Fukushima: Overview of relevant international experience

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When considering the environmental and health impacts of radioactivity released from the Fukushima Dai-ichi power plant, international comparison to date has focused very much on Chernobyl and there has been significant effort invested to determine what could be learned from this and other high profile reactor incidents such as Three Mile Island. In fact, Fukushima releases are very different to these cases and comparisons may not only be misleading, but could cause unnecessary public concern – especially when coupled to images of the Chernobyl "dead zone". A wider review of the global history of incidents at nuclear reactors, "Cold War" waste management procedures and other releases of radioactivity into the environment provides a better background to put Fukushima in perspective. This also identifies experience that could be utilised to facilitate stabilisation and decommissioning of the damaged Fukushima units and clean-up of contaminated areas, both on- and off-site. International comparisons also highlight the special sensitivity of Fukushima due to intensive media coverage and failures in communication worldwide, where lessons could be learned by the entire nuclear industry.

Keywords: Fukushima, remediation, international experience, knowledge management, communication

1 Introduction

Due to great public concern, any nuclear problem tends to be presented by the media as a "disaster" or "catastrophe". Unfortunately, such terminology also creeps into technical publications. In absolute terms, if impact is measured by actual or potential loss of life and damage to the environment, only nuclear weapons are really catastrophic: all other nuclear incidents are minor on the scale of natural disasters or even "conventional" industrial accidents (e.g. http://www.world-nuclear.org/info/inf06app.html). In this paper, therefore, the neutral term "incident" will be used for all cases discussed. Nevertheless, due to high public sensitivity, it is recognised that the net impact of an event releasing radioactive material can be very much greater than would be expected on the basis of purely technical assessment of hazards.

The spectre of Chernobyl was raised from the earliest stages of the Fukushima Dai-ichi incident, as soon as it was reported that emergency power had been lost and TEPCO teams were struggling to cool Units 1-3. These three reactors had shut down automatically, as designed, when the magnitude 9.0 (Richter) Tohoku earthquake occurred. The other three reactors on site were already shut down for routine maintenance. Within a few days it was clear that the risk of a Chernobyl-style runaway criticality-driven explosion was remote, but the destructive hydrogen explosions in Units 1, 3 and 4 caused confusion in many media reports, especially when this hydrogen generation was linked to fuel melting. Although evidence of meltdown led to many references to Three Mile Island (TMI), the comparison with Chernobyl continued to dominate reporting, especially when the International Nuclear and Radiological Events Scale (INES) rating of Fukushima was raised from an initial 5 to 7, based on estimates of total activity releases. The INES is a 7 point scale, where 7 is the most extreme. Chernobyl is the only previous event rated as 7: TMI is rated as 5. After this, Chernobyl analogies were used increasingly to assess the impact of releases and a number of literature studies were initiated to see what could be learned from clean-up actions carried out in the Ukraine.

Although technical experts may understand the fundamental differences between Chernobyl and Fukushima, these differences are not being communicated clearly to the public or, indeed, even to technical audiences who are unfamiliar with this aspect of the nuclear field. This is very evident in the current discussion of the extent of the evacuation zone: comparison of Fukushima fallout radiocaesium levels with those in the Chernobyl exclusion zone are not only fundamentally misleading, as discussed below, but could also lead to unnecessary public concern and misdirection of limited resources through focusing on less important issues. The following is intended to put Fukushima Dai-ichi in context by providing an overview of Chernobyl and other reactor incidents, as well as other activities that have resulted in radioactive releases into the environment. These often provide better sources of experience to help with optimising recovery and remediation in Japan.

2 Reactor incidents

Chernobyl is, by far, the most radiologically significant reactor incident to date, but is only one of a series of incidents that have resulted in significant damage to reactors (Table 1: modified from http://www.world-nuclear.org/info/inf06app.html). Furthermore, this list is certainly incomplete because of the close military links to some reactor programmes, which resulted in secrecy regarding all aspects of their operation. Gorbachev, a former President of the Soviet Union, recently claimed that 150 significant radiation leaks had occurred at reactors prior to Chernobyl [1]. Although the author was certainly in a position to have access to such information, the claim is difficult to verify in detail.

The incidents listed in Table 1 all had large economic

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consequences in terms of resultant corrective actions or even writing-off of the nuclear power plant involved. However, only a few resulted in direct deaths or any significant releases of radioactivity to the environment. This background is the basis of claims of the relative safety and low environmental impact of nuclear compared to other major power sources (oil, coal, gas, large dam hydro – see http://www.world-nuclear.org/info/inf06app.html for further details). Nevertheless, as well illustrated by Fukushima, public concern about all issues nuclear results in the net impact of reactor accidents being greater than would be assessed by simple measures of radiological hazard.

