# 18 Late lessons from Chernobyl, early warnings from Fukushima

Paul Dorfman, Aleksandra Fucic and Stephen Thomas

The nuclear accident at Fukushima in Japan occurred almost exactly 25 years after the Chernobyl nuclear accident in 1986. Analysis of each provides valuable late and early lessons that could prove helpful to decision-makers and the public as plans are made to meet the energy demands of the coming decades while responding to the growing environmental costs of climate change and the need to ensure energy security in a politically unstable world.

This chapter explores some key aspects of the Chernobyl and Fukushima accidents, the radiation releases, their effects and their implications for any construction of new nuclear plants in Europe. There are also lessons to be learned about nuclear construction costs, liabilities, future investments and risk assessment of foreseeable and unexpected events that affect people and the environment.

Since health consequences may start to arise from the Fukushima accident and be documented over the next 5–40 years, a key lesson to be learned concerns the multifactorial nature of the event. In planning future radiation protection, preventive measures and bio-monitoring of exposed populations, it will be of great importance to integrate the available data on both cancer and non-cancer diseases following overexposure to ionising radiation; adopt a complex approach to interpreting data, considering the impacts of age, gender and geographical dispersion of affected individuals; and integrate the evaluation of latency periods between exposure and disease diagnosis development for each cancer type.

Given the degree of uncertainty and complexity attached to even the most tightly framed and rigorous nuclear risk assessment, attempts to weight the magnitude of accident by the expected probability of occurrence have proven problematic, since these essentially theoretical calculations can only be based on sets of pre-conditioning assumptions. This is not an arcane philosophical point but rather a very practical issue with significant implications for the proper management of nuclear risk. With its failure to plan for the cascade of unexpected beyond design-base accidents, the regulatory emphasis on risk-based probabilistic assessment has proven very limited. An urgent reappraisal of this approach and its real-life application seems overdue.

Whatever one's view of the risks and benefits of nuclear energy, it is clear that the possibility of catastrophic accidents and consequent economic liabilities must be factored into the policy and regulatory decision-making process. In the context of current collective knowledge on nuclear risks, planned pan-European liability regimes will need significant re-evaluation.

## 18.1 Introduction

The chapter on climate change has demonstrated the need to plan for a low-carbon energy future, and an ambitious long-term target of 80–95 % reductions in greenhouse gases by 2050 has been set by the European Union (EU) (EU, 2011). Although some scenarios suggest that future energy demands could be met without nuclear electricity production ([1]) (IPPC, 2011; SRU, 2011b), others suggest greater reliance on new nuclear capacity in Europe ([2]), as well as Asia (Yi-chong, 2011).

At present, nuclear energy is used in 30 countries and Taiwan, producing roughly 13 % of the world's commercial electricity, and currently 14 countries and Taiwan are in the process of planning the building of new nuclear capacity. There are 435 nuclear power reactors in operation around the world — at the peak of nuclear generation in 2002 there were 444 — of which 189 are in pan-Europe and the Russian Federation, comprising about one third of the world's 146 civil reactors, with France alone generating close to half of the EU's nuclear production from 58 plants (Schneider et al., 2011).

With mounting public concern and policy recognition over the speed and pace of low carbon energy transition needed to mitigate climate change, nuclear power has been reframed as a response to the threat of global warming. Proponents conclude that nuclear provides a secure supply of low carbon base-load energy, safe in operation and powered by a reliable source of uranium supplies (IAEA, 2000; EDF, 2012; NIA, 2012; WNA, 2012). However, at the heart of the question of nuclear power are differing views on how to apply foresight, precaution and responsibility in the context of the possibility of accidents.

## 18.2 Chernobyl

On the 26th April 1986 an explosion at the Chernobyl Nuclear Power Plant No. 4 in Northern Ukraine resulted in widespread cross-boundary atmospheric pollution by fission-product radioisotopes. Following what is understood to have been a misconceived reactor experiment, a positive void coefficient caused reactivity excursion, resulting in a steam explosion that destroyed the plant. Over the six days of open containment 30–60 % of the Chernobyl reactor core's fission products were released to the atmosphere, 6.7 tonnes of material from the core. This material was projected high into the atmosphere, spreading radioactive isotopes over more than 200 000 square kilometres ($km^2$) of Europe (UNDP, 2002). In response, the authorities evacuated and subsequently relocated around 115 000 people from areas surrounding the reactor; after 1986, a further 220 000 people from Belarus, the Russian Federation and Ukraine were re-settled (UNSCEAR, 2008).

Each day some 3 500 workers enter the 30 kilometre exclusion zone, established by the Ukraine, to monitor, clean and guard the site, where remediation work is likely to continue until 2065 — although less than half the resources needed to fund the remediation have been raised, and the completion date has slipped by a decade. The work includes managing the long-term storage of waste from Reactor 4, and more than 20 000 spent fuel canisters from the site's other reactors. Significant quantities of radioactive waste continue to be generated — partly due to ongoing flooding in some areas of the waste-storage buildings and Reactor 4's turbine hall, forcing the pumped discharge and on-site storage of around 300 000 litres of radioactively contaminated water per month (Peplow, 2011).

### *18.2.1 Post-Chernobyl meta-analyses*

Whilst it is outside the remit of this discussion to rehearse in detail the very broad literature on radiation risk epidemiology, it is sufficient to note that the precise estimation of acute and long-term health effects as a result of the Chernobyl accident remains problematic and subject to ongoing critique. This is because epidemiological evidence on health impacts is contradictory and conflicting. The link between radiation and the aetiology of cancer and leukaemia is well established — but the debate continues about the risks of those diseases, in particular childhood cancer and leukaemia, from Chernobyl releases and in the vicinity of other operational nuclear installations elsewhere (Box 18.1).

It is therefore unsurprising to see significant differences in the understanding and interpretation

([1]) The German governments Energiekonzept involves a reduction in primary energy consumption by 50 % between 2008 and 2050, a reduction in electricity consumption of 25 %, and a reduction in carbon emissions by 80 % (SRU, 2011a).

([2]) Planning for the same carbon target as the German government, the UK government's National Policy Statement on Energy envisages a doubling of electricity demand by 2050 and a potential trebling of total installed capacity (DECC, 2011). As a result, the policy foresees the construction of a series of new nuclear plants in the United Kingdom.

**Box 18.1 Low level radiation epidemiology**

There are significant uncertainties associated with the choice of differing models used to interpolate radiation risk between populations with different background disease rates; for the projection of risk over time; for the extrapolation of risks following primarily a single external high dose and a high dose-rate in contrast to cumulative low dose and low dose-rate exposures (ARCH, 2010). Despite this, the analysis of incidence and distribution of disease (epidemiology) remains fundamental to radiation-risk determination and standard setting. Epidemiological investigations ranging from the Japanese atomic bomb life span survivor studies to more numerically and temporally limited studies have provided a weight of evidence about the effects of ionizing radiation on humans. Whilst a range of studies suggests no causal or associative link between routine discharges from operating nuclear plants (Jablon et al., 1991; Yoshimoto et al, 2004; Evrard et al., 2006; COMARE, 2011), this important debate is ongoing.

One of the most significant data sets in this debate comprises a national case-control study, funded and published by the Federal Office for Radiation Protection on behalf of the German Federal Ministry for the Environment and conducted by the German Childhood Cancer Registry on childhood cancer near nuclear installations. This study investigated childhood leukaemia and cancer incidence near nuclear plants from 1980 to 2003, providing evidence of a significant increase in childhood leukaemia and cancer risk near to nuclear plants in Germany (Kaatsch et al., 2007; Kaatsch et al., 2008a; Kaatsch et al., 2008b; Spix et al., 2008). The German Federal Office for Radiation Protection formally confirmed these findings, stating that 'in the vicinity of nuclear power plants, an increased risk of 60 % was observed for all types of childhood cancer, and for childhood leukaemia the risk doubled equaling a risk increase of approximately 100 %' (BfS, 2008). In response, the UK scientific advisory body Committee on Medical Aspects of Radiation in the Environment (COMARE) 14th Report (2011) critiqued the German study, and discounted the findings, noting that COMARE's primary analysis of the latest British data had revealed no significant evidence of an association between risk of childhood leukaemia and living in proximity to a UK nuclear facility (COMARE, 2011). The Committee also pointed to the role of unidentified viral infections rather than radiation exposure in the aetiology of childhood leukaemia near nuclear power plant (Kinlen, 2011).

