Fukushima and its consequences

Jim Thomson gives a wide-ranging account of the effects of the Fukushima disaster

The Fukushima Daiichi accidents following the earthquake and tsunami on 11 March 2011 were the most serious nuclear reactor accidents since Chernobyl in 1986. The devastation caused by the earthquake and tsunami left the operators in a hopeless situation.

Misunderstanding and misrepresentation of nuclear risks are threatening nuclear programmes in several countries, notably Germany and Japan itself, while many other countries are delaying their nuclear build programmes, or at least not pursuing them with vigour.

Delays and closures of nuclear plants are a particular threat at a time when many countries have ageing electricity generation infrastructure.

Delays and closures are also a threat because, in seeking to avoid the risk of blackouts, utilities will most probabably be forced into using gas-fired generation (instead of nuclear) as a stop-gap. This will occur at a time of rising fuel prices as the world approaches peak oil, thereby forcing prices even higher.

Global warming may be exacerbated by delays in nuclear new build. Global warming is a major risk to the planet in the latter part of the 21st century.

Circumstances of Fukushima during and after the tsunami

The Japanese government has published [1] its preliminary report on the Fukushima accident. This is a large report (750 pages) detailing the circumstances and chronology of the accident.

The earthquake occurred 130km from the coast and was a magnitude 9 event – the fourth biggest earthquake in the world since 1900. Some aftershocks exceeded magnitude 7. However, it does appear that, in general, Japanese nuclear plants survived the actual earthquake and its aftershocks.

The subsequent tsunami, which hit the coastline some 26 minutes after the earthquake, was responsible for major damage. It was the worst tsunami suffered by Japan since the Jogan earthquake of 896 AD. As the report records laconically:

"The total inundated area was up to 561km^2... The total number of residential buildings damaged was approximately 475,000 including fully destroyed, half destroyed, partially destroyed and inundated structures. The number of cases of damage to public buildings and cultural and educational facilities was as many as 18,000… In addition, approximately 460,000 households suffered from gas supply stoppages, approximately 4,000,000 households were cut off from electricity, and 800,000 phone lines were knocked out… 24,769 people have been reported as dead or missing."

It was in this context – one of overwhelming national disaster – that the Japanese people and government, and not least the staff of Fukushima Daiichi themselves, had to cope with an emerging nuclear accident.

The Japanese government report goes on to record that seawalls in many places, behind which the population felt secure, were found to be of inadequate height or strength to withstand the tsunami:

"The tidal embankment in the Taro area of Miyako City in Iwate Prefecture is referred to locally as the 'Great Wall of China' as it towers 10 metres high. However, even this collapsed when hit by a tsunami that was 15m high, or possibly higher, and significant damage occurred within the embankment [as shown in Figure 1]. Incidentally, the 15.5m embankment [as shown in Figure 2] was installed in the Ootabu area, Fudai village in Iwate Prefecture, following a strong desire of the village chief learning from previous experiences with tsunami. This embankment was able to resist the 15m tsunami and prevented the damage within the embankment zone... These areas are rias-type coastlines that have, historically, suffered significantly from giant tsunamis in the 15m range, such as the Meiji Sanriku Tsunami (1896) and the Showa Sanriku Tsunami (1933), the lesson of preparation against a 15m-class tsunami has been instructed [sic]... Against these tsunamis, there was a sharp contrast between the Ootabe area, which heeded the lessons of the past, and the Taro area.

"In the Aneyoshi area, Miyako City in Iwate Prefecture, there is a stone monument with the warning not to build houses in the area lower than that point [as shown in Figure 3] at the entrance (height 60m) of the village, showing lessons learned from run-ups of the two historical tsunamis... By observing this lesson, the area was able to avoid casualties this time even though the tsunami ran up (the actual run-up height was

Figure 1: *The 10m seawall was destroyed in Taro district, Miyako City, Iwate Prefecture [1]*

Figure 2: *The 15.5m-high seawall was left intact in Ootabe district, Fudai village, Iwate Prefecture [1]*

Figure 3: *The stone monument at Aneyoshi [1]*

Figure 4: *A photo taken slightly below the stone monument [1]*

38.9m) near the village [as shown in Figure 4]."

