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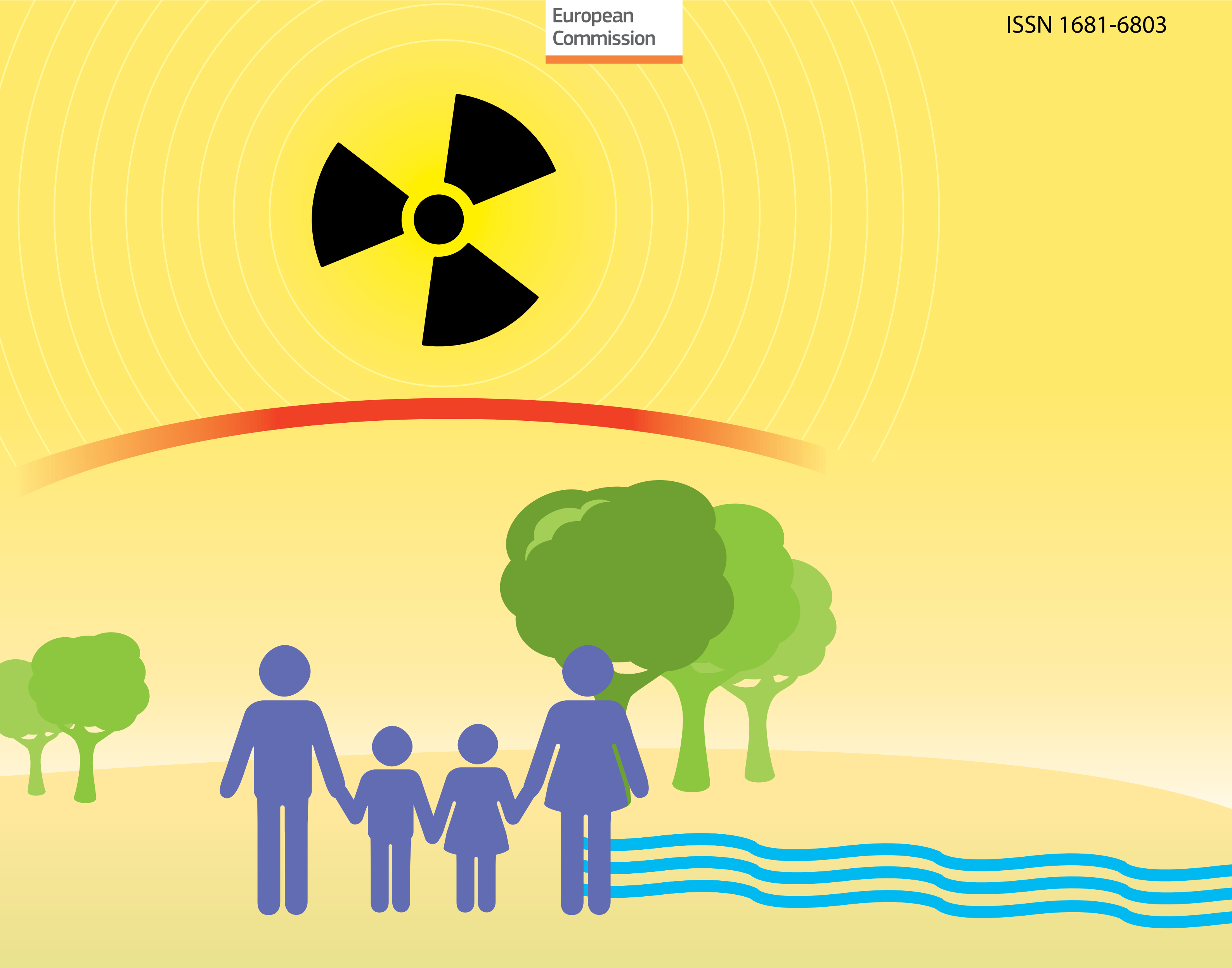

Radiation
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EU Scientific Seminar 2014
"Fukushima – Lessons learned and issues"

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RADIATION PROTECTION N° 183

EU Scientific Seminar 2014

"Fukushima – Lessons learned and issues"

Proceedings of a scientific seminar held in Luxembourg on
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Working Party on Research Implications on Health and Safety
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FOREWORD

Luxembourg, November 2015

The European Commission organises every year, in cooperation with the Group of Experts referred to in Article 31 of the Euratom Treaty, a Scientific Seminar on emerging issues in Radiation Protection – generally addressing new research findings with potential policy and/or regulatory implications. Leading scientists are invited to present the status of scientific knowledge in the selected topic. Based on the outcome of the Scientific Seminar, the Group of Experts referred to in Article 31 of the Euratom Treaty may recommend research, regulatory or legislative initiatives. The European Commission takes into account the conclusions of the Experts when setting up its radiation protection programme. The Experts' conclusions are valuable input to the process of reviewing and potentially revising European radiation protection legislation.

In 2014, the EU Scientific Seminar covered the issue *Fukushima – lessons learned and issues*. Internationally renowned scientists working in this field summarised current knowledge of the accident in Fukushima and presented

- Introduction to the Accident at Fukushima Dai-ichi Nuclear Power Station;
- Expected influence of the accident on thyroid cancers;
- Exposure and doses – lessons learned;
- Risk assessment – lessons learned;
- Worker dose assessment – lessons learned;
- Emergency preparedness – discussions on a review of the current strategy;
- Ethical issues debated after Fukushima.

The presentations were followed by a round table discussion, in which the speakers and additional invited experts discussed potential *policy implications and research needs*.

The Group of Experts discussed this information and drew conclusions that are relevant for consideration by the European Commission and other international bodies.

I. Alehno
Head of Unit Radiation Protection and Nuclear Safety

CONTENTS

1 INTRODUCTION TO THE ACCIDENT AT FUKUSHIMA DAI-ICHI NUCLEAR POWER STATION

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The Fukushima Dai-ichi ("Number One") Nuclear Power Station (NPS) is situated on the east coast of Japan approximately 200 km north of Tokyo in Fukushima Prefecture. When operational it consisted of six Boiling Water Reactors (BWRs): Unit 1, ~0.5 GW, Units 2-5, ~0.8 GW and Unit 6, ~1.1 GW. The station was operated by the Tokyo Electric Power Company (TEPCO) and the six BWRs came into operation throughout the 1970s.

On 11th March 2011, three reactors at Fukushima Dai-ichi NPS were in operation (Units 1-3) at the time of a major earthquake (magnitude 9.0) off the eastern coast of Japan. The earthquake caused severe shaking of the ground along the coast of Fukushima Prefecture, resulting in the automatic shutdown, as designed, of the three operating reactors at Fukushima Dai-ichi NPS, apparently with no serious damage that would compromise safety. The earthquake brought down electrical power lines and cut external supplies of electricity to the station, but the emergency diesel generators started up as designed to maintain electrical power on the site.

Approaching an hour after the earthquake, the Fukushima Dai-ichi NPS was engulfed by a large tsunami, of an estimated height of ~15 m, which had easily passed over the site's tsunami protection barrier of a height ~6 m. The tsunami caused substantial damage, including to the reactor cooling water heat exchangers, but most importantly the diesel generators, electrical switchgear and batteries (located in building basements) were drowned, essentially leaving the site without emergency electrical power. This was a very serious situation since although the nuclear fission chain reactions had been terminated in the three operating reactors following the emergency shut-down, significant fission product radioactive decay heat (a few tens of megawatts) was still being generated in the fuel, with no effective means of removing this heat from the reactor cores, despite desperate measures that eventually included the use of fire-pumps to inject borated seawater into the cores and helicopters dropping water onto the affected units. Inevitably, therefore, the temperatures in the fuel of the three recently operating reactors steadily began to rise.

The first overt consequence of the severe damage caused by this uncontrolled increase in temperature was an explosion on 12th March in the upper part of the building housing Unit 1, which destroyed much of the upper part of the building and which was clearly visible many kilometres away. The explosion had been caused by the accumulation in the building roof-space of hydrogen generated by the reaction of steam with the hot zircalloy cladding of the fuel; the hydrogen (with steam and other gases) had been vented from the reactor to reduce pressure, and then reacted explosively with oxygen in the air. There then followed, on 14th March, a similar but even larger hydrogen explosion in Unit 3. There was no obvious external sign of a hydrogen explosion in the other recently operating reactor, Unit 2, although the sound of an explosion in this unit had been heard on site, and it was assumed that a hydrogen explosion had also occurred in this unit, but within the reactor containment system rather than outside the containment within the working space of the building, as had happened in Units 1 and 3.

Of considerable further concern at the time was a large hydrogen explosion on 15th March in the building housing Unit 4, since the reactor had not been operating at the time of the earthquake and in fact contained no fuel. There was speculation that the hydrogen was being generated by the irradiated fuel in the interim spent fuel storage pond situated in Unit 4, level with the top of the reactor pressure vessel, and that earthquake damage to the pond structure had allowed the water in the pond to escape so uncovering the fuel and producing a rise in fuel temperature. This would have significantly increased the problems posed at the site, but it was difficult to see how relatively cool fuel could generate so much hydrogen in such a short period. Indeed, there was no evidence on site for a catastrophic loss of cooling water from the pond. It eventually transpired that ventilation piping between Units 3 and 4 had permitted hydrogen generated in the damaged reactor in Unit 3 to pass to Unit 4, and that this had accumulated in the roof-space of the building housing Unit 4 before exploding.

Soon after the tsunami had crippled Fukushima Dai-ichi NPS it was clear that there were serious problems at the site in that the three recently operating reactors could not be effectively cooled. Significant releases of radioactive materials into the environment were therefore a real prospect as severe damage to fuel increased. Under these circumstances, the realistic decision was taken to evacuate the public from areas that could be badly affected by major releases, and after areas of increasing radii from the site were selected during 12th March, an area of compulsory evacuation within 20 km of Fukushima Dai-ichi NPS was eventually decided upon, with sheltering (and subsequently voluntary evacuation) recommended for the area within 20-30 km of the site. Around 100,000 people were evacuated over the next few days, which was clearly a difficult operation given the damage to infrastructure in the area caused by the earthquake and tsunami (which caused nearly 20,000 deaths).

Evacuation of the area immediately surrounding Fukushima Dai-ichi NPS was an eminently sensible decision given the situation at the site. However, it should not be thought that evacuation can be carried out without any cost to human health. Evacuation has (non-radiological) health consequences and early deaths due to the evacuation (mainly among the elderly and chronically ill) have been reported. Therefore, the need for evacuation has to be carefully weighed, although the balance clearly fell towards evacuation under the circumstances prevailing in Fukushima Prefecture. Nonetheless, substantial discussion took place at the time as to whether a sufficiently large area around Fukushima Dai-ichi NPS had been evacuated, and as the situation at the site worsened, with growing evidence of significant releases of radionuclides from the site, many people in nearby communities made the decision to leave the area, and there was even discussion about an evacuation of Tokyo.

In difficult situations such as this, great care has to be exercised to avoid the encouragement of public panic and chaotic population movements, which could produce many casualties through, for example, traffic collisions. Unfortunately, the then EU Commissioner for Energy, Herr Günter Oettinger, was widely reported in the media as saying on 16th March of the situation at Fukushima Dai-ichi NPS,

“There is talk of an apocalypse[1] and I think the word is particularly well chosen. Practically everything is out of control. I cannot exclude the worst in the hours and days to come.”

It may well be that this is what Herr Oettinger genuinely believed at the time, but whether someone in his position of authority should be saying this publicly, given the circumstances in Japan, is a matter that requires careful consideration. For example, how many deaths might this public statement by an EU Commissioner have caused by promoting panic in, and uncontrolled flight from, Tokyo? This illustrates the caution needed in the avoidance of further destabilising a sensitive situation such as existed at that time in Japan.

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[1] Apocalypse – an event involving destruction or damage on a catastrophic scale.

It was clear from 12th March onwards, after the first hydrogen explosion in Unit 1, that radioactive material would be released from the reactors at Fukushima Dai-ichi NPS. It was hoped that most of the activity would be carried by the prevailing westerly winds out over the Pacific Ocean, but an aerial survey carried out during 17th - 19th March on behalf of the Japanese Government by the US Department of Energy using sensitive gamma radiation detectors mounted under a light aircraft, showed a “finger” of radioactive contamination of the ground stretching out from Fukushima Dai-ichi NPS to the north-west. This “finger” extended beyond the 20 km evacuation zone, out to 40 km or more from the site. This contamination was attributable to the releases from Unit 3 and, in particular, from Unit 2, the plume being carried by a south-easterly wind, with deposition of radioactive material being exacerbated by rain, sleet and snow.

Much of the radioactive material released to atmosphere was composed of noble gases (mainly xenon-133, with a physical half-life of ~5 days) and radioisotopes of the volatile elements caesium and iodine. It was known from the Chernobyl Unit 4 accident in the Ukraine that commenced with a reactor explosion on 26th April 1986 that the major radiological protection issue soon after an operating reactor accident is exposure to radioisotopes of iodine, particularly I-131, with a half-life of ~8 days. This is because iodine concentrates in the thyroid gland, which is known to be particularly radiosensitive to the induction of cancer, especially in children. Following the Chernobyl accident, the Soviet authorities were slow to take action: evacuation of local communities was delayed for around 36 hours and food restrictions, in particular a milk ban, in the heavily contaminated areas around Chernobyl were not put in place. This resulted in tens of thousands of children receiving thyroid doses from I-131 that exceeded 1 Gy, and this has led to several thousand excess cases of thyroid cancer (with several thousand more cases expected in future). Given this experience it was imperative that children in the contaminated area to the north-west of Fukushima Dai-ichi NPS should have their exposure to I-131 reduced to a minimum through food restrictions (to limit ingestion), sheltering (to limit inhalation), and possibly also through the administration of preparations of stable iodine to block the uptake of radioiodine by the thyroid (in that if the thyroid is saturated with stable iodine it is less likely to accumulate radioiodine). Given the difficult circumstances being experienced by the population in the affected area, these radiological protection measures appear to have been largely successful in limiting the thyroid doses received by children, as indicated by measurements of thyroid I-131 concentrations that were performed soon after the contamination.

Iodine-131 is a problem that is limited in time by its eight-day half-life, such that radioiodine contamination will be reduced to a low level after three months (i.e. greater than ten half-lives). A longer-term problem arises from contamination by radioisotopes of caesium: Cs-134 has a half-life of ~2 years, and Cs-137 a half-life of ~30 years. In the area surrounding the Chernobyl site, during the period since the accident in 1986 Cs-134 contamination has now reduced to a very low level, but the Cs-137 released by the accident has only decayed to approaching one half of its original value, so that substantial deposits of Cs-137 remain in the heavily contaminated areas around Chernobyl. In the absence of appreciable efforts to remove Cs-137 from the environment (through remediation measures such as soil removal and pressure hosing of contaminated surfaces) significant contamination can be expected to persist in the area to the north-west of Fukushima Dai-ichi NPS for a prolonged period. Thus, long-term radiological protection measures have to be in place that control radiocaesium in foodstuffs, and also limit the dose received from gamma radiation “groundshine” from radiocaesium deposited in the environment, which may necessitate the continued restriction of the return of residents to the more heavily contaminated areas.

Recent estimates of the activities of radionuclides released to atmosphere from Fukushima Dai-ichi NPS are 120 PBq of I-131, 9.0 PBq of Cs-134, and 8.8 PBq of Cs-137. In comparison the Chernobyl accident released 1800 PBq of I-131, 50 PBq of Cs-134, and 85 PBq of Cs-137, so that the releases of activities of the main radionuclides from Fukushima are around 10-15% of those from Chernobyl. On the basis of these levels of activity releases, the Fukushima accident, along with the Chernobyl accident, was rated as 7 (i.e. the highest rating) on the International Nuclear Event Scale (INES). Of some interest is the comparison with the activities of radionuclides released to atmosphere during above-ground nuclear weapons testing, particularly in the late-1950s and early-1960s: 675 000 PBq of I-131 and 948 PBq of Cs-137. Although the activities of radionuclides in nuclear weapons testing fallout are substantially greater than those released in the Chernobyl and Fukushima accidents, it should be borne in mind that atmospheric nuclear weapons testing took place over a number of years whereas the reactor accident releases occurred in a matter of days and were localised, leading to higher concentrations of radionuclides close to the affected reactors.

To the north-west of Fukushima Dai-ichi an area stretching ~20 km beyond the 20 km radius initial evacuation zone was assessed to give sufficient exposure to gamma radiation “groundshine” from deposited Cs-134 and Cs-137 that evacuation was required; the criterion was that this “groundshine” could lead to an effective dose of 20 mSv or more in one year. Unlike the evacuation of the 20 km radius area immediately around Fukushima Dai-ichi NPS, which was done to protect residents in the event of a substantial release of radioactive material from the site, the contaminated area beyond 20 km to the north-west of the NPS required evacuation because of existing (rather than potential) contamination. So, given the level of dose from “groundshine” (which was up to a few tens of millisieverts per year above the 20 mSv/year decision level for evacuation), identified communities in this area could be evacuated over a period of a few weeks rather than immediately, since there was no imminent danger of large doses being received. Residents are now starting to return to evacuated areas with low levels of contamination.