Chernobyl (1986) certainly resulted in regional-scale contamination. Operator error in reactor Unit 4 during unauthorised tests led to runaway criticality, causing an explosion and subsequent fire that distributed core material around the immediate surroundings and dispersed more volatile radionuclides widely throughout the western Soviet Union and northern Europe (described in detail by the IAEA [2]). In terms of comparison with Fukushima, it is important to note the following for Chernobyl:

1. Explosion of the core during reactor operation and absence of secondary containment resulted in a vast release of radioactivity – both short-lived mobile species that dominate early doses and long-lived, relatively immobile actinides and fission products that give long-term remediation problems.
2. Poor communication and political attempts to play down the enormity of the event delayed evacuation of populations at most risk and there was no systematic distribution of iodine tablets (hence subsequent cases of thyroid cancer in those, especially children, exposed to radio-iodine).
3. Emergency teams (“liquidators”) were confronted with a fully exposed, burning core – resulting in huge doses to many of those involved, leading to 47 direct deaths and thousands of serious cases of radiation poisoning.
4. Although the wind direction changed during the 10 days before the burning core was finally brought under control, deposition from the plume covered extensive areas of land before marine systems were reached.
5. Absence of secondary containment meant that molten core flowed into lower reactor areas and eventually solidified (as a material termed “corium”), in some cases in direct contact with rock /groundwater.
6. The main emphasis at early stages was on extinguishing the fire and then building a shelter to prevent further mobilisation of radioactivity by wind and rain.
7. The most highly contaminated region, more than 25 years later, is an exclusion zone due to the presence of a wide spectrum of radionuclides from the explosively dispersed core. There has been little effort on remediation as such within this region and, currently, effort is concentrated on rebuilding the original sarcophagus, which is leaking and

Table 1 Incidents involving fuel / core damage at nuclear power plants (deaths as a direct result of the accident noted, consequences of activity released discussed in the text)

Reactor	Date	Immediate deaths	Environmental effect	Follow-up action
NRX, Canada (experimental, 40 MWt)	1952	Nil	Nil	Repaired (new core), closed 1992
Windscale-1, UK (military plutonium-producing pile)	1957	Nil	Widespread contamination (ca. 1.5 x 10^{15} Bq released)	Entombed (filled with concrete); decommissioning planned 2037
SL-1, USA (experimental, military, 3 MWt)	1961	Three operators	Very minor radioactive release	Decommissioned
Fermi-1 USA (experimental breeder, 66 MWe)	1966	Nil	Nil	Repaired and restarted (decomm.1972)
Saint Laurent-A1, France (commercial, 480 MWe)	1969	Nil	Minor radiation release	Repaired (decomm. 1992)
Lucens, Switzerland (experimental, 7.5 MWe)	1969	Nil	Very minor radioactive release	Decommissioned and site cleaned up
Three-Mile Island-2, USA (commercial, 880 MWe)	1979	Nil	Delayed release of 2 x 10^{14} Bq of Kr-85	Clean-up programme complete, in monitored storage stage of decommissioning
Saint Laurent-A2, France (commercial, 450 MWe)	1980	Nil	Minor radiation release (8 x 10^{10} Bq)	Repaired (decomm. 1992)
Chernobyl-4, Ukraine (commercial, 950 MWe)	1986	47 staff and firefighters (32 immediate)	Major radiation release across western Soviet Union and northern Europe (11 x 10^{18} Bq) , very high local contamination	Entombed
Fukushima 1-3, Japan (commercial, 1959 MWe)	2011	Nil	Significant releases of volatile radionuclides and of some contaminated water into the sea	Units 1-4 to be decommissioned and regional clean-up being planned

in danger of collapse.

By comparison, for Fukushima:

1. Reactors were shut down for hours / days before core melt and first venting of volatile radionuclides took place. The releases of the most active, short-lived, volatile radionuclides were thus greatly decreased and off-site releases of non-volatile radionuclides are limited. Debris distributed by the hydrogen explosions would be only relatively lightly contaminated.
2. Authorities were immediately notified of the accident and, despite the chaos caused by the tsunami, nearby populations were evacuated and iodine tablets distributed before significant venting occurred. Both these actions significantly reduced off-site radiation hazard.
3. On-site workers have, in a few cases, been exposed to radiation levels higher than regulatory limits, but no case approaching acute radiation poisoning has been reported or is anticipated in the future.
4. During much of the time when the reactors were vented to release pressure, the wind direction was towards the sea, which resulted in very low radiological risk from any fallout. The most significant plume over land resulted from a period when winds were blowing towards the northwest.
5. Most molten core appears to be contained within the primary containment, although a very small extent of melt-through to the secondary containment cannot be precluded at present. In any case, there seems little risk that corium could directly contact the accessible environment
6. The primary emphasis on site has been on establishing reactor (and fuel pond) cooling and proceeding towards cold shutdown. A particular effort has involved the large volumes of contaminated cooling water and setting up a system that will allow it to be decontaminated and recycled for closed-loop cooling.
7. The evacuation zone around the damaged reactors is established on the basis of measured activities of fallout, now predominantly attributed to radiocaesium isotopes. Despite reports to the contrary, the health hazard of such radionuclides is very much smaller than the material in the Chernobyl exclusion zone and, if anything, would be more similar to areas more remote from Chernobyl that received volatile deposition (e.g. Northern Scandinavia) as opposed to particulates from the exploded core.