Subsequently, in early 2012, a further nation-wide case-controlled investigation by Institut Nationale de la Santé et de la Recherche Medicale (INSERM) on behalf of France's nuclear safety research body, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), demonstrated a statistically significant doubling of the incidence of leukaemia near to nuclear plants in France between 2002 and 2007 (Sermage-Faure et al., 2012). However, neither a causal link nor an association between gaseous discharges and ill health were established.

of Chernobyl health effects. The problem may be exacerbated by the nature of previous studies, which have been described as forming a patchwork rather than a comprehensive, structured attempt to delineate the overall health consequences of the accident (ARCH, 2010). Nevertheless, despite differences in the types of exposure, doses, dose rates and applied methodologies, data on the health consequences of the Chernobyl accident add to knowledge collected from atomic bomb victims and from populations over-exposed during nuclear accidents and nuclear weapons testing. Integration of the available data on related health risks gives added value in preparing radiation protection protocols and in the management of subsequent nuclear accidents, such as Fukushima.

Focusing only on Belarus, Ukraine and the Russian Federation, and no other exposed countries and populations, the International Atomic Energy Authority (IAEA) convened the Chernobyl Forum (2005) that predicted a potential total mortality of about 4 000. Discounting the significantly raised childhood thyroid cancer incidence ([3]), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2008) found no evidence of increases in overall cancer incidence or mortality rates or in rates of non-malignant

([3]) In Belarus, the Russian Federation and Ukraine nearly 5 000 cases of thyroid cancer have now been diagnosed to date among children who were aged up to 18 years at the time of the accident (WHO, 2006).

disorders that could be related to radiation exposure. Both of these estimates were subject to critical analysis by Yablokov et al. (2006), who suggested a higher death toll as a consequence of the Chernobyl fall-out. Based on Belarus' national cancer statistics, the study predicted approximately 270 000 cancer incidences — of which 93 000 would prove fatal. A follow-up meta-analysis, which included Belarus, Russia and Ukraine, suggested further increased predicted premature deaths as a result of the radioactivity released (Yablokov et al., 2007).

It is worth noting that UNSCEAR (2008) decided not to use models to project absolute numbers of effects in populations exposed to low radiation doses from the Chernobyl accident, because of unacceptable uncertainties in the predictions. Given that UNSCEAR (1993) and IAEA (1996) estimate a total world-wide collective dose of 600 000 person-Sieverts over 50 years from Chernobyl fallout, and the standard risk estimate from the International Commission on Radiological Protection (ICRP, 2005) is 0.057 fatal cancers per Sievert, this suggests an estimate of about 34 000 fatal cancers over that time period (Ramana, 2009). Given the widely accepted linear no-threshold radiation risk model may overstate or understate risks by a factor of two (BIER VII, 2006) — then estimates for post-Chernobyl cancer mortality extrapolation may range from 17 000 to 68 000 over 50 years.

These differences in meta-analysis estimates also obtain around post-Chernobyl leukemia aetiology: Whilst UNSCEAR (2008) suggests that the incidence of leukaemia in the general population, one of the main concerns owing to the shorter time expected between exposure and occurrence compared with solid cancers, does not appear to be elevated, the UK government scientific advisory Committee Examining Radiation Risks of Internal Emitters (CERRIE, 2004) concluded that, in the judgment of a large majority of committee members, it is likely that radioactive fallout from the Chernobyl accident resulted in an increased risk of infant leukaemia in the exposed populations.

In addition, there were immediate deaths of emergency workers and firefighters resulting from acute radiation exposure. Treatment of these people also placed hospital staff and funeral workers at risk of radiation over-exposure (Box 18.2).

### *18.2.2 Post-Chernobyl cancer risk*

The most susceptible populations for thyroid disease development after nuclear overexposure are pre- and post-natally exposed children, young people and women (Shimizu, 1991; Nagataki and Nystrom, 2002; McCarthy, 1997, Prysyazhnyuk, 2007). As both external and internal exposure to ionizing radiation can cause thyroid cancer, similar incidences were detected amongst those exposed in Hiroshima, Nagasaki, and following the Chernobyl accident, with a much higher prevalence in children than adults (Larsen et al., 1982; Pacini et al., 1999). Increased levels of anti-thyroid antibodies, hyper- or

**Box 18.2 Acute medical care of Chernobyl radiation casualties**

'By May 5, 10 days after the accident, 172 individuals, 47 of them fire fighters, had been admitted Hospital #6 with the most severe form of radiation sickness. All had visible burns, were in severe pain and had little chance of survival. It should be remembered that all medical staff entering the rooms of irradiated patients were also exposed to intensive radiation from victims whom they were supposed to treat. We should express deep gratitude to all personnel, from the reception area, sterile rooms, specialized offices and laboratorie, to dosimeter controllers for their tireless service and sacrifice. As experienced radio-biologists, we understood that some of our patients would not survive — they had received radiation doses of more than 1 000 rad, which resulted in large and deep radiation burns and the penetration of their bodies by significant amounts of radioactive material. Therefore, we planned for their funerals, including the selection of appropriate location(s) and estimates of the necessary depth of tombs to avoid increases in the radiation level above the tomb. We needed to equip vehicles that would transport the dead bodies with strong protection layers quickly so as not to harm the drivers and to avoid radiation pollution between the hospital and the cemetery' (Grigoriev, 2012).

Despite these challenging circumstances it is important to note that, thanks to round-the-clock care over many months by a dedicated team of doctors, and through a wide range of holistic treatments, the lives of many patients with acute radiation sickness were saved (Grigoriev, personal communication, 2012).

hypothyroidism and thyroid cancer have different latency periods after exposure, even at relatively low doses of less than 1 Sv (Nagataki, 1994), and the data from the Chernobyl and atomic bomb victims should be of significance in bio-monitoring exposed subjects following the Fukushima accident.

In recent years, an increased incidence of leukaemia has been described among clean-up workers and the population aged 0–5 years at the time of the Chernobyl accident (Noschenko et al., 2010; Romanenko et al., 2008). Such a trend may continue as the latency period for leukaemia can exceed more than 40 years, as shown for myelodisplastic syndrome (pre-leukaemia) and the related increased risk for acute myeloid leukaemia after the Hiroshima and Nagasaki A-bomb detonations (Iwanaga et al., 2011).

Lactating women may be more susceptible to ionizing radiation, as breast tissue bio-accumulates iodine as part of the physiological process of its accumulation in breast milk. These levels of accumulated radioiodine in breast milk may also increase the risk of thyroid cancer in newborns (Bland et al., 1969; Tazebay et al., 2000; Hatch et al., 2005). This information may prove necessary and significant for breastfeeding sub-populations in cases of increased radioiodine levels. Similar results were shown for breast cancer incidence after Hiroshima and Nagasaki, as the highest dose-specific excess relative risk was among women exposed prior to the age of 20 years (Land et al., 2003), with the latency period for breast cancer development at approximately 10 years for both those affected by the atomic bombs and Chernobyl (Tokunaga, 1979; Pukkala et al., 2006), with raised incidence of breast cancer found among young and pre-menopausal women exposed during the Chernobyl accident.

In order to improve preventive measures following over-exposure to ionizing radiation, it is imperative that the latency period between exposure and disease development be re-evaluated for each cancer type; as the currently approved 10-year latency period of international radiation protection agencies does not seem in accord with data reported for certain solid cancers, with a 4-year latency period reported post-Chernobyl (UNSCEAR, 2008; Ivanov et al., 2009). The question of latency in cancer induction is further complicated through radiation biology discoveries about the underlying complex cellular response mechanisms by which radiation interacts with living organisms (Box 18.3).

### *18.2.3 Post-Chernobyl non-cancer health consequences*

Evaluation of health risks relating to accidental overexposure to ionizing radiation is usually limited to estimations of increased cancer incidence; however, current knowledge of complex interactions of ionizing radiation and living systems demonstrates that in addition to increasing cancer risk, exposure to radiation may disturb a number of other biological pathways. For example, analyses of the Japanese A-bomb survivor Life Span Studies mortality data (1950–1997) show a statistically significant dose-response pattern for death from diseases other than cancer, and these excesses do not seem limited to any particular disease (Preston et al., 2003; Yamada et al., 2004). Disturbance of pathways by ionizing radiation may be modified by age, gender, psychological status of a person (stress) or diet, all of which impact on the final increase of health risk and its duration.