Apart from atmospheric releases of radionuclides being deposited in the Pacific Ocean, contaminated water from the attempts to cool the damaged reactor cores inevitably reached the sea, with an estimated 15 PBq of I-131 and 5 PBq of Cs-137 being directly released to the marine environment. This led to a ban on the consumption of seafood from the vicinity of Fukushima Dai-ichi NPS. As contaminated cooling water accumulated on the site, the need to find a means of cleaning and storing this water mounted in urgency. In an effort to create much needed liquid storage capacity, mildly contaminated water that was already stored at Fukushima Dai-ichi NPS was released to sea so that much more highly contaminated water could be stored on-site, and temporary storage tanks were assembled to increase the volume of liquid that could be retained. Liquid treatment plants of increasing sophistication have been introduced to enable the recycling of cooling water, although large volumes of treated water have not yet been discharged to sea, mainly because of concerns over tritium levels. The need to continue to cool the irradiated fuel during decommissioning operations will mean that storage and treatment of contaminated water will remain an issue for some time to come.

In the confused conditions during the early stages of the Chernobyl accident, some workers dealing with the emergency received high doses of gamma radiation from fragments of irradiated fuel scattered in the vicinity of the affected reactor, and for 134 of these workers the doses were sufficiently high to produce acute radiation syndrome (ARS). Of these workers who suffered from ARS, 28 died in 1986, i.e. within a few months of exposure. Clearly, very careful monitoring of radiation levels commencing from the initial stages of a serious nuclear accident is required to prevent unacceptable doses being received by workers, especially of a magnitude that leads to deaths and deterministic effects. Fortunately, during the accident at the Fukushima Dai-ichi NPS no deaths resulting from radiation exposure occurred and no deterministic effects were reported among the hundreds of workers involved in dealing with the emergency, although it is clear that conditions at the site were very serious and highly unstable during the first few days of the accident, which on occasions necessitated the temporary evacuation of workers from the site. Initially, an emergency effective dose limit for workers of 100 mSv was put in place, but as the seriousness of the situation at the site increased this limit was raised to 250 mSv, which was a balance between the prevention of deterministic effects and limiting the risk of radiation-induced stochastic effects, and having experienced workers available to deal with events as they developed at the site. Six emergency workers received effective doses in excess of the 250 mSv emergency effective dose limit, mainly as a result of inhaling I-131, so that the thyroid doses received by these workers exceeded 1 Gy; the health of these workers will have to be monitored over the remainder of their lives, especially for any thyroid abnormalities. Thousands of workers continue to be involved in recovery operations at Fukushima Dai-ichi NPS, which will last for many years, but from the beginning of 2012 the annual effective dose limit for these workers has been reduced to 50 mSv.

That a severe nuclear reactor accident could take place in a technologically advanced country like Japan clearly raises difficult and important questions. One of these must be how the emergency diesel generators and other essential equipment could have been incapacitated by a tsunami. Although large tsunamis are not common in Japan, they are not especially rare events – for example, a large tsunami in 1896 caused by an earthquake located close to that in 2011 resulted in more than 20,000 deaths – and "tsunami stones" can be found along the north-east coast of Japan marking the extent of the ingress inland of past tsunamis, to warn people of the dangers of living too close to the seashore. Indeed, it was only on 26th December 2004 that an earthquake off the coast of Sumatra triggered a large tsunami that killed nearly a quarter of a million people – a stark reminder of the damage and deaths that can be caused by a tsunami. The tsunami that struck Fukushima Dai-ichi NPS was undoubtedly of an exceptional size, and under these circumstances it is perhaps not too surprising that it washed over the barrier designed to protect the site; but one has to ask how the emergency diesel generators were so vulnerable to drowning should the tsunami barrier have failed to prevent a significant flooding of the site. "Defence in depth" would seem to demand substantial protection of essential equipment should the first line of defence fail, and the magnitude of the accident only serves to reinforce this point. Remarkably, all this appears to have been more or less known before the accident, but failure to act on this information in a timely manner made a major accident in the event of Fukushima Dai-ichi NPS being struck by a large tsunami almost inevitable.

Two official Japanese inquiries were highly critical of the Japanese system for ensuring the control of nuclear plant safety: the "Hatamura Commission" was established by the Japanese Cabinet while the "Kurokawa Commission" was set up by the Diet (the Japanese Parliament). Both committees reported in July 2012. The "Kurokawa Report" spoke of "collusion between the government, the regulators and TEPCO" and that the accident at the Fukushima Dai-ichi NPS was a "disaster 'Made in Japan'". The reports' criticisms were very strong, particularly in the context of Japanese culture.

The serious question then arises as to how to prevent the situation occurring in other countries that allowed safety standards to fall to a level that permitted the accident to take place in Fukushima. It is obvious that a good safety culture in companies that operate nuclear installations, together with strong and independent regulation, is essential, but how can this be guaranteed? For example, there is a proposal to build nuclear power reactors in the Kaliningrad enclave of the Russian Federation, which is completely surrounded by countries that are members of the European Union. How does the European Union ensure that adequate, internationally recognised nuclear safety measures are adopted and maintained in Kaliningrad? In using this example of Kaliningrad, it should not be taken that I am implying that the nuclear safety standards of the Russian Federation are in any way inadequate, only that this is a European example that poses the question of how the European Union can be assured that safety standards are adequate in a neighbouring country, in much the same way as Korea and China would have a justified interest in nuclear safety standards in Japan. Perhaps there is a role for inspection by the International Atomic Energy Agency, analogous to its role in inspecting nuclear plants for the possible diversion of nuclear materials for weapons purposes? If the Agency was to be involved in the audit of national operational and regulatory systems then it would have to be within a framework that gave it "teeth" (i.e. sanctions against those countries falling short of internationally accepted minimum safety standards), or it is unlikely that such an inspection process would succeed. Clearly, this raises difficult issues of national sovereignty, but such a system would provide assurance that basic safety standards were in place in those countries operating nuclear power stations and other nuclear installations. At another level, the involvement of local communities, shareholders, insurers and other stakeholders could contribute to the assurance that adequate safety standards at nuclear installations are adopted and maintained.

In conclusion, it is difficult to improve upon the summary of Acton and Hibbs (2012) from their Carnegie Paper on the Fukushima Dai-ichi NPS accident:

“In the final analysis, the Fukushima accident does not reveal a previously unknown fatal flaw associated with nuclear power. Rather, it underscores the importance of periodically reevaluating plant safety in light of dynamic external threats and of evolving best practices, as well as the need for an effective regulator to oversee this process.”

The serious accident at Fukushima Dia-ichi NPS unfortunately illustrates the dangers of familiarity and complacency – just because a nuclear installation has operated without a major incident for many years does not mean that one will not happen tomorrow. Those responsible for nuclear safety must continually be alert to the need for critical evaluation and external audit to maintain adequate safety standards, and to strengthen them in the light of experience.

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2 EXPECTED INFLUENCE OF THE ACCIDENT ON THYROID CANCERS

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2.1 Introduction

An expected increase of thyroid cancer incidence is one of the major concerns after the accident at the Fukushima Dai-ichi nuclear power plant (NPP). The concern is caused by the massive increase of thyroid cancer among those who were highly exposed during childhood due to the Chernobyl accident (Kazakov et al. 1992; UNSCEAR 2011). It has been assessed that nearly two thirds of the thyroid cancers operated in the period 1990 to 2001 among Belarusians, who were 18 years or younger at the time of the accident, are attributable to the radiation exposure caused by the accident (Jacob et al. 2006).

In order to monitor thyroid cancer, periodic thyroid ultrasonography screening has been introduced for all living in the Fukushima Prefecture and having been 18 years old or younger at the time of the accident (Yamashita 2014). In this paper we address three questions related to thyroid cancer in the Fukushima Prefecture under the condition of continued thyroid screening:

- Is the prevalence detected by the first screening consistent with what has been observed after the Chernobyl accident?
- If yes, what are our expectations of future thyroid cancer incidence?
- Will a radiation effect become detectable?

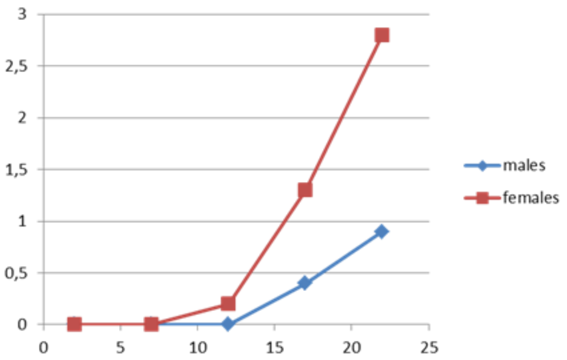
2.2 Prevalence in the Fukushima Prefecture (first screening)

Prevalence in screened cohort and country-specific incidence rate

As of 30 June 2014, results of the first ultrasonography screening were known for 295,689 persons (FMU 2014). Fine needle aspiration (FNA) biopsies were recommended to persons with nodules larger than 5 mm or cysts larger than 20 mm. Cytology indicated thyroid cancer for 104 persons; one of which turned out to be a benign nodule as shown by pathological examination after surgery. These numbers correspond to a prevalence in the Fukushima Prefecture, $\boldsymbol{P_{FP}}$, of 0.035%. However, for some biopsies results of cytology were not yet available, and some people denied FNA although it was recommended to them. Assuming the same prevalence for these two population group as among those, for whom cytology results were available, results in a theoretical prevalence of $\boldsymbol{P_{FP}}$ of 0.042%. Similar prevalence has been observed in the three prefectures of Aomori, Yamanashi and Nagasaki, in which only negligible exposures due to the accident in the Fukushima Dai-ichi NPP occurred (Taniguchi et al. 2013).

It has been attempted to relate the prevalence detected during the first screening to the thyroid cancer incidence rate in Japan before the accident. The rate increases strongly with age (Figure 1). According to these data, the incidence rate in Japan in 2007 for a population with the same age-sex distribution as the screened population in the Fukushima Prefecture at the time of the first screening, $\boldsymbol{\lambda}_{Jp,FP}$, is 0.3 cases per year among 100,000 persons.

Figure 1: Thyroid cancer incidence rate (cases per 100,000 person-years) in Japan in 2007 in dependence of age (years) and sex (Ganjoho 2012)



There is no straightforward way, to compare prevalence and incidence rate. The prevalence was derived from a screening that lasted about 30 months (October 2011 to March 2014). Probably, a similar number of cases would have been performed, if the screening was performed within 3 months or within 60 months. So, it is not clear over what time period the incidence rate should be integrated to compare it with the detected prevalence. Independent of this difficulty, the numbers clearly indicate that the number of cases detected by the screening is much larger than the number of cases that is reported to the cancer registry in times when such a screening is not performed. There are two reasons for this: i) tumors are detected earlier, and ii) tumors that never in life cause any symptoms are detected by the screening. There is large pool of such so called occult tumors that amount to about 5% in the adult Japanese population (Hayashi et al. 2010). Radiation exposure is not expected to contribute to thyroid cancer prevalence or incidence rate before three years after the exposure (Heidenreich et al. 1999).

Since thyroid cancer incidence before the accident is of no help to understand the prevalence detected by the first screening, we chose to compare with the prevalence in another population screened with an equipment not too different from the modern equipment used in the Fukushima Prefecture. Most screenings were performed in adult populations (e.g., Yuen et al. 2011). However there is no straightforward way to relate prevalence in adult populations to prevalence among very young populations. Thyroid cancer screening was also performed in the UkrAm cohort that consists of Ukrainians having been exposed during childhood or adolescence to radiation caused by the Chernobyl accident (O’Kane et al. 2010). The age distribution in the UkrAm resembles more to the age distribution of the screened population in the Fukushima Prefecture than other screening studies. Therefore, an assessment of the impact of the screening in the Fukushima Prefecture on thyroid cancer has been based on data from the UkrAm cohort (Jacob et al. 2014). The transfer of the results is facilitated by the fact that thyroid cancer incidence rates in Ukraine (Fedorenko et al. 2002) and Japan (Ganjoho 2012) are quite similar.

Expectation of prevalence based on UkrAm cohort

The first screening of the UkrAm cohort was performed 12 to 14 years after the accidental exposure (Tronko et al. 2006). It was assessed that 11.2 (95% CI: 3.2; 22.5) of the cases detected among 13,127 participants were not related to radiation exposure. This corresponds to a prevalence, $\boldsymbol{P}_{UkrAm}$, of 0.09% (95% CI: 0.02%; 0.17%). In order to transfer this result to the prevalence in Fukushima Prefecture, $\boldsymbol{P}_{FP}$, two factors have to be taken into account: i) the average age in the UkrAm at the time of the screening was 22 years and thus higher than in the Fukushima Prefecture; and ii) a different study protocol was applied.

In order to take the age effect into account we multiply P_{UkrAm} by the ratio of the country-and-cohort specific incidence rates, $\lambda_{Jp,FP}/\lambda_{Ukr,UkrAm}$. The incidence rate in Ukraine in 2000 for a population with the same age-sex distribution as the UkrAm cohort at the time of the first screening, $\lambda_{Ukr,UkrAm}$, is about 1.8 cases per year among 100,000 persons.

Differences in the study protocol lead to a higher detection rate of tumors in the Fukushima Prefecture as compared to the UkrAm cohort. We express this by a factor f_{sp}:

$$P_{\mathrm{FP}} = f_{\mathrm{sp}}\, P_{\mathrm{UkrAm}}\, \lambda_{\mathrm{Jp,FP}}/\lambda_{\mathrm{Ukr,UkrAm}}. \qquad (1)$$

The main difference in the study protocol relates to a selection of nodules larger than 5 mm for FNA in the Fukushima Prefecture, while in the UkrAm cohort nodules larger than 10 mm were selected. Thus, f_{sp} can be estimated by the ratio of the numbers of tumors larger than 5 mm and larger than 10 mm. The author is not aware of information on this ratio in the screening results for the Fukushima Prefecture.

In an ultrasonography screening of thyroid cancer in Hong-Kong (Yuen et al. 2011), the ratio of the numbers of tumors larger than 5 mm and larger than 10 mm was 2.2 (11/5). The ratio of the numbers of nodules larger than 5 mm and larger than 10 mm was 2.4 (398/169). The similarity of these values indicates that the ratio for nodules may be used as a surrogate for the ratio for tumors. As of 30 June 2014, in the first screening in the Fukushima Prefecture 2218 nodules were of size larger than 5 mm, and 647 nodules were of size larger than 10 mm (FMU 2014). The resulting ratio of 3.4 may be taken as an upper estimate of f_{sp}, because in the UkrAm study FNA biopsy has also been performed for a few tumors in the size range of 5 – 10 mm.

Based on data as of 31 July 2013, Jacob et al. (2014) used for f_{sp} a symmetrical triangular distribution with a lower bound of 1 and an upper bound of 3.2, and derived an expectation of the prevalence in the Fukushima Prefecture, P_{FP}, of 0.035% (95% CI: 0.010%; 0.086%). The good agreement of this expectation with the screening results in the Fukushima Prefecture (see above) indicates that results of the UkrAm cohort may also be used to derive an expectation of thyroid cancer incidence in the subsequent screenings in the Fukushima Prefecture.

2.3 Result Expected incidence in the Fukushima Prefecture (subsequent screenings)

Thyroid cancer risk due to exposure to ionizing radiation has been derived from the life span study (LSS) of the survivors of the atomic bombings of Hiroshima and Nagasaki in various studies differing in the type of tumors included (micro-carcinoma included or not) and taking into account the screening effect in the sub-cohort of the adult health study (AHS). Micro-carcinoma are registered in the screening population in the Fukushima Prefecture, and the screening differs from that in the LSS. Jacob et al. (2014) included in their analysis of the LSS data micro-carcinoma and derived a risk function that excludes the AHS screening effect.

The excess relative risk per unit dose (ERR_{LSS}) is estimated to be about 6/Gy for females of age of 30 years after exposure at age of 10 years. Thus the total thyroid cancer risk after an exposure with a thyroid dose of 1 Gy is about 7 times larger than the risk without exposure. For males, the ERR per unit dose is about 3.5/Gy. The ERR decreases with increasing age at exposure and with increasing age attained.

The excess absolute risk per unit dose (**EAR_{LSS}**) is estimated to be about 0.8 per 10,000 person-year Gy for females at age of 30 years after exposure at age of 10 years. For males, EAR is about half of the EAR of females. The EAR decreases with increasing age at exposure and with increasing time since exposure.

According to approaches used previously, the excess absolute risk in the Fukushima prefecture, **EAR_{FP}**, would be derived by multiplying **ERR_{LSS}** with the baseline incidence rate **$\lambda_{Jp,FP}$**. However, in this approach **EAR_{FP}** is zero for boys generally and for girls younger than 10 years (see Figure 1). As a consequence, a mixed transfer of **ERR_{LSS}** and **EAR_{LSS}** has been chosen in more recent studies (WHO 2013, UNSCEAR 2014, Jacob et al. 2014).

