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

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Considerations in relation to off-site emergency procedures and response for nuclear accidents

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ABSTRACT

The operation of nuclear facilities has, fortunately, not led to many accidents with off-site consequences. However, it is well-recognised that should a large release of radioactivity occur, the effects in the surrounding area and population will be significant. These effects can be mitigated by developing emergency preparedness and response plans prior to the operation of the nuclear facility that can be exercised regularly and implemented if an accident occurs. This review paper details the various stages of a nuclear accident and the corresponding aspects of an emergency preparedness plan that are relevant to these stages, both from a UK and international perspective. The paper also details how certain aspects of emergency preparedness have been affected by the accident at Fukushima Dai-ichi and as a point of comparison how emergency management plans were implemented following the accidents at Three Mile Island 2 and Chernobyl. In addition, the UK's economic costing model for nuclear accidents COCO-2, and the UK's Level-3 Probabilistic Safety Assessment code "PACE" are introduced. Finally, the factors that affect the economic impact of a nuclear accident, especially from a UK standpoint, are described.

1. Introduction

Since the development of civil nuclear power in the 1950s, it is fortunate that relatively few accidents have occurred with off-site consequences. Such events are rare due to the effort expended to provide the necessary preventive, protective, and mitigative safety measures for all types of nuclear facility. These measures span structures, systems and components (SSC), along with the management of the facility. The potential for high-consequence accidents to occur, albeit with very low probability, motivates the high financial costs observed in nuclear safety.

However, it is impossible to eliminate the possibility of accidents with off-site consequences entirely. With each accident

that has occurred, our conception of what the overall impacts associated with the accident, along with the policies and practices that are put in place to mitigate the consequences of the accident, has been challenged. For instance, a recent analysis has posited that, from an economic perspective, large-scale permanent relocation of people within the evacuation zones of Chernobyl has proven significantly less optimal than an alternative policy that could have been adopted: short-term evacuation coupled with aggressive remediation followed by a later return of those displaced (Waddington et al., 2017a). Two examples of such challenges from the incident at the Fukushima Dai-ichi in 2011 are as follows: (a) in the instance of protracted radionuclide releases it has been suggested that short-term sheltering may be detrimental if later evacua-

tion is required (due to the potential for increased radiation dose received whilst evacuating) (Gering et al., 2013); (b) that whilst there have been no radiation-induced deaths from the accident at Fukushima Dai-ichi, an estimated 1793 have lost their lives during the subsequent evacuation and relocation (The Reconstruction Agency, 2014), with a much greater number experiencing detrimental health effects (Yabe et al., 2014).

Nuclear safety in most countries is assessed against the five levels of the defence-in-depth philosophy (IAEA, 2012a) in which the first four levels rely mainly on SSC on the site. SSC can be costly and, particularly if they are only required for unlikely events, a decision has to be made on whether they are cost effective.[1] Off-site emergency preparedness is the main mitigative safety measures in Level 5. However, although such arrangements are generally benchmarked against international guidelines (e.g. IAEA, 2002a), significant variations are seen between different national policies depending on: (a) their political acceptance, (b) public perception and aversion to radiological risk, (c) public trust of the relevant authorities, and (d) national approaches to dealing with civil contingencies. Arrangements and approaches to emergency response have changed over time and a synopsis of lessons that have been learnt over the last 70 years can be found in IAEA (2012b).

This paper reviews international guidance on emergency preparedness and responses to accidents and provides a review of the UK's approach. Section 2 details current emergency preparedness and response procedures and the effect of events at Fukushima Dai-ichi on these guidelines. Section 3 details the UK's approach to performing economic assessments of nuclear accidents; whilst Section 4 outlines the factors that affect the severity of a nuclear accident from both health and economic perspectives and how these can be assessed by a Level-3 Probabilistic Safety Assessment. For a discussion surrounding the UK's nuclear liability regime post-Fukushima, the reader is referred to (Heffron et al., 2016).

This review considers the health and safety aspects during an accident as well as remediation to reduce radiation doses post-accident, paying due attention to economic factors. Aspects such as decommissioning and dismantling of the facility, replacing the facility and/or the lost electricity, are not included. Whilst these may be of significant concern to the licensee and/or government, they do not impact directly on the risks from ionising radiation to people and the environment (cf. the Safety Objective in IAEA, 2006). In line with this consideration, risks from conventional hazards have been considered only where they result from actions to prevent radiation doses.

This review article was prepared as a background paper for the study of the likely effects of a major nuclear reactor accident in the UK, where Public Health England's PACE program suite and COCO-2 economic costing model (Charnock et al., 2013; Higgins et al., 2008) was applied to assess the economic and health costs of a hypothetical release from a fictitious nuclear power station with realistic demography (Ashley et al., 2017).

2. Phases of an accident

Emergency preparedness for a nuclear accident can be considered within three chronological phases: planning phase, response phase, and recovery phase. The phases are not entirely separate and the boundaries should not be viewed as definitive as overlap can occur.

2.1. Planning phase

2.1.1. Requirements

It is fundamental in all countries that there should be some form of emergency planning and preparedness around nuclear facilities in case an accident should happen. This requirement is generally enshrined in some form of legal enactment, though this varies between countries as does the responsibility for drawing up these plans, assessing their basis, exercising them and, if needed, implementing them. Internationally, this is underpinned by Article 16.1 of the Convention on Nuclear Safety (IAEA, 1994) which states: "Each Contracting Party shall take the appropriate steps to ensure that there are on-site and off-site emergency plans that are routinely tested for nuclear installations and cover the activities to be carried out in the event of an emergency. For any new nuclear installation, such plans shall be prepared and tested before it commences operation above a low power level agreed by the regulatory body." The Convention of Nuclear Safety has 77 contracting parties with 65 signatories, including the United Kingdom and European Union (under the auspices of EURATOM) (IAEA, 2014a).

In the UK, the Nuclear Installations Act 1965 (HM Government, 1965), as amended by the Energy Act 2013 (HM Government, 2013), refers to emergency preparedness within Section 4.3[2]:

> "Conditions that may be attached to a licence by virtue of subsection (1) may in particular include provision—"

clause (c):

> "with respect to preparations for dealing with, and measures to be taken on the happening of, any accident or other emergency on the site;"

The Office of Nuclear Regulation (ONR) is responsible for administrating these Acts and the requirements regarding emergency preparedness are covered in standard Licence Condition 11 (Office of Nuclear Regulation, 2013a, p. 11). The ONR in its guidance document, "Licencing Nuclear Installations" (Office of Nuclear Regulation, 2014), states as part of the supporting evidence required when applying for a Nuclear Site Licence the applicant should include:

> "details of appropriate emergency arrangements and a suitable emergency plan (this may be limited in extent for the period before nuclear fuel is brought onto the site);"

The ONR also requires that before the start of active commissioning, adequate emergency arrangements should be in place and exercised as appropriate.

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[1] In the UK, the requirement for not implementing additional safety measures is the legal requirement to show that risks to the health and safety of employees and people not in the employer's employ have been reduced so far as is reasonably practicable (see e.g. Health and Safety Executive, 2001).

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[2] Although the Nuclear Installations Act 1965 was amended by the Energy Act 2013, the sections regarding emergency preparedness remained unchanged.

The Health and Safety at Work Act 1974 (HM Government, 1974) covers protection of employees and the public from work activities and under it specific regulations are made that deal with radiation and nuclear emergencies such as the Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPIR 2001) (Health and Safety Executive, 2002). A separate Act, the Civil Contingencies Act 2004 (HM Government, 2004) centres on the roles for responders to all kinds of emergencies.

Article 9 of REPPIR 2001 covers off-site emergency plans, and Item #1 requires that the local authority should draw up guidelines to restrict exposure from a reasonably foreseeable off-site radiation emergency (REPPIR defines a radiation emergency as an event which is likely to result in a member of the public receiving an effective dose in excess of 5 mSv over the first year). It is ONR's duty to determine whether the local authority and operator has met the requirements of REPPIR. As stated by the Office of Nuclear Regulation (2013b): "REPPIR presents the legal framework for protection of the public through emergency preparedness for all radiation accidents." and "REPPIR addresses the need for both on-site and off-site emergency planning. However, for operators of nuclear licensed sites the requirement for an on-site emergency plan[3] is already covered by the existing nuclear site licence conditions (LC11 and LC9). For operators of nuclear licensed sites, compliance with the LCs should satisfy equivalent provisions in REPPIR. For operators of nuclear licensed sites REPPIR mandates additional legal requirements for off-site emergency planning and the provision of information to the public." Also, ONR is empowered under Regulations 9(1) and 16(1) to determine the areas of the Detailed Emergency planning Zone (DEPZ) and Public Information Zone.

REPPIR is the UK Regulation that puts into force the EC Basic Safety Standards Directive 96/29/EURATOM (European Commission, 1996) and Public Information Directive 89/618/EURATOM (European Commission, 1989). Since the accident at Fukushima Dai-ichi, these directives have been repealed and replaced by 2013/59/EURATOM with a deadline of February 6 2018 for Member States to ensure their legislation is in compliance (European Commission, 2013, p. 59). The revision of the EC Basic Safety Standards Directive was in part due to the IAEA's Basic Safety Standards being revised as part of changes suggested by the International Commission for Radiological Protection (ICRP) as detailed in IAEA (2014b) and also due to events at Fukushima Dai-ichi.

National level emergency planning for civil nuclear installations is co-ordinated in the United Kingdom by the Department for Business, Energy and Industrial Strategy (BEIS), and is facilitated through various fora. In 2015, the Department's predecessor (the Department for Energy and Climate Change, DECC) published revised guidance, the "National Nuclear Emergency Planning and Response Guidance" which was compiled with input from those with

expertise in and responsibilities for nuclear emergency planning (HM Government, 2015).