It is in the context of this overwhelming widespread damage that the response to the accident must be judged. After the tsunami inundated the site, the following situation faced the station staff:

- the station was cut off from all grid connections;
- back-up diesel electricity supplies failed and hence all long-term, post-trip cooling was inoperative;
- the roads were impassable;
- communications were poor;
- station staff will have been concerned about their families and their homes;
- there were ongoing major aftershocks;
- after the batteries ran out, the power plants were literally blacked-out – staff could only find their way round the plant using torches and there were no control room screens or other indications of plant state; and
- station staff will have been keenly aware of the time pressures to try to restore post-trip cooling.

> "It does appear that, in general, Japanese nuclear plants survived the actual earthquake and its aftershocks"

On a personal note, writing as a former shift manager of a nuclear power station, I find it difficult to imagine how this situation must have felt for the operators. The staff must have felt helpless and hopeless.

Lessons learned from Fukushima

The Japanese report details the circumstances of the reactor loss-of-cooling accidents (LOCAs), core melts, the hydrogen discharges (and subsequent explosions), and the gradual and ongoing recovery operations. These have been described elsewhere (not least in *Nuclear Future*) and will not be repeated here.

The Fukushima accident will drive much of the nuclear safety agenda, possibly for decades, in the same way that other accidents have done previously. The Japanese report gives an unflinching review of lessons learned. These are summarised in Figure 5, and can be categorised as follows:

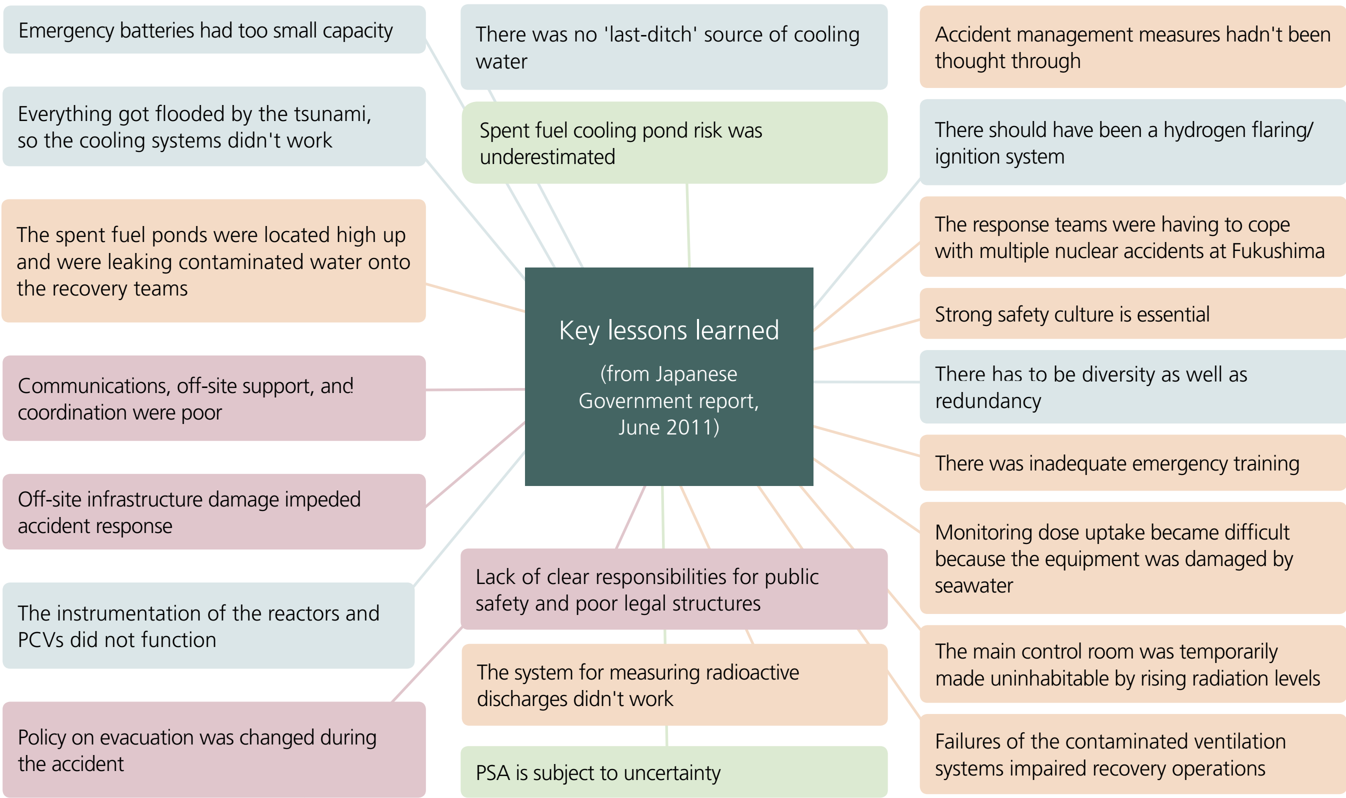
1. Underestimation of risk in prior engineering risk assessments.
2. Poor accident response (either due to inadequate preparation or because accident response was impaired by the tsunami damage).
3. Inadequate engineering design (which allowed all safety systems to be made ineffective, and allowed the accident to escalate), including:
   - failure of all diesels;
   - complete failure of post-trip cooling; and
   - lack of a hydrogen flaring/ignition system.
4. Poor offsite communications, support and response.

