2 calculations, the discussion is structured in the following manner. The present limitations of the calculations performed and the present limitations with PACE and COCO-2 methodologies are described in Sections 5.1 and 5.2. Section 5.3 compares the hypothetical source term used in this study to the source terms for the accidents at Chernobyl, Fukushima Dai-ichi, and to that of a Gen III+ reactor, namely the European Pressurised Reactor (EPR). Finally, areas where PACE and COCO-2 may be used in the future, such as comparing results with recent cost estimates for a hypothetical nuclear accident in France and in an appraisal of the recent Swiss policy on iodine pre-distribution are briefly described in Section 5.4.

5.1. Limitations of the calculations performed

The PACE calculation for a hypothetical nuclear reactor accident at a fictitious nuclear site explored the effectiveness and consequences of applying countermeasures based on the UK ERLs. As the demography of the site is precise, the results of this calculation cannot be transferred directly to other locations within the UK. In particular, most UK nuclear facilities (including all operating and planned nuclear power reactors) are on the coast; so the area of land affected by any potential accident is likely to be smaller although not necessarily socially or economically less important. In any event, the additional effects on marine life, including seafood, are not included in the scenario considered. Similarly, the consequences will depend on the isotopic composition of the source term, which is based on generic aspects of an accident to a nuclear reactor. Variations in the timing of release and isotopic composition of the material released could lead to significant differences: for example, iodine is unlikely to be of concern for non-reactor accidents, so that iodine prophylaxis would not be needed and would not be considered. To this end, and in common with all PSA systems, each of the component models used by PACE relies on the best estimate results derived at earlier model stages. Evaluating the uncertainties and correlations associated with each of the hundreds of parameter values used in these specific calculations goes well beyond the remit of this study. The results can be presented in several ways, and to some extent the intended use of the results will influence how this is done. The full use of the model, with a probabilistic distribution of source terms, as well as meteorology and behaviour of people is, of course, possible but is well beyond the scope of this study. In any modelling there will be uncertainties, both aleatoric and epistemic, and the value of using the models must take these aspects into account. Using a mean value as a risk metric is one approach, but it must be compared with a target based on the same assumptions—it has no actual meaning without being set within the assumptions made. Upper and lower bounds, with confidence levels if they can be estimated, can provide guidance on the range of possible consequences. With these caveats, the results provide a broad understanding of the range of costs that may arise.

5.2. Present limitations of the PACE and COCO-2 methodologies

The PACE model, including the COCO-2 economic model, provides a wide-ranging picture of the expected consequences of a nuclear accident. The consequences and the context in which they arise are constrained by the parameters of the case study, in particular, the selection of the fictitious nuclear site and the use of a restricted source term that only considers a few of the isotopes that could be released. However, independent of the constraints of the case study the economic assessment is not entirely complete; as discussed in the COCO-2 report (Higgins et al., 2008) there may be aspects of an accident that are difficult to fully or even partially quantify and these are not currently captured within the PACE assessment. For example, COCO-2, as a cost model for off-site consequences, does not consider the capital loss at the

| Sample percentile | Total economic cost to business and people (£M) | Total cost of health effects (£M) | Total cost to agriculture (£M) | Total cost (£M)* |
|-------------------|-----------------------------------------------|---------------------------------|---------------------------------|-----------------|
|                   | UIL | LIL | UIL | LIL | UIL & LIL | UIL | LIL | UIL | LIL |
| 5th               | 0.4 | 5.0 | 64  | 43  | 2.2       | 74  | 58  |
| 25th              | 2.4 | 20  | 170 | 130 | 9.1       | 220 | 190 |
| 50th              | 12  | 51  | 370 | 310 | 35        | 450 | 430 |
| 75th              | 34  | 97  | 810 | 730 | 130       | 110 | 1000|
| 95th              | 390 | 470 | 1900| 1800| 590       | 2800| 2800|
| Mean              | 96  | 140 | 580 | 520 | 130       | 800 | 780 |
| Max.              | 4000| 4000| 3100| 3100| 1200      | 5100| 5100|

* The percentile results of this column are derived independently and without reference to other percentile columns.
site of an accident or any associated clean-up costs. Additionally, no impact is assumed on other power production facilities and ultimately the cost of electricity even though, following a large accident, the Office for Nuclear Regulation might require a safety review of nuclear reactors elsewhere in the country that could conceivably lead to reactors being temporarily or permanently closed.