2.1.2. *Contents of an emergency plan*

An off-site emergency plan needs to classify the locality surrounding the facility where various actions may or may not take place. These actions, called 'countermeasures', are identified and a plan for implementing such measures is developed in an attempt to minimise the risks arising from exposure to ionising radiation and risks associated with public anxiety. Countermeasures typically span: evacuation, sheltering, administering stable iodine, decontamination, and food banning. Some measures may be implemented over short time frames (typically in early response when a release is threatened or during the release) and others over long time frames (typically in the recovery phase). In addition to countermeasures, off-site emergency plans also detail the procedures for establishing command and control, communication flows, transport and traffic, maintenance of essential infrastructure, and so forth.

A summary of policies that detail emergency planning zones over various OECD countries (before the incident at Fukushima Dai-ichi) can be found in OECD (2003).

Within the UK, the area covered by emergency planning encompasses the facility and the area where precautionary and immediate countermeasures might typically need to be enacted first; it also extends beyond this to include communities who might also be affected by the consequences of an accident (e.g. by longer-term countermeasures or the indirect effects of a nuclear emergency). For most cases, the areas where immediate or precautionary countermeasures are planned in detail extend radially outwards by a few km (ranging from 1 km for Heysham and Hartlepool to ~6–7 km for Sellafield), as detailed by the Office of Nuclear Regulation (2016). To prevent only part of a settlement being included, this emergency planning area often forms an irregular shape such as that for Sizewell. At the (first) Hinkley Point C inquiry in 1990, the concept of "extendibility" of the emergency response was discussed, and an 'Extended Emergency Planning Zone' (EEPZ) was derived. The EEPZ could extend up to a 15 km radius (Health and Safety Executive, 1990). Due to the persistence of contamination and potential for long-term ingestion, countermeasures restricting food and drinking water may be in force well beyond the EEPZ and such restrictions may exist for long times (potentially years). Since the accident at Fukushima Dai-ichi, the concept of the EEPZ has been superseded by recommending that 'extendibility assessments' are performed on a site-by-site basis extending incrementally from the site up to a distance of 30 km (HM Government, 2015). The value of, and the capability to extend, are influenced by the characteristics and the local geography surrounding the site. Extendibility assessments enable the operator and local authorities to work together to determine what urgent countermeasures and public communication strategies would be most effective at each particular site in the remote event it was necessary to invoke extendibility.

The plan will also determine what pre-accident information is supplied to local residents (in line with REPPIR 2001) and whether stable iodine[4] is pre-distributed or stored for dis-

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[3] The authors note here that ONR's 'on-site emergency plan' terminology differs from that contained in REPPIR, which requires an 'Operator's Emergency Plan' (which is the duty of the operator to prepare), a 'Carrier's Emergency Plan' (which is the duty of the carrier to prepare) and an 'Off-site Emergency Plan' (which is the duty of the local authority to prepare). The Operator's Plan extends to legal responsibilities beyond the site boundary, e.g. off-site monitoring and the provision of off-site technical advice. NB 'Carrier' refers to an employer undertaking the transport or transfer of any radioactive substance.

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[4] In the UK, potassium iodate is used to protect against radioactive iodine accumulating in the body, particularly the thyroid, by swamping the body with non-radioactive iodine. These 'stable

tribution as necessary. It is noted in Part 2 of the National Nuclear Emergency Planning and Response Guidance (HM Government, 2015) that stable iodine may be pre-distributed in various different ways, namely (1) pre-distribution including schools, hospitals, and evacuation reception centres; (2) distribution on the day by specified organisations either 'door-to-door', or at the reception centres; and (3) pre-distribution to collection centres. Further discussion surrounding stable iodine prophylaxis is provided in Section 2.3.

It should be noted that there is no standard template for what should be contained within public information, though REPPIR sets minimum requirements. Significant variation in the amount of information contained within available off-site emergency plans for the different nuclear power plants operating in the UK is observed. Detailed off-site emergency plans are publically available (and online) for Sizewell (Suffolk Resilience, 2017), Hinkley Point (Somerset County Council, 2008), Dungeness (Kent County Council, 2015), Wylfa (Isle of Anglesey County Council, 2011), Hunterston (Ayrshire Civil Contingencies Team, 2015), and Torness (East Lothian Council, 2016)—however, such plans are not publically available for Heysham and Hartlepool. It is noted that some details on off-site arrangements are provided in the Emergency Plan produced by the operator for each nuclear power plant, for example for Heysham (British Energy Generation Ltd., 2007a) and Hartlepool (British Energy Generation Ltd., 2007b).

As part of the off-site emergency plan, the location of some facilities, such as emergency control centres (if not adaptable from those for other civil contingencies) and reception centres for evacuees, will need to be identified. Emergency services, particularly health services, will need to have the capability to deal with the monitoring and treatment of contaminated people as well as those that have inhaled or ingested radiation. In addition, the off-site emergency plan outlines the requirements for specific equipment, such as protective clothing and radiation monitoring devices.

Off-site emergency plans should indicate what countermeasures will be adopted. The general principle of such countermeasures in the UK differs from that suggested by the IAEA and the wider global community. In the UK, the countermeasures are called "Emergency Reference Levels" (ERLs) (Morrey, 1997), based on the dose avoided if the action is taken (this does not mean that no dose has been received, only that which is avoided by the action) as shown in Table 1. The ERLs have both a lower and upper limit which are based on the benefits and disbenefits that are provided to the affected population. Action is not recommended below the lower ERL because the conventional risks and social disruption resulting from the countermeasure are likely to outweigh the benefits, whereas action is always recommended if the upper ERL is exceeded. The most recent IAEA guidance on nuclear emergency planning (IAEA, 2015) centres on the use of Operational Intervention Levels (OILs) which are prescriptive limits based on dose rates which may evolve over the period of the accident, as outlined in Table 2. Furthermore, ICRP uses the concept of reference levels for existing and emergency exposure situa-

Table 1 – UK Emergency Reference Levels (ERLs) that provide guidance for when specific countermeasures should be adopted (Morrey, 1997).			
Countermeasure	Body organ	Dose equivalent level[a] (mSv)	
		Lower	Upper
Sheltering	Whole body[b]	3	30
	Thyroid, lung, skin[c]	30	300
Evacuation	Whole body[b]	30	300
	Thyroid, lung, skin[c]	300	3000
Administration of stable iodine	Thyroid	30	300

[a] These values should be interpreted as approximate figures.
[b] The numerical values for whole body ERLs may also be used for comparison with the quantities of effective dose and effective dose equivalent.
[c] These single organ ERLs were specified prior to the definition of effective dose by the ICRP. With exception to stable iodine ERLs, their use now would not normally be expected.

tions (ICRP, 2009a). Reference levels for emergency exposure situations should be set in the band of 20–100 mSv effective dose (acute or per year). The reference level represents the level of residual dose, or risk, above which it is generally judged to be inappropriate to plan to allow exposures to occur. ICRP considers that a dose rising towards 100 mSv will almost always justify protective measures; and that protection against all exposures, above or below the reference level, should be optimised. Euratom's Basic Safety Standards Directive also details the use of reference levels (European Commission, 2013).

In the case of countermeasures for foods, the UK uses Community Food Intervention Levels (CFILs) set by the EU under Council Regulation (Euratom) 2016/52 (European Commission, 2016). The values used throughout Europe differ from the intervention levels adopted in the United States and the levels that were in place shortly after the accident in Fukushima Dai-ichi. Table 3 summarises the differences between these intervention levels for foodstuffs. Food intervention levels are based on various assumptions on the food intake of representative persons: these may vary for different foodstuffs and whether they are only locally consumed or distributed more widely, including to other countries. Due to the requirement to ensure ingestion doses are limited to all potential consumers, the assumptions used in deriving the intervention levels are often very conservative (Waddington et al., 2017b).

From a UK perspective, the UK ERLs are presently being reviewed, though it is expected that any changes to this guidance will be minimal. Another open discussion surrounds the use of OILs compared to ERLs. Whilst OILs, due to their prescriptive nature, have the advantage of being straight-forward to implement, OILs rely heavily on assumptions and require a large number of accurate dose measurements. Also as OILs comprise single values, the corresponding cut-offs between an intervention taking place can be suboptimal (as detailed in Section 2.3). There may be advantages to using both ERLs and OILs in future emergency management plans, with ERLs being used in the early phase where accurate dose measurements may be limited and OILs (or equivalent) being used in the late-phase when such information may become available.

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iodine' prophylactics are only needed as a countermeasure for accidents at nuclear power plants as it protects mainly against ^{131}I which decays quite rapidly with a half-life of about 8 days and is otherwise not present in harmful quantities at other nuclear facilities. It is noted that other countries use potassium iodide instead of potassium iodate.

Table 2 – Dose rate limits as suggested by the IAEA (2013) and Operational Intervention Levels (OILs) contained in IAEA (2015). OILs are intended as prescriptive limits, as opposed to the indicative ERLs in Table 1.

Time after release	Dose rate limit	Intervention	Effective dose to representative person
<1 day (OIL1)	$\geq 1000\,\mu\text{Sv/h}$	OIL1: immediate safe evacuation (plus associated countermeasures)	100 mSv over 7 day exposure period
<10 days (OIL2)	$\geq 100\,\mu\text{Sv/h}$	OIL2: preparation for relocation (plus associated countermeasures) to be done within a week to a month thereafter	100 mSv over 1 year exposure period
>10 days – 1 month (OIL2)	$\geq 25\,\mu\text{Sv/h}$		
<7 days (OIL3)	$\geq 1\,\mu\text{Sv/h}$	OIL3: stop distribution and consumption of non-essential food and water that is potentially at risk. Assess thereafter using OIL7	10 mSv over 1 year of consumption
>2 days (OIL7)	1000 Bq/kg ^{131}I or 200 Bq/kg ^{137}Cs	OIL7: stop consumption if non-essential. Replace essential foods or relocate public if replacements are not available	10 mSv over 1 year of consumption

Table 3 – Countermeasure intervention levels for foodstuffs around the world. EU values are provided by the CFILs, as outlined in European Commission (2016). US Derived Intervention Levels are provided from U.S. Food and Drug Administration (2005). Intervention levels for Japan during the response phase "Japan (a)" and recovery phase "Japan (b)" of the accident at Fukushima Dai-ichi, obtained from Food Safety Commission of Japan (2011), and Ministry of Health, Labour and Welfare (2012).