The last (poor offsite support and response) can of course be explained by the difficulty of dealing with the nuclear accident during an immense civil emergency. As the report notes in its understated, matter-of-fact style:

> *"The situation has become extremely trying for Japan, insofar as it has had to execute countermeasures for the nuclear accident whilst also dealing with the broader disaster caused by the earthquake and tsunamis."*

In particular, the concern about underestimation or risk has led to the EU-wide review of nuclear plant external hazards – the 'stress tests'.

Figure 5: *Fukushima – Key lessons learned*



Comparing Fukushima health consequences with historical nuclear accidents

In the late 1980s, the present author wrote some articles and papers that attempted to put Chernobyl into a wider context (see e.g. [2]). This section updates that approach.

The problems with explaining the consequences of nuclear accidents include the following:

- Nuclear accident health consequence assessment is complicated.
- Attempts to simplify the explanation are sometimes too simplistic, or else too complicated.

Nevertheless, the industry must try to explain accident health consequences in an accurate and unemotional way, in the hope that interested parties and opinion formers will be listening. The explanation has two parts: first, the nuclear industry needs to explain clearly the nature of the health effects of radiation and the uncertainties surrounding them, and, secondly, we need to give realistic statements about possible health effects from nuclear accidents, and put those statements into clear context.

One difficulty is that many statements surrounding these issues have to be qualified. We can state with some certainty, however, that deaths to the general public from radiation sickness (Figure 6) have not arisen due to nuclear power accidents. The only real risk to the public is that of delayed health effects (cancers).

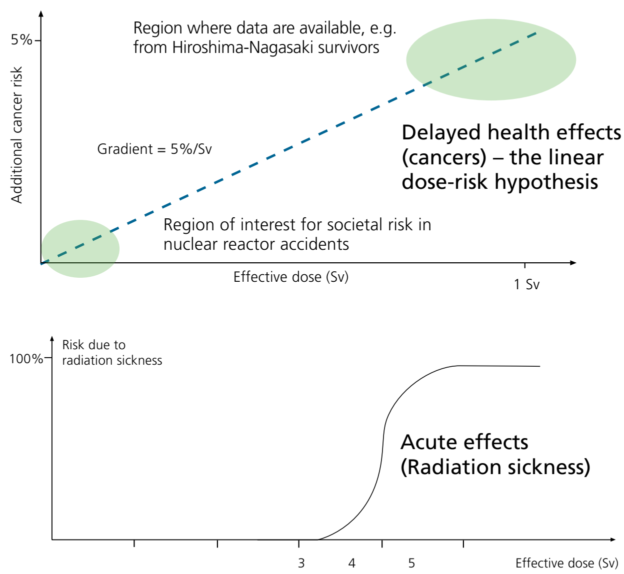
Unfortunately, this is not very comforting for most.