The other major reactor incident that is often mentioned in relation to Fukushima is TMI Unit 2 (1979), which has been extensively documented and analysed (e.g. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html). TMI was a case where fuel meltdown occurred as a result of equipment malfunction / operator error. However, the reactor type was different to Fukushima (with a much thicker containment vessel) and there was no loss of power or off-site services at TMI. Although major damage was caused to the TMI reactor core, releases of radioactivity were limited to some venting of noble gases, which did not actually exceed operational allowances. The more robust pressure vessel also ensured that there was no melt-through of the primary containment. An overview of experience from TMI and subsequent research that may be relevant to later analysis of the Fukushima accident and the decommissioning of the damaged reactors has been provided by EPRI [3].

An older incident which is more relevant to Fukushima in terms of radiological releases is the Windscale fire of 1957. As described in detail elsewhere [4], a fire in the number 1 pile, an air-cooled, graphite-moderated, uranium metal reactor used for military plutonium production, resulted in extensive releases of radioactivity – predominantly volatiles. The estimated release of I-131 was in the order of 600 TBq and Cs-137 around 10 TBq. Although some details of the accident were released at the time [5], a key fact that was kept secret was production of bomb triggers in the reactor, which led to significant releases of Po-210 (an alpha-emitter with a 5-day half-life). Subsequent reassessment of this accident [4], after the Po releases were finally admitted, concluded that, although no immediate deaths occurred, the absence of evacuation or other protective actions (apart from banning consumption of local milk) may have led to in the order of 100 premature cancer deaths – predominantly from Po-210, with I-131 being of secondary importance. As hoses were used to pump water onto the reactor to control the fire, there was also significant early run-off of contaminated water via the River Calder into the Irish Sea.

Although considered to be of less radiological significance, the distribution of fallout radiocaesium and its variation with time in agricultural produce was measured after the Windscale fire. Of possible relevance to Fukushima was the relatively rapid removal of Cs from grass and milk – far exceeding its rate of radioactive decay [5]. Since that time, the behaviour of such radionuclides in the foodchain has been studied extensively and is now well understood. There was no off-site remediation attempted after this accident; however it is notable that the affected area contains the Lake District, one of the most popular tourist destinations in the UK. The reactor building is still sealed and awaiting final decommissioning, planned for 2037 (80 years after the accident).

While the Windscale incident may be considered as effectively forgotten, some of the other reactor accidents noted in the table are almost unknown outside a small group of specialists. A good example here is the core damage to the experimental reactor at Lucens, Switzerland (1969). This was a novel, heavy-water moderated, carbon dioxide cooled, low enriched uranium design. A fundamental design flaw and associated corrosion resulted in local overheating of the core during early tests, leading to partial fuel melting and a magnesium fire [6]. Although this accident effectively destroyed the reactor, the fact that it was constructed underground, had a short period of operation prior to the accident and exhaust filters that remained intact ensured that releases of radioactivity to the environment were negligible. Damaged fuel was recovered and sent to Eurochemic in Mol (Belgium) for reprocessing, while the waste from decommissioning the reactor was stored initially in the reactor cavern until later transfer to the Swiss centralised interim storage facility (Zwilag). The old reactor cavern is now completely decontaminated and used as an archive.

In terms of incidents involving partial core melting, it is also worth mentioning the Enrico Fermi Atomic Power Plant, Unit 1 (Fermi 1). This was a fast breeder reactor cooled by sodium and operated at essentially atmospheric pressure. In 1966, a zirconium plate at the bottom of the reactor vessel became loose and blocked sodium coolant flow to some fuel sub-assemblies. Two sub-assemblies started to melt. Radiation monitors alerted the operators, who manually shut down the reactor. Despite damage to the core, no abnormal releases to the environment occurred. Less than four years later, the cause had been determined, clean-up completed, fuel replaced and Fermi 1 was restarted. A subsequent analysis identified the possibility of molten fuel reforming into a critical assembly due to the fuel's high enrichment – leading to the coining of the phrase "China Syndrome". In 1972, with the core approaching the burnup limit, the decision was made to decommission Fermi 1. The fuel and blanket sub-assemblies and radioactive primary sodium were shipped off-site and the site is now awaiting final decommissioning. Although an experimental reactor of completely different design, Fermi I provides experience related to clean-up of damaged fuel and may possibly be of relevance to the MOX fuel loaded at Fukushima.

Overall, technical experience from past reactor incidents can be summarised as follows:

a. With the notable exception of Chernobyl, past reactor incidents have had economic impacts, but little direct health consequences. Ever since 1979, when TMI occurred, any nuclear incident causes great public concern regardless of the magnitude, if any, of off-site impacts.
b. The INES ratings are rather misleading in terms of health risks. The long-term health consequences of Fukushima are in no way comparable to Chernobyl (both level 7). Although Fukushima is certainly more significant than TMI (level 5), it is difficult to imagine how the health risks to operators and the public could exceed those from Windscale (level 5) – and certainly not by the orders of magnitude implied by the logarithmic scale.
c. Damaged fuel has been recovered from reactors that have returned to service, while severely damaged reactors have been, or are planned to be, fully decommissioned. For large power reactors, delaying decommissioning to reduce activity of short-lived radionuclides is a common strategy.
d. Extensive off-site remediation has not been attempted in any of these cases. Public access to contaminated regions has been restricted only for Chernobyl.