Correspondingly, the Chernobyl nuclear accident also caused non-cancerous diseases, such as cardiovascular and immunological disorders, and cataracts (Hatch et al., 2005; Cardis, 2011). In children exposed to long-term low doses after the Chernobyl nuclear accident, a significant increase of cardiovascular diseases was reported, followed by decreased physical status (Kostenko, 2005). A significant increase in cardiovascular disorders was also recorded among adults (Bebeshko et al., 2007; Eglite et al., 2009), which was compatible with atomic bomb survivor data (Zubovksi and Tararukhina, 1999; Shimizu et al., 2010).

Immunological disturbances have been reported for both clean-up workers and the environmentally exposed population affected by the Chernobyl accident. In children, marked immune disturbances were detected after Chernobyl, with significant differences between directly exposed children and children born to irradiated parents (Baleva et al., 2011). In children residing in the zone 30–90 km from the Chernobyl site, immunological disturbances arising more than 20 years after the nuclear accident are still clinically presenting (Sajjadieh et al., 2009). Additionally, immunological disorders are combined with inflammations and an increased risk of cardiovascular disease in both those exposed to radiation following atomic bomb and the Chernobyl accident (Kusunogi et al., 1999; Hayashi et al., 2003; Kusunoki et al., 2010; Timoshevskiĭ et al., 2011). It has also been suggested that data regarding cataracts in subjects participating in the clean-up and building of sarcophagi in Chernobyl may fail to support the ICRP 60 risk guideline assumption of a

**Box 18.3 Genomic instability and the bystander effect**

The theoretical underpinning of the biological effects of ionizing radiation is based on sophisticated variants of target theory, such as track structure theory. Target theory stipulates that the biological targets damaged in the cell are relevant to the endpoint: for example, damage to a tumour suppressor gene might lead to cancer. Target theory holds for single locus hereditary disease but there were problems in applying it to somatic cell endpoints such as cancer. However, in 1992 evidence inconsistent with target theory emerged in the form of two effects, genomic instability (Khadim et al., 1992) and the bystander effect (Nagasawa and Little, 1992). Such effects are collectively known as non-targeted effects because the target is large enough to encompass the whole nucleus of the cell, and radiation does not directly affect the damaged cell. Genomic instability is characterised by the acquisition, *de novo*, of various kinds of damage, mostly to DNA, up to several cell generations after the exposure. Damage associated with genomic instability may not be directly caused by the radiation but is a secondary response of the cell to radiation insult. The bystander effect occurs in cells that experienced no radiation events, but are neighbours of cells that have.

These phenomena pose a set of significant research questions for the understanding of the underlying mechanisms involved, and could imply the need for a re-appraisal of the target theory approach, and the emergence of a new theoretical framework for the biological bases of the effects of radiation. Perhaps the most worrying aspect from the public health perspective is the potential for trans-generationally inherited genomic instability. A number of mechanistic hypotheses have been proposed to explain genomic instability (ARCH, 2011), and Baverstock and Karotki (2011) have suggested a further explanatory conceptual framework.

Whilst two European Commission projects, RISC-RAD (http://riscrad.org/) and NOTE (http://www.note-ip.org), specifically directed at obtaining a better understanding of genomic instability, have reported — so far no replacement for the underpinning framework based on target theory has emerged. This may be because, as usual with radiation biology, the picture is complex, especially in distinguishing between the interpretation of results from *in vitro* and *in vivo* studies. Yet more recent work indicates that additional mechanisms may also be important for the understanding of the impact of genomic instability and bystander effects on radiation protection regulation: Mukherjee et al. (2012) suggest that radiation-induced chromosomal instability may also result from inflammatory processes having the potential to contribute secondary damage expressed as non-targeted and delayed radiation effects. Lorimore et al. (2011) conclude that complex multi-cellular interactions resulting from bystander effects may influence carcinogenic susceptibility, with inflammatory processes responsible for mediating and sustaining the durable effects of ionizing radiation. Given that the genotype of each individual is a key determinant of carcogenic susceptibility, then genotype-directed tissue responses may be important determinants of understanding the specific consequence of radiation exposure in different individuals (ibid). One potentially significant implication of these finding is that differing people may have differing responses and susceptibilities to radiation insult.

5-Gy threshold for detectable opacities, but rather point to a dose-effect threshold of under 1 Gy (Worgul et al., 2007; Chumak et al., 2007).

One of the most at risk groups is infants and children (Box 18.4).

Although increased levels of stress and depression have been found in children and teenagers born to exposed parents (Panchenko et al., 2005); in general, post-Chernobyl psychological disturbances, stress, depression and suicides in children and adults have been poorly described. The significance of psychological impacts on survival rates after exposure may prove important, as there has been increased suicide rates among clean-up workers (Rahu et al., 1997).

## 18.3 Fukushima Dai-ichi

On 11 March 2011, the Japanese Great Easter Earthquake, involving 5 to 10 metres of slip motion on fault zones more than 100 kilometres in length along the Japanese Trench Subduction Zone, struck the east coast of Japan triggering the shut down of 10 operating nuclear power plants. At the time of the earthquake, Fukushima Dai-ichi units 1, 2, and 3 were operating at full power (Marshall and Reardon, 2011). The plants, designed to withstand a maximum 8.2 earthquake on the logarithmic Richter scale, received a seismic shock 9–15 times higher than the design limit (Park, 2011). At the time of the accident, the radiological inventory at risk within the 6 reactor cores comprised 487 tonnes of uranium, of which 95 tonnes include 6 %

**Box 18.4 Infants and children: susceptible sub-populations**

Children are generally more susceptible to ionizing radiation and other environmental pollutants, and may suffer from life-long health consequences, some of which may be pre-natally determined (EEA, 1999; BCPT, 2008; Fucic et al., 2008). Pathological changes in reproductive function, peri-natal illnesses and mortality were reported several years after the Chernobyl nuclear accident. The birth rate was additionally influenced by migration of the population, use of contraceptives, stress and induced abortions (Kulakov et al., 1993), and a peak in Down Syndrome cases was observed in newborns born in 1987, one year after the Chernobyl nuclear accident (Zatsepin, 2007). New DNA mutations in children born after the accident to irradiated parents and living in non-contaminated territories confirm the long-term health risks in the exposed population (Aghajanyan and Suskov, 2009; Weinberg et al., 1997). Additionally, trans-placental exposure to radioisotopes may significantly increase the rate of spontaneous miscarriages without clinical symptoms in mothers or difference in level of genome damage between women exposed to external and internal radiation by radioisotopes (Fucic et al., 2008).

plutonium from the MOX assemblies ([4]). There were a further 1 838 tonnes of stored spent fuel on the site, including 1 097 tonnes in the central pool store (Large, 2011a).

At the Fukushima Dai-ichi No. 1 plant, site emergency diesel generators provided on-site power to the reactor cooling pumps and other essential services of the three operating nuclear plants, as well as cooling for the six-reactor unit spent fuel ponds, and also for the central spent fuel store (Brumfiel and Cyranoski, 2011a). On-site power supplies continued in operation for just over one hour until the entire site was swamped by a 15 metre tsunami with the total wave height amplified by the backwash as the tsunami wave was contained and reflected by the heavily terraced western section of the site. This part of the site contained four reactors, three of which had been fully operational at the time of the earthquake, resulting in the failure in two or three of the nuclear power plants robust sealed containment structures as water poured into the plants (Large, 2011b) ([5]) (Box 18.5).

The collapse of the Japanese electricity distribution grid resulted in the shut-down of individual nuclear power plant's electricity systems, resulting in loss of essential reactor fuel cooling and crucial instrumentation and control systems. This loss of offsite power and onsite AC power combined with the rapid discharge of DC batteries led to a complete station blackout which disabled the emergency core cooling systems which, in turn, disabled the monitoring of critical parameters such as reactor water levels and open critical

**Box 18.5 Japanese earthquakes and tsunamis**

Minoura et al. (2001) conclude that traces of large-scale invasion tsunami recorded in the coastal sequences of the Sendai plain show an approximate 1 000-year re-occurrence interval, noting that more than 1 100 years have passed since the historic Jgan tsunami and, given the reoccurrence interval, the possibility of a large tsunami striking the Sendai plain was high. Their findings indicated that a tsunami similar to Jgan would inundate the present coastal plain for about 2.5 to 3 km inland. More recently, post-Fukushima, the University of Tokyo's Earthquake Research Institute concluded that risk of a large-scale earthquake in the region has risen considerably since the Great East Japan Earthquake of 2011. This implies that, since neither practical nor theoretical models can properly determine the dynamics of imminent large earthquakes, much greater emphasis may need to be placed on natural hazards for nuclear risk assessment (Park, 2011).