	Location	Infant uptake (Bq/kg)	Milk (Bq/kg)	Foodstuff, excl. liquid (Bq/kg)	Liquid foodstuff (Bq/kg)
^{131}I	Japan (a,b)	100	300	2000	300
	EU[c]	150	500	2000	500
	USA[d]			170	
^{134,137}Cs	Japan (a)[a]	200	200	500	200
	Japan (b)[b]	50	50	100	10
	EU[c]	400	1000	1250	1000
	USA[d]			1200	
^{90}Sr	EU[c]	75	125	750	125
	USA[d]			160	
^{239}Pu	EU[c]	1	20	80	20
	USA[d]			2	

[a] These values include take into account the contribution of radioactive strontium.

[b] These values include take into account the contribution of other radioisotopes (except iodine), e.g. radioactive strontium, plutonium, etc.

[c] EU legislation uses different terminology to that in the table. ^{131}I corresponds to the 'sum of isotopes of iodine, notably ^{131}I'; ^{90}Sr corresponds to the 'sum of isotopes of strontium, notably ^{90}Sr'; ^{239}Pu corresponds to the 'sum of all α-emitting isotopes of plutonium and transplutonium elements, notably ^{239}Pu and ^{241}Am, and ^{134,137}Cs corresponds to the 'sum of all other nuclides of half-life greater than 10 days, notably ^{134}Cs and ^{137}Cs.

[d] ^{239}Pu corresponds to ^{238,239}Pu and ^{241}Am. In addition, separate consideration is given to ^{103}Ru and ^{106}Ru based off summed individual concentration levels.

2.2. Response phase

The response to any event on a nuclear facility site depends on its magnitude and potential to cause harm. In particular, events that involve, or have the potential to involve, a significant release of radioactivity off-site mean that countermeasures involving the public may need to be invoked. Depending on the event, there may be a sufficient delay between the initial incident and a release such that actions can be taken before the release occurs: in some cases countermeasures may be unnecessary as the event is terminated by on-site actions without an off-site release occurring. The response phase can therefore be considered to comprise two sub-phases: pre-release and post-release actions.

2.2.1. Pre-release

The pre-release stage is that part of the response phase before an actual release has occurred and when an initiating event has the potential to lead to a significant probability of a radioactive release. As soon as the operator considers that there is the potential for an off-site release it would trigger the site's full nuclear emergency arrangements. This would include notifying off-site bodies as well as implementing measures aimed at restoring the facility to a safe state and preventing (or at least mitigating) any releases from the site.

The period of time between the initial alarm being raised and a subsequent release can vary significantly for different technologies and designs of nuclear power plants and different accident sequences. For example, from the Level-2 PSA of

the European Pressurised Reactor (EPR), the containment is predicted to stay intact for at least twenty-four hours, but in a small number of cases the release phase is predicted to start in less than two hours after the initiating event (AREVA and EDF Energy, 2012). It should be noted that short release times do not necessarily correspond to larger magnitudes of release.

Part of the provisions within the Operator's emergency plan is to determine at what stage the off-site plan is initiated by declaring a radiation emergency. The off-site plan in the UK is effectively run by the local police emergency organisation, headed by a senior police commander who is advised by representatives of many agencies. The effective management of a radiation emergency will require access to specialist scientific and technical advice. Prior to 2015, this was offered by a Government Technical Advisor, who was a senior member of ONR on temporary attachment to DECC to provide independent advice. Since 2013, at the local level, local responders will be advised by the site operators and a Science and Technical Advice Cell (STAC), who would provide independent science and technical advice using all available resources, including ONR, Environment Agency, Food Standards Agency, etc. At the national level, Lead Government Departments (LGD) are responsible for ensuring they have effective arrangements in place to access technical and scientific advice in a timely manner during an emergency situation. The establishment of a Science Advisory Group for Emergencies (SAGE) would normally provide such advice. The roles of STAC, SAGE and the response structure are detailed further in the 'Concept of Operations' section of the National Nuclear Emergency Planning and Response Guidance (HM Government, 2015).

Precautionary countermeasures, such as sheltering or evacuation may be instigated to mitigate the probability of a dose being received. These countermeasures would be initiated by alerts from the local radio/TV when the emergency siren has been sounded and people follow the guidance in the pre-distributed information.

In general, decisions on precautionary measures prior to a release are taken on the basis of judgement of the potential for the incident to escalate, allied to wind speed and direction and predictions of changes to meteorological conditions. If there is sufficient information on the likely source term, and time is available, predictions of the prospective releases emanating from the facility, calculated using specific emergency management software (such as RODOS Ehrhardt and Weis, 2000), can assist in deciding whether precautionary countermeasures should be adopted. Such modelling may be performed even with relatively sparse data.

No precautionary measures were undertaken during the accidents that took place at Three Mile Island 2 (TMI-2) (Moss and Sills, 1981) and Chernobyl (Medvedev, 1990). In both cases this was because of the nature of the event. At TMI-2 it only became apparent there was a problem well after the accident had progressed and fuel melt and hydrogen release to the containment had occurred, but the containment building meant that there was virtually no release of activity to the environment. At Chernobyl, the event was very rapid due to safety systems being overridden and the reactor being placed in an unstable condition; the explosion occurred within one minute of the low-power experiment taking place. Hence, there was no time to take precautionary measures close to the site (Smith and Beresford, 2005). Even if there had been time for such measures, the local population had received no prior information of the hazards of radiation nor what would happen in the instance of an accident (International Chernobyl Project and IAEA, 1991).

The off-site emergency countermeasures at Fukushima Dai-ichi on 11 March 2011 are set out briefly in Table 4. The initial seismic event took out off-site power, but the on-site systems worked satisfactorily. However the associated tsunami, which hit the site about 45 min later flooded the emergency power systems so all on-site power was lost. Note that fuel damage in Unit #1 started ∼4 h after the tsunami struck (roughly when a nuclear emergency was declared) and the reactor pressure vessel was damaged after ∼11 h.

Fukushima Dai-ni, a nearby nuclear power station located ∼16 km from Fukushima Dai-ichi lost off-site power due to the earthquake but not its on-site emergency back-up diesel generators. Residents within 3 km were ordered to evacuate whilst those within 10 km were ordered to shelter.

Whilst precautionary measures for nuclear-related incidents may be able to limit the radiological risk, there is the potential for such actions to induce wide-scale panic. For example, as detailed in Section 2.3, at TMI, although it was only suggested pregnant women and children may wish to leave the area, many residents did self-evacuate. The resultant risks from such panic may well be significantly greater than the radiological risks.

2.3. Post-release

At the point when an environmental release occurs, the emergency plans aim to manage the consequences of such a release, including wider consequences such as the health of the public, by implementing effective immediate countermeasures. The actual countermeasures implemented are very much dependent on the amount and isotopic composition of the radioactive material released from the facility. It is also dependent on the different parts of society that are affected by the release.

For those located relatively close to the site covered by the detailed plans for precautionary and immediate countermeasures and who may prospectively be susceptible to the largest off-site radiation doses, the administration of stable iodine in the aftermath of the release is one of the key interventions that can be performed to limit the intake of the short-lived radioisotope ^{131}I (as noted earlier the use of iodine prophylaxis would only be potentially appropriate in the vicinity of the release). The rationale behind stable iodine prophylaxis is detailed further by the World Health Organization (1999). As mentioned in Section 2, various methods may be employed to pre-distribute stable iodine. As an aside, there is similar variation in the ways of pre-distribution of stable iodine in the United States within the 10-mile Emergency Planning Zone surrounding the nuclear power plant, but it is noted that there is a wide range of efficacies of such schemes ranging from 3.5% to 70% (National Research Council, 2004). From a UK perspective, one particular study on the efficacy of stable iodine distribution surrounding the site in Barrow-in-Furness suggested that the scheme employed there was 60% effective after two years of adoption (Astbury et al., 1999). Further discussion surrounding the issues of iodine distribution and administration following a nuclear accident is provided in Johnson, (2003). Further details on iodine distribution across Europe are presented in European Commission Directorate-General for Energy et al. (2010).

Sheltering and iodine prophylaxis may suffice for small releases but if the dose is projected to exceed the ERLs for

Table 4 – Brief timeline for countermeasures at Fukushima Dai-ichi. Data taken from Government of Japan (2011).
Friday 11 March
14.46: Earthquake occurred: off-site electrical power lost
15.27: TEPCO (the utility) reported the site struck by three tsunami waves, on-site emergency diesel back-up generators affected and became inoperative
15.42: TEPCO first emergency report to government
19.03: Nuclear emergency declared
20:50: Evacuation within 2 km of plant by Fukushima Prefecture
21:23: Prime Minister extended evacuation to 3 km and sheltering for 3–10 km
Saturday 12 March
05:44: Evacuation extended to 10 km
18:25: Evacuation extended to 20 km
Tuesday 15 March
11.01: Government ordered sheltering 20–30 km

evacuation (or distribution of iodate tablets outside the pre-distribution area for a nuclear power plant is difficult) then evacuation may be necessary. Evacuation needs to be carried out in an ordered manner and will be subject to the nature of the demographics, e.g. schools, hospitals, and domestic property. Whilst schools and hospitals may possibly be evacuated in a single process, domestic property may be scattered and so evacuation may be more difficult. The age of the potential evacuees is also a factor as young children have a higher radiological risk and therefore may need to be evacuated at an early stage, along with their families if possible. Evacuating those who are infirm or elderly may lead to a greater harm due to stress and/or medical complications.