Jacob et al. (2014) estimated the excess absolute risk per unit dose **$EAR_{FP}(s,a,e)$** for sex **s**, attained age **a**, and age at exposure **e** by introducing three additional factors to take into account

- the uncertainty in transferring the LSS results to low-dose and low-dose-rate exposures, **f_{DDREF}** (Jacob et al. 2009)
- the minimal latency period of 3 years, **$f_L(a-e)$** (Heidenreich et al. 1999)
- the screening effect, **f_{scr}** (see below):

$$EAR_{FP}(s,a,e) = f_{scr}\, f_L(a-e)\, f_{DDREF}\, (ERR_{LSS}\, \lambda_{Jp,FP} + EAR_{LSS})/2 \qquad (2)$$

The screening factor in the Fukushima Prefecture, **f_{scr}**, has been assessed by multiplying the screening effect in the second to fourth screening of the UkrAm cohort (Brenner et al. 2011) with the factor **f_{sp}** for differences in study protocol. The resulting distribution had a best estimate of 7.4 with a 95% confidence interval from 0.95 to 17.3.

Incidence risk attributable to radiation exposure at age **e**, **$ARR(s,e)$**, is estimated by integrating the product of **$EAR_{FP}(s,a,e)$** and the thyroid dose over the lifetime period of interest. Incidence risk in the cohort is obtained by integrating the product of **$ARR(s,e)$** and the age-at-exposure density distribution in the cohort over age-at-exposure and summing over both sexes.

Table 1: Estimated thyroid cancer incidence for two periods since the accident and assumed average thyroid dose in two population groups (after Jacob et al. 2014)

Sex and age at exposure	Time period (years)	Thyroid cancer	**Assumed** thyroid dose (mGy)	Incidence risk (%)
Distribution as in screened cohort	10	Baseline	-	0.06 (0.006; 0.14)
		Attributable	10	0.003 (10^{-4}; 0.013)
	50	Baseline	-	2.2 (0.3; 5.3)
		Attributable	10	0.07 (0.003; 0.20)
Females exposed at age of 1 year	10	Baseline	-	0.003 ($2\ 10^{-4}$; 0.009)
		Attributable	20	0.003 ($6\ 10^{-5}$;0.014)
	50	Baseline	-	2.3 (0.3; 5.5)
		Attributable	20	0.3 (0.02; 0.9)

Baseline incidence risk (risk without radiation exposure from the accident at the Fukushima Dai-ichi NPP) during the first 50 years after the accident is about 2%, i.e. it is estimated that thyroid cancer will be detected for 2 of 100 persons, if the screening would be continued all the time (Table 1). The contribution of the radiation exposure to this risk is expected to be small.

2.4 Detectability of radiation effect

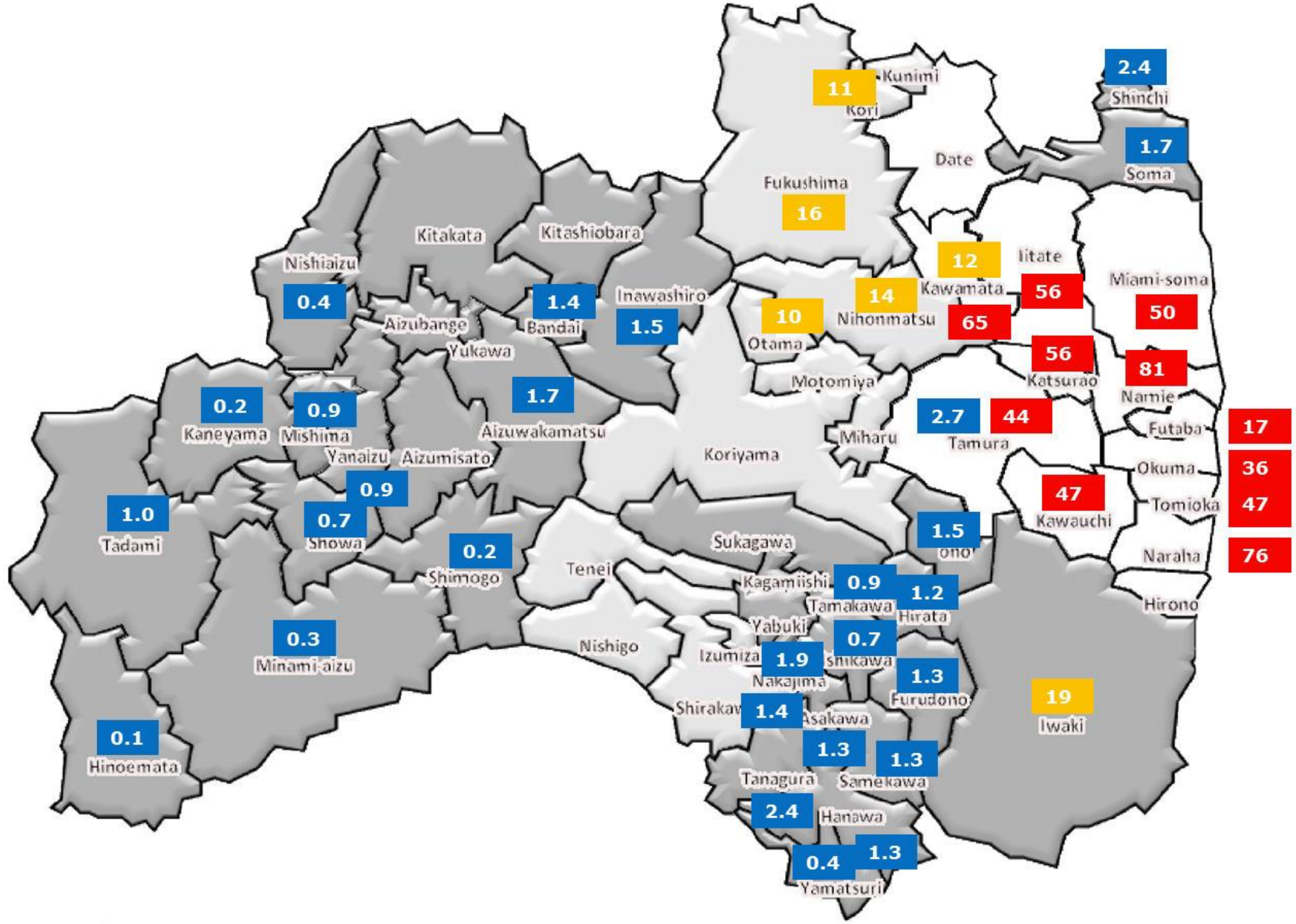
The distribution of average thyroid dose estimated by UNSCEAR (2014) for the districts of the Fukushima Prefecture (Figure 2) is used here to define low and higher exposed population groups. The population in non-evacuated districts with average thyroid doses of infants due to inhalation of radioactive substances and exposure to external radiation of less than 3 mGy is assumed to constitute the low-exposed group, and the higher-exposed population to live in districts with corresponding doses exceeding 10 mGy. Probably, ingestion doses in these two areas were different. However, there were not sufficient data to quantify this difference. The population in the low-exposed districts amounts to 440,000, in the higher-exposed districts to 740,000 (UNSCEAR 2014). Based on population statistics, we assume that 15% of the population were 18 years or younger at 1 April 2011, and that 1.5% were female infants.

Further we **assume**, that the difference of average thyroid doses in the two regions amount to 10 mGy for the whole of the screened population, and to 20 mGy for infants. Under these conditions the statistical power of the study would be very low (Table 2). The power would be higher, if thyroid cancer risk per unit dose is higher than presently assumed, or if the low-dose group would be increased by screening people outside of the Fukushima Prefecture. Because of the relatively small number of evacuees no better detectability of a radiation effect is expected for them compared to the non-evacuated population despite of their higher thyroid doses.

Table 2: Power of hypothetical studies to detect a change of thyroid cancer incidence due to radiation exposure caused by the accident at the Fukushima Dai-ichi NPP

Population	D_{higher}-D_{low} (mGy)	Risk per unit dose	Power for 20 years study (%)	Power for 50 years study (%)
Screened	10	Best estimate	< 50	< 50
		2.5 * best estimate	< 50	70
Girls < 3 years	20	Best estimate	<50	< 50
		2.5 * best estimate	< 50	87
Girls < 3 years, low-dose group doubled	20	Best estimate	< 50	< 50

Figure 2: Average first-year thyroid doses of infants in non-evacuated districts of Fukushima Prefecture due to inhalation and external radiation below 3 mGy (blue) or exceeding 10 mGy (yellow), and in evacuated settlements due to all pathways (red) (after UNSCEAR 2014)



2.5 Discussion

A prevalence of about 0.04% (95% confidence interval: 0.01%; 0.09%) of thyroid cancer in the screened population of Fukushima Prefecture has been derived based on experiences gained after the Chernobyl accident, especially the first screening in the UkrAm cohort. This prediction agrees well with the number of 103 suspicious thyroid cancer cases identified by fine needle biopsy cytology up to 30 June 2014 that have not been falsified by pathological examination after surgery. Because of a minimal latency time of three years, the accidental radiation exposure is not expected to contribute to these prevalent cases. This is supported by a study in three prefectures of Japan not affected by the accident. The study showed a similar prevalence as in the Fukushima Prefecture.

Based on the second to fourth screening in the UkrAm cohort, it is predicted that thyroid cancer incidence in the screened population will be higher than thyroid cancer incidence in Japan in 2007 by a factor of about 7 (95% CI: 1; 17). Thyroid cancer incidence during the first fifty years after exposure is expected to be about 2% (95% CI: 0.3%, 5%).

Thyroid cancer risk due to exposure to ionizing radiation has been derived from the incidence data for the LSS. These data start in 1958, thirteen years after exposure. Studies of thyroid cancer risk after the Chernobyl accident indicate that this risk function may underestimate the risk in the first decade after the exposure. This has, however, only a small impact on the results presented here, because most of the calculated excess cancer cases do not manifest before several decades after exposure.

For an **assumed** thyroid dose of 10 mGy, the contribution of the radiation exposure to the 50-years thyroid cancer incidence would be small, about 0.07% (95% 0.003%; 0.2%). The prediction has a large uncertainty caused by uncertainties in the screening factor, the radiation risk per unit dose for high doses, and the extrapolation of this risk factor to low-dose and low-dose-rate exposures. No evidence is available for excess thyroid cancer risk after exposures as low as those received by the population after the accident in the Fukushima Dai-ichi NPP. Thus, the radiation risk values given above are nothing but notional.

The risk values given above apply to an assumed thyroid dose. There are still discrepancies between dose modelling performed by international organizations and considerably lower dose assessments based on measurements by Japanese scientists. These discrepancies need to be resolved.

If present best estimates of radiation risk are correct, then there is a low probability that a radiation effect on thyroid cancer incidence will become detectable. If, however, real radiation risks correspond to high but still probable risk values, then a radiation effect might become detectable after several decades of observation, but are still not expected to be detectable for shorter periods.

2.6 Acknowledgements

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3 EXPOSURES AND DOSES: LESSONS LEARNT FROM THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

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3.1 Introduction

The accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) resulted in the release of large quantities of radioactive materials to the environment. There was wide interest both at the time of the accident and subsequently in assessing the potential radiation exposures and doses. There have been two major international dose assessments, for the World Health Organization (WHO) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). An assessment by the International Atomic Energy Agency (IAEA) is still in progress.

This presentation discusses the assessment of doses received by members of the public in the event of a radiological incident, either by an accident or a deliberate release, and considers what lessons can be learnt from the accident at the Fukushima Daiichi Nuclear Power Plant.

3.2 Background

Assessments are undertaken for different reasons after a release of radioactivity. Three of the most significant are:

- Assessments of public doses in the early emergency phase. These are undertaken to inform health protection decisions, to determine whether actions are needed rapidly to reduce doses from exposure and if so what measures are required.
- Assessments in the emergency and post-emergency phases. These are undertaken to determine what, if any, longer term measures (such as recovery options or longer-term restrictions on foodstuffs) are required to reduce exposures delivered beyond the emergency phase.
- Assessments in the post-emergency phase. These are often undertaken for health-related reasons (for example, for comparison with medical observations, or for planning medical surveillance, for input to epidemiological studies, and also for public reassurance).

The data requirements and timescales for these applications are somewhat different. The urgency with which decisions are required on emergency countermeasures is likely to preclude full information being available to the assessors, and the time focus is predominantly short-term. Retrospective assessment of exposures for input to dose reconstruction requires a fuller spread of data, both spatially and temporally, and includes a combination of information from measurements and modelling.

This paper focuses on:

- What is ideally required rapidly in the emergency phase to assess public doses.
- What is ideally required in post-emergency phase assessments of public doses.
- What lessons may be learnt from the Fukushima accident.
- What are the key uncertainties associated with assessments.
- Research priorities.

3.3 Summary of key dose aspects of the accident at the Fukushima Daiichi Nuclear Power Plant

In general, for releases to atmosphere the important exposure pathways are:

- external irradiation from radionuclides in the atmosphere;
- external irradiation from radionuclides deposited on the ground;
- internal irradiation following the inhalation of radionuclides in the atmosphere;
- internal irradiation from the ingestion of radionuclides transferred to the terrestrial food chain and to drinking water.

Other pathways such as inhalation of radionuclides deposited on the ground and then resuspended into the atmosphere are usually, although not invariably, less important.

For releases to the aquatic environment the important exposure pathways are external irradiation from radionuclides transferred to sediments; internal irradiation from radionuclides transferred to aquatic foods; internal irradiation from radionuclides in drinking water (freshwater discharges only).

As mentioned above, major international dose assessments have been published by WHO (WHO, 2012) and by UNSCEAR (UNSCEAR, 2014), and other aspects of dose estimation have been published by individual research groups. The main source of information on the radiation doses received in Japan and the rest of the world is the comprehensive study carried out by UNSCEAR and published earlier this year. The key radionuclides contributing to dose are ^{131}I, ^{134}Cs and ^{137}Cs, and the key exposure pathways are external irradiation from deposited material, inhalation and in most locations distant from the release point the ingestion of food. Doses delivered in the first days following the accident were a significant proportion of the first year's dose and are particularly uncertain due to lack of early measurement data. This is especially the case for food, where the doses were mainly due to iodine-131 in the first month after the accident, when measurement data are relatively scarce. However, countermeasures significantly reduced the possible doses.

The following illustrations are taken from recent work at Public Health England (Bedwell, P, *et al*, to be published), which has assessed public doses in Japan largely on the basis of an estimated source term and atmospheric dispersion modelling. The UK Met Office's NAME atmospheric dispersion model (Jones *et al*, 2007) was used, in conjunction with meteorological data from the World Meteorological Organisation; NAME is a Lagrangian particle dispersion model and describes the atmospheric dispersion and deposition of gases and particulates. Analysis of the estimated doses has focused on the geographic irregularity, the impact of the meteorological conditions, and the variability as a function of radionuclide and exposure pathway. The focus of the dose was on the regions which were not affected by evacuation or sheltering, but the ingestion dose estimates took into account the effect of food restrictions.

Figures 1 and 2 illustrate the geographical variability of the contributing exposure pathways to the estimated lifetime effective and first year thyroid doses (for an individual who was an infant at the time of the accident). Most of the effective dose in the regions relatively close to the release comes from external irradiation from deposited radioactivity, whereas most of the thyroid dose in the same regions comes from inhalation of radioactivity in the plume. However, there are estimated to have been some significant differences in the contributions of the exposure pathways regionally (see for example the differences shown in Figure 2), primarily predicted due to the difference in the meteorological conditions which occurred in the areas at the time of the releases. Some areas were associated with relatively little precipitation while others had significant wet deposition due to rain and snow (see also Leadbetter *et al*, 2013 and UNSCEAR, 2014). At greater distances from the release the contribution to dose from the ingestion exposure pathway becomes increasingly significant (although the magnitude of the dose itself decreases).

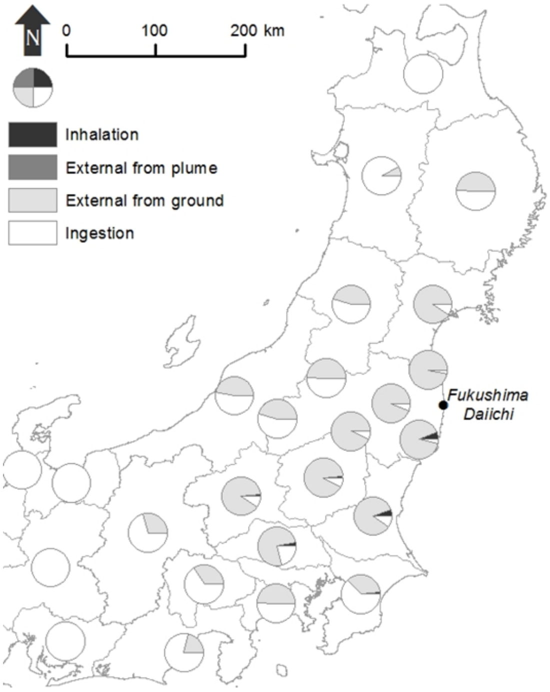

Figure 1: Geographical variability of effective dose to an infant over their lifetime as a function of exposure pathway

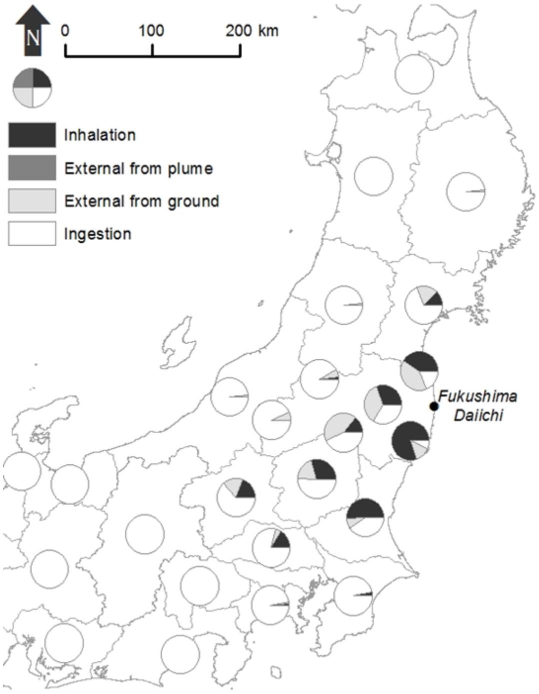

Figure 2: Geographical variability of thyroid dose to an infant over first year as a function of exposure pathway

Figures 3 and 4 illustrate the geographical variability of the contributing radionuclides to the estimated lifetime effective and first year thyroid doses (for an individual who was an infant at the time of the accident). This variability links to the relative significance of the exposure pathways seen in the previous figures. For example, in the areas where ingestion is a dominant pathway, ^{131}I is a major contributing radionuclide, whereas in the areas where doses are dominated by external irradiation the contribution of ^{134}Cs and ^{137}Cs becomes important. Not surprisingly, ^{131}I is a major contributor to thyroid dose in all areas but there are predicted to be areas to the west of the release location where the contribution of ^{134}Cs, ^{137}Cs and other radionuclides become significant due to the importance of external irradiation in delivering a dose to the thyroid.