Any public response associated with political and social considerations might well depend on proximity to the stricken plant. On the other hand, widespread concerns within the population at large could lead to additional costs in terms of medical services (including mental health costs) and clean-up requirements. The resulting purchasing decisions made to assuage public concerns would be on top of the costs predicted by PACE.

One area of particular concern not accounted for above is the consequence to the UK economy from a possible decline in international visitor numbers and their discretionary spending following a major accident. The assumption of COCO-2 is that the economy as a whole recovers rapidly. Empirical evidence is limited but Wu and Hayashi (2014) indicate that inbound tourism recovered rapidly despite Japan experiencing both a nuclear accident and large-scale structural damage along the Eastern seaboard following the Great East Japan Earthquake of 2011.

### 5.3. Comparison of the accidents at Chernobyl and Fukushima Dai-ichi

As seen in Table 9, the source term for the hypothetical UK accident considered in this study is not as severe as the source terms for the accidents at Chernobyl and Fukushima Dai-ichi. Nevertheless, the source term is realistic for a potential severe nuclear accident at a modern nuclear power plant, as illustrated in Fig. 5, which shows the cumulative probability of a large nuclear accident for a Gen III+ European Pressurised Reactor (a type that being constructed in Finland, France, and China, and planned for the UK) as a function of its radiological release. With the exception of $^{133}$Xe, which is overestimated to provide an approximate surrogate for the effects of the other short-lived nuclides released, the release considered in this work would be similar to an event with a frequency of $10^{-7}$–$10^{-8}$ per reactor year.

As the source term is less severe, a certain degree of care is needed in comparing this release (and the response to this release) with the releases at Chernobyl and Fukushima Dai-

icher. However, it is interesting to highlight the differences between the numbers of people affected by these different accidents. It should be noted that the release timescales were different in these cases and differ from that in the analysed source term. At Chernobyl the release was immediate and continued for several days, whereas at Fukushima Dai-ichi the initial release was some hours after the event from the first reactor and then there were additional releases from two further reactors over several days. The source term used in this work assumes a relatively early release at two hours (compared with predictions for modern designs such as the EPR for which it is predicted in nearly 95% of fault sequences the containment would survive for more than 24 h (AREVA and EDF Energy, 2012), and to only last for only a short period of a few hours. The time before a release is fundamental in implementing early countermeasures effectively.

As mentioned in the report of the International Chernobyl Project (IAEA, 1991), the initial decision to evacuate was based on an individual receiving 100 mSv absorbed dose during the first year after the accident. However, the decision to evacuate Prypiat and nearby villages was made 36 h after the accident, where decision making was made on limited radiological data. Five days after the accident, the evacuation zone was expanded to a radius of 10 km, and was then expanded the next day to a radius of 30 km, which took four days to evacuate. Thereafter, an absorbed dose rate map was drawn up with the following isoleths: 0.2 mGy/h formed the boundary of the prohibited zone (about 1100 km² in area), 0.05 mGy/h formed evacuation zone boundary (3000 km²) and 0.03 mGy/h formed the strict controlled zone (8000 km²). The long-term relocation policy for those living within the vicinity of Chernobyl was based on limiting the overall lifetime dose to 350 mSv per person. The decision on whether to relocate people was translated into an operational criterion of whether the $^{137}$Cs equivalent ground contamination level was above $1480$ kBq/m² (or above $555$ kBq/m² for pregnant women and families with children under 12). Following a relocation of 115,000 people in 1986, a further 220,000 people were relocated in 1990, making a total of 335,000. Waddington et al. (2017a) have suggested that significantly fewer people should have been relocated following the accident at Chernobyl. This suggestion is based on the results of a j-value analysis, a technique based on economic utility theory and life-quality index that can be used to assess the cost-effectiveness of accident countermeasures.

