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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.



## 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 (Strawn, 2013), and the larger accident at Chernobyl where losses have been estimated in the region of hundreds of billions of dollars (IAEA, 2002).[1]

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., 2016 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.

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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[2] 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, "MACCS2" (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-

[2] And to a limited extent indicate some of the effects these protective actions have on the environment.