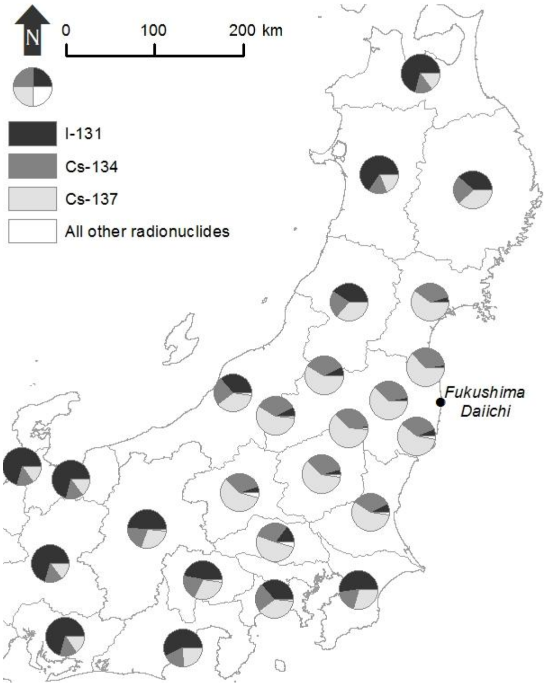

Figure 3: Geographical variability of effective dose to an infant over their lifetime as a function of radionuclide

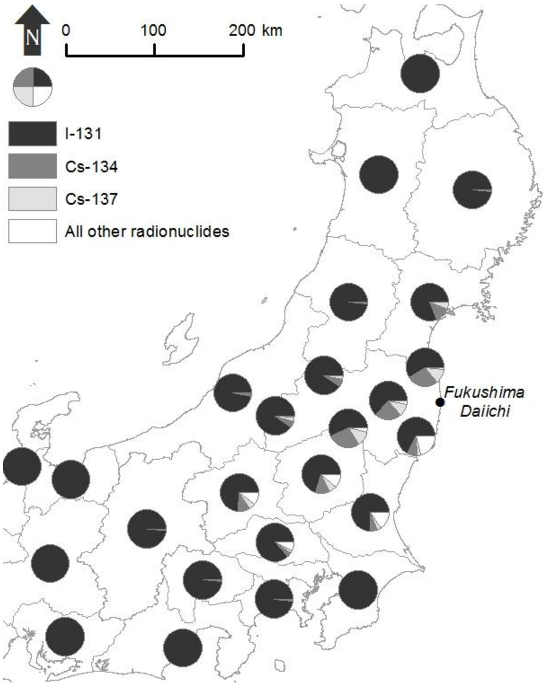

Figure 4: Geographical variability of thyroid dose to an infant over first year as a function of radionuclide

Collectively, the figures illustrate the impact of meteorological conditions on dose, specifically the significance of the prevailing wind direction and the impact on both deposition and on the resulting exposure pathways of temporally and spatially variant precipitation, including the highly non-uniform nature of doses and the importance of localised weather patterns. Comprehensive spatial and temporal coverage of all significant radionuclides in all significant mediums cannot readily be achieved by a measurement program alone and dose assessments based on dispersion modelling are a useful tool in better understanding the full picture. The ideal would be to develop an assessment procedure which can effectively integrate both monitoring and modelling in a unified and robust manner.

In general there is consistency between the available measurement data and the estimates in, for example, the UNSCEAR assessment, in particular for the observed versus estimated levels of ground deposition; the extent of a comparison between observed versus estimated air concentration measurements can only be very limited due to there being relatively few such measurements. It should be remembered that the majority of the estimated doses across Japan are very low. The evacuation measures implemented by the Japanese authorities were effective in significantly reducing the dose to individuals living close to the Fukushima NPP at the time of the accident, as demonstrated by the UNSCEAR (2014) assessment, and the food restrictions in combination with the time of year in which the accident occurred were also effective in limiting doses from this pathway.

3.4 Early emergency assessments

In the event of an accidental release of radioactivity to atmosphere, decisions must be made rapidly on the necessity for actions to avoid or reduce serious health effects (both deterministic and longer term health effects such as cancers). Possible early actions include evacuation, advice to shelter, the administration of stable iodine, and restrictions on the movement, sale and consumption of foodstuffs. While protective actions within a few kilometres of the release will usually be triggered on the basis of a pre-existing emergency plan, large releases of radioactivity require decisions on the possible need for actions over larger areas.

The understanding of the situation and the estimate of both short term and projected doses is likely to very uncertain, possibly even somewhat chaotic in the first few hours; the inevitable emphasis will be on major health protection decisions rather than on detailed and comprehensive coverage. Measurement information may initially be limited and contradictory. Modelling has a role in developing an improved comprehension, but will also contribute substantial uncertainties. Aspects that may well not be known, or will be at best poorly understood, include what has been released (amounts and radionuclides), what the time distribution of the release has been and how this may continue, what influence the weather has had in the affected area (for example, in conjunction with particle size and release energy), and various alternative estimates of future weathers which will influence the dispersion and deposition of continuing releases. Decisions require estimates of projected dose across the affected area, and these in turn require estimates of activity concentrations in air and deposited activity on the ground. These estimates should include all that is currently known of the nature of the emergency and, as importantly, what potentially significant information is not yet known. Decisions on protective actions must be taken in spite of lack of knowledge. However, in decision-making the large uncertainty that is likely to be associated with early estimates of dose needs to be counterbalanced by the known health risks associated with early emergency countermeasures, and in particular the risk associated with evacuation; for example, the rapid evacuation of large numbers of people has the potential to cause more health injuries than exposure to radiation from remaining in sheltering, and needs to be justified by the severity of the situation.

Early measurement information may come from automatic static monitoring devices, monitoring teams in the field, or aerial monitoring. Each measurement will be associated with a particular time and place. Early measurements are likely to be gamma dose rates (e.g. mSv s^{-1}) and activity concentrations in air (eg Bq m^{-3}), followed by levels of deposition on the ground (e.g. Bq m^{-2}). Information on what radionuclides are present is likely to be lacking in the first few hours. A response assessment will take the information that is currently available and will combine this with information on the weather in the affected area to build up a picture of the radiological situation.

Information ideally required for early phase decisions on sheltering, evacuation and stable iodine:

- Estimates of the amount of key radionuclides released to atmosphere at different times, taking into account the measurements available and what is known about the condition of the site.
- Information on the meteorological conditions temporally and spatially during the period when releases to atmosphere were occurring, for input to dispersion and deposition predictions.
- Activity concentrations in air: ideally a full radionuclide breakdown including noble gases and short lived radionuclides. Ideally as a sequence over time (Bq m^{-3}) and/or as integrated concentrations (Bq s m^{-3})

- Total depositions on the ground (Bq m^{-2}): ideally a full radionuclide breakdown with particular emphasis on areas with the highest depositions (usually areas of rain) which may not be those nearest to the release point.
- External dose rates over wide spatial areas: useful to distinguish between different sources (air and deposit) and contribution from short lived radionuclides.

Information ideally required for early phase decisions on food and water restrictions (however, the need for restrictions on some key foods such as green vegetables may need to be anticipated before many measurements are available):

- Activity concentrations in terrestrial foods for a variety of foods as a function of time and for different locations (including information on the limits of detection).
- Activity concentrations in aquatic media (seawater, fish and other foods, sediment) from different times and locations.
- Activity concentrations in drinking water at different locations and times.

Regarding the specific situation at Fukushima, it is unclear to this paper's authors to what extent monitoring data or modelling predictions were available and applied to support the earliest decisions on emergency countermeasures. The availability of early information was severely limited by the damage due to the earthquake and tsunami. However, as the releases in this particular accident were so extended over time the emergency phase was lengthy and more information to support decisions gradually became available over the course of days and weeks.

3.5 Later assessments

Eventually an accidental release will stop and the radiological picture will become more static, apart from the effects of radioactive decay and the relatively minor effects of wind-driven or mechanical spread of contamination. From this point, a comprehensive database of radiological measurements can be built up to more fully characterise the contamination, however realistically there are likely to remain gaps in information from the early phase which would ideally be needed to support post-event dose estimates. For example, for Fukushima the data on short-lived iodine and tellurium radionuclides is very limited, and this is also true for the early distribution of the noble gases.

Post-event, the focus of dose assessments is to support medical investigations into possible health impacts, to provide reassurance to limit anxiety, and to provide continuing data to determine the usefulness and need for longer term recovery activities such as decontamination. An important element is the reconstruction of population activity and movements, and the countermeasures actually undertaken as opposed to those ordered or recommended. An important input is radiological measurement information, but again this is a snap shot of information spatially and temporally and some modelling is required to extend this to times before and after the measurement and to locations where measurements have not been taken.

The following table shows the key information required for post-event dose assessment/reconstruction and comments on the extent to which it was available following the accident at Fukushima Daiichi Nuclear Power Plant (FDNPP).

Information required	**Availability for the releases from the FDNPP**
Activity concentrations in air with a full radionuclide breakdown including noble gases and short lived radionuclides. Ideally as a function of time (Bq m^{-3}) and integrated concentrations (Bq s m^{-3}).	Very limited due to the earthquake and tsunami making many air samplers not operational. Results are available for some locations, however these are all some distance from the FDNPP site.
Total depositions on the ground (Bq m^{-2}) with a full radionuclide breakdown, and particular emphasis on areas with the highest depositions (eg rain locations) which may not be those nearest to the release point.	Comprehensive measurements available for longer lived radionuclides (^{134}Cs and ^{137}Cs), and some information for ^{131}I but little information for shorter lived radionuclides.
External dose rates over wide spatial areas, ideally for different times to distinguish between different sources (air and deposit) and contribution from short lived radionuclides.	Comprehensive aerial and vehicle based monitoring at particular time points, showing the spatial distribution of gamma doses and some radionuclides in the environment at the time of measurement. Results converted by modelling and assumptions to estimate depositions which could be compared with the measured depositions.
Activity concentrations in terrestrial foods for a variety of foods as a function of time and for different locations. It is important to distinguish between food that represents that consumed by the public and that sampled to establish where restrictions are needed. Limits of detection information also required.	Very few measurements were possible quickly, and only limited measurements available for the first month but later more comprehensive measurement data for the whole of Japan. Due to the number of measurements the limit of detection was relatively high and many measurements were below the level. Extensive work subsequently carried out to include the measurements on a database with consistent terminology.
Activity concentrations in aquatic media (seawater, fish and other foods, sediment) from different times and locations.	Levels of radionuclides in marine foods that were marketed were included in the food database. Additional measurements were carried out both close to the site and discharge point plus at different locations in the ocean. Limited information at short times and for ^{131}I, most data for ^{137}Cs.
Activity concentrations in drinking water at different locations and times.	As for food the emphasis was determining whether restrictions were required but a number of measurements were taken. Again many were less than limits of detection.
TLD measurements of ambient dose equivalents received by people living in different areas.	There are detailed measurements for some locations but mainly at later times (beyond the first year after the accident).
Measurements of the radionuclide content of people – whole body and thyroid. These can be used with information on the likely timing of intakes by inhalation and ingestion to estimate radiation doses	Some information available but mainly a few months after the accident which causes assessment difficulties for short lived radionuclides. The early measurements tended to be for screening purposes with short count

from internal exposure. Measurements of the amount of ^{131}I in the thyroid are particularly important for infants and children.	times and uncertainties over background and contamination. Other uncertainties include whether the person ate any locally produced food or not.
Estimates of the amount of each radionuclide released to atmosphere at different times taking into account the various measurements available and what is known about what happened at the site at different times. These are particularly important to estimate doses from short lived radionuclides which are not included in measurement data and so which have to be scaled.	Considerable work has been done to estimate these but significant uncertainties remain due to difficulties in determining the integrated deposition over all areas (much was over the ocean), plus in knowing what happened at the different reactors at various times.
Estimates of the amount of each radionuclide released to the ocean as a function of time. There are two components - releases to atmosphere which blew over the ocean and deposited there and releases directly to the ocean.	Various estimates have been made of both components but again there are significant uncertainties especially for the amount deposited from the releases to atmosphere. The information for ^{137}Cs is better than that for ^{131}I.
Detailed information on the meteorological conditions as a function of time and space during the period when releases to atmosphere were occurring. This needs to be as required by the atmospheric dispersion models that are now available.	This information was available and was exchanged through the World Meteorological Organization

In addition to the information outlined above, an assessment requires knowledge of other parameters, for example, inhalation rates, occupancy times for different building types and associated factors for the reduction of external irradiation indoors. Dose coefficients appropriate to the population, for intakes of each radionuclide by inhalation and ingestion, are also ideally required.

Environmental monitoring results are essential input to assessments, and in particular *in-vivo* human measurements are important as they enable comparison between doses estimated on the basis of measured levels of radioactivity in individuals and doses based on modelling. However, there are limitations associated with measurement information which should be borne in mind when the data are used:

- Measurements are a snapshot of the levels in the medium at a particular time. For example, measurements of radioactive material in humans reflect only the intakes into the body up to the time of the measurement and cannot include intakes that may take place later in time.
- Without subsequent adjustment, monitoring does not allow for decay of short-lived radionuclides up to the time of measurement. For example, the results of thyroid monitoring require adjustment to include the contribution to dose from material that has decayed prior to the time of measurement, and this will require assumptions to be made of the intake pathways and timing of intakes, leading to some uncertainty in the final results.

- Measurements of internal human radionuclide content indicate only the content incorporated into the body by internal exposure, and not doses arising from external exposure (from groundshine and cloudshine).
- Environmental monitoring reflects the activity present in the measured media at the time and location of measurement, but does not provide information about activity present in different locations or at different times. Conversely, monitored individuals will have had a history of location movements and varying habit data (such as time varying ingestion intake rates, inhalation rates and personal metabolism) which would lead to no two individuals even following exactly the same locational movements showing the same levels of body content.
- All measurements are uncertain, due to differences in monitor type and useage, and this may be compounded by errors in reporting, data transmission and interpretation.

3.6 Lessons learnt

- *The purpose of the dose assessment has a major bearing on what is required in terms of information needs.* For example, different inputs and results are required if the assessment is to be used for a health risk assessment than when the doses alone are the endpoint. For a health risk study the populations and ages of concern need to be clearly defined, more detailed results may be required with information for different time periods and for a range of organs. In other cases effective and thyroid doses may be sufficient. The assessment may also be different if it is intended to demonstrate the effectiveness of countermeasures or the need for longer term clean-up.
- *Measurements are very unlikely to be sufficient basis for a dose assessment.* The emphasis of an early measurement programme will be to inform decisions on countermeasures such as evacuation and restrictions on food or drinking water. It takes time for resources to be mobilised so that more comprehensive measurement programmes can be developed. Measurements also cannot provide the full answer for dose assessments projected into the future – modelling of future environmental transfer processes is needed for these.
- *The first few days are likely to contribute substantially to the 1st year total dose but often this is a time when measurement information has more limited coverage.* It is likely to be difficult to get reliable information for short lived radionuclides and some form of scaling based on estimates of the source term will be needed to retrospectively estimate early doses. Measurements are also likely to be scarce in areas which were evacuated and it may therefore be necessary to use atmospheric dispersion modelling based on source term estimates, recognising the uncertainties associated with this approach.
- *Direct measurements of people are very useful but require interpretation.* In the short term measurements may be carried out for screening purposes with short count times and hence relatively high limits of detection plus possible confounding effects of surface contamination. Finding a suitable background can also lead to uncertainties. Converting levels of radionuclides in people to dose requires assumptions on the timing of intakes by inhalation and ingestion.
- *The best approach to exposure and dose assessment is to use a combination of different methods and data recognising uncertainties.* Due to the inevitable gaps in

data and associated uncertainties the best approach is to base the dose assessment on a range of calculations and measurements. For example, an assessment may be started based on measured deposited activities and the subsequent dose estimate may then be compared with those based on measurements in people plus doses derived from atmospheric dispersion modelling. In all cases there will be uncertainties and these need to be recognised and efforts made to assess their extent. However, it is unlikely that there will be the information available to carry out a full quantitative uncertainty analysis.