| Radionuclide | Fictitious UK accident | Fukushima Dai-ichi (UNSCAR) | Chernobyl (OECD) |
|--------------|------------------------|-----------------------------|-----------------|
| $^{134}$Cs   | $1.5 \times 10^{15}$   | $9.0 \times 10^{15}$        | $1.6 \times 10^{17}$ |
| $^{131}$Cs   | $1.0 \times 10^{15}$   | $8.8 \times 10^{15}$        | $9.9 \times 10^{16}$ |
| $^{137}$Cs   | $1.0 \times 10^{16}$   | $2.9 \times 10^{16}$        | $2.6 \times 10^{17}$ |
| $^{132}$I    | $1.2 \times 10^{17}$   | $1.2 \times 10^{17}$        | $3.9 \times 10^{18}$ |
| $^{135}$I    | $1.5 \times 10^{17}$   | $2.9 \times 10^{16}$        | $2.9 \times 10^{18}$ |
| $^{132}$Te   | $9.6 \times 10^{15}$   | $7.3 \times 10^{18}$        | $–$             |
| $^{90}$Sr    | $1.2 \times 10^{19}$   | $6.6 \times 10^{18}$        | $–$             |
| $^{238,240}$Pu | $–$                     | $2.0 \times 10^{17}$        | $–$             |

Data taken from Table 2 of UNSCEAR (2014).

Values shown are averaged from data published in Devell et al. (1995).
The evacuation policy at Fukushima Dai-ichi was based on fixed radial distances from the centre of the damaged plant. In the first instance, those living within 0–20 km were ordered to evacuate to temporary shelters; followed by a voluntary order for those living in the band 20–30 km from the site to evacuate. In total, over 160,000 people were evacuated from the vicinity of Fukushima Dai-ichi and ~110,000 of these people were from areas that had restrictions imposed on them (Ranghieri and Ishiwatari, 2014). On April 21, the Government of Japan established a “Deliberate Evacuation Area” that included areas where the projected dose criterion of 20 mSv received within the first year of the accident might be exceeded, with an order for people to be relocated from this area within one month after its issuance (Government of Japan, 2011). This extended
part of the evacuation areas out toward ~50 km. As shown in Fig. 6, most of the vicinity surrounding the nuclear power plant is still considered as a restricted area. It is estimated that ~48,000 people who lived in the restricted area have moved outside of the Fukushima prefecture (Fukushima on the Globe, 2014).

Therefore, it is interesting to compare Fig. 6 with that shown in Fig. 4 on the estimated timescale of relocation; noting that for the current UK calculations, short-term, “temporary” relocation (under 90 days) dominates over long-term, “permanent” relocation. From Table 3, even at the 95th percentile, ~36,000 people would need temporary relocation whereas ~2300 people would need permanent relocation following the release from the hypothetical nuclear reactor considered in this work. The mean number of people relocated permanently from this severe hypothetical nuclear accident is ~620, based on a no-return criterion of 10 mSv per year determined three months after the end of the emergency phase. However, it should be noted that the 10 mSv per year criterion employed in the PACE calculation assumes normal living and not the potential dose received from being permanently outside. This dose is expected to decline with time through the combination of radioactive decay, weathering, and the migration of radioactivity through the soil. It is generally represented by an initially dominant short-term component, with a characteristic time of a few years, in combination with a longer term residual component, with a characteristic time constant of a few tens of years. This combination is representative of the decay of the short-lived radionuclides initially present superimposed on the more gradual decline of longer-lived radionuclides, principally $^{137}$Cs (Golikov et al., 2002). Using CLEARE program (Change of Life Expectancy due to Atomic Radiation Exposure) based on the extended Marshall model (Marshall et al., 1983; Thomas et al., 2006, 2007; Jones et al., 2007b,c; Jones and Thomas, 2009; Thomas and Jones, 2009), a dose of 10 mSv per year for 50 years will reduce the life expectancy of the affected population in the UK by about four and a half months—this reduction in life expectancy is not inconsequential and is thought to be that experienced by 6 More people would be able to return if the decision was delayed until a year or two years after the accident.

Fig. 6 – Status, as of April 2014, of areas where evacuation orders have been issued following the accident at Fukushima Dai-ichi. The arc labelled “20 km” shows the 20 km radial distance from the Fukushima Dai-ichi Nuclear Power Plant. Figure taken from Ministry for Economy, Trade and Industry (2014).
the average Londoner (Darzi, 2014) as a result of the capital’s air pollution (nine months at birth). The mean increase in cancer incidence expected to occur over the decades following the accident and reported in Table 3 for the lower intervention level (2000) is a small fraction of the 357,000 cases that occur annually in the UK (Cancer Research UK, 2017) so that even in areas where higher doses were received any increase may be difficult to detect and separate from the confounding, but beneficial, effects of enhanced screening.