Typically, evacuation may include decisions based not on the intervention levels themselves, but on a precautionary basis from predictions of the course of the accident. Political and public pressure may not significantly factor in the immediate aftermath of the release. However, as the response phase evolves, such pressure may affect the emergency plan. We posit that the emergency plan must be adaptive to account for the evolution of the release but be robust enough to withstand political and public pressure.

In the immediate aftermath of a major release, countermeasures (particularly food bans) may be needed up to 40 km from the facility (Health and Safety Executive, 1994), though as time progresses after an accident, this distance may increase. Note that the affected zone would tend to be wedge-shaped rather than circular, though this may change as the weather conditions change (e.g. as depicted in Figs. 1 and 2 for the accident at Fukushima Dai-ichi).

It is worth considering the emergency response at the three most well-known nuclear power plant accidents.

The following information about the response to the accident at TMI-2 is taken from Moss and Sills (1981). Evacuation at TMI-2 was not initially recommended by the U.S. Nuclear Regulatory Commission. An advisory note suggested pregnant women and preschool children within 5 miles of the station might wish to evacuate. However, two days after the initial accident, (i.e. when initial difficulties were seen at the plant) a significant amount of individually-driven, voluntary self-evacuation was observed that was prompted by the potential release of material from the reactor's containment. From NRC estimates, voluntary self-evacuation comprised: ~21,000 people (60%) living within 5 miles of the plant; ~56,000 people (44%) living within a 5–10 mile annulus of the plant; and ~67,000 people (32%) living within a 10–15 mile annulus of the plant. Most of these people left two days after the accident and the median time period before returning was seven days after the accident.

The lead-up and the response to the accident at Chernobyl is well documented (International Chernobyl Project and IAEA, 1991; Smith and Beresford, 2005), and is briefly summarised here. The steam explosion at 01:24 on 26 April 1986 destroyed part of the graphite core and the roof of Reactor #4. This led to fires throughout the turbine hall and also inside the building. Two on-site workers were killed by the explosion. Firefighters from Pripyat, the nearest town to Chernobyl located ~3 km from the site, arrived at the site within minutes and within half an hour were joined by other firefighters. It is noted that these firefighters did not have specialist training for events involving radioactive materials. The radiation levels in some of the accessible places to fight the fires exceeded 100 Gy/h[5] and due to the lack of radiation monitoring, personal dosimetry, and awareness, no measures were taken to limit the exposure and doses to the emergency personnel. 132 emergency workers were affected by Acute Radiation Sickness in the first twelve hours following the accident and were initially hospitalized in Pripyat. Small squads of emergency personnel on site provided first aid, evacuated those who needed further medical assistance, and distributed potassium iodide tablets. After twelve hours, a specialised emergency team arrived and within 36 h examined more than 350 persons on-site. In the first three days of the accident, 299 people suspected of acute radiation sickness were sent to specialised treatment centres and hospitals; thereafter approximately 200 people were admitted to these centres and hospitals for monitoring of acute radiation sickness. By 10 May 1986, the fire at Reactor #4 was extinguished and efforts were in place to stabilise the site (as briefly described in the Recovery section). In the months that followed, a total of 28 workers died from acute radiation sickness, as reported in Table 1 of the International Chernobyl Project and IAEA (1991).

From an off-site perspective, no official information had been given to those living in Pripyat on the day of the accident. Around 44,000 people were evacuated ~36 h after the accident to Polesskoe. Once they arrived in Polesskoe, it took a further three days for doctors to perform blood tests and to refer those showing acute radiation sickness to nearby hospitals. The evacuation zone was expanded to a radial distance of 10 km on 1 May 1986 and the decision to evacuate radially out to 30 km on 2 May 1986 and took four days to complete. In total, ~116,000 people and 60,000 cattle were evacuated from

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[5] For further details on the definition Grays (Gy), Sieverts (Sv), and Becquerels (Bq), the readers is referred to the glossary of (ICRP, 2007) and (Till and Grogan, 2008): basically Gys are a measure of deposited energy, Svs are the dose that results and Bqs are a measure of the number of radioactive disintegrations.
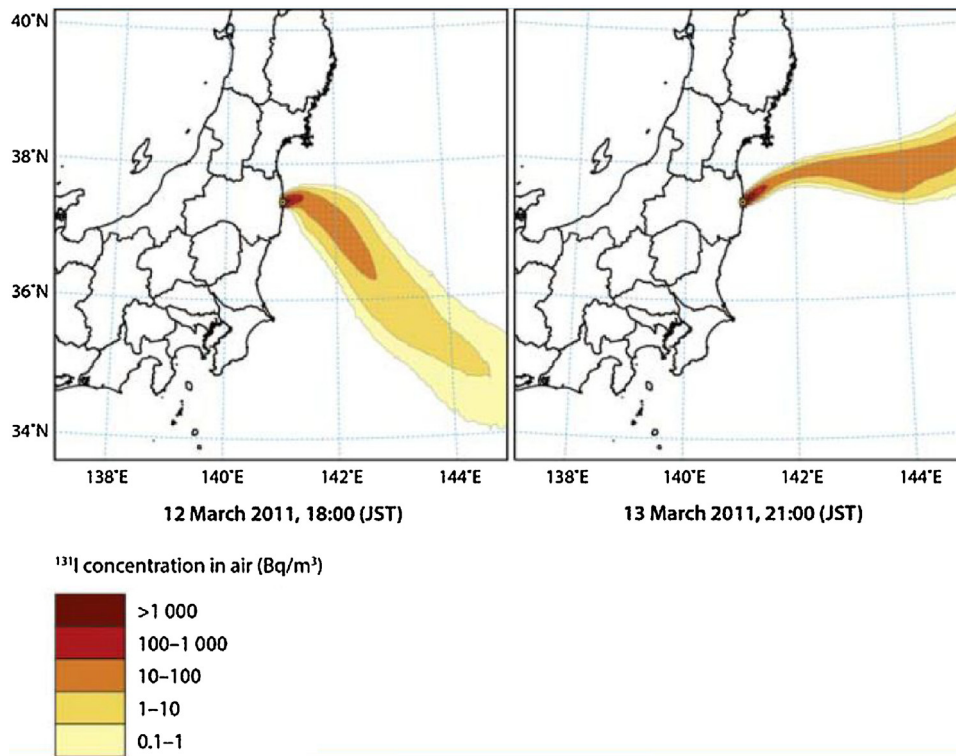
Fig. 1 – Simulated ¹³¹I release following the accidents at Units #1 and #3 at Fukushima Dai-ichi. Figures taken from UNSCEAR (2014).

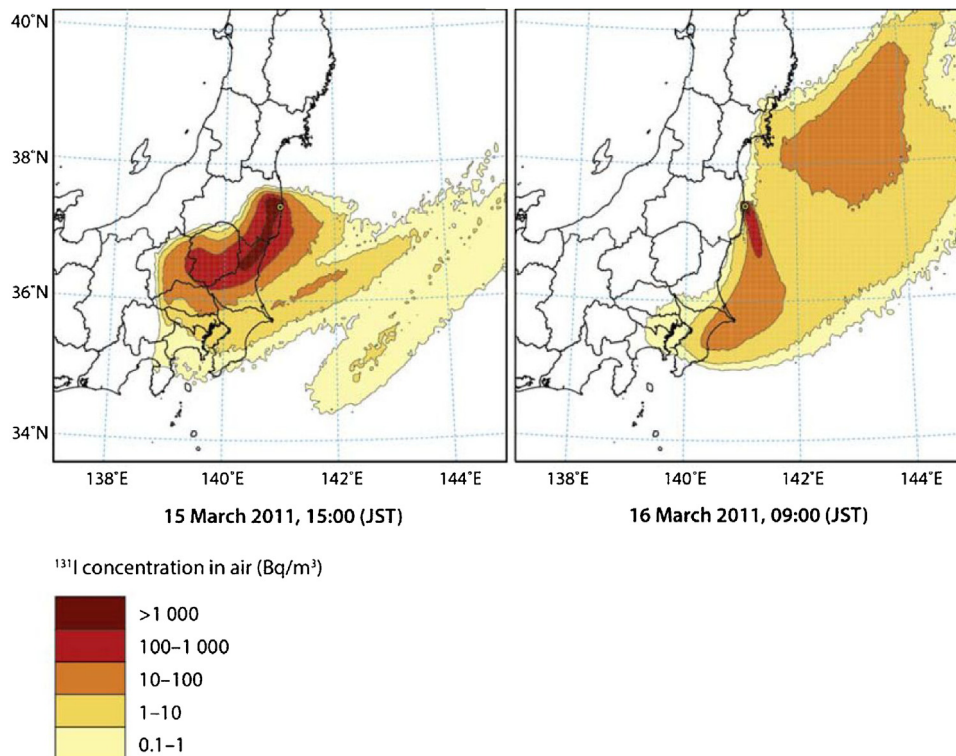**Fig. 2 – Simulated ¹³¹I release following the accident at Units #2 at Fukushima Dai-ichi. Figures taken from UNSCEAR (2014).**

an area of 3500 km² although a number either refused to leave or returned surreptitiously. From 10 May 1986, absorbed dose rate contours were produced that defined three separate areas: prohibited zones (200 μGy/h totalling 1100 km²); the initial evacuation zone (50 μGy/h totalling 3000 km²); and a strict-controlled area (30 μGy/h totalling 8000 km²). Further areas where the dose rate exceeded 50 μGy/h were evacuated after 10 May 1986. Since the accident at Chernobyl, ~350,000 people