The basis for estimating the risks of delayed health effects from radiation exposure is the linear dose–risk hypothesis (Figure 6). This is because:

Our knowledge of delayed health effects is largely based on studies of Hiroshima-Nagasaki survivors, most of whom received

Figure 6: *Radiation doses and radiation hazards*

- Other issue – Doserate effects – uncertain
- Normal cancer risk ~ 30%



doses of several hundred milliSieverts or more.

It is difficult to know the extent of additional cancers caused by radiation when so many people contract cancer in any case (in excess of 30 per cent). (In engineering terms, the signal-to-noise ratio is high.) Hence it is impossible to know with confidence the effects of low-level radiation on cancer risk. Although many people

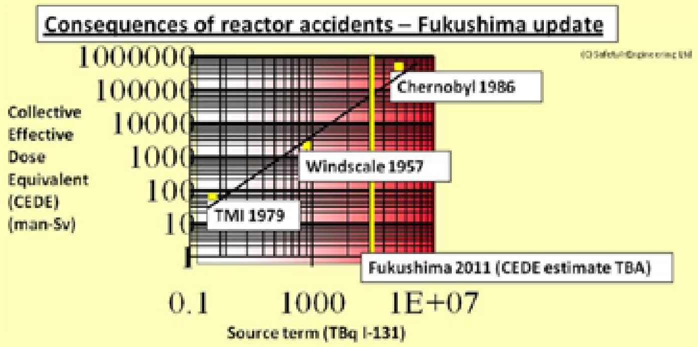


Figure 7: *Consequences of reactor accidents*

Notes

1. The graph uses I-131 as a surrogate measure of radiological release. Other isotopes (notably Cs and Pu) will also have been significant. I-131 is used for simplicity as a common single measure of the magnitude of radioactive release.
2. CEDE estimates are taken from the relevant recognised 'definitive' reports (Kemeny, NRPB, IAEA).
3. Using the ICRP risk coefficient of 5E-02/man-Sv leads to deduced cancer mortality estimates from the accidents as follows: TMI, c.1; Windscale, c.100; Chernobyl, c.10000.
4. Airborne releases after the Fukushima accidents were estimated to be 1.5E+5TBq I-131 by the Japanese government in their June 2011 report. CEDE estimates are not yet available. Fukushima also led to significant water-borne releases.
5. If the empirical correlation for the first three major accidents (the straight line on the graph) holds true for Fukushima also, then the deduced long-term cancer mortalities for Fukushima are likely to be of the order of 1000.

have proposed theoretical models for this, the empirical data are absent because it is impossible to remove the background 'noise'.

However, in nuclear reactor accidents, exposures faced by the general population will only be of the order of a few milliSieverts or less.

So, the linear dose–risk hypothesis is used to estimate risks from small doses in the absence of better information. The individual risks will represent small additions to the pre-existing 30 per cent or so 'normal' risk of acquiring cancer. However, in major nuclear accidents, when millions of people are exposed to small increases in their individual risk, the result of multiplying a very small theoretical individual risk by an extremely large number of people can give rise to a large number. Furthermore, this calculated result is subject to great uncertainty, is probably conservative and is completely unverifiable (because of the signal-to-noise ratio problem mentioned above).

Nevertheless, great efforts have been made to: (a) calculate the amounts of all the major isotopes released during nuclear accidents (the 'source term'); (b) determine exposure pathways for all the principal radioactive isotopes; and (c) assess (by measurement and calculation) the total all-time population radiation exposure (the Collective Effective Dose Equivalent or CEDE). For the major accidents (Windscale fire 1957, Three Mile Island 1979 and Chernobyl 1986), authoritative estimates for these data are available.

Figure 7 presents these data using iodine-131 as a surrogate single measure of source term. The available data for CEDE and source term yield an approximate straight line on a log-log plot.

In due course, detailed assessments of the CEDE for Fukushima will be published, based on measured dose uptake from samples of the exposed population, calculations of plume dispersal and uptake of contaminated food and water among the population of Japan and elsewhere. In the meantime, the Japanese report [1] contains a first authoritative estimate of the source term for Fukushima: about 1.5x105 TBq of iodine-131 (together with other isotopes).