It is also noted that non-nuclear related accidents can also lead to large numbers of people requiring evacuation. For instance, 1.5 million people, aged 16 and above, were evacuated from their homes in Louisiana, Mississippi, and Alabama in August 2005 due to Hurricane Katrina; ~410,000 people (29%) had not returned home fifteen months after this natural disaster (Green and Polikov, 2008). The 1979 Mississauga Train Derailment led to more than 213,000–226,000 people being evacuated for six days at a total cost of £22.5–24.5 million (Burton et al., 1981). Using a World Bank deflator of 2.42 to convert 1979 CAD to 2004 CAD (World Bank, 2017) and a Purchasing Power Parity (PPP) factor of 0.56 to convert from 2004 CAD to 2004 GBP (OECD, 2017), the evacuation costs spanned £30.4–33.1 million in 2004 GBP. This would imply that the cost per person evacuated in the Mississauga Train Derailment, including lost income, spans £134–155 cf. short-term accommodation costs of £79 per person for the mean case from Tables 3 and 4. Whilst such comparisons are inexact, it is indicative that the Mississauga Train Derailment evacuation costs are of a similar order of magnitude to that predicted for the hypothetical nuclear accident in the UK.

In summary, it is noted from Table 8 that for an idealised response to the hypothetical nuclear accident in the UK, the economic costs associated with health for both the lower and upper intervention levels dominate over the economic costs to people and businesses; and that the sum of these values plus agriculture costs lead to an estimated total cost of less than £3 billion at the 95th percentile. By implementing expensive interventions, such as long-term relocation, there is the potential for a significant imbalance between the additional economic costs of these actions compared to the health costs that are saved. This can be further exacerbated by the psychological and physical trauma of relocation, which has been found to lead to premature deaths amongst the elderly (Murakami et al., 2015). On the other hand, psychological trauma and additional health costs might occur amongst people not relocated from areas affected by the release, especially if they were worried about their on-going risk from radiation and were unsure that it was small.

5.4 Potential future PACE and COCO-2 calculations

Since the accident at Fukushima Dai-ichi, researchers at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) have performed calculations to ascertain the cost of a potential nuclear accident occurring in France (Pasucci-Cahen and Momal, 2012, 2013). The calculations by IRSN suggest that for a similar radionuclide release a much higher cost may be borne than those calculated in this work. Given the differences between the calculation methodologies, a detailed like-for-like comparison is not yet possible but this could be explored in the future.

Also, Switzerland has revised its emergency preparedness plans such that stable iodine tablets are now pre-distributed to 50 km from each of their nuclear power stations, which covers 4.6 million people, at a cost of US$31 million (Bosley and Bennett, 2014).

If the same pre-distribution plan was considered in this work, then ~3.5 million sets of iodine tablets would need to be distributed. However, as shown in Table 4, for the hypothetical nuclear accident with the lowest intervention levels the number of people who would require to take stable iodine would range from 89,000 (5th percentile) to 810,000 (95th percentile). This compares to 1500 people (5th percentile) to 140,000 people (95th percentile) who would require stable iodine at the higher intervention level.

Paying regard to the size of the accident considered (as highlighted in Table 9) and its very low probability (as detailed in Fig. 5), as well as the evidence for targeting stable iodine pre-distribution to specific demographics (i.e. to those under 40) (National Research Council, 2004), it is not clear that blanket pre-distribution of stable iodine to 50 km is the most cost-effective countermeasure. However, this is not an entirely conclusive suggestion, as a more complete and specific cost-benefit analysis surrounding stable iodine distribution, and the efficacy of such distribution, is needed. The results from this PACE calculation indicate that it is feasible to further analyse this issue; and we note the results of such calculations may subsequently be used in a J-value analysis (e.g. see Waddington et al. (2017a) and references therein) to assess the cost-benefit relationship.

As mentioned in Higgins et al. (2008), the cost of stable iodine production and distribution is not included within the COCO-2 costing methodology, as it is generally considered as a sunk cost of the licensing conditions and not a cost arising from the event. Given the potential for countries to adopt very precautionary stable iodine pre-distribution plans, the costs may be worth including in future versions of this code.

It may be tempting to compare the relative size of the exclusion zone in this work (the red and orange zone in Fig. 4) to the exclusion zone surrounding Fukushima Dai-ichi. However, such a comparison is invalid due to the differences in source term, demographics, and in particular the idealised response to the accident provided by PACE. A study by Waddington et al. (2017a) focussing on some aspects of accident response has suggested that the responses of the authorities after both Chernobyl and Fukushima Dai-ichi may have been exaggerated. A further study (Waddington et al., 2017b) also considers the efficacy of a number of remediation measures instituted after the Chernobyl and Fukushima Dai-ichi accidents. Uncertainty at the time decisions are made and the need to reassure the population are key to understanding why more actions may be taken than required by a post-hoc cost-benefit analysis. Further work is required to understand the consequences of slow or exaggerated responses on the short- and long-term wellbeing of the population and the eventual cost commitment.