have been evacuated from the areas surrounding the plant. According to the IAEA (2005) report, no deaths in the public have been directly attributed to the accident though official estimates are that ~4000 deaths are likely to result from the doses received. Since that report was released UNSCEAR (2008) concluded that the contamination of milk with ¹³¹I, for which prompt countermeasures were lacking, resulted in large doses to the thyroids of members of the general public; this led to
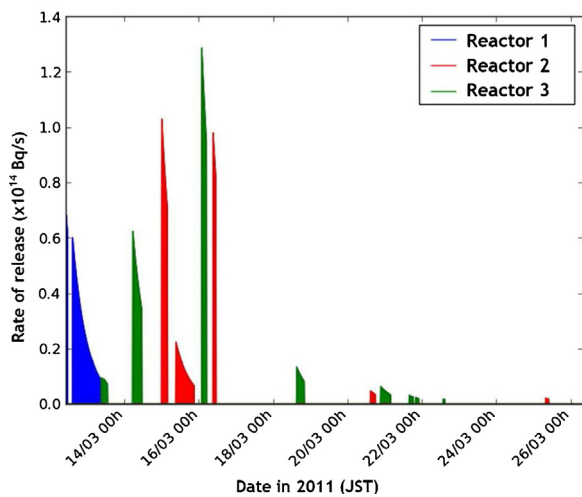
Fig. 3 – Rate of all radionuclides released into the atmosphere from the accident at Fukushima Dai-ichi. Blue denotes unit #1, red denotes unit #2, and green denotes unit #3. Figure taken from IRSN (2012).

a substantial fraction of the more than 6000 thyroid cancers observed to date among people who were children or adolescents at the time of the accident (by 2005, 15 cases had proved fatal). Furthermore, current radiation-induced thyroid cancer risk models predict that the excess risk continues into later life as a proportion of the background risk of thyroid cancer, which increases with attained age (Wakeford, 2016).

Aspects of the response phase from the accident at Fukushima Dai-ichi are contained in the "Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety" (Government of Japan, 2011) and are presented below. Upon the release caused by the hydrogen explosion at Unit #1 of Fukushima Dai-ichi, the evacuation zone was extended to a radius of 20 km from the nuclear power plant (at 18:25; March 12) — this was partly driven by the anticipation of the potential for further incidents to occur at the other Units. This order was given at 18:25 on March 12. At 17:39 on March 12, the evacuation zone for Fukushima Dai-ni was also extended to 10 km. The evacuation involved 78,200 people from both of these areas. On March 15 at 11:00, ~62,400 residents within the 20–30 km annulus of Fukushima Dai-ichi were ordered to 'stay-in-house'. However, this order went well beyond the typical times associated with sheltering. It was observed that within the extended 'stay-in-house' zone that voluntary self-evacuation was evident especially as time progressed and that the standard of living for those within that area significantly decreased as time progressed. On March 25, the zone was reclassified and voluntary self-evacuation was supported. Given the damage caused by the earthquake and tsunami, roads and other infrastructures that would have assisted the emergency management plan were severely damaged which hampered the evacuation.

An observation from the incident at Fukushima Dai-ichi is that what may be an optimal response for one particular release (i.e. sheltering, which is typically limited to a maximum of two days), may become sub-optimal if there are subsequent releases (i.e. people sheltering for too long, or evacuating through the plume of the second release) (Gering et al., 2013). This is highlighted (as shown in Fig. 3) by the release pattern from Fukushima Dai-ichi, with the main releases from Units #2 and #3 occurring two days after the release at Unit #1. For the last set of evacuees within the

20 km radius additional stable iodine needed to be administered as they evacuated through the plume. In total, 164,218 people evacuated, including those who voluntarily evacuated (Yasumura, 2014).

UNSCEAR have reported that "No radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident." and "The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants. The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation" (United Nations, 2013). The UN also note that an estimated 160 workers received doses in excess of 100 mSv, but the associated increased incidence of cancer is expected to be indiscernible in this cohort (United Nations, 2013). Yasumura (2014) points out that whilst there have been no prompt radiation-induced deaths, prompt deaths arising from the evacuation were observed, especially with the elderly and infirm. We posit that radiation-induced deaths and deaths arising from implementing the evacuation policies should both be considered as part of the nuclear accident. By doing this, it can hopefully lead to more effective emergency management procedures.

One way in which evacuation related deaths can be gauged is by looking at the total distances that evacuees travel in (person-km or vehicle-km) and to compare this against associated deaths per person-km and/or vehicle-km associated with car travel. A compilation of fatalities per vehicle-km can be found in World Health Organization (2013). An initial study of non-radiological evacuation risks was performed by Aumonier and Morrey (1990) and suggested that within the UK an upper risk estimate of 1×10^{-8} per person-km should be assigned for both fatality and injury, although it is noted in that work that such risks are likely to be lower during an evacuation; and the risk from preparing to evacuate were difficult to assess, but presumably would be higher than the domestic daily accident rate of 3.3×10^{-7} per person for fatalities. It also noted that stress from the evacuation is inseparable from the stress of the accident itself; and that self-evacuation poses an issue in assessing the overall collective risk associated with evacuation.

2.4. Recovery phase

The recovery phase begins once the event is brought under control. Following certain immediate countermeasures, such as short-term evacuation, decisions on whether the affected population should be relocated or the timescale on which they can return need to be made based on the monitoring of radiation contamination. Before returning to their homes it may be necessary that the land is remediated so that the occupants will not incur unacceptable levels of dose. This will require one of various techniques to be employed and some form of disposal of materials affected. Food bans can be expected to continue for a significant period following the accident.

It is seldom that the affected region can be expected to return to its previous state entirely. Perhaps the site, the region or environment is damaged beyond repair. Even when the system can be physically rebuilt as it was previously, those involved, their communities and the operator, will have the

memory of the incident with them for a long time. Managing realistic expectations of what will happen during the recovery phase is far more important than often thought. The stress impacts of the Chernobyl accident arose partly through poor information and expectation management.

In the United Kingdom, management options for both the pre-release phase and long-term recovery phases are outlined in the UK Recovery Handbook for Radiation Incidents (Health Protection Agency, 2009). The handbook was developed by the Health Protection Agency (now Public Health England), in consultation with various stakeholders including the government, public service agencies, regulatory bodies and professional bodies. The purpose of the handbook is to offer guidance in non-crisis times to national and local authorities, emergency services, radiation protection experts, agriculture and food production sectors, the water industry and others who may be affected by a radiological instance in developing their recovery strategies. A useful extension of the handbook may involve coupling it to a Geographical Information Systems database to allow an immediate comparison between different management strategies throughout the UK. Further information on the underpinning science, the range and complexity of the issues responders will face, and pointers to delivering a recovery strategy are provided in Part 3 of the National Nuclear Emergency Planning and Response Guidance (HM Government, 2015).

At the time of the accident at Fukushima Dai-ichi, international guidance on the protection of people in emergency exposure situations and for those living in long-term contaminated areas was provided by ICRP 109 (ICRP, 2009a, p. 109) and ICRP 111 (ICRP, 2009b, p. 111; ICRP, 2009c) respectively. This guidance uses the concept of reference levels for existing and emergency exposure situations, with recommended reference levels for emergency exposure situations in the band of 20–100 mSv effective dose (acute or per year). The reference level represents the level of residual dose or risk above which it is generally judged to be inappropriate to plan to allow exposures to occur. ICRP considers that a dose rising towards 100 mSv will almost always justify protective measures; and that protection against all exposures, above or below the reference level, should be optimised. [For comparison and contrast, in ICRP 103 (ICRP, 2007), reference levels for existing exposure situations are recommended to be within 1–20 mSv of projected dose per year. Euratom's Basic Safety Standards Directive also details the use of reference levels (European Commission, 2013)]. The accident at Fukushima Dai-ichi has led to unforeseen issues and concerns with this guidance; notably, the guidance had not covered the necessary remediation level explicitly, so it implicitly assumed that it should be performed down to the baseline level of 1 mSv per year over background, which is the dose limit to the public from normal operations. Whilst remediation to a low threshold may be sensible from a cost-benefit perspective in densely populated urban areas, it is not necessarily sensible from a cost-benefit perspective in areas where there are lower levels of permanent occupation. Another factor that requires further consideration in this guidance is the time required to remediate the contaminated area. It can be argued that in the majority of cases, evacuation followed by swift remediation and repopulation is more beneficial to those affected than protracted evacuation and relocation (Yumashev et al., 2017). Present guidance suggests that relocation is allowed if doses in contaminated areas do not exceed 20 mSv per year on the basis that further remediation will take place. However, the available workforce to perform the remediation can be significantly diminished by the scale of the work needed and hence this may inhibit the ability for those people who are relocated to return.

In short, there are still unanswered questions that surround the transition from the response phase to the recovery phase, and whether there can be a transition from recovery to normality.

A detailed timeline of the events of both the on-site and off-site recovery of TMI-2 is presented in IAEA and JRC (2012) and is detailed in the USNRC "Programmatic Environmental Impact Statement" NUREG-0683 (U.S. Nuclear Regulatory Commission, 1981). As mentioned earlier, following the very limited release of radioactivity at TMI-2, the majority of those who self-evacuated returned within two weeks and there were no detectable health effects on plant workers or the public. Estimates suggest that ∼52% of people living within 20 miles self-evacuated (including ∼72% of mothers who had preschool children) (Dohrenwend, 1983). For those who were living in the affected areas at the time of the accident, a sharp rise in non-specific distress, "demoralization", was observed in April 1979 which appeared to sharply reduce toward background levels in follow-up measurements made in May 1979 and mid-July 1979; this contrasts with public distrust which remained high during this period (Dohrenwend, 1983).