3 Other major releases of radioactivity

In terms of radiotoxicity of material dispersed into the atmosphere, the Kyshtym accident comes closest to Chernobyl (extensive background now available on the internet, e.g. http://en.wikipedia.org/wiki/Kyshtym_disaster). The event occurred in the town of Ozyorsk, a closed city built around the Mayak plant. Since Ozyorsk/Mayak (also known as Chelyabinsk-40 and Chelyabinsk-65) was not marked on maps, the disaster is often named after Kyshtym, the nearest known town.

After the Second World War, the Soviet Union started a rapid research and development programme to produce weapons-grade uranium and plutonium. The Mayak plant was built in a great hurry between 1945 and 1948 and a storage facility for high-level liquid nuclear waste was added around 1953. It consisted of steel tanks mounted in a concrete base, 8.2 metres underground. Because of the high level of radioactivity, the waste produced significant decay heat and thus a cooler was built around each bank containing 20 tanks. Facilities for monitoring operation of the coolers and the content of the tanks were not adequate. The Kyshtym accident occurred on 29 September 1957 when the cooling system in one of the tanks, containing about 70–80 tons of liquid radioactive waste, failed and was not repaired. The temperature rise resulted in evaporation and a chemical explosion of the dried waste, consisting mainly of ammonium nitrate and acetates.

The explosion, estimated to have a force of about 70–100 tons of TNT, threw the concrete lid, weighing 160 tons, into the air. There were no immediate casualties as a result of the explosion, which released an estimated 70 to 1900 PBq of radioactivity. In the next 10 to 11 hours, the radioactive cloud moved towards the northeast, reaching 300–350 kilometres from the accident. The fallout of the cloud resulted in long-term contamination of an area of more than 800 square kilometres, primarily with caesium-137 and strontium-90. This area is usually referred to as the East-Ural Radioactive Trace (EURT – Fig. 1). The accident was rated as INES Level 6. Because of the secrecy surrounding Mayak, the populations in the affected areas were not initially informed of the accident. A week later, an operation to evacuate 10,000 people from the affected area started, still without giving an explanation of the reasons for evacuation. Even though the Soviet government suppressed information about the figures, it is estimated that direct exposure to radiation caused at least 200 cases of premature death from cancer.

The seemingly casual response to such releases reflects the extreme secrecy that prevailed at the time and the immense military pressures that existed in the former Soviet Union during the Cold War. A total of 10 different reactors operated at the Mayak site, predominantly for production of nuclear weapons materials (http://en.wikipedia.org/wiki/Mayak). Apart from a history of problems with these reactors, associated reprocessing

Fig. 1 The East-Ural Radioactive Trace

produced huge volumes of liquid radioactive waste, much of which was simply disposed of into surface water bodies. Direct disposal of long-lived radionuclides into Lake Karachay has been estimated as 20 EBq – at least an order of magnitude higher than Chernobyl releases. During a dry period in 1967 when the lake partially dried up, high winds distributed fine sediment containing an estimated 200 TBq of longer lived radionuclides over an area of several thousand square kilometres. Currently the estimated content of Lake Karachay is around 4 EBq, making it one of the most highly active areas on earth.

This situation with regard to rather causal treatment of radioactive contamination at a level up to, or beyond, that from Fukushima was common in military facilities around the world which, during the '40s, '50s and '60s, released considerable quantities of radioactive wastes to the atmosphere and surface water bodies (e.g. http://www.nukefreetexas.org/downloads/radioactivity_military_installations.pdf). Apart from technology developed for later remediation as considered below, the analysis of the resulting health consequences forms a database for chronic, long-term radiation exposure far beyond that from Chernobyl and other reactor incidents.

It also has to be recognised that, during the '60s and '70s, atmospheric testing of nuclear weapons was common, resulting in the order of 2 EBq of longer lived radionuclides being distributed around the globe [7]. Furthest distribution of activity resulted from high-yield tests, which were often conducted in remote locations, with lower yield tests giving more localised distribution of contamination. For example, over 1000 nuclear explosions were carried out in the US Nevada Test Site (NTS), resulting in major releases of activity off-site. This again provides a huge database of information on the environmental behaviour of radionuclides from atmospheric fallout and their resultant health effects.

Apart from atmospheric deposition that has directly or indirectly ended up in the Pacific, the Fukushima incident has resulted in direct input of contaminated water into the ocean. Although the inventory of activity in this water is very uncertain, estimates lie in the order of about 3 PBq for I-131 and 1 PBq for Cs-137. Due to its short half-life and high dilution by stable iodine in seawater, the former is of little concern. Cs-137 (certainly associated with other mobile fission products) can be put in context by looking at past aqueous releases into the environment (see e.g.
http://www.nukefreetexas.org/downloads/radioactivity_military_installations.pdf;
http://www.physics.harvard.edu/~wilson/publications/pp747/techa_cor.htm):

- ORNL into Clinch River (1944-1963)
  ~6 PBq (90% ^{3}H, rest mixed fission / activation products)
- Hanford into Columbia River (1944-1970)
  ~20 PBq (^{65}Zn), ~4 EBq (shorter lived radionuclides)
- Mayak into Techa River (1949-1951)
  ~100 PBq (longer-lived fission products)
- Windscale into Irish Sea (late '70s)
  up to 5 PBq/year (^{137}Cs), 3 PBq/year (^{3}H), 200 TBq/year (^{99}Tc), 100 TBq/year (^{241}Am), …