3.7 Gaps and future work

- *Enhancing the value of monitoring data.* Gamma dose measurements are results which are most likely to be reported with the greatest frequency in the early hours, and work to extract the maximum information including early estimates of source term data from these is in progress in France, Germany and the UK.
- *Developing additional resources to estimate source terms based on, for example, plant conditions.* Early source term estimates based on plant knowledge in combination with early measurements is vital to early dose estimates.
- *Further enhancement of tools which rapidly combine and interface the results of monitoring with the use of real-time modelling of dispersion and deposition processes based on fine resolution meteorological information.* This is needed to develop ‘surfaces’ of present and future radionuclide concentrations in air and in depositions as a basis for early decisions as well as longer term ones.
- *The automated development of systems which can reflect what is not fully known at each point* (for example, alternative release durations and alternative weather developments).
- *International intercomparison of key features of major European assessment tools*, so that the reasons for differences between early dose estimates are to some extent at least understood.

Every radiological accident is different. Fuskushima differed from Chernobyl, and both were different to the Windscale Fire, Three Mile Island, and other major events such as Goiânia and in the UK the ^{210}Po contamination. It is important not to focus overmuch on the lessons learnt from the last accident, but rather on cumulative experience over decades, as the next accident is likely to be very different to the last.

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4 FUKUSHIMA HEALTH RISK ASSESSMENT: LESSONS LEARNED

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4.1 Introduction

On 11 March 2011, an earthquake and tsunami in Japan led to reactor-damage at the Fukushima Dai-ichi nuclear power station. The accidental releases of radio-nuclides (including iodine-131, caesium-134 and caesium-137) from the damaged reactors into the environment, resulted in persons, living and working in this area, being exposed to ionising radiation. This situation has led to world-wide concerns about possible radiation-related detrimental health effects.

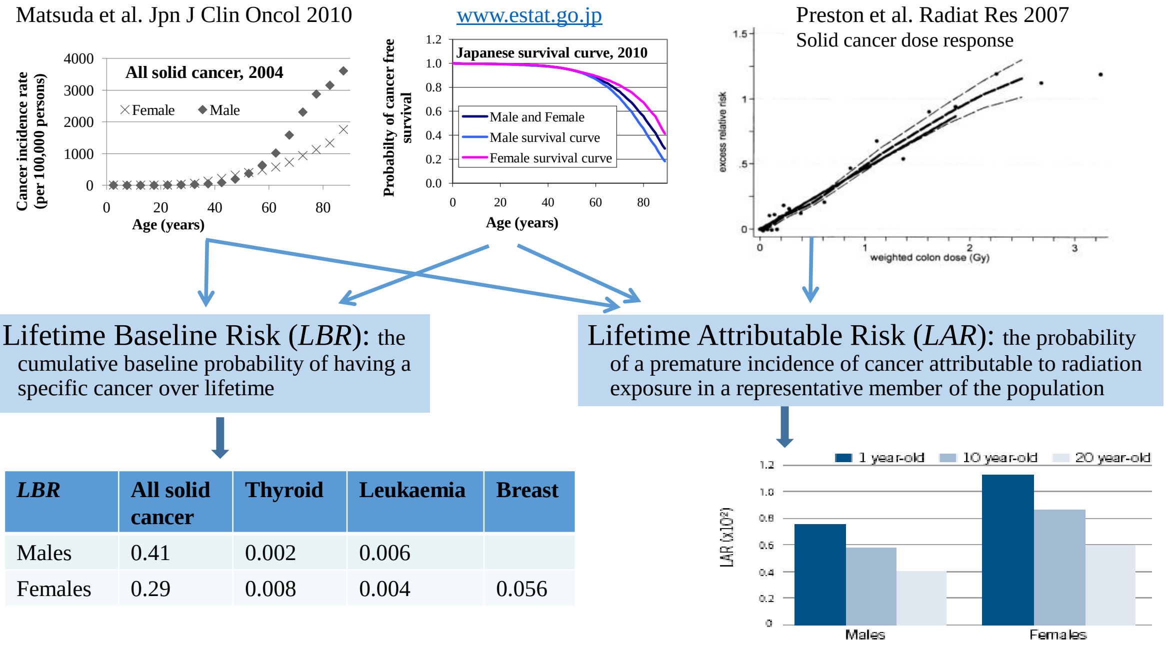
Since the accident, a substantial body of literature has been published relating to Fukushima health risk assessments (HRA) and, at this point in time, it is pertinent to draw together the lessons learned from such risk assessments. This report will first briefly review the literature on Fukushima HRA and then address the lessons learned from two different aspects: from the assessed magnitudes of radiation-related health risks; and from the practical issues arising during the HRA work (5 points). It is recommended that the lessons learned from the practical issues could be applied to improve the HRA-part of the overall planning for emergency preparedness for future nuclear accidents/events. Suggestions relating to policy implications and research needs are also given.

4.2 Review of the literature on Fukushima HRA

Since the Fukushima Dai-ichi nuclear power station accident, the magnitudes of health risks from human exposure to the radioactive releases have been comprehensively evaluated by international bodies (WHO 2013, UNSCEAR 2014, Walsh et al. 2014, Etherington et al. 2014). The first evaluation was by the World Health Organisation (WHO), in fulfilment of WHOs responsibility for the coordination of advice and assistance on public health risk assessment after the Fukushima accident (WHO 2013). Two international expert groups were set up by WHO: a group for hazard identification and exposure assessment; and a group for HRA.

The HRA group provided a comprehensive assessment of carcinogenic and non-carcinogenic detrimental health effects from the radiation releases (WHO 2013). Non-cancer effects (e.g., thyroid nodules, thyroid dysfunction, developmental changes in embryo and foetus, hereditary effects and other non-cancer effects) were assessed, based on the current literature and expert opinion, but the radiation-related risks were not calculated by the expert group. Cancer effects were quantified by providing Lifetime Attributable Risk (LAR) estimates of radiation-related cancer incidence risk based on the organ/tissue doses to representative individuals and also Lifetime Baseline cancer Risk (LBR) for comparison. Figure 1 gives the definitions of LBR and LAR, shows schematically, for all solid cancer, what is required in order to calculate these two quantities and gives examples of the results.

Figure 1: The definitions of Lifetime Baseline Risk (LBR) and Lifetime Attributable Risk (LAR) of cancer. Requirements for calculating these two quantities, for all solid cancer, are shown in a simplified schematic representation at the top of the diagram and some examples of the results are shown at the bottom. The requirements are from left to right: age specific cancer incidence rates for 2004 in Japan (Matsuda et al. 2014), Japanese survival curves for 2010 (calculated with data from www.estat.go.jp) and radiation dose response curves for the excess relative risk as a function of colon dose (Gy) from the most recent analysis of cancer incidence in the life span study (LSS) of Hiroshima and Nagasaki A-bomb survivors (taken from figure 3 of Preston et al. 2007). The bottom of the figure shown the results for LBR on the left, and an example of the LAR calculated for a town in the evacuation zone where the colon dose in first 4 months was estimated to be between 22-26mGy, depending on age at exposure (taken from figure 11 of WHO 2013).



Lifetime Baseline Risk (*LBR*): the cumulative baseline probability of having a specific cancer over lifetime

Lifetime Attributable Risk (*LAR*): the probability of a premature incidence of cancer attributable to radiation exposure in a representative member of the population

LBR	**All solid cancer**	**Thyroid**	**Leukaemia**	**Breast**
Males	0.41	0.002	0.006	
Females	0.29	0.008	0.004	0.056

The cancer types considered for the risk analysis were all solid cancer, leukaemia, thyroid cancer and female breast cancer. LAR estimates were provided for different geographical locations (mainly in the Fukushima Prefecture) and for different age groups.

In terms of specific cancers, for people in the most contaminated location, the estimated increased risks over what would normally be expected (i.e., LAR/LBR, in percentage) are:

1. All solid cancers – up to around 4 % in females exposed as infants;
2. Breast cancer – up to around 6% in females exposed as infants;
3. Leukaemia – up to around 7% in males exposed as infants;
4. Thyroid cancer – up to 70% in females exposed as infants (the normally expected risk of thyroid cancer in females over lifetime is 0.75% and the additional lifetime risk assessed for females exposed as infants in the most affected location is 0.50%).

For people in the second most contaminated location of Fukushima Prefecture, the estimated risks are approximately one-half of those in the location with the highest doses. For all other locations in Japan and world-wide – radiation-related cancer risk were estimated to be much lower than usual fluctuations in the baseline cancer rates.

The methodology adopted by the WHO-HRA (WHO 2013) has also provided a framework for estimating risks from the nuclear accident (Walsh et al. 2014). Since the WHO-HRA (WHO 2013) could only be based on dosimetric information available up to mid-September 2011, it was decided to re-publish the results (WHO, 2013) in terms of *LAR* results based on either a reference first-year organ/tissue dose (10 mGy) or a reference lifetime organ/tissue dose (20 mGy) so that risk assessment may be applied for relocated and non-relocated members of the public, as well as for adult male emergency workers (Walsh et al. 2014). Such LAR results may be scaled to actual dose levels, after consideration of caveats given in the article (Walsh et al. 2014) and the framework may be used to update the risk estimates, when new population health statistics data, dosimetry information and radiation risk models become available.

In comparison to the WHO report (WHO 2013), the 2014 report from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2014) could use more recent and more comprehensive data in their dose assessment, which is of direct relevance to the health risk assessment. Dose estimates from UNSCEAR (UNSCEAR 2014) and WHO (WHO 2013) were, however, generally consistent with each other but the WHO estimates were higher for some evacuated settlements in the Fukushima prefecture. The UNSCEAR 2014 report stated (on p. 250) that: ‘‘The WHO estimates of risks per unit dose were compatible with estimates of the committee in its earlier reports“, (i.e., this statement referred to an earlier report (UNSCEAR 2008) which had provided lifetime cancer risks based on Japanese population data from 1994 and acute exposures (see also Little et al. 2008)). WHO (WHO 2013) also included four exposure scenarios constructed for evaluating workers risks. The reliability of these scenarios was subsequently confirmed (UNSCEAR 2014, Etherington et al. 2014) – see the paper in this collection by J. R. Jourdain on lessons learned from worker dose assessment for more details.

4.3 Lessons learned on the magnitudes of the health risks

Radiation doses from the damaged nuclear power plant are not expected to cause an increase in the incidence of miscarriages, stillbirths and other physical and mental conditions that can affect babies born after the accident (WHO 2013). WHO (WHO 2013, p. 90-91) stated that the psychosocial impact may have a consequence on health and well-being and UNSCEAR (UNSCEAR 2014, p. 248) reported that “ The most important and manifest health effects of the nuclear accident in the short term would appear to be on mental and social well-being“ (Bromet, J Radiol Prot 2012). However both WHO (WHO 2013) and UNSCEAR (UNSCEAR 2014) noted that the quantitative assessments of mental health risk was beyond the scope of their HRAs.

The main lessons learned from the levels of risks are that increases in incidences of human diseases, attributable to the radiation exposure from the accident, are likely to remain below detectable levels – although the overall influence of cancer screening programs on cancer incidence rates in exposed and unexposed groups of persons requires careful evaluation. Please see the paper in this collection by P. Jacob on the expected influences of the accident, and subsequent screening programs, on thyroid cancer incidence rates, for more details.

4.4 Lessons learned from the practical issues arising during the WHO-HRA

Some aspects of the practical experience gained during the WHO-HRA, could be applied to improve the HRA-part of the overall planning for emergency preparedness for future nuclear accidents/events. Five aspects are listed below.

4.4.1 Obtaining the first year and lifetime dosimetric quantities required for input into the cancer risk models.

It was initially assumed that the WHO-HRA group would be able to directly apply the results from the WHO group for hazard identification and exposure assessment (WHO 2012) for input into the cancer risk models required for the calculations of LAR. However this was not directly feasible since the dosimetry report published results in wide dose bands (e.g., 1 to 10 mSv, 10 to 50 mSv, 10 to 100mSv) for first year doses (i.e., effective doses and equivalent doses to the thyroid) in several geographical areas (WHO 2012). Consequently the WHO-HRA group needed to do further dosimetric work to derive the dosimetric quantities specifically required for HRA i.e., organ/tissue doses to the colon, breast, thyroid and red bone marrow (see Figure 2). In this respect, the WHO group for hazard identification and exposure assessment (WHO 2012) could be seen as being too compartmentalized from the WHO-HRA group (WHO 2013). Based on this experience a suggestion for emergency preparedness policy implications is that HRA specialists need to be involved in dosimetry assessments right from the beginning of the overall assessments in future nuclear accidents/events.

4.4.2 Adoption or development of flexible software for quantitative HRA of radiation-related cancer risks.

At the time of the WHO assessment, no flexible software was generally available for calculating the LAR and LBR for cancer incidence. While the WHO-HRA group included three scientists who were able to perform this type of calculation, each needed to develop his/her own software. While this provided an advantage of very valuable cross checking of results, it was very time consuming. Consequently, a suggestion for emergency preparedness policy implications and research needs is to either adopt or develop a standard program for calculating risks in future HRAs after nuclear accidents/events. One possibility would be to adopt the National Cancer Institutes (NCI, USA) RadRAT software (Berrington et al. 2012) because RadRAT follows the methodology of the WHO-HRA framework (Walsh et al. 2014) very closely. Although RadRAT is currently only available with USA population data, data for other countries are due to be included within the next year (private communication from Dr. A. I. Apostoaei). It is also suggested to make a decision, in advance, on total dose levels below which no quantitative HRA is required. For example, UNSCEAR recommended caution in estimating cancer cases among populations exposed to very low doses, i.e., doses below 10 mSv (UNSCEAR 2014).

4.4.3 Incorporation of quantitative uncertainty assessments into HRAs

The WHO-HRA group did not have enough time to undertake a full quantitative assessment of uncertainties in the radiation-related cancer risk calculations. Therefore a suggested research requirement is to either adopt or develop a standard program for calculating and combining uncertainties in risks in future HRAs after nuclear accidents/events (Note: NCI-RadRAT has a quite comprehensive evaluation of uncertainties, but ignores uncertainties in the time and age related radiation risk effect modifiers)

4.4.4 Acquisition of population data (including age-specific cancer incidence rates from registries)

Population data could only be quickly acquired from either web sites or published material. This was not optimal for three reasons:

1. The data was not as "up-to-date" as potentially possible, i.e., cancer rates for 2004 and not 2011 were applied.
2. The data was not as precise as potentially possible, e.g., thyroid and breast cancer incidence rates per 100,000 person-years in Japan were only found to be given to one decimal place in journal publications (i.e., any rates under 5 cases per 10 million person-years were numerically rounded to zero cases, which leads to zero radiation risk with a multiplicative radiation risk model).
3. The ICD codes for some of the cancer sites of interest (all solid cancer and female breast cancer) did not match exactly between various input requirements for the LAR calculations i.e., between the models for radiation-related cancer (from the life span study of Japanese A-bomb survivors) and Japanese age-specific cancer rates (see Figure 1).

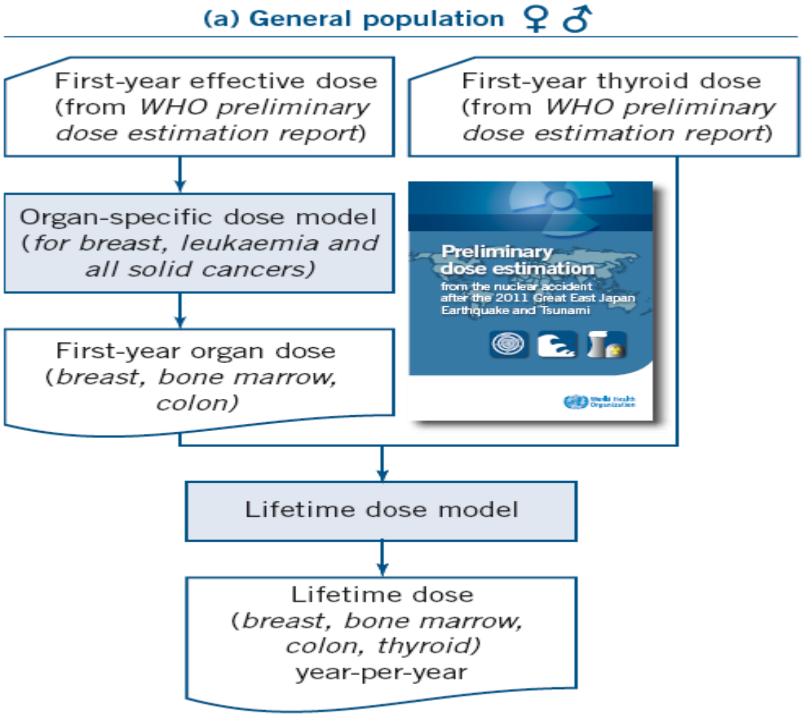
Here, a suggestion for emergency preparedness policy implications and research needs is to build a data-base with contact information of cancer registry staff, able to quickly supply precise and up-to-date cancer rates for the country or state of interest for any ICD grouping. Also, the further support and development of cancer registries in general is highly recommended.