A significant amount of research has been performed and published on the recovery phase of Chernobyl and is encompassed in research presented in this special issue. Further information can be found in IAEA (2002b), IAEA (2002b), IAEA (1996), International Chernobyl Project and IAEA (1991), Medvedev (1990), and Smith and Beresford (2005).

Details of the continuing off-site recovery at Fukushima Dai-ichi are best described in Chapter 36 of 2014 World Bank publication "Megadisasters" (Ranghieri and Ishiwatari, 2014). Following the incident ∼160,000 left their hometowns for transition shelters. As of mid-2012, ∼62,000 of those within the evacuation zone had evacuated away from the Fukushima prefecture, with this number decreasing to ∼48,000 by mid-2014. The location of these people across Japan is shown in Fig. 4. It is noted that the displacement of people from the Fukushima prefecture has placed strains on housing and other civic services within other prefectures hosting those evacuated and that in certain places tensions exist between the hosts and evacuees.

3194 premature deaths have been ascribed to "physical and mental fatigue" from the Earthquake (Table 5). As of September 30 2014, 1793 deaths have been recorded from those within the Fukushima prefecture which have been ascribed to physical and mental fatigue from the accident at Fukushima Dai-ichi (The Reconstruction Agency, 2014).

Preliminary investigations into the psychological distress caused by those evacuated due to the Great East Japan Earthquake and accident at Fukushima Dai-ichi have recently been published (Yabe et al., 2014) and show protracted mental health trauma up to the end of the 2012 Japanese financial year. The percentage of those who were surveyed from the evacuation zones with serious mental illnesses are between 4–5 times higher than background (∼12–15% cf. 3%). It would be of interest to see how these numbers, and those reported in Table 5, are related to other measures of morbidity (such as Quality Affected Life Years). Nearly four years on from the accident at Fukushima Dai-ichi the majority of the evacuated areas are still yet to be repopulated, as shown in Fig. 5. Even once an area has been rehabilitated, only a fraction of those people may return due to the lack of public services. This
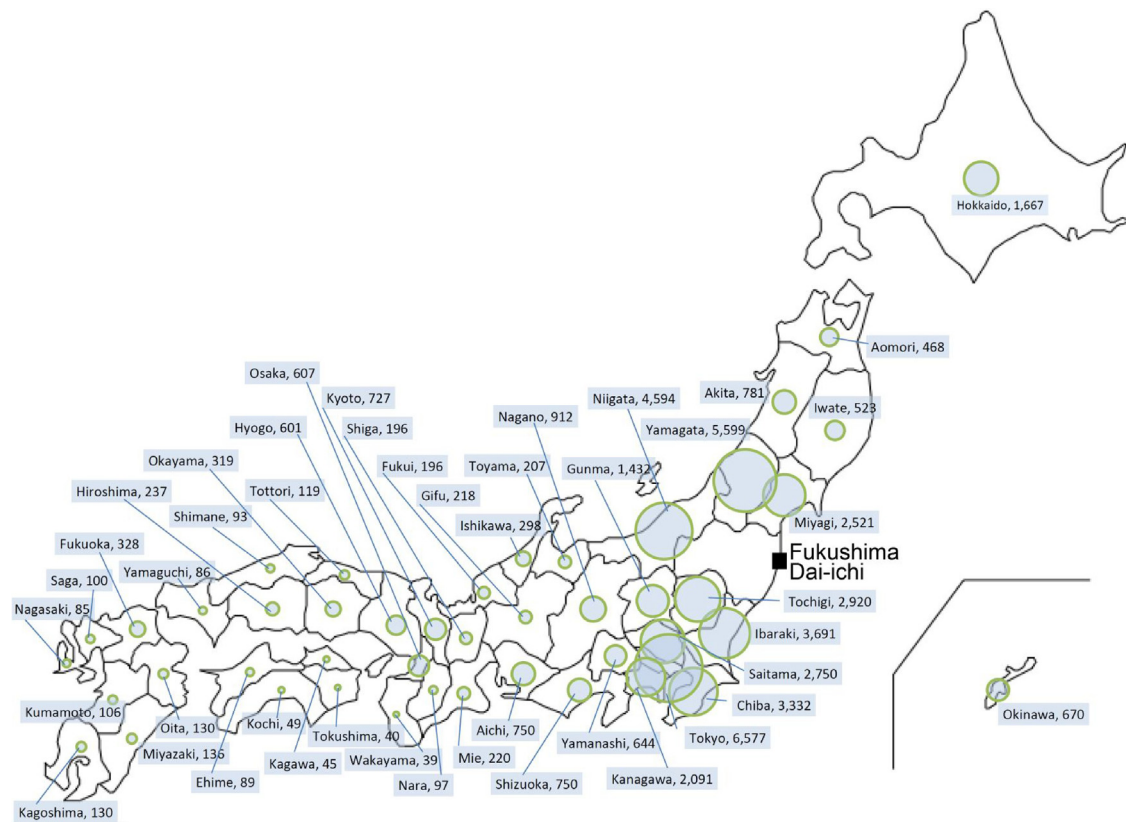
Fig. 4 – The number of evacuees from the Fukushima prefecture, as of February 13th 2014. Figure adapted from Fukushima on the Globe (2014).

Table 5 – The number of earthquake-related deaths in the Great East Japan Earthquake (by both prefecture and time) up to September 30 2014. Data taken from The Reconstruction Agency (2014).

Prefecture	Number of attributable deaths in the time period since the Great East Japan Earthquake										Prefecture total
	<1 week	1 week–1 month	1–3 months	3–6 months	6–12 months	–18 months	18–24 months	24–30 months	30–36 months	36–42 months	
Iwate	93	120	116	59	36	14	5	1	2	0	446
Miyagi	232	332	212	77	28	8	5	3	2	1	900
Yamagata	0	1	0	0	0	1	0	0	0	0	2
Fukushima	111	256	333	315	349	189	129	82	29	0	1793
Ibaraki	19	12	5	4	4	0	0	0	0	0	41
Saitama	1	0	0	0	0	0	0	0	0	0	1
Chiba	2	1	0	1	0	0	0	0	0	0	4
Tokyo Met.	1	0	0	0	0	0	0	0	0	0	1
Kanagawa	2	1	0	0	0	0	0	0	0	0	3
Nagano	1	1	1	0	0	0	0	0	0	0	3
Total	462	724	667	456	414	212	139	86	33	1	3194
Cumulative total	462	1186	1853	2309	2723	2955	3074	3160	3193	3194	3194

has been observed with the lifting of evacuation orders for Hirono Town, where only ~25% of the town's inhabitants have returned within 15 months of the evacuation orders being lifted (Ranghieri and Ishiwatari, 2014). It is noted that this effect has also been observed following the evacuation of New Orleans due to Hurricane Katrina in August 2005. The population of New Orleans 11 months after the hurricane was only ~47% compared to what was recorded in the 2000 US Census; which by July 2014 had risen to ~79% (Plyer, 2015).

Experience from the world's previous major nuclear accidents provides us with two important lessons:

(a) well-meaning countermeasures introduced purely on the basis of radiological protection "rules" can do harm as well as good; and

(b) more generally, that the non-radiological health consequences of a nuclear accident may well be more significant than those caused directly by exposure to radiation (World Health Organization, 2005a,b, 2006; Waddington et al., 2017a).

Given these important and now well-documented findings, there is a need to guard against the danger that future international guidance on nuclear emergency planning will not be driven by radiation dose-related criteria to the exclusion of
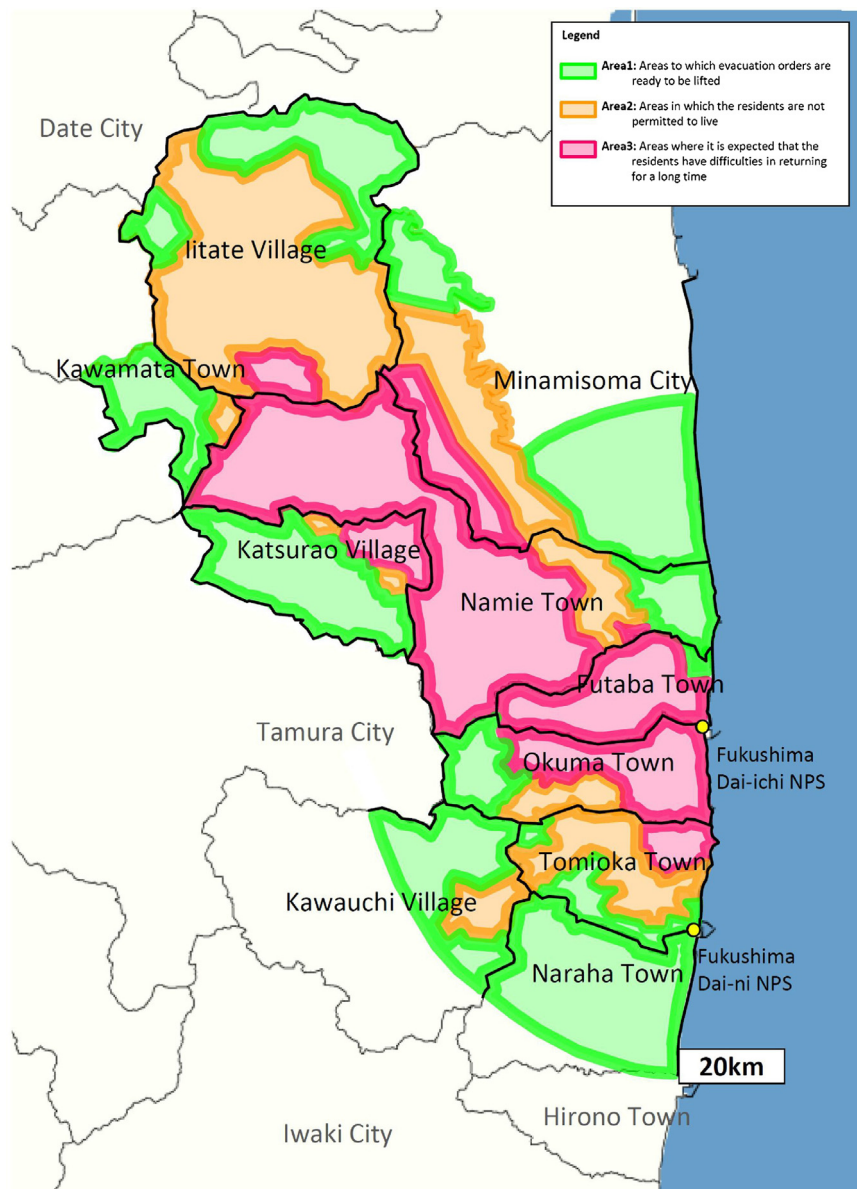
Fig. 5 – Areas where evacuation orders have been issued following the accident at Fukushima Dai-ichi. Figure adapted from Ministry for Economy, Trade and Industry (2014).