It should be emphasised that the releases from Windscale were unrelated to the fire noted above, but correspond to operational releases from the reprocessing plant at the site (renamed Sellafield in the early '80s). The release of Cs-137 was accompanied by a wide range of other radionuclides and, in fact, it was lower releases of Ru-106 that transpired to have the largest radiological impact due to high re-concentration in the foodchain (uptake by Porphyra seaweed which, unusually in the UK, is used locally to make a special type of bread). Although the concentrations of mobile radionuclides in these historical releases have been reduced to insignificance by dilution and dispersion, low-mobility / high-toxicity radionuclides (e.g. actinides) remain a concern – particularly if present as "hot particles" (see below). An overview of releases of radioactivity into the marine environment of northwest Europe and their radiological significance is provided by Kershaw [8]. Although early inventories were dominated by releases from reprocessing plants, fallout from atmospheric weapons testing and Chernobyl, it is interesting to note the increasing significance of "NORM" (naturally occurring radioactive material) input, particularly from the oil and gas extraction industries.

From this very brief overview, it is evident that the science of radioecology and the associated assessment of the health consequences of long-term exposure to radioactive contamination are both based on a huge reservoir of experience accumulated over the last half century. This contrasts with the general impression of this being a very theoretical field, dependent on small databases from the nuclear attacks on Hiroshima and Nagasaki and a few isolated events like Chernobyl. In particular, for the case of both atmospheric deposition and marine releases, there are direct measurements of the rate of redistribution of activity and the rate of dilution / "self-cleaning" under different climatic and land-use conditions.

Although there has been little effort invested in remediation of weapons test sites, studies have looked at the technology and associated costs of clean-up after potential attacks with nuclear weapons or "dirty bombs" [9]. Such literature may, in particular, be useful to assessing approaches to decontamination of urban areas. A further, more specific source of information on localised urban decontamination is associated with incidents involving lost or stolen radioactive sources. In terms of Cs-137, the most relevant case is probably that which occurred from destruction of a stolen radiology source in 1987 in Goiânia, Brazil (details in the associated IAEA report [10] and references therein).

4 Site stabilisation, clean-up and remediation

For the damaged nuclear facilities at the Fukushima Dai-ichi site (reactors, fuel storage ponds, support infrastructure) and the surrounding area contaminated by releases of radioactivity, the main challenges include:

1) Achieving safe cold shutdown
2) Providing weather cover for sensitive parts of the facility
3) Blocking all leakage of contaminated water
4) Developing a detailed inventory, and assessing the potential health hazard of:
    a) All atmospheric releases
    b) All marine releases
    c) Local releases to groundwater
    d) Site infrastructure contamination
    e) Radioactivity within the primary and secondary containment
5) Establishing a clean-up and decommissioning plan, including waste conditioning, packaging and management options (transport, storage, disposal)
6) Developing a communication portal to establish dialogue with key stakeholders (especially local communities) and involve them in the decision-making process for remediation options.

Issue (1) is very specific to the Fukushima site, although the need to achieve a closed system allowing decontamination and recycling of cooling water could gain from experience in cleaning up aqueous releases from major reprocessing plants (e.g. La Hague and Sellafield). Some commonly used methods are listed in Table 2.

Issue (2) appears to be proceeding well at present and work related to the Chernobyl "sarcophagus" offers some obvious parallels (http://en.wikipedia.org/wiki/Chernobyl_Nuclear_Power_Plant_sarcophagus). However, it should be emphasised that the Chernobyl sarcophagus was built under time pressure and conditions of extremely high radiation, and lessons learned are derived more from the problems encountered, which have resulted in current pressure to replace it with a new design. Although the new design meets specific requirements for the Chernobyl site, the fundamental modular approach to construction might provide hints that could help improve similar operations at Fukushima in the future (http://www.ebrd.com/downloads/research/factsheets/chernobyl25.pdf : video on http://www.youtube.com/watch?v=jvEDVuGOJ6Y).

Issue (3) is again specific to the site, but considerable experience exists in identifying and blocking leakages in transfer and storage systems for contaminated water, especially in older nuclear facilities. Possibly of most relevance is experience accumulated at complex sites such as Sellafield, with similar coastal settings and climate (e.g. http://www.sellafieldsites.com/land/pages/investigations_to_date.html). There is also a huge amount of knowledge from US military sites, but this may be less relevant because of generally dry (desert) conditions.

Issues 4 and 5 are closely coupled technically and can be linked to extensive experience – both positive and negative – in the remediation of contaminated sites. Although a recent guideline has been published by EPRI for nuclear power sites 11), this is rather simplistic and should be used with great care. A more useful source of information results from the large

Table 2 Examples of methods used for management of contaminated fluids

Technique	Application	Comments
Filtration / ultrafiltration	Removal of hot particles	May be needed if any risk of contact with fuel
Ion - exchange	Removal of specific dissolved species	Both general (cation / anion) and highly specific (e.g. for Cs) exchangers available
Reverse osmosis	Concentration of all solutes	Lower volume of more concentrated water to be managed
Co-precipitation / scavenging	Removal of a wide range of reactive solutes	May remove other potentially problematic non-radioactive species
Evaporation / distillation	Volume reduction	Effective if content of volatile radionuclides is low
Thermal / biological treatment, air flushing, etc.	Degradation of specific chemical components	More applicable to organics, trace metals, etc., but could be considered if complex mixed waste contaminant streams occur

investments of funding and effort associated with the "Superfund" clean-up of military sites in the USA – e.g. Hanford, Rocky Flats, Savannah River, Oak Ridge, Fernald and Los Alamos. Even from the earliest stages of such work, manuals were produced that emphasised both the wide range of potential techniques that could be used and the importance of advance planning – in particular starting with a clear assessment of the inventory and characteristics of radioactivity at the remediation site [12]. Although again with the focus on historical contaminated sites, the emphasis on advance planning is also clear in the more recent IAEA Safety Guide [13].