4.4.5 Development of radiation risk models for all solid cancers other than those types of cancer requiring individual assessments after a nuclear accident

Applying the Japanese A-bomb survivors Life Span Study (LSS) models for all solid cancer along with the models for the specific sites (thyroid and female breast) in the LAR calculations, meant that some cancer types have an overlap in the risk evaluations. WHO (WHO 2013, p. 80) stated that "No model to calculate the risk for all other solid cancer excluding breast and thyroid cancer risks is available from the LSS data". Here a suggested research requirement is the development of such models (Walsh et al. 2014, in preparation). One argument against the development of such risk models is that it is possible, in theory, to add up the lifetime risks for all other solid cancers from the individual site-specific lifetime risks (e.g., as in UNSCEAR 2008). However, the process of adding various site-specific LAR leads to a very large overall uncertainty in the final risk estimate. By developing special radiation risk models for all solid cancers other than those types of cancer requiring individual assessments after a nuclear accident, the overall uncertainties on the final risk estimate are much smaller than the uncertainties obtained from adding individual site-specific lifetime risks.

A description of the dosimetric work that the WHO-HRA group needed to do, beyond that provided by the exposure assessment group (WHO 2012), in order to derive the dosimetric quantities specifically required for HRA i.e., organ/tissue doses to the colon, breast, thyroid and red bone marrow.

Figure 2: Part of figure 3 taken from the WHO-HRA report (WHO 2013)



4.5 Summary and concluding remarks

WHO (WHO 2013) and UNSCEAR (UNSCEAR 2014) both reported that very important aspects of health effects related to the nuclear accident in the short term would appear to be connected with mental and social well-being of persons in the affected area. For this reason it is proposed to be well prepared in advance of any future nuclear accidents/events by taking into account the lessons learned from some practical issues arising during the WHO-HRA. A summary of the main points presented in this report is as follows:

1) It is suggested to include HRA experts in the dosimetry assessments right from the beginning of the overall assessments.

2) It is suggested to make a decision, as part of emergency preparedness policy, on total dose levels below which no quantitative HRA is required. For example, UNSCEAR recommended caution in estimating cancer cases among populations exposed to very low doses that is doses below 10 mSv (UNSCEAR 2014).

3) It is suggested to construct and maintain an up-to-date list of cancer registry staff able to quickly provide precise population data for any ICD grouping of diseases and for any country or state or “representative” country.

4) It is suggested to either: adopt (and maintain) previously existing software; or construct (and maintain) standard software for risk calculation (in advance) that:

    a) Could be based on the framework applied in the WHO 2013 report (Walsh et al. 2014)

    b) Includes a full treatment of all sources of uncertainty

    c) Either includes, or is flexible enough to input, up-to-date radiation risk models for cancer incidence

   d) Either includes, or is flexible enough to input, up-to-date population data for any "representative" country.

5) It is suggested that risk communication specialists could then present the results of such an HRA, within a few months of the accident/event, to members of the public in the affected area.

This latter point, which is, in turn, dependent on the other points, could aid in the reassurance of persons in the affected area, by mitigating levels of increased mental anxiety and thereby generally increasing social well-being. It is recommended that the information presented here on lessons learned from the practical issues arising during WHO-HRA, could be applied to improve the HRA-part of the overall planning for emergency preparedness for future nuclear accidents/events.

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5 FUKUSHIMA WORKER DOSE AND HEALTH RISK ASSESSMENTS: LESSONS LEARNED

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5.1 Introduction

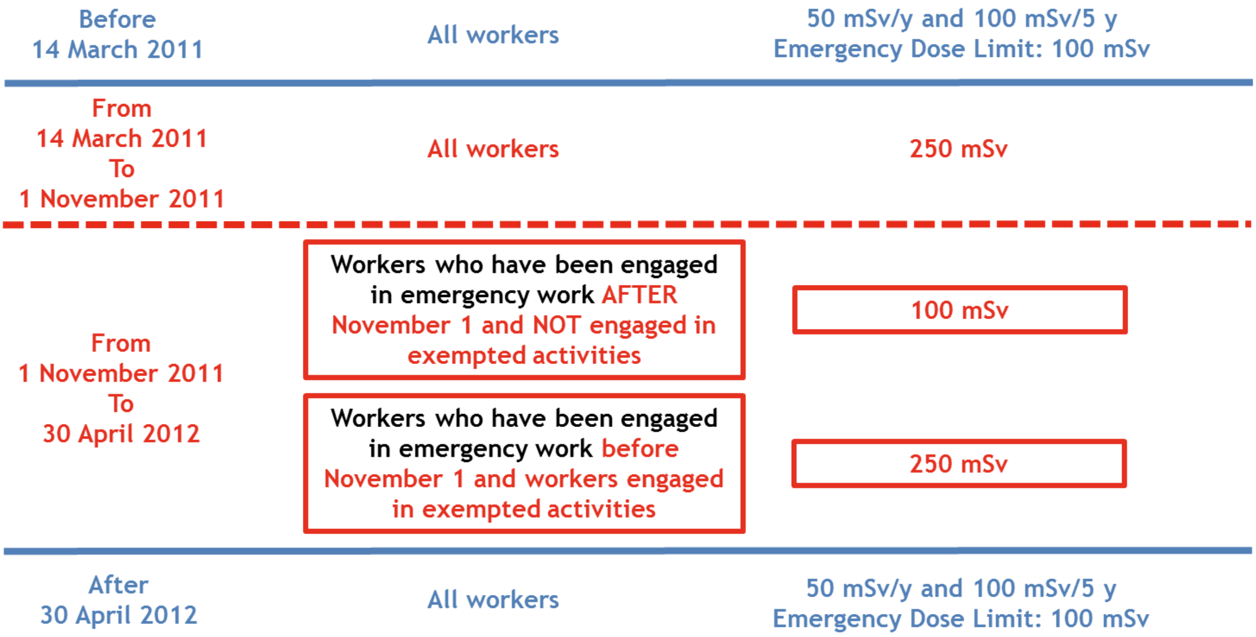
Tens of thousands of workers have been and are still involved in the mitigation activities implemented in the aftermath of the accident that occurred in March 2011 at the Fukushima Daiichi nuclear power plant in Japan. This paper summarizes available information on the doses received by the TEPCO employees and contractors engaged, and the main findings of health risk assessments conducted under the auspices of the United Nations Scientific Committee on the Effects of Atomic Radiation and the World Health Organization.

5.2 Dose assessment

5.2.1 Emergency dose limits for workers engaged in emergency work

At the time when the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi Nuclear Power Plant (NPP) accident occurred, the standard worker dose limit for Japanese workers was 50 mSv/year and 100 mSv over 5 years. According to the Japanese legislation, the emergency dose limit was set at 100 mSv but was raised to 250 mSv by an exemption ordinance issued on 14 March 2011, and that became effective on 15 March 2011 [1]. On 1 November 2011, it was decreased to 100 mSv for new workers but was kept at 250 mSv for workers engaged in activities aiming to maintain functions for cooling reactor systems and spent fuel storage pools, and functions for suppressing the release of radioactive materials to offsite areas (Figure 1). Approximately 50 TEPCO employees were concerned by these exempted activities. The dose limit exemption of 250 mSv was applied until 30 April 2012.

Figure 1: Exposure dose limits for workers engaged in the Fukushima Daiichi NPP activities



Before 14 March 2011	All workers	50 mSv/y and 100 mSv/5 y Emergency Dose Limit: 100 mSv
From 14 March 2011 To 1 November 2011	All workers	250 mSv
From 1 November 2011 To 30 April 2012	Workers who have been engaged in emergency work AFTER November 1 and NOT engaged in exempted activities	100 mSv
	Workers who have been engaged in emergency work before November 1 and workers engaged in exempted activities	250 mSv
After 30 April 2012	All workers	50 mSv/y and 100 mSv/5 y Emergency Dose Limit: 100 mSv

5.2.2 Doses received by the workers engaged from March 2011 through July 2015

TEPCO has been monitoring emergency workers for external dose throughout the accident and its aftermath. TEPCO has also performed internal dose assessments for some workers thanks to whole-body counting and urine measurements. Over the period of time from March 2011 through July 2015, 44,531 TEPCO employees (4,578 individuals) and contractors (39,953 individuals) were monitored according to the report on the exposure dose evaluation that TEPCO submitted on 31 August 2015 to the Japanese Ministry of Health, Labour and Welfare [2].

As of 31 July 2015, the average total accumulated dose is 12.47 mSv for all workers (22.64 mSv for TEPCO employees and 11.30 mSv for contractors). The maximum total dose recorded to one worker was 678.80 mSv, six workers have received doses in excess of the emergency dose limit of 250 mSv, and 174 workers were estimated to have received cumulative doses in excess of 100 mSv (Table I). An analysis of the evolution of data that TEPCO has published since March 2011 shows that the total number of workers with cumulative doses exceeding 100 mSv has not changed since March 2012 (i.e. 150 TEPCO employees and 24 contractors); between November 2011 and April 2012, one worker only received a cumulative dose above 100 mSv. Also these data demonstrate that the average internal dose decreased dramatically from March 2011 through June 2011 (8 mSv in March, 0.27 mSv in April, 0.13 mSv in May, and no internal dose recorded after June 2011).

Table I: Worker dose distribution from March 2011 through July 2015 (adapted from reference [2])

Cumulative dose	TEPCO	Contractors	Total
> 250 mSv	6	0	6
200 – 250 mSv	1	2	3
150 – 200 mSv	26	2	28
100 – 150 mSv	117	20	137
75 – 100 mSv	301	219	520
50 – 75 mSv	335	1,514	1,849
20 – 50 mSv	627	6,100	6,727
10 – 20 mSv	605	5,521	6,126
5 – 10 mSv	496	5,199	5,695
1 – 5 mSv	837	9,261	10,098
< 1 mSv	1,227	12,115	13,342
Total	4,578	39,953	44,531
Maximum (mSv)	678.80	238.42	678.80
Average (mSv)	22.64	11.30	12.47

5.2.3 The UNSCEAR assessment

5.2.3.1 Introduction

Shortly after the Fukushima Daiichi accident, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) agreed to produce an authoritative and independent report providing the United Nations (UN) General Assembly with an assessment of the levels of exposure and radiation risks due to the accident. This report relies on information from Japan itself, together with data supplied by UN Member States and a number of international organizations including the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, the Food and Agriculture Organization, the World Health Organization, the International Atomic Energy Agency, and the World Meteorological Organization. The UNSCEAR report draws on the work of over 80 experts from 18 countries, and is the product of more than 3 years' work. It underwent a review process involving 120 experts representing 27 UN Member States. The report focuses on the measurements of radiation and radioactivity, the release and dispersion of radioactive material, particularly iodine-131, and caesium-134 and 137, the exposure of the general public, the exposure of workers at the nuclear power plant, and the exposure of plants and animals [3]. The UNSCEAR released on line its report on 2 April 2014 [4]. The main outcomes of the chapter devoted to the workers are presented in the section 5.2.3.2 of this paper.

5.2.3.2 Worker assessment

To make a judgment on the quality of doses assessed in workers who were involved in the emergency response and clean-up operations before 31 October 2012, the UNSCEAR reviewed reported effective doses and absorbed doses to organs, and assessed the reliability of reported doses using information on exposures provided from Japan. Also the Committee reported on observed health effects, and estimated risks to worker health. Recognizing that a review of approximately 25,000 individual worker dose assessments would not have been possible, a two-stage approach was adopted to assess the reliability of reported doses: (i) a review of methodologies for monitoring and dosimetry used in Japan, and (ii) an independent dose assessment for selected workers completed by a comparison with reported doses for those workers.

5.2.3.2.1. Review of methodologies for monitoring and dosimetry

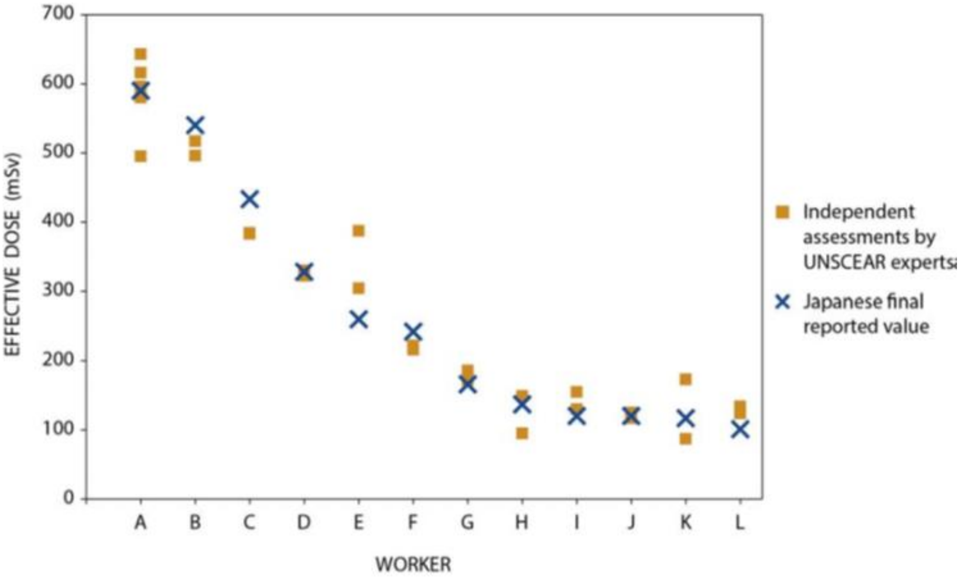
The review of external dosimetry methods identified the use of shared dosemeters as the most significant issue of concern and concluded that "*in the absence of information on the extent to which the conditions described* (i.e. the dose for the task was less than 10 mSv, the workplace environmental dose rate was known, variations in dose rate with location at the site of the task to be performed were not large, members of an operational group were always together at the work site) *were met for individual workers, some reservations remained about the reliability of the external dosimetry performed before 1 April 2011*".

With regard to methods used for internal contamination monitoring and dosimetry, the Committee judged that "*the measurement systems, calibration phantoms and methods, and quality control procedures, were adequate*", and considered as "*appropriate*" the software used for assessing intakes, committed effective doses and absorbed doses. The most significant issue raised is about the delay in commencing reliable *in vivo* measurements of iodine-131 in the thyroid. Indeed because such measurements were implemented in mid- to late-May 2011 for most workers, shorter-lived radionuclides (Te-132, I-132, I-133, Cs-136) would have been undetectable in the body at the time of measurement. For workers engaged in emergency work during the period 12-19 March 2011, the potential additional contribution to internal dose from those radionuclides was estimated in the range 6-45%, relative to dose from I-131 intake, and not significant for workers who commenced work after 19 March 2011.

5.2.3.2.2. Independent dose assessments for selected workers

UNSCEAR experts assessed independently internal doses for 12 of the 13 workers with internal doses above 100 mSv (it is noted that since the publication of the UNSCEAR report, the estimated number of workers with internal doses above 100 mSv has risen from 13 to 14), as well as for 42 randomly-selected workers among those who have received internal doses of less than 100 mSv.

Figure 2: Assessed committed effective doses for workers with the highest internal exposures (contribution from iodine-131 intake only; taken from reference [4])



The assessment performed for workers who received the highest internal doses brought to a good agreement between independent assessments and reported values from TEPCO (Figure 2). For those workers the absorbed doses to the thyroid were estimated in the range of 2 to 12 Gy.

The TEPCO reported values for less exposed workers (below 100 mSv) were confirmed as reliable where a positive measurement of iodine-131 in the thyroid was made, but the reliability was not confirmed where the iodine-131 in thyroid measurement was below the detection limit. Also the Committee was unable to confirm reliability of values reported by contractors for their workers at the time of the UNSCEAR assessment. However, some discrepancies were resolved after a later re-assessment of doses reported in Japan.

5.3 Health risk assessment

5.3.1 Introduction

The World Health Organization (WHO) and UNSCEAR have assessed the health impacts of the Fukushima accident for members of the public and for emergency workers. The findings of their health risk assessments (HRA) have been published in two reports in 2013 (WHO report) [5] and 2014 (UNSCEAR report) [4]. The overall findings of the UNSCEAR report are in good agreement with the WHO report. Both reports conclude that the predicted health risks remain low and that no observable increases in cancer risks above baseline rates are anticipated for members of the public in Japan and elsewhere. Likewise, no discernible increases in cancer or other diseases are expected among the majority of workers, even though the most exposed workers should continue to receive regular health checks.

Concerning the health risk assessment for workers, the two reports differ in terms of follow-up time. Indeed the WHO report considers 23,172 workers during the first 12 months, compared with 24,832 workers during the first 20 months as reported by UNSCEAR. However Etherington *et al* reported in 2014 an investigation which confirmed the reliability of exposure scenarios used in the WHO's health risk assessment for Fukushima workers and the consistency of reported risk assessments for workers with the UNSCEAR's commentary on health implications for workers [6].

5.3.2 Cancer risk assessment

The WHO HRA expert working group defined four exposure scenarios for workers (Table II). Scenarios S1 and S2 represent the emergency workers who received small doses and intakes, less than 30 mSv in total. Scenarios S3 and S4 represent the emergency workers who received the highest external doses (S3) and the highest internal doses (S4). Scenario S1 fits approximately two thirds of the workers and the two last scenarios (S3 & S4) represent less than 1% (for S3) and less than 0.01% (for S4) of the emergency workers considered in the WHO report [5].