([4]) MOX (mixed oxide) is a form of nuclear fuel designed for use in breeder reactors, consisting of a blend of uranium and plutonium oxides.

([5]) According to the Japanese Commission tasked with reviewing the disaster, the tsunami that struck the plant was twice as high as the highest wave predicted by previous risk assessments, and the assumption made by Tokyo Electric Power Company (TEPCO) that the plant's cooling system would continue to function after the tsunami struck worsened the disaster (The Investigation Committee, 2011).

safety valves, cascading to significant fuel and containment overheating and damage (Buongiorno, 2011). As Tokyo Electric Power Company (TEPCO) was unable to restore either on or off-site power; the entire Fukushima Dai-ichi nuclear complex went into, and remained, in station blackout.

The blackout meant that no safety systems remained intact, just passive design features and defense in depth layers — representing a beyond design base accident. In Unit 1, steam was bubbled through the suppression pools, further increasing water temperature, and water leaving the core was not replaced. As the water dropped below the top of the fuel, the temperature in the fuel and cladding began to rise rapidly, causing fuel degradation. The zirconium in the cladding oxidized, releasing hydrogen into the containment dry-well, and after a short time, pressure levels in the containment were at or above the design pressure, raising risk of containment rupture. In response, operators manually opened valves to release steam from containment into the reactor building, and the vented steam containing hydrogen violently and exothermally ignited, destroying the reactor building, allowing gaseous fission products to escape, and exposing elements of the spent fuel to open containment.

Units 3 and 4 soon experienced similar beyond design-based cascading conditions. At this point, elevated radiation levels of several fission products including Caesium 137 and I-131 were detected at the reactor buildings, and the plant boundary; providing the first indication that some fuel in the reactor had already melted (Butler, 2011). The presence of hydrogen and these volatile fission products in the released steam suggested that the temperature had severely damaged the fuel cladding inside the reactor pressure vessel (Bonin and Slugen, 2011).

Backup generators and batteries arrived some hours later, restoring partial power to plant, but these were insufficient to power any of the cooling pumps; instead smaller ad hoc fire pumps were used to pump boranated seawater into the reactor core and containment.

Within a few hours the reactor cores of the three operating units were subject to varying degrees of meltdown. The molten fuel had slumped to the bottom of the reactor pressure vessels, the reactor pressure vessels themselves had failed and, in various degrees, the primary containment of the pressure suppression system had failed. What remained of the reactor instrumentation clearly indicated an ongoing and deteriorating situation — with thermal activity within the reactor buildings resulting in sharp perturbations in containment pressure and radiation levels, particularly within what remained of the primary containment. Doubts about the effectiveness of water injection, and increasing concerns about the volumes of highly contaminated water have been linked to TEPCO's necessary emergency seawater cooling strategy, which also involved unconventional cooling efforts with helicopter and water cannons over the period of a week.

### *18.3.1 Fukushima Dai-ichi radiation releases: cross boundary pollution*

The multiple meltdown of reactors at the Fukushima Daiichi nuclear plant released more radiation than any accident since Chernobyl. Japanese regulatory officials initially assessed the accident as Level 4 on the International Nuclear Event Scale (INES), with the risk level successively rising to 5 and eventually to the maximum of 7 — a rating equal to the Chernobyl disaster. Of primary concern were fission products, readily absorbed by the human body, and the actinides, which act as heavy metal poisons. Caesium 137 (Cs-137) represents the most significant long-term hazard since it is readily taken up in human metabolic, environmental, and agricultural systems.

Early measurements reported from the United States, more than 7 000 km from Fukushima, confirmed maximum concentrations of radioxenon (Xe-133) in excess of 40 becquerel per cubic metre ($Bq/m^3$) — more than 40 000 in excess of normal expected average concentration (Bowyer et al., 2011). High activity concentrations of several man-made radionuclides (I-131, I-132, Te-132, Cs-134 and Cs-137) were detected along the Iberian Peninsula from 28 March to 7 April 2011, deduced through back-trajectories analysis, and verified by activity concentrations (Lozano et al., 2011). Other elevated levels were recorded in air sampling, rainfall and sheep's milk at Thessaloniki, Greece (Manolopoulou et al., 2011). In April and May 2011, fallout radionuclides (Cs-134, Cs-137, I-131) were detected in environmental samples in Krasnoyarsk, Russian central Asia. Similar maximum levels of I-131 and Cs-137/Cs-134 and I-131/Cs-137 ratios in water samples collected in Russia and Greece suggested the high-velocity global movement of radioactive contamination from the Fukushima nuclear accident (Bolsunovsky and Dementyev, 2011); as did results from the Russian rapid response Typhoon monitoring system (Box 18.6).

**Box 18.6 Typhoon monitoring system**

For hazardous facilities located close to larger cities, early stage accident detection, monitoring and warning systems are critical — as they allow for better impact prediction and mitigation of human and environmental consequences. During the Fukushima accident, Typhoon, the early monitoring network associated with the Russian Early Warning and Emergency Response System (REWERS), carried out operational analysis and forecasting for this large-scale radioactive emergency. The monitoring was achieved through a network of observational stations, with radiometric laboratories providing the measurement data for environmental samples. The first Fukushima air mass transfer dispersion calculations made by Typhoon's experts were carried out on the evening of 11 March and on 12 March 2011 — the radiation monitoring network of Roshydromet in the Russian far east was set to rapid measurement mode to obtain radionuclide dose rate measurements every hour. Throughout the accident period at Fukushima, Typhoon cooperated with the IAEA and the World Meteorological Institute in performing calculations and assessments of trans-boundary emissions (Shershakov, 2011).

### *18.3.2 Post-Fukushima Dai-ichi radiation releases: Japan*

The very high population density near the damaged reactors and spent fuel dispersions implies increased risk for local communities. The regulators conducted an initial evacuation of 100 000 people from around Fukushima, and after some hesitation, Japan's Nuclear Safety Commission established a new 20 km evacuation zone, with a further 90 000 people evacuated. Because damaged plant monitoring proved unreliable — on at least four occasions TEPCO retracted findings on the amount and composition of radionuclides in areas in and around the plant, or on reactor parameters — it has been suggested that more complete analyses of reactor-event scenarios and release fractions can be derived from outside Japan (Nature, Editorial, 2011a).

The radiation releases dispersed according to the wind direction and weight of the particles. The radionuclides of interest were I-131, primarily linked to thyroid cancer; Cs-134 and Cs-137, primarily linked to bladder and liver cancer; and strontium, primarily linked to bone disorder and leukaemia. Significantly, there is confirmed isotopic evidence for the release of plutonium into the atmosphere and deposition on the ground in northwest and south of the Fukushima nuclear site (Zheng, 2012).

In September 2011, Japan's Nuclear and Industrial Safety Agency (NISA) estimated that the Fukushima Daiichi plant had released 15 000 terabecquerels Cs-137 to air. Other estimates vary. However, it may well be too early to accurately estimate or determine the scale of the damage and radiological releases (Cyranoski and Brumfiel, 2011). A meta-analysis comprising radionuclide measurement data and atmospheric dispersion modeling (Stohl et al., 2011), reported in Nature (Brumfiel, 2011), suggested that the disaster at Fukushima Daiichi may have released far more radiation than Japanese regulatory estimates; concluding that the emissions started earlier, lasted longer, and were therefore higher than earlier official estimates assume. The study noted that:

> 'While at first sight it seemed fortunate that westerly winds prevailed most of the time during the accident, a different picture emerges from our detailed analysis. Exactly during and following the period of the strongest Cs-137 emissions on 14 and 15 March as well as after another period with strong emissions on 19 March, the radioactive plume was advected over Eastern Honshu Island, where precipitation deposited a large fraction of Cs-137 on land surfaces. The plume was also dispersed quickly over the entire Northern Hemisphere, first reaching North America on 15 March and Europe on 22 March. In general, simulated and observed concentrations of Xe-133 and Cs-137 both at Japanese as well as at remote sites were in good quantitative agreement with each other. Altogether, we estimate that 6.4 TBq of Cs-137, or 19 % of the total fallout until 20 April, were deposited over Japanese land areas, while most of the rest fell over the North Pacific Ocean. Only 0.7 TBq, or 2 % of the total fallout were deposited on land areas other than Japan' (Stohl et al., 2011, p. 28 322).