The starting-point for determination of all inventories at Fukushima is the calculated radionuclide content in each reactor core at the time they were scrammed. Although there are associated uncertainties related to the operational record up to this time, this initial total inventory and its variation with time can be reasonably well estimated with current codes, as can the inventory within fuel in the storage ponds. The subsequent time-line of progression of the incident after emergency power was lost (available from TEPCO) will provide input to estimate the extent of release of volatile radionuclides into the atmosphere and of any contamination of cooling water, which is either currently stored or has been discharged to the sea.

There are undoubtedly large uncertainties in this process: these are estimated by modellers to be around a factor of 5 for atmospheric releases [14], but could well be much larger if the time variation in the relative activities of different radionuclides contributing to total gamma dose cannot be better defined. Here, experience with "post-mortem" analysis of past core melt incidents (especially TMI) may give indications of some of these model uncertainties. For the specific case of spent fuel in ponds, which may be partially damaged but not actually exposed to high enough temperatures to cause meltdown, experience on vulnerability to leaching by water (including saltwater) and mechanical degradation may be obtained from remediation work in Russia – particularly in the Andreev (or Andreeva) Bay site, which contains an estimated inventory of 21,000 spent fuel rods [15].

Such release estimates can be combined with redistribution (taking into account temporal variations in wind direction, weather, coastal currents, etc.) and associated biosphere uptake models and their output compared to measured activity in the environment to check compatibility. As noted above, it is very important to combine time and / or space profiles of global parameters like gamma dose rate with detailed isotopic analysis of representative samples (air, water, soil, biota,…) to allow concentrations of individual radionuclides to be accurately quantified. As some of the shorter-lived radionuclides have now decayed to insignificance, limited direct measurements at early times may need to be complemented with more sophisticated assessment of stable isotope ratios to quantify their decay products.

A comprehensive, regional-scale model of the processes giving rise to the current distribution of radionuclides is the key to determination of both health risks and the future evolution of the area for a "do nothing" scenario. Although there is a published commitment to remediate contaminated areas, past experience shows that many environments show marked "self-cleaning" as rain washes away radionuclides, eventually dispersing them into the sea. Such processes may reduce contamination in some areas to levels that are of no concern – but can also potentially lead to formation of new contamination hotspots, such as sewers, drains, etc.

In practice, management of radioactive releases will require consideration of all options on a regional basis, perhaps using a form of "triage" to focus efforts most effectively. Such options include:

- do nothing
- replace locally derived food sources with food imported from uncontaminated areas, change land use, crops, etc. to minimise impact of contamination
- restrict access to contaminated areas
- dilute contamination by mixing with uncontaminated soil, deep ploughing, etc.
- stabilise surfaces, cap areas to reduce direct irradiation, spread of contaminated dust, surface run-off, etc.
- immobilise contamination on-site or retard radionuclide migration by use of barriers
- physically remove contamination and dispose of in an engineered repository, either on-site or elsewhere

Ideally the model used to assess such options should incorporate a description of:

- radionuclides present, concentrations and distribution (speciation, association with specific solid phases or biota)
- short-term redistribution processes ongoing (especially associated with extreme weather, human activities)
- other contaminant materials present
- local and regional backgrounds of the radionuclides of concern
- geology and hydrogeology at local and regional scales
- soil types, vegetation, land-use, aquiculture
- population distribution, habits and lifestyle.

This model can then be used to identify priorities for remediation and form the basis for quantitative assessment of the pros and cons of different remediation options (as indicated in Fig. 2). Although the figure emphasises the technical aspects of decision-making, it should be emphasised that there are also highly subjective considerations involved – particularly associated with public acceptance. This requires that, to the maximum extent possible, affected stakeholders should be integrated into the process – requiring that they be fully informed on what is involved, as discussed further under communication below.

From a purely technological viewpoint, a useful overview of remediation technologies used by the US Department of Defence (DOD) has recently been published [16]. Although the review addresses a wider range of contaminants than just radionuclides, the general findings and conclusions may be relevant, especially in areas where radionuclides are present together with other hazardous materials (e.g. as a result of tsunami damage to oil storage facilities, chemical plants, sewage works, etc.: see also IAEA [2]). It describes current DOD groundwater remediation technologies and examines whether any new technologies are being used or developed outside the Department that may have potential for DOD's use and the extent to which DOD is researching and developing new approaches to groundwater remediation. The DOD identified nearly 6,000 sites at its facilities that require groundwater remediation and has invested $20 billion over the past 10 years to clean up these sites. In the past, DOD primarily used "pump-and-treat" technologies to contain or eliminate hazardous contaminants in groundwater. Pump-and-treat is often expensive because of long clean-up times, inefficiencies in removing contaminants from the subsurface and the costs associated with disposing of the contaminants and treated water. Recently, DOD has begun to use alternatives to pump-and treat technologies that rely on a variety of biological, chemical or physical processes to treat the contaminated groundwater underground (in-situ). Fifteen types of generally accepted technologies currently available to remediate groundwater were reviewed, including 6 ex-situ and 9 in-situ technologies, each of which can be used to treat a variety of contaminants (Table 3).