Figure 7 shows the Fukushima data added to previous data. A reasonable working assumption is that the CEDE vs source term trend from other accidents (the straight line) will give a first approximation for determining the CEDE for Fukushima. (It may even be conservative, since much of the radioactive plume from Fukushima may have drifted out to sea.) If the CEDE vs source term trend shown by the previous accidents is repeated, then the CEDE for Fukushima may be of the order of 30,000 man-Sieverts. This would equate (using the ICRP dose–risk coefficient of 5x10-2 per man-Sievert) to around 1000 premature deaths over the next 40 years or so.

These numbers should be treated carefully: (i) they are approximations, (ii) even if they were accurate, they are subject to large uncertainties, and (iii) they need to be put into context.

The context here is as follows: First, about 30,000 people died in the earthquake and tsunami. Secondly, the calculated value of CEDE will affect a huge population – the population of Japan alone is about 127 million, of whom tens of millions will normally die of cancer anyway. Hence (as noted earlier) any assessed value of early deaths will be completely unverifiable.

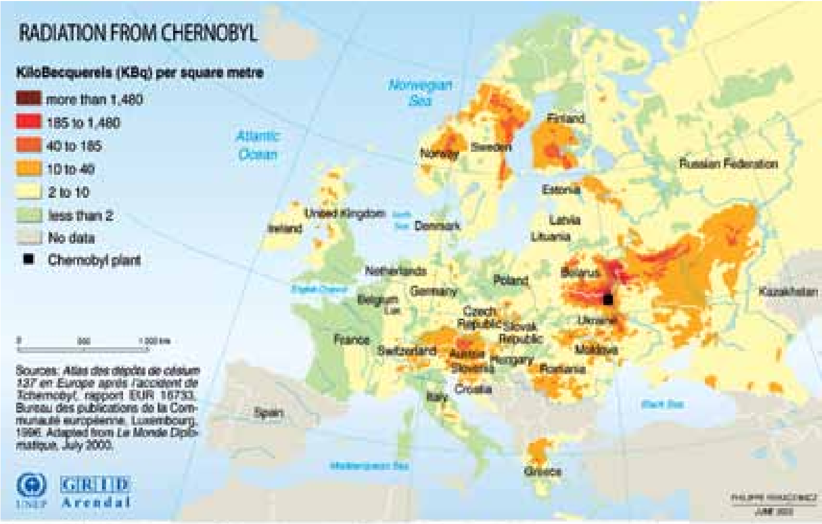
Environmental radioactive contamination – Fukushima compared with Chernobyl

Maps of radioactive contamination in Europe arising from the Chernobyl accident have been published by the International Atomic Energy Agency (IAEA). Preliminary maps showing the contamination arising from Fukushima have now been published also, and Figure 8 presents a comparison. The comparison is not perfect, because different scales and colours have been used, but, broadly speaking, the brown colour in the Chernobyl map corresponds to the blue colour in the Fukushima map. The large difference in the scale of the contamination is self-evident.

Before Chernobyl, nuclear accident consequences estimates were purely predictive, based on code analyses and various assumptions. Chernobyl gave the nuclear industry a clear demonstration of how bad a nuclear accident could really be; indeed, it is extremely difficult to imagine a worse case. The reactor became prompt-critical, the containment was ruptured, and the core burned for several days. Fukushima has now given the industry a benchmark for LOCA accidents.

Wider consequences: delays to new build, early nuclear shutdowns, peak oil, global warming

A direct consequence of the accident has been that, throughout the world, nations have been reviewing their plans for new nuclear build, and reviewing their existing plants.



Sources: UNEP/GRID-Arendal, European Environment Agency; *AMAP Assessment Report : Arctic Pollution Issues*, Arctic Monitoring and Assessment Programme (AMAP), 1998, Oslo; European Monitoring and Evaluation Programme (EMEP): Co-operative programme for monitoring and evaluation of the long range transmission of air pollutants in Europe, 1999. Adapted from *Le Monde Diplomatique*, July 2000.