In other words, Fukushima releases may have contained an estimated 3.5 × 1 016 Bq Cs-137 — roughly twice the official government figure, with almost one fifth falling on the Japanese mainland. This means that the Fukushima release can be

estimated to equal to 40 % of the Cs-137 release from Chernobyl.

By November 2011, the air radiation level in Ibaraki Prefecture was about 0.14 microsievert per hour, equivalent to an annual dose of about 1 millisievert, the safety limit for exposure under normal standards (Ishizuka, 2011). On 14 December 2011, the Japanese Science Ministry assessed caesium fallout in Fukushima Prefecture in the four months after the March 11 disaster at 6.83 MBq/m$^2$ — 94 % of which was concentrated in March, an indication of the severity of radiation discharge shortly after the onset of the accident (Asahi Shimbun, 2011).

Fallout attaches strongly, through ion exchange, to soil — in particular to clay soils common throughout Fukushima. From there the radiocaesium will move slowly into plants, at a rate, and level of risk, that remains unclear. Cs-137 strongly contaminated the soil in large areas of eastern and northeastern Japan, whereas western Japan was relatively sheltered by mountain ranges. The soils around the Fukushima nuclear site and neighboring prefectures have been extensively contaminated with depositions of more than 100 000 and 10 000 megabecquerel per square kilometre (MBq/km$^2$), respectively (Yasunaria et al., 2011).

Correspondingly, it was reported that Fukushima Prefecture survey conducted in June and July 2011 found 33 Cs-137 hot-spots in excess of 1.48 MBq/m$^2$, the level set by the Soviet Union for forced resettlement after the Chernobyl accident. A further 132 locations had combined Cs-137/134 of more than 0.555 MBq/m$^2$, the level at which the Soviet authorities called for voluntary evacuation and imposed a ban on farming (Obe, 2011). Further reports suggest that radiation pollution is widely dispersed in Japan, with the Japanese Science Ministry confirming that Cs-134 and Cs-137 fallout was present in all prefectures, with the highest combined cumulative density of Cs-134 and Cs-137 found in Hitachinaka, Ibaraki Prefecture, at 0.0408 MBq/m$^2$, followed by 0.0226 MBq/m$^2$ in Yamagata, the capital of Yamagata Prefecture, and 0.0174 MBq/m$^2$ in Tokyo's Shinjuku Ward (Ishizuka, 2011). Further reports indicated that the Japanese Environment Ministry estimated the contaminated zones at circa 2 400 km$^2$ over Fukushima and four nearby prefectures, with Cs-134 and Cs-137 the dominant contaminants, mainly contained in the topsoil layer. By definition, shorter-lived isotopes decayed promptly (Reuters, 2011).

The Fukushima accident contaminated large areas of farmland and forests, albeit not as severely or extensively as at Chernobyl. But lacking land for resettlement and facing public outrage over the accident, the Japanese government has embarked on an unprecedented decontamination effort. The Japanese Ministry of the Environment estimates disposals of 15–31 million m$^3$ of contaminated soil and debris by the time the decontamination projects finish (Bird, 2012). The total remediation programme may cover about 500 km$^2$ where radiation dose levels are above 20 millisieverts per year (mSv/year), and about 1 300 km$^2$ where radiation dose levels are between 5 mSv/year and 20 mSv/year (IAEA, 2011a). In order to cope with this level of contamination, and in contradiction to international radiation protection standards, Japanese regulators have raised dose constraints to 20 mSv/year — thereby subjecting schoolchildren to exposures normally only tolerated by adult nuclear workers.

Over the time of the accident, the amount of highly contaminated water on the site rose from 10 000 to 100 000 tonnes, presenting storage capacity difficulties (Reardon, 2011). The French Institute for Radiological Protection and Nuclear Safety estimated that between March and mid July, the amount of radioactive Cs-137 discharged into the Pacific from the Fukushima Daiichi plant amounted to 27.1 million megabecquerels — the greatest amount known to have been released to water from a single accident (Brumfiel and Cyranoski, 2011b).

### *18.3.3 Fukushima Dai-ichi aftermath*

The Japanese government established an independent Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company on June 7, 2011. The Committee's December 2011 Interim Report strongly criticised both central government and TEPCO, noting that both seemed unequal to the task of making decisions in order to stem radiation leaks as the situation at the coastal plant worsened in the days and weeks following the disaster. The Interim Report also noted that Japan's response to the crisis was flawed by poor communication and delays in releasing data on dangerous radiation leaks at the facility, and was critical of the regulatory authorities' 'inappropriate preparation' of nuclear disaster emergency planning (Investigation Committee, 2011).

In a commentary published in *Nature*, committee members Tomoyuki Taira and Yukio Hatoyama, both also members of the House of Representatives in the Japanese Diet, with Hatoyama having served

as Prime Minister of Japan from 2009 until 2010, noted that their investigation had

> 'shown that key pieces of evidence remain incomplete… Particularly important is finding out whether the worst-case scenario occurred: that is, whether self-sustaining nuclear reactions were re-ignited in the core (re-criticality), creating more fission products and heat damage; whether the explosions that rocked the plant days after the earthquake were nuclear in origin, releasing radioactive metals from damaged fuel rods; and whether molten fuel has broken through the reactor's base, threatening environmental contamination' (Tomoyuki and Hatoyama, 2011).

These internal critiques were compounded by others, questioning the relative independence of Japanese regulators:

> 'The Japanese government's main sources for scientific information for Fukushima were the industry ministry's Nuclear and Industrial Safety Agency and the Nuclear Safety Commission. Although these bodies might have expertise in nuclear reactor physics, they also have ties to the nuclear industry that create a conflict of interest. And they were not an effective and prompt source for quick decisions on decontamination or health risks' (Nature, Editorial, 2011b).

Despite these ongoing difficulties, on 16 December 2012, the Japanese Prime Minister, Yoshihiko Noda, declared that the Fukushima nuclear plant had entered the state of cold shutdown; with cold shutdown confirmed by IAEA in their Status Report (IAEA, 2011b) ([6]). However, whilst the reactor temperatures had fallen, there still remained uncertainty about a series of ongoing problems, including the state and level of the nuclear fuel, particularly after confirmation that molten fuel may have eaten through three-quarters of the concrete under unit 1 and damaged the bases of two of the other reactors (TEPCO, 2012). A revised TEPCO timetable suggests that decommissioning, including melted reactor fuel, fuel rod removal, and repair of containment vessels, will take up to 40 years (ibid).

Extrapolating from monthly trade ministry data, the average Japanese nuclear power plant utilisation rate fell to 15.2 % in December 2011 from 67.9 % a year earlier (Reuters, 2012) and, following a further reactor shut-down in January 2012, to 10.3 % (Japan Times, 2012). With almost all of Japan's 54 reactors either offline in early 2012, or scheduled for shutdown, the issue of structural safety looms over any discussion about restarting them. Japan, traditionally a pro-nuclear country, derived about 30 % of its electricity from nuclear plants in 2010 — however opposition has been emerging as an important political issue, and the country's nuclear industry has been repositioning itself for a significantly less attractive market, halting plans to build 14 further reactors by 2030 (Crooks, 2011).

Although post-Fukushima plans for bio-monitoring and epidemiological assessment are still not finalised, it is clear that there will need to be a significant assessment of a wide range of environmental risk factors. Because some of the evacuees have started to settle across the country, long-term follow-up of the victims will need to account for geographic dispersion (Sugihara and Suda, 2011).

The final Report of the National Diet of Japan noted the severity of the future decontamination challenges that Japan faces, and strongly criticised the underlying organisational, institutional and legal framework that resulted in the 'regulatory capture' of safety systems. The Independent Investigation Commission also concluded that the Fukushima accident was a man-made disaster, pointing to the key role of human agency in radiation risk controversies, see Box 18.7.