Apart from such general information, there are large bodies of experience obtained at specific sites. Probably the most significant of these is Hanford, which is an extensively contaminated site covering over 1500 km^2, located just upriver from a major urban centre (population around 200,000). Despite major efforts over the last 2 decades, the effectiveness of remediation efforts has been mixed and has led to criticism by external reviewers [17,18]. While technology may not be directly transferable due to differences in the contamination characteristics and the geology / climate of the site, the positive and negative experiences with different approaches and, in particular, the identified need for a rigorous modelling approach to assess the advantages and disadvantages of different treatment options could be useful.

Although on a somewhat smaller scale, there have also been increased efforts recently to remediate sites in the former Soviet Union. From the point of view of climate and geological setting, some of these examples may be more directly relevant for Fukushima. A good overview of the current status is provided by Schweitzer et al. [19]

In general, releases of radionuclides into the marine environment – whether due to fallout from the atmosphere, indirect run-off from land or direct liquid releases from the reactor site – will have limited radiological significance due to the results of dilution and dispersion. The critical concern, as mentioned above, might be the presence of "hot particles", which can require a very long-term remediation programme. Although this is a concern predominantly at UK sites at present (e.g. Dounreay [20], Sellafield - http://www.environment-agency.gov.uk/homeandleisure/110563.aspx), it is likely that similar problems exist at other older coastal nuclear sites.

The final issue – communication – has such a key role that it is considered in a wider context in the following section.

5 Communication

The challenge of establishing a communication portal was noted in the previous section, but this must be seen within the context of both the history leading up to the Fukushima incident and the more general history of communication of accidents and subsequent remediation by the international nuclear community.

In terms of the former, TEPCO, regulatory organisations, overview bodies and the Japanese government have already been accused of underestimating the risk associated with the Fukushima Dai-ichi site and overestimating the robustness of the older reactors there to extreme natural hazards. The basis for this

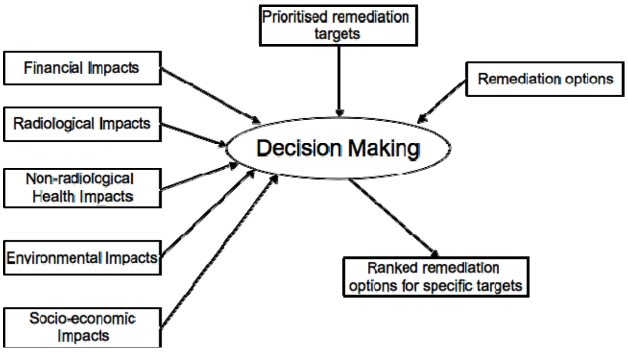

Fig. 2 Basis for decisions on preferred remediation options (modified from Fellingham [25])

Table 3 Remediation techniques reviewed by the US DOD [16]

Ex-situ application	**In-situ application**
Advanced oxidation	Chemical oxidation / reduction
Air stripping	Air sparging
Bioreactors	Bioremediation
Constructed wetlands	Phytoremediation
Ion exchange	Permeable reactive barriers
Adsorption	Multiphase extraction
	Enhanced recovery with surfactants
	Monitored natural attenuation
	Thermal treatment

criticism is certainly well founded; several studies had already highlighted both the potential for extreme earthquakes / tsunamis in the Tohoku region and also the risks to nuclear facilities in such settings (e.g. as overviewed in McKinley et al. [21]). Nevertheless, the fundamental problem of properly assessing low probability, high-consequence events has been recognised to exist throughout the nuclear industry and the experience in Fukushima has led to a number of proposed improvements to national nuclear programmes.

The attribution of blame for this and past incidents is less important than identification of the root causes: in most cases a breakdown in the communication of complex, multi-disciplinary issues that have large social and commercial consequences. This fundamental weak point is directly associated with the cause of the damage at Fukushima, its progress and the difficulties in recovering from it. It can also be seen in many of the case histories noted above, where accidents, mismanagement of wastes, ineffective remediation, etc. can, at least to some extent, be attributed to poor communication of limitations of technology, previous problems experienced and developments in system understanding – what would now be termed a breakdown of information / knowledge management. The recognition of this problem has led to increased investment in advanced knowledge management tools in the nuclear industry over the last decade although, clearly, there is still much room for further improvement in terms of widespread implementation.

In contrast to such internal communication problems, the need for effective external communication following an incident is a relatively new phenomenon and here there is little evidence of the nuclear industry using modern media anything like as effectively as opponent groups. As noted above, many of the earlier incidents were kept secret or their impact deliberately played down at the time. Indeed, many incidents from the early days of nuclear power are only now coming to light (e.g. http://en.wikipedia.org/wiki/Lists_of_nuclear_disasters_and_radioactive_incidents).