Table II: Exposure scenarios assumed for the WHO workers' health risk assessment (adapted from reference [5])

Scenario	Total effective dose (mSv)	External exposure (mSv)	Internal exposure (mSv)
S1	5	5	-
S2	30	24	6

S3	200	200	-
S4	700	100	600

While evaluating scenarios that WHO considered, Etherington *et al.* found for scenario S1 that a total effective dose of 2.5 mSv is more representative than the value of 5 mSv specified in the WHO report as a “reasonably conservative” value. The same authors confirmed the relative contribution from external and internal dose as reasonable for scenario S2. Scenarios S3 and S4 were found to be broadly representative of the maximum exposure of workers that meet their inclusion criteria. However Etherington *et al.* emphasized that the main contribution to internal dose for the majority of workers was from iodine-131, rather than intake of caesium-134 and 137 as assumed by the WHO in scenarios S1 and S3 [6], although internal dose contributes only about 6% of the total effective dose for S1 workers and approximately 13% on average for S3 workers.

The main conclusions of the worker health risk assessments are as follows ([5], [6]):

- An increased relative risk of thyroid cancer above baseline rates is estimated for S4 workers, especially for young workers (lifetime attributable risk of 3.5%, to be compared with the corresponding lifetime baseline risk of 0.2%). However, because only 13 workers are represented by S4, of which only a fraction was represented by the “20-year-old” age classification, an increase in thyroid cancer is unlikely to be observed.
- Additional risks of leukemia are estimated around or even below 0.1% for the 4 scenarios. According to Etherington *et al.* [6], the predicted numbers of excess leukemia are less than one for the two higher dose scenarios (S3 & S4), and so increased leukemia rates are unlikely to be observed.
- The predicted numbers of excess solid cancers vary from one case (S4, 20-year-old) to 10 cases (S2, 20-year-old), compared with a baseline incidence rate of about 1,000 cases. Again increased solid cancers are unlikely to be observed due to variability in the baseline rates.
- No observable increases in cancer risks above the baseline rates are anticipated for S1 workers (representing approximately 70% of the workers).

5.3.3 Non-cancer risk assessment

None of the so far reported deaths among emergency workers is attributable to radiation exposure. In contrast with the Chernobyl accident, no acute effects of radiation exposure such as acute radiation syndrome (ARS) were reported after the Fukushima Daiichi NPP accident [7]. Dicentric chromosome assay performed by Suto *et al.* in 2013 for 12 workers suspected of being acutely overexposed confirmed that no ARS effects were to be expected for the selected workers [8].

By end of September 2014, 754 workers received medical treatment at the Fukushima Daiichi site. Among them, only 12 people had contamination with radioactive substances. In 2011-2014, heat illness increased in May-July, and 88 workers suffered from heat illness. However, no severe cases, such as heatstroke, were reported [7].

According to its report published on line in 2014, UNSCEAR considers that risks for circulatory disease due to radiation exposure among the workers who were most exposed are very low. The UNSCEAR’s considerations are consistent with the conclusions of the WHO HRA report stating that an increased risk of long-term circulatory disease among workers with the highest doses (scenarios S3 & S4) is likely to be substantially smaller than any additional cancer risk.

Also UNSCEAR considers that there is insufficient information on exposures of the eye lens of workers from beta radiation to reach an informed judgment on the risk of cataracts [4]. The WHO HRA expert group concluded that there should be no expectation of cataract among exposed workers [5].

Finally UNSCEAR considers that hypothyroidism is possible in the more exposed workers among the thirteen individuals who were estimated to have received absorbed doses to the thyroid in the range of 2 to 12 Gy from inhalation of iodine-131. Also UNSCEAR reports that no immediate side effects, such as anaphylaxis with iodine hypersensitivity, were observed following the distribution of approximately 17,500 stable iodine tablets (50 mg as potassium iodide) to about 2,000 workers involved in the emergency response.

5.3.4 Psychological effects

After the Fukushima Daiichi NPP accident, TEPCO workers were stigmatized and discriminated, and suffered from rejection from the society [9]. In a study done 2-3 months after the accident, TEPCO workers who had experienced discrimination were two or three times more likely to have adverse psychological effects than those without such exposure [10]. Results of a follow-up study showed immediate and long-lasting psychological effects of discrimination [11].

5.4 Lessons learned and conclusion

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. In order to maintain an acceptable level of protection for on-site emergency workers, a range of impromptu measures was implemented. The dose limit for emergency workers undertaking specific tasks was temporarily increased to allow the necessary mitigatory actions to continue. Medical management of emergency workers was also severely affected, and major efforts were required to meet the needs of on-site emergency workers [12].

The Ministry of Health, Labour and Welfare of Japan issued guidelines on maintaining and improving health of emergency workers at the TEPCO Fukushima Daiichi NPP. These guidelines addressed in particular actions for long-term health care, development of a database for workers who have engaged in emergency work and support provided by the Japanese Government [1].

The experience gathered in the aftermath of the Fukushima Daiichi accident showed the need for resilient monitoring systems and equipment, and confirmed that individual monitoring of workers needs to be carried out promptly (and provided) to judge on the reliability of the dose assessment. Capabilities for radiation monitoring and dose assessments for other (“non-radiation”) categories of personnel involved in the mitigation activities in the event of a major accident should be thought in advance and set up promptly. However, if capacity is severely reduced, monitoring of a limited number of workers is better than no monitoring. Also the access to clear and comprehensive information about the activities carried out by the first hours/days is highly desirable with the view of assessing as precisely as possible the doses received to workers engaged in mitigation activities. Finally a on-site health care system should be established, appropriate to the scale of each workplace to implement the relevant medical examinations.

Because estimates of increased relative risk of cancer and non-cancer diseases, including psychological effects, above baseline rates carry large uncertainties, long-term investigations and health monitoring of workers should be implemented shortly after the accident.

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6 EMERGENCY PREPAREDNESS: DISCUSSIONS ON A REVIEW OF THE CURRENT STRATEGY

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6.1 Introduction

The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) asked the German Commission on Radiological Protection (SSK) to review the current legislation on nuclear emergency preparedness and response in light of the Fukushima accident. The SSK performed an extensive review of the insights gained from the Fukushima accident, discussed the lessons learned that were published worldwide, and performed an investigation as to whether these findings are of importance to emergency preparedness and response in Germany. In addition, the SSK considered the process to update international regulations and legislation that was launched in the wake of the reactor accident and included the results of these changes in its investigation. The “Fukushima Working Group” of the SSK was supported by the Federal Office for Radiation Protection (BfS) and the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS). The working group of the SSK also worked closely together with the interstate “Fukushima” working group of the Commission of the States’ Ministers and Senators of the Interior (IMK). The States` Ministers and Senators of the Interior are responsible to issue the emergency response plans. To some extent, the SSK worked also together with the German Reactor Safety Commission (RSK).

6.2 Nuclear accidents happen even those of the INES Level 7

The risk studies and accident analyses that have been in use in Germany since the 1970s also include accidents whose effects are classified as today’s INES level 7. The range of accidents adopted for German nuclear power plants has been revised over the last 40 years to maintain pace with the state of the art in science and technology. The latest analyses /1/ also include accidents where the radiological effects mirror those that occurred in Fukushima. This means that no new findings were gained from the Fukushima accident in terms of the extent of potential releases. The radiological impact of the Fukushima accident is therefore comparable with the results of analyses of potential major accidents at nuclear power plants in Germany.

However, due to their low calculated likelihood of occurrence, the consequences of accidents now classified as an INES level 7 were not used as a basis for determining requirements in terms of special emergency response plans required near nuclear power plants in addition to general emergency response plans.

The SSK believes that the range of accidents included in emergency response planning should be redefined to more closely reflect an accident's potential impact rather than its likelihood. The SSK therefore considers it necessary to expand the range of accidents included in the emergency planning and also add to emergency response planning and planning area considerations the INES level 7 accidents whose radiological effects mirror those of Fukushima. This important change of the concept has been discussed very controversial in Germany.

6.3 Reference source terms and reference accidents

Unlike in other countries no reference source terms have been defined in Germany so far. The SSK believes that reference source terms are required as a basis for emergency planning.

Figure 1: Reference source terms for INES 7, INES 6 and INES 5 accidents

	Release Iod-131 Bq	Release Cs-137 Bq	Assumed start of major release (assumption for planning purposes) Hours [h] after shutdown	Duration of the Release	Release via ..	
Q1	3.0×10^{17}	3.0×10^{16}	6	48 hours	Roof of Building	INES 7
Q1L	3.0×10^{17}	3.0×10^{16}	6	14 days	Roof of Building	INES 7 long
Q2	2.0×10^{16}	3.0×10^{14}	12	48 hours	Roof of Building	INES 6
Q2L	2.0×10^{16}	3.0×10^{14}	12	14 days	Roof of Building	INES 6 long
Q3	3.0×10^{15}	3.0×10^{11}	12	48 hours	Stack	INES 5
Q3L	3.0×10^{15}	3.0×10^{11}	12	14 days	Stack	INES 5 long

The "INES 7 Source Term" was already used to determine new planning areas. The implementation of Level 6 and Level 5 source terms and source terms for long lasting releases is discussed.

6.4 Planning areas for emergency response

Based on the reference source term for INES 7 accidents and the radiological parameter of the "Basic Radiological Principles for Decisions on Measures for the Protection of the Population against Accidental Releases of Radionuclides"(/2/; revised after the Fukushima accident; see also www.ssk.de) the SSK suggests an update to Germany's emergency response planning areas.

An analytical method was developed to determine the planning areas. The decision support system RODOS (Realtime Online Decision Support System) (/4/; see also http://www.rodos.fzk.de) was used to select a reference source term for determining planning areas which was also used to determine areas where, under the given conditions, high doses and major deterministic effects may occur and trigger values for protective measures may be exceeded. The areas determined using this method are proposed as planning areas. Any other important influencing factors in terms of emergency response will be taken into account when selecting the reference source term and determining the parameters for calculation and evaluation. The individual steps of the method are described below:

- Determination of parameters for the accidental release of radioactive substances,
- Selection of reference source terms including scenarios comparable with the Fukushima accident,
- Selection of representative nuclear power plant sites in Germany,
- Determination of parameters for the RODOS calculations,
- Stipulation of evaluation method used to determine planning areas for protective measures,
- Performance of RODOS calculations to determine areas where the dose criterions are reached, where major deterministic effects may occur, and where protective measures would be necessary based on the emergency trigger levels set out in the revised “Basic Radiological Principles for Decisions on Measures for the Protection of the Population against Accidental Releases of Radionuclides” /2/.

This “Level 7 source term” with the short release duration (see figure 1) was used as a basis for performing the calculations with RODOS.

Three regions representing the various climatological conditions in Germany were defined in order to perform these calculations. The following areas were chosen:

- A flat orography, on average with high wind speeds
- A moderately structured orography in a valley, on average with moderate wind speeds,
- A pronounced valley with a moderate orography, on average with low wind speeds and frequent inversions.

Nuclear power sites in such areas were then selected (Unterweser, Grohnde and Philippsburg) and calculations were performed using these sites.

The period from October 2011 to September 2012 was selected as the period to be used for the (annual) calculations. This ensures that every season and their specific meteorological characteristics are sufficiently accounted for. Investigation of the meteorological data from the plants meteorological instrumentation for each plant over a number of years also showed that the investigated period does not significantly differ from other years, meaning that it can be seen to be a typical year. In order to achieve a sound statistical basis for every day and every plant within the given period, a dispersion calculation based on the reference source term was started using RODOS. This produced a total of 1,095 calculations for 365 days and 3 plants. Individual calculations were initiated at precisely midnight on the respective day. By starting the calculation at this time, the results were conservative as night-time weather with its stable stratification leads to a reduction in the vertical exchange of contaminated air masses at the start of the release where it is at its highest.

In order to determine the area where major deterministic effects could occur, additional calculations of the red bone marrow dose were performed for adults and small children. For each calculation the maximum distance from the point of release up to which the calculated doses exceed 1,000 mGy (red bone marrow) in adults and small children was determined. Calculations for the foetus have to take account of the various development stages of the foetus which lead to differing levels of sensitivity to radiation. For each calculation the maximum distance from the point of release up to which the calculated doses exceed the above mentioned thresholds for the foetus was determined. About 5000 calculations have been done in connection with the determination of the planning areas.

For each plant and emergency response measure, a statistical distribution of the measure's maximum distance can be plotted. The cumulative frequency is used to determine the distance up to which a certain measure should be planned and also provides the percentage of calculated weather situations in which the areas where the respective emergency trigger level is exceeded are within the given distance. Taking several aspects into account (for example: conservative assumptions and parameters were used as a basis, including in particular the assumption of spending 7 days outdoors without protection), the SSK stipulated the 80th percentile as the cumulative frequency for the maximum distance of a specific measure. In order to derive the planning radius for the top-priority area (central zone), the mean value of all three plants was calculated for adults and children. For the foetus, this process also included the results of the various stages of development. The mean values of all locations for adults were used as a basis for determining a planning area where the emergency trigger levels for all designated protective measures may be exceeded. The determined maximum distances for administering iodine blockade to adults and children are relevant to planning areas situated further away from the plant.

Details about method and results are given at the SSK- recommendation "Planning areas for emergency response near nuclear power plants" (/3/ see also www.ssk.de).

The previous and the new planning areas are shown at figure 2.

Figure 2: Planning Areas around Nuclear Power Plants

Previous	New
Central zone with a radius of 2 km	Central zone extends up to about 5 km around NPPs
Middle Zone with a radius of 10 km	Middle zone extends up to about 20 km around NPPs
Outer Zone with a radius of 25 km	Outer zone extends up to about 100 km around NPPs
Remote zone with a radius of 100 km	Entire Territory of Germany

The competent authorities already have taken the first steps to implement the new planning areas.

The protection measures which have to be planned for the different zones are also described in /3/.

6.5 Scenarios

During the accident at Fukushima Dai-ichi different institutions and authorities as well as advisory boards in Germany were occupied with the situation inquiry, the situation assessment and the development and realisation of measures. Tasks were for example the information and advice of German citizens and German companies staying in Japan and the control of the import of goods from Japan. Within the scope of the activities it became clear that there are though planning for accidents in nuclear power plants in Germany and also planning for accidents abroad exists whose impacts correspond to the reactor accident in Chernobyl, but there is not a sufficient planning in place for accidents in other distances as far for example as Japan. It became clear furthermore that on account of the globalized economy the impact of accidents in nuclear installations will be always international. Therefore it is necessary, to be prepared to deal with the effects of accidents, which do not cause an emergency situation in Germany.

In order to close the “planning gaps” future planning should cover these scenarios:

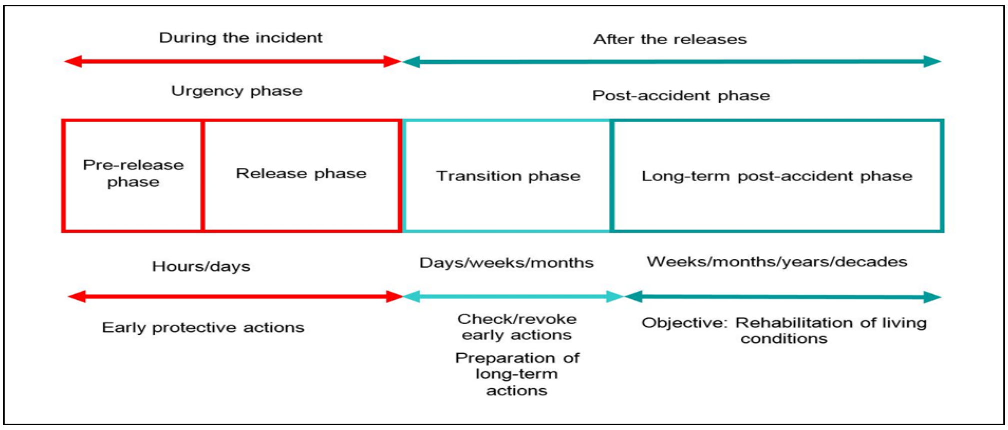
- Accident in a nuclear power plant in Germany
- Accident in a nuclear power plant in a neighbouring country (not more than 100 km distance from the German border)
- Accident in a nuclear power plant in the rest of Europe
- Accident in a nuclear power plant outside Europe.

In order to initiate further development of nuclear emergency response planning a scenario catalogue is discussed, which consist of accidents in nuclear power plants as mentioned above, accidents in nuclear installations, which aren't nuclear power plants, radiological emergencies, terroristic or otherwise motivated attacks using radioactive material, transportation accidents and crashes of nuclear powered satellites.

6.6 Accident phases

The Fukushima accident shows that detailed planning is needed for all phases of a nuclear accident. The phase model of /2/ is shown below.

Figure 3: The phase model for a nuclear accident /2/



For the urgency phase a tool is needed which supports the situation judgement when only few facts are available. HERCA/WENRA just published a method, which can be a basis for such a tool.

In particular, the planning for the post-accident phase must be improved so that lives of people affected can be normalized as soon as possible. Planning for the post-accident phase shouldn't only focus on the radiological impact on the affected people. Psychological and social effects caused by the accident itself and by the protection measures should be taken into account. The accident in Japan shows that the harm caused by these effects could be much greater than by the effects of the radiation exposure.

Transition from an emergency exposure situation to an existing exposure situation shall be included in the planning too.