social and economic needs. It is sensible to bear in mind at all times the principles of radiological protection, as codified by the ICRP (2007), which require that

- "any decision that alters the radiation exposure situation should do more good than harm" (the "principle of justification"); and
- "the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors" (the "principle of optimization").

3. Economic costs within the phases of an accident

A balance needs to be struck between the costs of implementing safety measures to reduce the frequency and/or mitigate the consequences of an accident and the costs of the accident should it occur. This requires a consideration of what the costs of an accident would be. In general, the costs of developing

and exercising an emergency plan, and the implementation costs if an accident occurs, are not specifically considered. The following paragraphs provide a brief synopsis of typical economic consequences associated with nuclear accidents. In the UK, the computer model COCO-2 has been developed to assess these economic consequences as outlined in Higgins et al. (2008).

3.1. Factors affecting the economic costs of a nuclear accident

Details on the basis of economic costs are taken from an overview into the economic implications of a nuclear accident that can be found in the Organisation for Economic Development's report "Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents" (OECD-NEA, 2000).

From an economic perspective, the cost of a nuclear accident can be viewed as the cost of restoring those affected by such an accident to their pre-accident state, as far as possible. Some of these costs are tangible, in that these are quantifiable

costs that relate to an identifiable asset or source, but there are also intangible losses such as the stress suffered by people who have had their lives disrupted. Costing intangible losses of this kind is extremely difficult a priori. These issues are discussed in Higgins et al. (2008).

Tangible losses can involve both direct and indirect costs. Direct costs are those that are directly attributable to the accident. Indirect costs can be defined as those that are secondary effects from the accident. Direct costs are typically easier to quantify than indirect costs. It is also noted that certain benefits may be observed by placing certain countermeasures or actions in place[6] and these have to also be factored in to the economic costing.

Due to the immediate and potentially protracted effects from a radiological release, both "short-term" and "long term" costs need to be accounted for, ranging from the costs of prompt countermeasures to the costs associated with latent and hereditary health effects. Countermeasures thus have the important role in cost-effectively counterbalancing detrimental health and social effects.

The costs associated with countermeasures span population movement, agricultural countermeasures and restrictions, and decontamination. Population movement covers evacuation (transportation, temporary accommodation, and food); managing the evacuation, the evacuees, and the evacuated area; loss of income, capital value and investment on land and property; and the health effects from the worry and upheaval of the accident. Costs associated with agricultural countermeasures and restrictions include: the loss of food (including the replacement cost of alternative supplies); the loss of capital value of land and stock during the period of restriction[7]; and storage/processing/disposal costs. Decontamination costs include: providing the necessary labour (and accounting for adverse health effects), equipment and materials, as well as transporting and disposing of the generated waste. Microeconomic approaches can be used to ascertain these costs if the accident only affects a single country (e.g. the accident at TMI-2), whereas macroeconomic approaches may also need to be used if an accident has ramifications beyond the directly affected country (e.g. in the instance of Chernobyl).

The costs associated with radiation-induced health effects span: early effects, such as acute radiation sickness, see e.g. UNSCEAR (1962); latent effects, such as radiation-induced cancers, detailed further in National Research Council (2006) and UNSCEAR (2008); and hereditary effects (UNSCEAR, 2001). In addition, non-radiological health effects must be accounted for including the health effects caused by applying countermeasures (such as physical injury caused by evacuation and psychological detriments caused by the upheaval). Thus there are direct health costs, indirect health costs (e.g. loss of salary whilst recuperating), and non-market costs arising from the anguish. It appears that there is no overall consensus in how such health costs can be accounted for over both the short-term and the long-term. The human capital (HC) approach although simple is limited and outmoded as it is restricted to considering the direct and indirect costs of the lost output

from the working production, whilst willingness to pay (WTP), which allows for the inclusion of non-market costs, is difficult to evaluate. However, recent research has raised severe doubts on the WTP valuations used in the UK for the finding the value of a prevented fatality (Thomas and Vaughan, 2015a,b,c) as well as the validity of the concept in the context of radiological protection (Thomas and Vaughan, 2013; Thomas and Waddington, 2017a; Thomas, 2017a).

A more modern and objective technique, the Judgement- or J-value method (Thomas et al., 2006a,b; Thomas et al., 2010) has now been developed, based on the life-quality index (Nathwani and Lind, 1997; Nathwani et al., 2009). The J-value is a revealed preference method that is able to place an objective value on the increase in life expectancy that the safety measure brings about by balancing this against the utility that the person being protected loses by his notional payment of the cost of protection in line with the Kaldor–Hicks compensation principle (Kaldor, 1939; Hicks, 1939). Rather than being reliant on the subjective opinions of a small group of people, the J-value is instead grounded in objective actuarial and economic statistics that characterise the lives and behaviours of millions of citizens. Recently validated (Thomas, 2017b; Thomas and Waddington, 2017b) the J-value allows immediate fatalities and loss of life in the longer term (e.g. after exposure, either of workers or of the general public, to nuclear radiation) to be differentiated but measured on the same scale.

The J-value methodology has been applied as part of the NREFS study (NREFS, 2017) to assess the relocation measures after Chernobyl and Fukushima Dai-ichi (Waddington et al., 2017a), the remediation measures taken after those two accidents (Waddington et al., 2017c) and the sheep meat restrictions in the UK after Chernobyl (Waddington et al., 2017b).

3.2. Economic modelling in the UK

To assess these costs in a UK perspective, the COCO-2 model developed by the Health Protection Agency (now Public Health England) (Higgins et al., 2008), is included within the Level-3 Probabilistic Safety Assessment code "PACE" (Charnock et al., 2013). COCO-2 uses an input-output methodology to represent the effect of lost production. The model accounts for various economic activities in terms of Gross Value Added (GVA) representing the benefit that businesses provide on a square-km basis, which are lost as a result of the accident. It also accounts for losses in the supply chain caused by the primary loss of GVA. Furthermore, direct and indirect health costs are accounted for by including net output losses, the costs of medical treatments, and WTP costs for both fatalities and morbidities.

The types of short-term and long-term countermeasures that are included in COCO-2 are presented in Table 6. COCO-2 does not account for costs of producing and distributing iodine prophylactics, as such costs are typically low when compared to the costs of sheltering, evacuation, and relocation; such costs would also need to account for the shelf-life of such prophylactics which is typically given as 5 years. From the 2004 US study (National Research Council, 2004) a range of costs for producing and distributing stable iodine are seen. This variation depends on how stable iodine is distributed (e.g. door-to-door delivery cf. pick-up from a distribution centre); in certain cases costs are approximately centred around $0.50 per distributed tablet. Switzerland has recently brought in a new emergency preparedness plan that involves pre-distributing

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[6] Restorative actions can have an overall benefit by more than compensating for a particular loss due to the accident. However, it may not be the optimal use of the funds when contrasted with the situation if no accident had occurred (i.e. opportunity cost).

[7] It must be noted that there may be alternative uses for the land which may help preserve its value.

Table 6 – Countermeasures and associated breakdown of costs that are considered in the COCO-2 methodology, as described further with formulae to calculate Gross Value Added (GVA) in Higgins et al. (2008).

Action	Losses
Sheltering	Cost of lost GVA[a]
Evacuation	Cost of population movement[b] Cost of temp. accommodation and temporary lost use of domestic assets Cost of lost GVA[a]
Relocation	Cost of population movement Cost of temp. accommodation and temporary lost use of domestic assets Permanent loss of housing and domestic assets Cost of lost GVA[a] Loss of industrial buildings and assets[c]

[a] Both direct and indirect business losses, and direct and indirect tourism losses are accounted for.
[b] Cost of population movement for evacuation is not yet implemented in PACE.
[c] Including capital value of industrial, commercial, and retail buildings.

stable iodine to everyone living within 50 km of a nuclear power plant (4.6 million out of a total population of 8.1 million) at a reported cost of $31 million (Bosley and Bennett, 2014).

Agricultural costs in COCO-2 account for various foodstuffs with modifiers that attempt to incorporate any seasonality of product into the GVA and output estimates generated. COCO-2 also includes indirect losses, and the loss of capital stock. It is noted that in an emergency situation, a wide range of countermeasures are available, as outlined in the UK Recovery Handbook (Health Protection Agency, 2009) and for such a range of countermeasures, a wide range of costs estimates can be derived (e.g. placing ferrocyn in animal feed that limits ^{137}Cs transfer to milk which would be a cheaper countermeasure compared to slaughtering and disposing of livestock).