### *18.3.4 Post-Fukushima nuclear policy impact*

Before the Fukushima accident, most planned nuclear power plant projects were in Asia and Eastern Europe, extending a trend from earlier years, including a dispersion of proposed new reactors around the Pacific seismic region. Between 2009 and April 2011 construction started on nine units; and where projects are going ahead, they do so with strong government support, including implicit or explicit public subsidy (Box 18.8).

Since the Fukushima accident, the number of operating reactors fell from 441 at the beginning of 2011 to 435 in early 2012, with a total net installed

([6]) 'Cold shutdown' normally refers to a state in which a reactor has become subcritical, with the temperature having been brought to a stable level below 95 °C through the operation of normal systems.

**Box 18.7 The Fukushima Nuclear Accident Independent Investigation Commission (NAIIC, 2012)**

'The earthquake and tsunami of 11 March 2011 were natural disasters of a magnitude that shocked the entire world. Although triggered by these cataclysmic events, the subsequent accident at the Fukushima Daiichi Nuclear Power Plant cannot be regarded as a natural disaster. It was a profoundly manmade disaster.'

'The Commission recognizes that the residents in the affected area are still struggling from the effects of the accident. They continue to face grave concerns, including the health effects of radiation exposure, displacement, the dissolution of families, disruption of their lives and lifestyles and the contamination of vast areas of the environment. There is no foreseeable end to the decontamination and restoration activities that are essential for rebuilding communities. The Commission concludes that the government and the regulators are not fully committed to protecting public health and safety; that they have not acted to protect the health of the residents and to restore their welfare.'

capacity of just more than 368 gigawatts (GW), representing a decrease in installed nuclear capacity of around 10 GW or 3 %. Similarly, construction starts fell from 15 in 2010 to just 2 in 2011. New nuclear plant construction is progressing in Brazil, China, India, and Russia. Iran has recently completed its first reactor. New-build orders have been placed in the United Arab Emirates and the United States, with a planned call for tender in South Africa. Ordering continues in China, India, Korea and Russia.

In Europe, Finland and France are completing their new Generation III European Pressurized Reactor (EPR) at Olkiluoto and Flammanville (Box 18.9), with the Finnish parliament and regulators having granted permits for construction of the country's sixth and seventh commercial reactors to Teollisuuden Voima (TVO) and Fennovoima (a subsidiary of E.ON), with a further reactor to be built at Olkiluoto by TVO. In October 2011, Fennovoima announced that it had chosen Pyhäjoki, in northern Finland, as a site for further nuclear expansion, with construction expected to start in 2015. Elsewhere, the United Kingdom's government, excluding Scotland, has in principle approved the concept of a new generation of up to eight nuclear power plants, subject to reactor generic design approvals; Bulgaria has begun detailed planning for a reactor at Belene; Romania has issued a planned call for tender; Poland's state utility, PGE, has shortlisted three sites as possible locations for their first nuclear power plant; and the Czech Republic is progressing with planning new-build — despite downsizing the proposed Temelin site tender from five to two reactors and Austria's strong objection to the expansion of the Temelin plant, which is situated near the border of the two countries.

Although Sweden formerly had a nuclear phase-out policy aiming to end nuclear power generation by 2010, on 5 February 2009, the Swedish Government announced an agreement allowing for the replacement of existing reactors. However, the

**Box 18.8 Nuclear costs**

A key challenge for nuclear power has been the high cost of construction (Davis, 2011). Nuclear new builds are high value and high risk construction projects with a marked tendency for significant delay and delay claims, cost growth and investor risk (KPMG, 2011). Based on the experiences of 52 United States investor-owned utilities that built nuclear power plants in 1960–2011, the Texas Institute (2011) concluded that building nuclear power plants provide significant economic risks involving a 70 % certainty that a power utility would see borrowing costs rise due to the downgrading of credit rating once construction began, with plant construction marred by significant cost overruns and electricity tariff increases. Nuclear plants, which are among the largest and most complex engineering projects in the world, also carry high technical and regulatory risks, with World Nuclear Association figures showing very significant cost overruns for most projects, implying that utilities may only be able to pay for new plants if governments guarantee their income (Thomas, 2010a). Thus, costs and risks associated with nuclear construction may mean that plants may only be built with implicit and explicit public subsidy, including long-term power purchase agreements (Professional Engineering, 2011).

**Box 18.9 European Union Nuclear New-build Experience**

The Olkiluoto 3 EPR in Finland was originally planned to go online early in 2009, but is now predicted to start generating in late 2014 (Thomas, 2010c). The new 1.6 GW AREVA designed EPR is conceived as first of type, with Siemens responsible for steam turbines and electricity generators. Originally priced at EUR 3 billion, the project is now estimated at EUR 5.7 billion and rising. The fixed price turn-key contract is subject to an ongoing dispute between the French manufacturer AREVA and TVO with the former claiming compensation of EUR 1 billion for alleged failures, and the latter demanding EUR 2.4 billion in compensation for delays (Thomas, 2010b). Similarly, in France, EDF confirmed the EPR Flamanville project was running late and increased its estimate of the cost. Originally scheduled to start operating in 2012, it is hoped that the reactor may be operational by 2016. Originally priced at EUR 3.3 billion, the reactor completion is currently estimated at EUR 6 billion (Thomas, 2011).

Fukushima disaster may have reversed prior public support of nuclear power, with a BBC World Service — Globescan (2011) poll showing that 64 % of Swedes opposed new reactors while 27 % supported them. Similarly, whilst Spain has no plans for expansion or closure, public opposition to new nuclear build remains very high at 55 %. The United Kingdom is more favourable towards the use of nuclear energy than any other European country, with 37 % in favour of building new nuclear infrastructure (ibid).

Given that Germany uses around 20 % of all EU electricity, the government's March 2011 decision to close 7 of its 18 reactors, followed in June by the German Parliament vote to phase out nuclear power by 2022 and to invest in renewables, energy efficiency, grid network infrastructure, and plan for trans-boundary pumped-storage hydroelectricity (PSH), may prove significant for European energy policy as a whole. In June 2011, Italian voters also passed a referendum to cancel plans for new reactors, with over 94 % of the electorate voting in favour of the construction ban. Because 55 % of the eligible voters participated, the vote is binding. Elsewhere, six months after the Fukushima plant catastrophe, strong Swiss public opposition to nuclear led to a decision not to replace the country's five reactors when they come to the end of their operation in 2034. Belgium also confirmed a nuclear phase-out, with no firm date set for end of operation, whilst the only Dutch reactor at Borssele will remain open until 2033 if it can comply with the highest safety standards. It is also worth noting that, at a ministerial meeting in Vienna; ministers and heads of delegations of Austria, Greece, Ireland, Latvia, Liechtenstein, Luxembourg, Malta and Portugal, observed by ministers from Cyprus, Denmark and Estonia, concluded that nuclear power was not compatible with the concept of sustainable development, suggesting that nuclear power does not provide a viable option in combating climate change (Vienna Declaration, 2011).

Before Fukushima, the IAEA had predicted that around the world nuclear plants would add 360 GW of generating capacity by 2035, the equivalent of over 200 new reactors. Post-Fukushima, it has halved this forecast, partly due to diminishing public acceptance of nuclear energy, but also to the increased costs of nuclear security improvements and of insurance premiums for accident-related damages (Leveque, 2011). France has set radical safety standards for the industry. However the required plant upgrades are both technically difficult and expensive, with the French nuclear authority, ASN, estimating the cost of necessary improvements at the country's 58 nuclear reactors at around EUR 10 billion (Nature, Editorial, 2012).

Western European Nuclear Regulators Association (WENRA) 'Stress Tests' comprised a targeted reassessment of the safety margins of nuclear power plants in the light of Fukushima, including extreme natural events which challenge plant-safety functions, leading to severe accident (WENRA Task Force, 2011). However, since the European Nuclear Safety Regulators Group (ENSREG, 2011) decided that security issues were outside WENRA's remit, post-Fukushima stress tests of EU's 143 nuclear power reactors did not include accident and incident from an aeroplane strike or terrorist attack. The exclusion of these security issues seems unfortunate given that, for example, all UK civil nuclear infrastructures are uniquely implicated in all four high priority tier-one threats identified in the UK National Security Strategy (HM Govt., 2010).