The PACE program considers various remediation techniques to minimise long-term dose rates; and we observe that the efficacy of remediating an affected area is reliant on the area being accessible (i.e. the rate of remediation may well be slower in a larger area with more people evacuated than it is in a smaller area with fewer people evacuated). A further study to assess remediation rates and their effect on long-term relocation would be needed to assess this.

Finally, the efficacy of countermeasures depends on the ability to provide off-site support, including transport both to the site and from the surrounding area, so assump-
tions of their effectiveness are important. As the accident at
Fukushima Dai-ichi has demonstrated, countermeasures can
be compromised if the accident is initiated by external hazards
which also affect the surrounding area. External hazards also
can affect several facilities on a site at the same time which
can complicate countermeasures and affect on-site recovery.
These are issues which need further consideration in devel-
opling emergency preparedness arrangements.

6. Conclusion

This paper has sought to determine the indicative costs of a
severe nuclear accident occurring within the UK by assessing
a hypothetical release from a fictitious nuclear power plant
site that has a realistic demography. These indicative costs
were determined by using the economic cost model COCO-2
coupled to the UK’s most up-to-date Level-3 PSA code PACE.
This paper has briefly outlined various Level-3 PSA codes and
corresponding economic costing models that are in operation
around the world. A brief introduction to the PACE code, and
the rationale behind the source term, weather conditions, and
the implementation of countermeasures based on UK ERLs
are provided. The source term is smaller than either that from
the Chernobyl or Fukushima Dai-ichi accidents and its tempo-
ral extent is far shorter. Nevertheless, it falls roughly within
the spectrum of very unlikely releases (within the range of 1 x 10−7–1 x 10−8 events per reactor year) that could occur due
on the accident in a modern nuclear power plant site.

As observed with the variation in economic costs over mul-
tiple trials, the effects on people and the environment vary
greatly depending on the weather at the time of the accident,
which emphasises the benefit from running multiple simula-
tions to determine the distribution and likelihoods of these
effects. Two intervention levels based on the lower and upper
intervention levels of the UK ERLs were considered. Little
difference was seen between the overall total costs for the various
percentile ranges, with greater disruption costs in the lower
intervention level matching greater health costs in the upper.

Whilst the accident model contains a large number of assump-
tions and idealisations, as explained, the mean outcome
suggests that the number of people needing to be perma-
ently relocated in the case of a severe, short-duration
release accident at a modern nuclear reactor in the UK
would be relatively small, possibly less than a thousand, based solely
on the reduction of physical harm from potential radiation
exposure. This contrasts sharply with the observed numbers
of those relocated by the authorities at Chernobyl and
Fukushima Dai-ichi, which was at least an order of magnitude
greater in each case.

The study has shown that there can be a large variation in
the possible costs imposed by a severe nuclear reactor acci-
dent. In the case considered here, the cost was estimated to
be several billion pounds in some instances. However, even in
the worst calculated case, the scale of costs is estimated to be
between one and two orders of magnitude down on the costs
incurred so far as a result of the approach taken at Fukushima
Dai-ichi. The extent to which this would be true for an actual
accident of the scale of Fukushima at a real reactor site in the
UK is of course impossible to derive from these results. They
should in no way be taken as indicative of the UK situation,
in the sense that it is an open question as to how far it is
inevitable that additional costs would be incurred in the case
of a major nuclear accident over and above those considered
in this paper, by the public demanding a greater effort driven
by a lack of confidence in the response provided.

The results show that the PACE and COCO-2 models can be
useful in determining the potential costs of accidents and the
nature of the emergency preparedness arrangements needed.
The use of these models for an actual reactor at a chosen
site would be a valuable addition to the understanding of the
effects of a nuclear accident in such a situation.

Further examination using PACE and COCO-2 of the recent
cost estimates in France and the recent policy stance on
the pre-distribution of iodine in Switzerland might provide
valuable insights. In particular, further work on whether
unavoidable intangible costs have been accurately assessed
or how other intangible losses may be avoided by appropriate
pre-emptive management actions would be beneficial.

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