TMI was the first nuclear incident that developed under intense public scrutiny. Any technical lessons that can be learned from this accident may well be dwarfed by issues raised by the extensively discussed failures in public communication (e.g. www.iaea.org/Publications/Magazines/Bulletin/Bull472/htmls/tmi.html). These issues included not only the critical need to make information rapidly accessible to all concerned audiences, but the consequences of failing to meet this need in terms of global impact on the nuclear industry. It also became clear that the health effects due to anxiety in the general public for cases like TMI may greatly exceed anything due to the releases of radioactivity involved and this factor should be explicitly included as part of a remediation plan. A study on spontaneous abortion following the TMI accident states that “Stress has been cited as an etiological factor in the occurrence of spontaneous abortion although quantification of the relationship has not been made. Any increase in spontaneous abortion in the TMI area might more likely be related to stress than to radiation” [22].

The communication culture within the Soviet Union prevented experience from TMI being taken over in the case of Chernobyl, where both internal and external communication problems are now acknowledged to have contributed to the poor response to this incident[1]. Further, it was also clear that communication failed throughout Europe, where lack of clear information from governments and professional organisations combined with contradictory rumours (or deliberate misinformation) from both nuclear opponents and the Soviet Union to create widespread fear (e.g. Rahu [23] and references therein). Even for technically educated stakeholders, it was impossible to determine from the media whether there were real health risks in countries distant from the incident that were recording measurable deposition of radioactivity. Interestingly, Rahu [23] notes that fear was increased by use of the recently adopted Becquerel unit for radioactivity rather than the previously used Curie, as the numerical value of measurements in the former seemed so extremely high.

Unfortunately, to date, it is evident that little learned from the past has been taken over to guide Fukushima communication. Although anti-nuclear groups and politicians have used a wide range of media to successfully spread their message of the hazards from Fukushima in particular – and nuclear power in general – both the Japanese national and the international nuclear communities have been slow to provide the clear and open messages needed to put the accident in context. This is apparent at all levels – turgid websites make it difficult even for nuclear professionals to get an up-to-date picture of the current status, the mass media give updated contamination measurements in units that are impossible for even experts to understand (maximum dose rate per prefecture in μSv/hr), experts give incorrect quotes (e.g. comparisons with Chernobyl) that are never corrected …

The remediation of the area influenced by Fukushima Dai-ichi will extend over years, if not decades. Although public acceptance was not an issue in the past, this project has a uniquely high profile – beyond that even of Chernobyl. It is thus critical that communication is given high priority and implemented using a full range of modern media.

Although there are technical aspects to all remediation options noted in the previous section, many involve decisions that affect the future life of communities and it is only fair that they are involved in such decisions. Involvement is only possible, however, when all are fully aware of the issues, are confident of presenting their viewpoints and are assured that these views will be taken seriously. Japan has, in other areas such as radioactive waste disposal, moved into the fore in the development of modern approaches to establish dialogue as a basis for public involvement [24]. The challenge will be to rapidly transfer such experience and tools to the Fukushima setting.

6 Conclusions and key messages

Fukushima will remain a name associated with “nuclear catastrophes” regardless of whether a legacy of contamination and public health risks remain (as for Chernobyl) or whether it can be shown that clean-up results in no significant environmental impact (as for TMI). In order to ensure that the latter is the case, it is important to learn from experience with past incidents – in particular to ensure that mistakes are not repeated that could decrease the effectiveness of remediation actions. There is, in fact, a vast literature available and a challenge may be accessing this effectively and transferring expertise to the Japanese teams that will actually manage clean-up actions. This knowledge management challenge is also related to the need to communicate with all stakeholders and establish dialogue with them, so that they can be involved in key decisions and build acceptance of the actions that will influence their future.

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【出版小委員会作成】

フクシマ：放射能放出事故に関連する国際的な経験の概要

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福島第一原子力発電所から放出された放射能の環境および健康への影響を考える際には，これまでチェルノブイリ原子力発電所事故との比較に大きな関心が集まるとともに，スリーマイル島原子力発電所事故のような他の注目すべき原子力事故から学べることが何かということにも数多くの調査が行われてきている．実際，福島第一原子力発電所からの放射能放出量はチェルノブイリやスリーマイル島の事故とは大きく異なり，特にチェルノブイリの「デッドゾーン（避難区域）」のイメージを引き合いに出してこれらの事故と比較することは，誤解を与えるだけでなく，公衆の無用な心配を引き起こすおそれがある．原子炉における過去の事象，冷戦時代の廃棄物管理手法や環境中への放射能放出を幅広くレビューすることは，福島第一原子力発電所事故の全体像をつかむためのよい背景情報の提供につながる．このようなレビューはまた，損傷した福島第一原子力発電所の安定化や廃止措置，および汚染された地域の浄化を促進することに役立つような経験を明らかにすることができる．国際的な比較はまた，原子力業界全体が学ぶべき，強いメディアの影響力や世界的に起きたコミュニケーションの失敗によって生じた福島第一原子力発電所事故に対する特別に大きな感受性を強調することになる．

Keywords: 福島第一原子力発電所事故，環境浄化，国際経験，知識管理，コミュニケーション