Despite further new-build plans in e.g. Finland, France and the United Kingdom; the general post-Fukushima situation in the EU implies that the limited construction of nuclear new-build since 2000, and potentially in the coming decade, combined with the ageing of nuclear power

plants and the finalisation of nuclear phase-out in Germany and other European countries, will lead to a relative decreasing share of electricity production sourced from EU nuclear energy after 2020. The emphasis is likely to shift towards maximizing output of existing reactors through extension, up-grade and retrofit (Leveque, 2011; Coenen and López, 2010).

The energy futures landscape within Europe is one of major national differences between state and market, choices and trade-offs over supply-side, demand-side, transmission and load-balancing infrastructure (Schiellerup and Atanasiu, 2011). Although EU Member States diverge in terms of cultural and industrial landscapes, public opinion, technological structures, institutions, regulatory practice and energy mixes (Box 18.10), the European energy policy offers a fairly open and flexible framework in which some Member States could develop collective action on energy issues. The development of sustainable and affordable low carbon energy remains a growing economic sector with huge potential for job creation (Andoura, 2010).

## 18.4 Nuclear liability

The risk to people, the environment and to the future of nuclear energy as a consequence of a major incident is significant. The cost of the Chernobyl accident can only be roughly estimated, but a variety of government estimates from the 1990s put the cost of the accident, over two decades, at hundreds of billions of dollars.

More recent events at Fukushima tend to support the conclusion that reactor accidents may prove the single largest financial risk facing the nuclear industry, far outweighing the combined effect of market, credit, and operational risks. Perhaps unsurprisingly, liability estimates vary with ongoing events. Japanese replacement power costs in 2011 alone have been estimated at EUR 6.5 billion (JPY 700 billion), with decommissioning costs for the six reactors are estimated at EUR 9 billion (JPY 1 trillion). On 20 May, 2011, TEPCO reported a net loss for the fiscal year ending in March 2011 of EUR 11.5 billion (JPY 1.25 trillion), the largest corporate loss in Japanese history outside the financial sector. By mid 2011, Bank of America Merrill

**Box 18.10 Cultural and policy diversity in energy governance**

**Finland:** The Finnish discussion culture can be summarised as one in which decisions are preceded by an open public and policy debate, but once the decision has been made, according to the rules and regulations in force, there should no longer be room for complaints and further debate. Provided that proper procedures have been followed, changing course would mean loss of face and identity. Correspondingly, nuclear power has acquired the reputation of being the cheapest, safest, and most reliable source of electricity generation. This is primarily because there have been no serious nuclear accidents in Finland, and their reactors maintain a high reliability and load factor. These advantages are coupled with arrangements under the Mankala Principle, whereby large industrial corporations such as forest and heavy industry — as shareholders in nuclear power companies — can buy electricity at cost price (Lehtonen, 2010a; Lehtonen, 2010b).

**Germany:** Decisions on nuclear power cannot be separated from prior energy policy choices, and Germany has demonstrated a very strong, historic commitment to renewables, with renewable electricity production doubling between 1998 and 2003 and again between 2003 and 2008. By 2010 renewables contributed 17 % of total electricity production, and there are plans to increase this to at least 35 % by 2020 (BMU, 2011). Innovative German practice includes the first implementation of a fixed price feed-in-tariff, and huge purchases of solar photo voltaics (PV), which have driven down the world price of modules. Energy futures have also devolved to the local level, with communities securing political agreements under which the *Bundesländer* (federal states) are enabled to set goals and locations for renewable generation. This ensures that local energy resources and financial subsidies — paid for by customers (through feed-in tariffs) or taxpayers (through cheap loans provided by the government development bank (KfW)) — benefit not only the energy companies but also the local people, with profits and employment kept in the region. Germany's non-nuclear energy policy is framed in the context of national pride and scientific-technological achievement, twinned with economic expansion: 'As the largest industrialized (European) nation, we can achieve a transformation toward efficient and renewable energy, with all the opportunities that brings for exports, and the development of new technologies and jobs' (Chancellor Angela Merkel, in German, 2011).

Lynch reported that compensation claims could total EUR 93–102 billion (JPY 10–11 trillion) over the next two years, with liabilities far exceeding the current market cap (Maloney, 2011). By September 2011, Fukushima liabilities stood at anywhere between EUR 76–152 billion, with the Japanese Centre for Economic Research estimating clean-up remediation at EUR 190 billion over the next 10 years (Kobayashi, 2011).

Currently, individual European nuclear accident liabilities are capped at EUR 169 million for operators. However, the Paris Convention on Nuclear Third Party Liability and Brussels Convention (2011) ([7]) aims to raise this to ensure that victims of a nuclear incident are compensated for resulting damage. Under the proposals, nuclear operators would be liable for the first EUR 700 million for any accident, with the national government having the option of adding a maximum of a further EUR 500 million towards the company's liabilities. Collectively, other signatory states could contribute a further EUR 300 million, potentially bringing the total available to EUR 1 500 million for any one accident.

Yet actuarial analysis suggests that even this level of cover may fail to account for liability in case of major accident. Versicherungsforen Leipzig GmbH (2011), a company that specialises in actuarial calculations, concluded that these costs were not adequately internalised, suggesting that full insurance against nuclear disasters would increase the price of nuclear electricity by up to EUR 2.36 per kilowatt hour (kWh) — a sum that may weaken the economic case for nuclear power compared to other low-carbon sources.

Both the required liability (EUR 6.09 trillion), based on an estimate of the average maximum damage and corresponding variance, and the resulting insurance premium, are significantly higher than the financial resources currently legally required of nuclear power plant operators. Versicherungsforen Leipzig's study estimated that future damage and liability insurance costs would exceed the financial resources that nuclear power plant licensees are currently required to maintain by several orders of magnitude. In this context, nuclear disasters seem uninsurable, due to a combination of methodological difficulties in estimating the probability of occurrence of damage, insufficient size of the risk pool, and the extent of potential maximum damage (ibid).

To the extent that liability rules provide incentives for prevention, the financial limit on the liability of an operator may lead to under-deterrence — since, as a result of the financial cap on liability, the potential complementary function of liability rules in providing additional deterrence may be lost. The financial limit, and the resulting nuclear subsidy, may also distort competition by unduly favoring nuclear energy compared to other energy sources (Faure and Fiore, 2009).

The issue of nuclear waste liability has also been subject to intense and prolonged debate, especially in the context of high burn-up fuel proposed for Generation III reactors (Box 18.11).

**Box 18.11 High burn-up fuel**

Following the liberalisation of the EU energy market, it was realized that a decrease in nuclear costs could be achieved if reactor power could be optimized by using more uranium as reactor fuel and keeping the fuel rods in longer. This means that generation III reactor high burn-up spent fuel will be significantly more radioactive than conventional spent fuel. Five years after discharge, each square metre of spent fuel in the proposed EPR cooling ponds may generate up to 17 kW of heat compared with 11 kW from more conventional spent fuel pool. And the high density of spent fuel racks from the proposed Westinghouse AP1000 reactor implies that 24–36 kW of heat may need to be removed from each square metre. Safety could depend on the effective and continuous removal of the significant thermal power of high burn-up spent fuel, potentially requiring additional pumps, back-up electricity supplies and back-up water supplies: all systems potentially vulnerable to mechanical failure or deliberate disruption. It is also likely that densely packed high burn-up spent fuel may require additional neutron absorbers, and greater radiation shielding during encapsulation and storage (Richards, 2009).

([7]) Note, not all EU Member States are signatories. Belgium, Denmark, Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Portugal, Slovenia, Spain, Sweden, the United Kingdom and Turkey are signatories to the Paris Convention on Nuclear Third Party Liability and Brussels Convention.