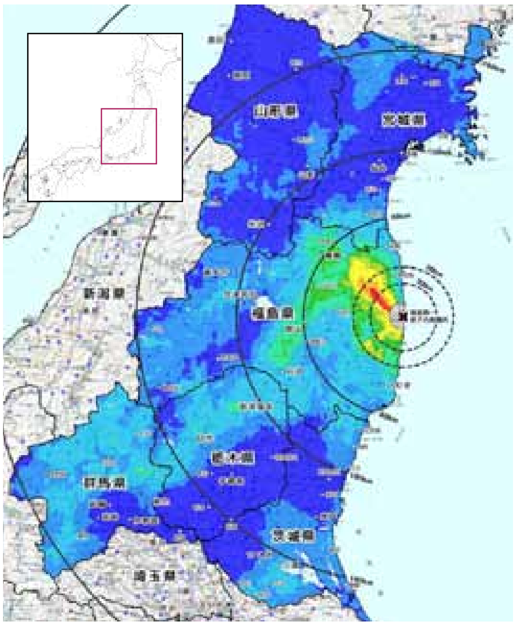
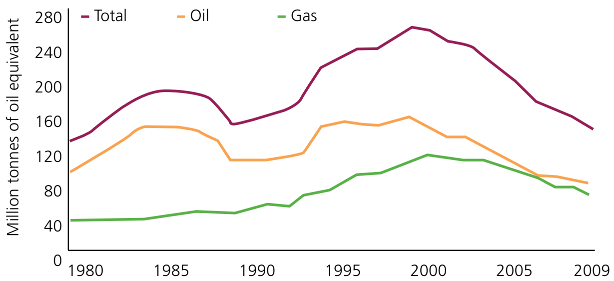


Figure 8: *Radioactive contamination: Fukushima preliminary data compared to Chernobyl*

Figure 9: *UK Continental Shelf oil and gas production (1980 – 2009) [3]*



In Europe, stress tests are being applied to existing plants to review their ability to withstand external hazards. This is right and proper.

Germany has decided to shut down its existing nuclear plant by 2022. Although renewable energy is being promised, it is likely that much of the replacement power will come from imported coal-fired generation.

Japan is suffering power shortages amidst delayed consents for its unaffected nuclear plants to re-start. There has been speculation that this will encourage major Japanese manufacturing companies to move abroad where stable power supplies can ensure reliable production. (This was becoming likely in any case because of Japan's demographic problems due to its aging population.)

In the UK, there are some delays to the Generic Design Assessment process. It is difficult to be clear how much this will affect new build, but EDF has announced (July 2011) that there will in any case be delays and the first European pressurised reactor (EPR) in the UK is unlikely to generate power in 2018 as planned. Also in the UK, there may be a crisis of electricity supply in the latter part of this decade after an old coal-fired plant is shut down in 2015 and some older advanced gas-cooled reactors are shut down at around the same time.

While it is possible that there may be some reduction in UK demand because of the ongoing slowing-down of the economy, the net effect of the shortfall in generating capacity may be that generating companies take short-term fixes by building more combined cycle gas turbines (CCGTs). CCGTs can be operational within about 18 months of start of construction. One problem will then be that, once the CCGTs are operational, the generating companies will feel less pressure to build new nuclear – nuclear will have 'missed the boat'.

Another problem will then be that this makes the UK even more dependent on imported fossil fuels at a time when many believe that we are close to 'peak oil'. (Gas prices tend to follow oil prices, so oil shortages will lead to high gas prices.) The production of oil and gas from the UK continental shelf has dropped steeply since production peaked in 1999 (Figure 9) and will continue to decline.

> “It is impossible to know with confidence the effects of low-level radiation on cancer risk”

Many estimates of global future oil production are available; among the more pessimistic are those presented in *www.theoildrum.com* (but the concerns expressed there seem reasonable to this author). World crude oil production has mostly been on a plateau since about 2005, and it seems credible that peak crude oil production may occur before 2020. (This refers to crude oil production from conventional sources, i.e. excluding natural gas liquids and oil sands.)

In the meantime, the UK and other nations have internationally agreed targets to meet for greenhouse gas (GHG) reduction.

It is worth reminding ourselves why there is concern about global warming, and why we urgently need new nuclear capacity. The Stern report on the economic consequences of global warming was an authoritative review of the evidence on global warming [4]. This report included a diagram summarising model runs showing the possible extent of average global warming by 2100 (Figure 10). (These model runs have built-in assumptions about measures being taken to limit GHG emissions within the next few decades, such as increased use of non-GHG means of electricity generation.)