Further details of modelling the economic effects of a large nuclear accident in the UK are provided in a companion paper (Ashley et al., 2017).

4. Factors affecting the health and economic costs of a nuclear accident

This section is concerned with a number of factors that will influence significantly the costs, in terms of both health and economics, involved with a big nuclear accident. The first of these is the fundamental initial condition particular to the nuclear plant, namely where it is sited, and how close it lies to population centres (Section 4.1). A further initial condition, this time specific to the accident, is the "source term", that comprises the quantity and isotopic constitution of the nuclear material released, the time delay before the release occurs and the duration of the release (Section 4.2). The weather at the time of the accident (wind speed and direction, dry or wet weather) is an exogenous variable that will then determine where the fallout is deposited (Section 4.3). The final factor is one that is to a large degree under the control of the authorities after a big nuclear accident, namely the extent of the harvesting and sale of food from areas subject to some degree of radioactive contamination (Section 4.4).

4.1. Siting and demography

A complete account of the history on the siting of nuclear power stations in the United Kingdom is provided in Grimston et al. (2014). In summary, past differences in attitudes to the siting nuclear power stations in the UK have occurred in four phases.

In the first phase (roughly 1945–1965, that included the Magnox reactor programme) siting decisions were made with considerable caution, with distance from populations being a key driver of siting policy. In the second phase (roughly 1965–1985, which included the AGR programme), siting, with regard to the density of local population, was more relaxed due to the belief that the safety and reliability of the reactors had been significantly improved. The third phase (roughly 1985–2005, which included the decision to build Sizewell B) reverted back to conservative siting plans. The main reason was the PWR technology was new to the UK, but other factors played a part such as the accidents at TMI-2 and Chernobyl, In the fourth phase (2005 onwards) a more positive attitude toward siting of future nuclear plants is observed, due to greater public and political support even after the accident at Fukushima Dai-ichi, although all the approved sites (with one exception) are those already used for nuclear power plants.

One of the earliest tools to account for the impact on the public located near a nuclear power station was developed by Farmer, who developed a methodology that considered the trade-off between the frequency and consequence of an accident occurring (Farmer, 1967). This work indicated that the relative risk for a remote site compared to a hypothetical 'town' is approximately a factor of 10 lower; and the relative risk for a remote site compared to a hypothetical 'city' is approximately a factor of 100 lower. Subsequent work has noted that certain risk factors may be increased at a remote site (compared to a 'town' or 'city' site), such as less reliable grid interconnections due to longer transmission lines. Since this report, probabilistic safety assessments (Fullwood, 1999), notably Level-3 PSAs as outlined in OECD-NEA, (2000), have been developed further to both ascertain the probabilities and corresponding consequences of various accident sequences for various reactor technologies.

Present UK policy has involved the use of strategic siting assessments to look at potential sites for new nuclear reactors in the UK (DECC, 2011a,b). The strategic siting assessment includes twelve factors that were used in aiding the decision to grant development consent, including:

(1) demographics;
(2) proximity to military activities;
(3) flooding, tsunami and storm surge;
(4) coastal processes;
(5) proximity to hazardous industrial facilities and operations;
(6) proximity to civil aircraft movements;
(7) internationally designated sites of ecological importance;
(8) nationally designated sites of ecological importance;
(9) areas of amenity, cultural heritage and landscape value;
(10) size of site to accommodate operation;
(11) access to suitable sources of cooling;
(12) capability of the site to store spent fuel and intermediate level waste.

It should be noted that the population around the nuclear facility is not uniform and varies throughout the year; also, certain demographics will be affected and will behave in different ways. For instance, for a specific incident, young families may be encouraged to evacuate whereas the elderly and infirm may be advised against evacuating. Self-evacuation is almost impossible to gauge, but is almost certainly going to happen in societies where access to personal transport is high, e.g. self-evacuation following the accident at TMI-2 whereas the evacuation of Pripyat following the accident at Chernobyl was organised by the authorities. Additional variability will depend on the nature of the surroundings, whether there are hospitals, schools, homes, etc.: and depend on what people are doing at the time of the incident, i.e. inside or outside buildings, in home or away from home.

4.2. Source terms

As alluded to earlier, the consequence of an event occurring is not just the number of people who may be affected but how they are affected. From a radiological stand-point, this centres on the quantities of radionuclides released over the timeframe of the accident, referred to as the 'source term'.

As there are various different accidents that can occur at a nuclear power plant, there are different modes in which nuclear material may be released that affect: (1) the quantities of radionuclides being released (generally described in terms of its activity), (2) the duration of pre-release (i.e. the time between the initial alarm and the release occurring), and (3) the duration of the release. For the accident of Chernobyl 5300 PBq of activity (excluding noble gases) was released, whereas for Fukushima Dai-ichi 520 (340–780) PBq of activity was released (Steinhauser et al., 2014). A summary of source terms for other nuclear incidents can be found in Sanderson et al. (1997).

It is worth noting here that there is no direct relationship between the overall amount of activity released and the dose received – the isotopic composition, the physical form and its exposure pathway (e.g. external "shine" from the ground or the air, ingestion, and inhalation) are all significant factors. Such conversion factors for each radionuclide are provided by the International Commission for Radiological Protection (Eckerman et al., 2013).

Other factors that can affect the severity of the source term are: whether the release is airborne or liquid in nature; the height of the release; and the energy (or heat) in the release.

4.3. Weather and dispersion

For airborne releases, weather plays a significant role in how radionuclides are dispersed. There are several factors here that affect how radionuclides disperse including: wind speed, atmospheric turbulence (typically, in the past, described by Pasquill atmospheric stability classes (Pasquill, 1961)), and precipitation. These may vary over the release time, as highlighted by the release pattern seen at Fukushima Dai-ichi, shown in Figs. 1 and 2. In general statistics on these aspects is available so as for the source term a statistical confidence level can be considered (though in this case on the basis of real statistics). A factor that influences weather is the time of year and the time of day, but it should be possible to include these in the statistical analysis.

The earliest dispersion models that have been used focussed on two-dimensional Gaussian techniques to char-acterise plumes; with two dispersion parameters used to approximate cross-winds and vertical winds, essentially fixed at the point of release, though some variation was possible by restarting calculations after some time. The outputs of such a code are given in the form of a series of graphs in the report NRPB-R91, (now Public Health England) (Clarke, 1979). More sophisticated codes have since been developed, such as the UK Met Office NAME III program (Jones et al., 2007) that uses Lagrangian modelling in three dimensions to calculate the behaviour of plumes, which allows actual meteorological data to be used, though these require more computing power and are typically much more computationally expensive.[8] A report by OECD-NEA (2000) discussed some aspects of emergency management codes as they were at that time.

It is important, however, to recognise that a pre-event calculation can only give a probabilistic view by compiling a set of calculations for different weather conditions derived from various meteorological data, which may be used in planning. For example, it will indicate the likely extent of areas for specific countermeasures, which as the figures show are not uniformly distributed about the site. This will also indicate the likely costs which can be included in calculations of whether safety measures need to be improved. During an event, the weather type and direction may change and it is unlikely that it will match any of the pre-event scenarios. Thus, emergency preparedness plans must be flexible enough to deal with real-time changes. The use of a code such as PACE may be used at this stage to predict behaviour, but this will require some way of postulating the source term also.

4.4. Food

The final major aspect concerns food. As the radioactive material is deposited it will move into the food cycle (and can affect sources of water). Besides what is grown in people's gardens, there is likely to be large areas which, even if for only a short time, will have bans on the sale (and hence distribution of) food both animal and vegetable. Two examples from UK experience are the banning of milk in Cumbria (then Cumberland) in 1957 for about a month in the vicinity of the plant, following the Windscale Piles accident (Arnold, 1992) and the long-term restrictions on sheep following the Chernobyl accident which continued for some UK farms for over 25 years (Waddington et al., 2017b). Clearly, as above, the time of year and, to a more limited extent the time of day, are both important factors. The levels of radiation in food which cause them to be banned also need to be established. Further details on how radionuclides enter the food-chain and how this is modelled can be found in Till and Grogan (2008).

5. Conclusions

The accident at Fukushima Dai-ichi has highlighted and reinforced the need for emergency preparedness and response plans to be prepared prior to the operation of any nuclear

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[8] Gaussian dispersion models treat the dispersed pollutant as having a Gaussian distribution, (i.e. a normal probability distribution). Lagrangian dispersion models treat the dispersed pollutant as individual packets (i.e. particles) that move via a random walk in the atmosphere. A discussion of the practical differences between these dispersion models can be found in Haywood (2011).

facilities that have the potential to release material to the environment.

This paper has reviewed, from a UK perspective, the role of emergency preparedness and response plans, drawing on information from both Chernobyl and Fukushima Dai-ichi. The phases of a nuclear accident leading to an off-site release have been considered, and a review has been provided of the measures that can be adopted at each phase to mitigate effects on the public. The current UK approach has been examined, and a comparison has been made of UK and international stances.

It is clear that a second major reactor accident has spurred efforts nationally and internationally to improve ways of coping with a big nuclear accident, should it happen. New analysis methods are emerging, and, in parallel, international committees of experts are attempting to refine the advice offered to governments who might face a large reactor accident in the future. One potential concern is the desire for too great a level of prescription, which might conflict with the degree of flexibility required by the fundamental principles of radiological protection as enunciated by the ICRP, specifically those of "justification" and "optimization". We observe also that it is necessary to consider societal effects, economic effects and non-radiological health effects in addition to radiological harm when drawing up plans and taking decisions after a major nuclear accident. The lesson from both Chernobyl and Fukushima Dai-ichi is that while great resources were put in place to keep radiation harm to the public to a very low level, this might have been at the expense of psychological and general health.

Acknowledgements

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