## 18.5 Nuclear risk: probabilistic risk assessment and beyond design-based accidents

Key to the analysis of nuclear safety is the analytical concept of probabilistic risk assessment (PRA) or probabilistic safety analysis (PSA). Whilst PRA calculations are not taken as absolute, but rather as significant indicators of plant weaknesses, they do underpin the concept of acceptable risks and tolerable consequences under fault conditions. In this context, the risk of an accident must be acceptable, and the radiological consequences tolerable, with more frequently occurring incidents countered by greater resilience through enhanced safety systems grounded in robust engineered structures. However, PRA has proven structurally limited in its ability to conceive and capture the outcomes and consequences of a nuclear accident resulting from a cascading series of events, as described in the Fukushima disaster and all previous major nuclear accidents. This implies that relatively simplified chain-of-event fault-tree models may not be sufficient to account for the indirect, non-linear, and feedback relationships common for accidents in complex systems. Here, modeled common-cause, common-mode, and dependent failures have proved problematic; partly due to data limitation (since major failures occur infrequently), and because failure mechanisms are often plant specific (Ramana, 2009).

Most PRAs assume failure likelihood can be captured through identical, independent log-normal failure distributions. Since strong independence assumptions employed in PRAs assume that reactor safety systems are duplicated and reliable, core damage frequency estimates are typically very low. Because of this, there may be good reason to question the conceptual and theoretical completeness, and empirical and practical reliability of PRA models. This is partly because PRA is prone to under-counting accident scenarios — since risk is estimated for enumerated reactor states, failure to account for unknown and serially cascading beyond design-base accident scenarios leaves an un-measurable model error in the core damage frequency estimate (Maloney, 2011).

Before the Fukushima accident, for example, the Japanese Nuclear Regulatory Commission Guidance (NSC, 2006), updated in early 2011, concluded that 'robust sealed containment structures would prevent damage from a tsunami… and no radiological hazard would be likely'. Whereas after the accident, the Chairman and President of the European Nuclear Society High Scientific Council stressed that 'the magnitude of the tsunami that struck Japan was beyond the design value to which the reactors were supposed to withstand' (Bonin and Slugen, 2011). These pre- and post-facto statements suggest that, although reactor design can prove relatively robust against specific accidents and specific modes, safety cannot be guaranteed for cascading beyond design-base accidents. In the case of Fukushima, because the cascade from earthquake, through tsunami, to reactor and spent fuel fault condition was discounted, no account was taken for the need to respond to the failure of three nuclear reactors and spent fuel ponds.

Pre-Fukushima probability estimates of a major nuclear accident were around 1:100 000 for the 440 reactors in operation over the next 20–25 years. Since Fukushima, estimated probabilities of major nuclear accidents have increased significantly. However, estimation of core melt and containment failure may still prove problematic. Chernobyl and Fukushima together comprise catastrophic meltdown in four nuclear reactors over the past few decades, implying that that the probability of a major accident in the current worldwide fleet over the next 20–25 years is around 1:5 000. Thus, whereas earlier estimates assumed a probability of one major nuclear accident over a 100-year period, reoccurrence of these events can be expected once every 20 years (Goldemberg, 2011). This reassessment of nuclear risk has been particularly apparent in Germany, where Chancellor Angela Merkel concluded that Fukushima 'has forever changed the way we define risk' (Schwägerl, 2011); an analysis echoed by Norbert Röttgen, Germany's Environment Minister, who noted that Fukushima 'has swapped a mathematical definition of nuclear energy's residual risk with a terrible real-life experience… we can no longer put forward the argument of a tiny risk of 10–7, as we have seen that it can get real in a high-tech society like Japan' (ibid).

Importantly, the governmental German Advisory Council on the Environment also concurred with this critique, suggesting that: 'The widespread view that the extent of the damage due even to major incidents can be adequately determined and limited in order to be weighed up… is becoming considerably less persuasive… The fact that the accident was triggered by a process which the nuclear reactor was not designed to withstand… casts a light on the limitations of technological risk assessment… based on assumptions, and that reality can prove these assumptions wrong' (SRU, 2011b, p.11).

Levels of reliability required for a complex interactive and tightly coupled nuclear power plant are very great (Perrow, 1984), with the range of

operating reactors having differing sets of designs and configurations. Because of their complexity and the physical conditions during reactor operation, the understanding of the reactor design and operation is always partial. Additionally, as system components and external events can interact in unanticipated ways, it is not possible to predict all possible failure modes. It follows that numerical estimates of probabilities of significant accidents remain deeply uncertain. As the Fukushima Investigation Committee concluded (2011, p. 22): 'The accidents present us (with) crucial lessons on how we should be prepared for… incidents beyond assumptions'.

## 18.6 Conclusion

Because it is likely that post-Fukushima health consequences may start to arise and be documented over the next 5–40 years, a key lesson to be learned concerns the multi-factorial nature of this event. It can be expected that a number of chemical agents were released and, hence, the final biological effect may depend on the consequential complex radiochemical environment. Thus, in planning future radiation protection, preventive measures and bio-monitoring of exposed populations, it is of great importance to:

- integrate the available data on both cancer and non-cancer diseases following overexposure to ionizing radiation;
- take a complex approach in the interpretation of data — considering the impacts of age, gender, and geographical dispersion of affected individuals, and the psychological, educational and social status of victims; and
- integrate the evaluation of latency periods between exposure and disease diagnosis development for each cancer type.

Bunn, the former adviser to the US Office of Science and Technology Policy, and Heinonen, the former Deputy Director General of the IAEA, also conclude that there is a need for more stringent nuclear safety standards, and propose six areas for improvement involving substantial cost and time investment:

- operators must plan for events beyond design bases;
- more stringent standards for protecting nuclear facilities against terrorist sabotage;
- a stronger international emergency response;
- international reviews of security and safety;
- binding international standards on safety and security; and
- international co-operation to ensure regulatory effectiveness (Bunn and Heinonen, 2011).

In addition, there is also the need to defend and adapt the coastal sites of nuclear plants to the hazards of rising sea levels, storm surges, flooding and the possibility of eventual nuclear site islanding (IME, 2009; Kopytko and Perkins, 2011). It should also be understood that it is very unlikely that current major accident liability regimes will prove adequate, and a significant re-adjustment may be essential.

This wide-ranging set of recommendations constitutes a significant step forward in radiation protection philosophy. However, there seem to be no resounding new revelations over the vulnerability of nuclear power to unforeseen natural disasters like earthquakes and tsunamis, or through human or engineering based fault conditions, including accidental or deliberate harm. Accidents are by nature, accidental, and the cost of ignoring this common-sense axiom can prove radiologically catastrophic (Stirling, 2011).

Whilst the imaginative use of foresight and precaution are key to the management of nuclear risks, a further paradox lies at the heart of the debate: Whereas fundamental radiation protection science is characterised by very real uncertainty, indeterminacy and contingency, the regulation and operation of nuclear facilities is based on the language of certainty. The nearer one gets to the fundamental science and engineering of complex technological systems, the greater the uncertainty and complexity; yet the nearer one gets to regulation and operation, the greater the certainty and simplicity. Since somewhere along this continuum, uncertainty has been translated into certainty, and risk has been translated into 'safety', the question remains: when, how, and why does this transformation happen?

Given the degree of uncertainty and complexity attached to even the most tightly framed and rigorous nuclear risk assessment, attempts to weight the magnitude of accident by the expected probability of occurrence has proven problematic, since these essentially theoretical calculations can only be based on sets of pre-conditioning assumptions. This is not an arcane philosophical point, but rather a very practical issue with

significant implications for the proper management of nuclear risk. With its failure to plan for the cascade of unexpected beyond design-base accidents, the regulatory emphasis on risk-based probabilistic assessment has proven very limited. An urgent re-appraisal of this approach, and its real-life application seems overdue.

Whatever one's view of the risks and benefits of nuclear energy, it is clear that the possibility of catastrophic accidents must be factored into the policy and regulatory decision-making process. In the context of current collective knowledge on nuclear risks, both the regulation of operating nuclear reactors and the design-base for any proposed reactor will need significant re-evaluation.

Given the size of the long-term investments that are now needed across the options of nuclear, carbon based fuels, renewables, energy efficiency and conservation, grid network infrastructure development and load balancing; it is clear that European public needs to play a key role in taking these critical, social, environmental and economic decisions ([8]). Here, public values and interests are central, and the role of public dialogue and the participatory practices that enable it are core to the building of mutual understanding between European states, governments, industry and people. If carried out in a truly involving way, the integration of public, policy, and expert scientific knowledge allows for greater accountability, transparency, and much better take-up of necessary change and improved long-term likelihood of problem resolution. This conclusion mirrors those from many chapters in this publication — from leaded petrol to nanotechnology: that wider public engagement in choosing strategic innovation pathways is essential.

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