It is difficult to look at this issue without sounding alarmist. For example, some have suggested that a global mean temperature rise of about 4 degrees by 2100 – the most likely outcome

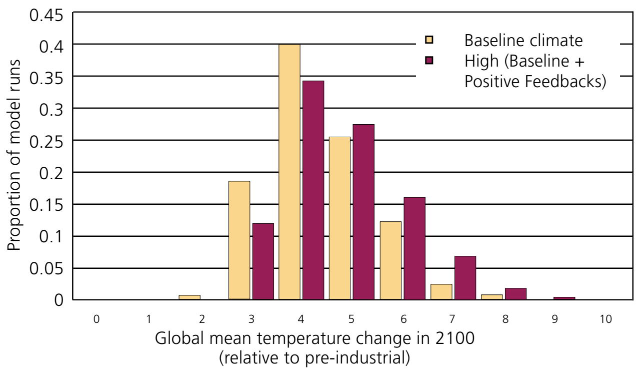


Figure 10: *Estimates of global mean temperature rise by 2100 [4]*

according to Stern – could make much of south and east Asia uninhabitable. Currently about 2.5 billion people reside there. The geopolitical situation that might arise is really quite frightening.

The world needs to press on with new nuclear build (and other non-GHG-emitting technologies also) as fast as possible, to limit the effects for succeeding generations. It would be wrong to allow the understandable concerns caused by Fukushima to override the greater imperative, namely that the world needs to press on with GHG-free generating capacity, including nuclear, with all reasonable speed.

Conclusions

This article has given a wide-ranging view of the Fukushima accident and its consequences. Among many important issues, the following points stand out.

- The earthquake and tsunami were an overwhelming (and ongoing) tragedy for Japan.
- The EU 'stress tests' were a good opportunity to review nuclear plant readiness against extreme external hazards.
- Nuclear safety cases perhaps need to go further in considering responses to extreme national emergencies.
- Peak oil is almost upon us and we need robust means of electricity generation that are not fossil fuel dependent. At the same time, there is a pressing need for greater use of nuclear and other non-GHG power technologies to deal with the very real threat of global warming.

It would be a great shame for subsequent generations if excessive concerns about Fukushima led to significant delays in nuclear new build decisions.

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After completing his PhD studies in process engineering at Aberdeen University, Jim started his career in 1979 at the Prototype Fast Reactor power station, Dounreay, latterly as a shift manager. He was a lecturer at Edinburgh University before joining NNC (now Amec Nuclear) in Knutsford to develop safety cases for Heysham 2/Torness nuclear power stations. In 1989 he moved to SSEB/Scottish Nuclear doing design/project management and managing PRA/QRA and reliability analysis, before becoming Nuclear Safety Manager and then Protection and Electrical Systems Manager at British Energy.

He left BE to become Technical Director/MD of Risktec (Glasgow). In 2007 he became Head of Technical Services in ESR Technology's Aberdeen office and later became Chief Operating Officer of ESR Technology, leaving the firm in 2011.

He completed the Advanced Management Programme at Oxford University in 1997 and the Senior Nuclear Plant Management Program at the Institute of Nuclear Power Operations, Atlanta, in 2000.

Jim specialises in consultancy in safety management, and also high-integrity C&I. He has delivered safety-related projects (either nuclear or oil and gas) in Canada, India, Japan, Kazakhstan, Qatar, Sudan, Romania, UK and USA, including third-party audits of high-integrity protection systems, development of PRINCE2/IEC 61508-compliant programmes for nuclear DPS replacement, and advice on C&I licensing for nuclear new-build in the UK. He has done project work on some 30 nuclear plants and 13 offshore oil platforms.

He currently works as an independent advisor to MoD/Rolls-Royce on the design of submarine reactor C&I systems, and as a consultant to Invensys.

He is the author of *Engineering Safety Assessment* (Longman, 1987) and *Elements of Nuclear Power* (Longman, 1989). He lectures on C&I to Imperial College Nuclear MSc students, and on safety management to Manchester University Chemical Engineering students; he has also been a visiting lecturer in the Department of Electrical and Electronic Engineering at Strathclyde University. He chaired the INucE C&I conferences in 2004 and 2007.

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