6.7 Optimal Protection Strategies

In case of an emergency, there is not enough time to design protection strategies. Prepared protection strategies for all types and phases of accidents are needed. In an emergency, a further optimization of protection strategies is necessary. Currently it is discussed whether the elaboration of a guideline is reasonable and whether the code RODOS can be used for development and optimization of protection strategies.

6.8 Methods for determining source terms

One of the Lessons Learned is that lack of information on the nature, course, and extent of the release of radioactive substances can complicate the crisis management very much. The SSK reviewed the currently used methods for determining source terms in emergencies. With its recommendation “Prediction and Estimation of Source Terms for Nuclear Power Plant Accidents” (/5/; see also www.ssk.de), the SSK suggested to install a computer code for the prediction of the release and the implementation of a method to estimate the release based on plant technical, radiological and meteorological information.

6.9 Quality assurance and quality assurance monitoring

Experience from Fukushima show how important the quality of planning is. SSK reviewed the methods for quality assurance and quality assurance monitoring in Germany. Currently it is discussed how quality assurance and quality assurance monitoring can be improved for the planning of the competent authorities.

6.10 Harmonization

Finally yet importantly, the harmonization is discussed. More harmonization is needed not only among neighbouring states but also in Europe. The Council Directive 2013/59/EURATOM /6/ could be a good basis for a new European approach.

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7 ETHICAL ISSUES DEBATED AFTER FUKUSHIMA

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7.1 Introduction

Since the Fukushima accident, a lot of meetings and workshops have been conducted throughout the world, international organizations dealing with nuclear safety have been working intensively and numerous papers have been published. Remarkably, all of them nearly constantly highlighted one or another aspect of this accident having an ethical component.

One of the most frequently highlighted issues was the need of a global approach, not limited to radiological protection but enlarged to all public health aspects and to societal aspects. Among others, the attention has been drawn on the negative side effects of some countermeasures and on the psychological and social consequences of the accident, as for example the risk of stigmatization of the victims in specific cultural contexts.

The need for taking better into account long term issues, including return to "normality", has also been frequently underlined.

While many of the above-mentioned issues have been largely recognized, other more challenging ethical issues have been mainly highlighted by people “outside” the nuclear and radiological world, as the media and non-governmental organizations (although some of these issues have been taken into account by national and international authorities and organizations). Among these challenging issues, appear the lack of independency of safety agencies, collusions between authorities and companies and the frequent reluctance of authorities to disclose information, as for example on doses or contaminations or on dose distributions. More touchy issues were also sometimes underlined, such as potential conflicts of interest of some involved experts and international organizations working in the field (due to their explicit mandates or to conventions).

May be the most touchy ethical issue concerned the fairness, quality and adequacy of risk communication to the affected populations and to people in general. Downplaying of the risk of health effects or even denying such risks by some experts or national authorities as well by some international organizations has been frequently denounced, not only by the media but also by other experts and organizations. On the other hand, experts asking for more fair risk communication were sometimes accused to be “anxiety-provoking experts“, while as well “reassuring“ experts or organizations as these “anxiety-provoking“ experts all claimed being following only ”science” .

The question is then: Who tells the “scientific truth“? And what is “science-based information”?

This is an insidious issue. Political reasons that can explain these discrepancies regarding judgment and evaluation of risks exist and play almost certainly a role, but there are also deep and somewhat hidden epistemological issues.

7.2 Epistemological and ethical questions at stake in risk evaluation and communication

There exist some fundamental epistemological and ethical issues that are at stake in risk evaluation and communication. The lack of recognition of the existence and of the consequences of these issues and the resulting expert quarrels threatens the social credibility of all the experts in (among others) radiological questions. These fundamental issues are the existence of non-recognized conflicts of interest, the misuses of the evidence-based approach and the questioning of the adequacy and legitimacy of the precautionary attitude within the scientific work.

7.2.1 Non-recognized conflicts of interest: danger for credibility

In the nuclear field, potential conflicts of interest are unavoidable for many countries – as they are or have been in the past responsible of major radioactive contaminations (or could be in the future…) – and for many international institutions whose official mandate is to promote some practices (as the pacific use of nuclear energy).

Other conflicts of interest are linked with the potential socio-political consequences of nuclear accidents.

The risk is serious that such conflicts of interest may interfere with risk evaluation and communication.

After the Fukushima accident, a clear goal for several influent national and international players was to “reassure” the Japanese population, particularly about the health of their children. A right (and then not necessarily reassuring) risk evaluation and communication was then jeopardized by the socio-political perceived need to reassure and then to relativize or minimize as much as possible the possible radiation effects from exposure. Such mixing of the roles creates a danger for the credibility.

7.2.2 Use and misuse of the evidence-based approach

Evidence-based approach is currently become a dominant scientific paradigm, particularly in the medical field, where it is the condition of agreement of any new drug and even of any treatment.

The basic concern is to avoid concluding that a causal relationship exists before it is strongly proved (hard evidence is required).

In other words, the main concern is avoiding the “false positives”.

Current dominant pressure of this paradigm leads some experts or groups to consider that this way to proceed (to avoid carefully false positives) is the only way compatible with science, which is based on the possibility of testing and falsifying any hypothesis.

They use as an argument that the scientific method is based on the principle that there is an underlying order to the nature of things, and that by following certain rules and guidelines this nature can often be revealed. Ideas (hypotheses) are generated from observations and then tested by controlled experiments or observational studies, leading to better understanding (empirical science). Yet the problem is that, particularly in the current world, new things (or situations) are introduced rapidly but have possibly long term consequences, unknown by definition, asking for vigilance and responsiveness for early indications of health effects. Potential observations may be only possible after a long time, generating hypotheses at a late stage, whose testing (if feasible) may again take a long time. But decisions most frequently are to be made about these new introduced things (or situations), while strong evidence or certainty is lacking. Such decisions must be based on available “evidence” (evidence, here not in the sense of “certainty”, but in the sense of ”indications” or “corpus of knowledge”), even if there persists uncertainties. Decision-makers need then a sound basis for informed decision-making and are asking scientific experts (groups, committees …) for science-based *balanced* information, including science-based inferences about the risks in the future.

These science-based inferences have to stick to scientific observations and are part of the scientific work. They are not “external to science” while decisions based on these inferences are “external to science”.

This very fundamental conceptual issue lies at the root of the discussions at the level of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), that, as a committee, tends these last years to give overwhelming importance to the avoidance of false positives, by highlighting all possible bias for an association between effect and exposure, in comparison with the avoidance of false negatives, while possible dismissal of real health effect of radiation is a major concern for responsible decision-makers. This attitude is good illustrated by the exclusively critical reactions about recent low dose reports on effects at low dose (Pearce 2012, Kendall 2013) in the UNSCEAR Report on Effects of radiation exposure of children (UNSCEAR, 2013). This attitude lies also at the basis of the minimized risk estimates of UNSCEAR regarding the health effects of Chernobyl and, recently, of Fukushima (UNSCEAR, 2014): there is indeed no “100 % certainty” for many of these effects.

Finally, and more importantly, this attitude of giving overwhelming importance to the avoidance of false positives was at the origin of the comeback of the 100 mSv “magic number”.

In recent discussions within UNSCEAR, several experts stated indeed that “attribution” (meaning for them “unequivocal attribution”, i.e. with 100 % certainty) of health effects to ionizing radiation is impossible under 100 mSv. They justified this statement by the fact that 100 mSv is currently the first statistically significant point in the dose-effect relation for all solid cancers together in the gender- and age-mixed population of the Japanese survivors to the atomic bombing (LSS) and that there are no other individual epidemiological study where the evidence is strong enough to draw 100% certain conclusions. As a consequence no effect could be "attributed" to radiation under 100 mSv and even inference of risk for the future under this dose would be "non-scientific". Such an approach is at the basis of the health evaluations in (and communications about) the last UNSCEAR report regarding Fukushima (UNSCEAR, 2014).

This is an unbalanced use of the evidence-based approach, looking only to the avoidance of false positives (100% certainty necessary before concluding anything), and by doing so ignoring the risk of dismissing real health effects. In fact, these statements give overwhelming importance only to epidemiology (and within this only to “strong epidemiological evidence”), while consistency of the corpus of knowledge coming from all epidemiological studies and from all concerned disciplines (including radiobiology) is an important part of a balanced scientific assessment. Another characteristic of these statements is that the epidemiological evidence concerning radiation-induced solid cancers in a mixed population is generalized to all types of health effects and populations (such as radiosensitive populations as young children, embryos or fetus or cancer-prone subgroups with genetic predispositions). In reality there *are* evidences below 100 mSv (or “about” 100 mSv), the population is not homogeneous regarding the risk and our knowledge is not uniform throughout the range from some mSv to 100 mSv. The issue of combined exposures is also ignored.

Yet there were recently some important changes. The UNSCEAR’s strategic objective for the period 2009-2013, endorsed by the General Assembly, in its resolution 63/89, is “to increase awareness and deepen understanding among authorities, the scientific community and civil society with regard to levels of ionizing radiation and the related health and environmental effects as a sound basis for informed decision-making on radiation related issues". Now, UNSCEAR underlined in a recent report to the General Assembly (General Assembly, 2012), that "this strategic objective highlighted the need for the Committee to provide information on the strengths and limitations of its evaluations, which are often not fully appreciated. This *involves avoiding unjustified causal associations (false positives) as well as unjustified dismissal of real health effects (false negatives*)." Formally it was an important step forward.

Unfortunately the culture is far to have changed in a large part of this committee and the use of the 100 mSv figure as a kind of pseudo-scientific general threshold is far from having disappeared and is implicitly used as well in the Fukushima report (UNSCEAR, 2014) as in the Children report (UNSCEAR, 2013).

The recently published UNSCEAR report on Attributing health effects to ionizing radiation exposure and inferring risks (UNSCEAR 2015) tries to clarify these concepts and the approach of UNSCEAR. After years of discussions, debates and amendments, the final text offers much more nuances than initially, particularly regarding inferences of risks for the future. Nevertheless, there is still a tendency towards black or white statements or approaches, particularly regarding attribution of observed health effects to ionizing radiation exposure, considered as necessarily unequivocal (100% certain), while the reality is that the vast majority of scientific evaluations are requested and necessary in situations where there is no 100% certainty and no 100% expert agreement. There are often "degrees" of attributability, with different levels of confidence.

7.2.3 Misunderstanding of the precautionary principle: Precaution in Science is relevant!

Precaution is relatively largely accepted regarding decision-making processes in situations of uncertainty (although the definition of this concept may be very different).

The point here is that the precautionary approach is also relevant and appropriate *within* science. This is frequently misunderstood.

As underlined in the COMEST report from UNESCO, the precaution approach in science includes:

- a focus on risk plausibility rather than on hard evidence
- a responsiveness to the first signals ("early warnings")
- a systematic search for surprises ("thinking the unthinkable"), particularly for possible long term effects

The first point is linked with the previous discussions concerning misuses of the evidence-based approach.

For society the main concern of the experts is expected to be the protection of health. When there is scientific plausibility ("enough" evidence) of the existence of a risk of serious harm, action is needed. Even if there is still uncertainty and no 100% evidence!

In other words, a main societal concern is also avoiding the false negatives.

Precaution in science means in fact focusing on (or at least giving attention to) risk plausibility and not only to hard evidence.

The corollary is the need of being vigilant and responsive to the first signals of potential health problems ("early warnings"), as for example is the rule for vigilance about drugs.

Recent developments regarding the late recognized radiation effects of low to moderate doses on the lens of the eye and on the circulatory system are good illustrations of a lack of vigilance and responsiveness regarding early warnings that were described many years ago.

The third point is the need of a systematic search for surprises ("thinking the unthinkable"), particularly for possible long term effects. In this respect, it is worth remembering the EC report on "Recent scientific findings and publications on the health effects of Chernobyl" (EC, 2011).

This EC report opens the discussion on the issue of the controverted reasons of children's morbidity in the most affected areas around Chernobyl. There are many claims concerning the health of children in the contaminated territories around Chernobyl, which seem to suffer from multiple diseases and co-morbidities with repeated manifestations. The reports from international organizations did not give until now much interest in the multiple publications by Ukrainian, Russian and Byelorussian researchers on children's morbidity. According to the EC report, this is partly due to the fact that many of these studies were not available in English but also to the fact that they often did not meet the scientific and editorial criteria generally required in the Western peer reviewed literature.

Anyway, all these health problems were generally collectively qualified as "psycho-social" side effects in the reports from international organizations.

More or less recent studies brought again this issue into light, including the debated publications of Bandazhevsky, linking ^{137}Cs body loads with ECG alterations and cardiovascular symptoms in children, and the studies on neurobehavioral and cognitive performances in children of the contaminated areas.

The EC report drew the attention on IRSN conducted series of animal studies. Rats were exposed to ^{137}Cs contamination during several months (generally 3 months, sometimes 9) through drinking water containing 6500 Bq/L. Intake of 137Cs was estimated to be 150 Bq/day/animal (500 Bq/kg of body weight), a figure that is considered by the authors to be comparable with a typical intake in the contaminated territories (based on Handl's evaluation in Ukraine: 100 Bq/day with variations, according to geographical location and diet, from 20 up to 2000 Bq/day as in the case of special dietary habits like excess consumption of mushrooms) .

Although the animals tested in these studies did not show induced clinical diseases, a number of important biological effects were observed on various systems: increase of CK and CK-MG, decrease of mean blood pressure and disappearance of its circadian rhythm; EEG modifications, perturbations of the sleep-wake cycle, neuro-inflammatory response, particularly in the hippocampus, etc. The report underlined that these somewhat unexpected results are obtained after relatively modest intakes of ^{137}Cs and that a fraction of the population in the contaminated territories has been shown to incorporate ten times more ^{137}Cs with their food.

Again according to the same EC report, on the ground of the fact that there is currently a lack of analytical studies in which dose and risks on non-cancer diseases in children were estimated on an individual level, a series of longitudinal studies have also been initiated in Ukraine in conjunction with the US University of South Carolina and were devoted to children's health, making use of the fact that all children in the studied territory had been obliged to participate in a yearly medical examination.

A first study investigated, for the years 1993 to 1998, the association between residential soil density of ^{137}Cs (used as exposure indicator) and blood cell concentrations in 1251 children. The data showed a statistically significant reduction in red and white blood cell counts, platelet counts and haemoglobin with increasing residential soil contamination. Over the six-year observation period, hematologic markers did improve. The authors draw the attention on the fact that similar effects and evolution were reported after the Techa River accident in 1957.

A second study investigated, for the same years 1993 to 1998, the association between residential soil density of ^{137}Cs and spirometry measures in 415 children. They found statistically significant evidence of both airway obstruction and restriction with increasing soil ^{137}Cs. The authors advance as possible explanation a radiation-induced modulation of the immune system leading to recurrent infections and finally to detrimental functional effects.

The authors of these studies conclude by saying that the current "optimism of the UN reports may be based on too few studies published in English, conducted too soon after the event to be conclusive").

Fundamentally, looking to such studies, the questions which should be considered are:

- whether the observed morbidity in children after the Chernobyl accident is <u>only</u> explained by psycho-social factors or whether it is at least partly due to currently not recognized *non-cancer* effects of chronic internal exposure
- whether there is always equivalence of risk for external and (chronic) internal exposures, and
- whether the currently used concept of equivalent/effective dose is a right risk indicator for *all* types of effects (including all types of non-cancer effects).

This issue is a major societal concern after large-scale contaminations and asks for adequate research.

Unfortunately the above-mentioned references were not even quoted in the UNSCEAR Fukushima report (although asked for) and there were practically no research published to try to verify the above-mentioned observations and experiments and to check the possible dose-dependence of the biological perturbations observed in the IRSN study.

Systematic search for surprises ("thinking the unthinkable") is a difficult challenge, because it means often challenging dominant paradigms or at least refusing to "follow fashion". It may seem strange or incredible but there are fashions in the scientific world. Example in the current radiation specialists' field is the lack of interest about hereditary effects, judged frequently as being practically inexistent or negligible just because nothing was seen until now (some tens of years …) in the survivors of the atomic bombing. Bad surprises may arrive in this field in the future. The same is true concerning non-cancer effects after in utero irradiation, where the dominant concept is currently that there is nothing to fear under 100 mGy, while the domain of long term Nervous Central System (NCS) effects, of effects of internal exposures and of potential long term effects linked to epigenetic effects, as perturbations of gene expression, is largely unexplored, with a few recent exceptions such as the CEREBRAD project (Cognitive and Cerebrovascular Effects Induced by Low Dose Ionizing Radiation), a collaborative European project funded in 2011 within the 7th EU framework programme, Nuclear Fission and Radiation Protection.

UNSCEAR reports (Fukushima, children) are based quasi exclusively on the "hard" evidence approach and generally fail to consider and discuss epistemic uncertainties. Science-based balanced information after Fukushima should have included at least mentioning and discussion of the above-mentioned studies and uncertainties, common to all nuclear accidental situations and frequently brought up by the media and the NGO's.

7.3 Fairness of risk communication: a fundamental ethical issue in accidental situations

As explained above, decisions are most frequently to be made about situations, where strong evidence or certainty is lacking. Such decisions must be based on available "evidence" (evidence, here not in the sense of "certainty", but in the sense of "indications" or "corpus of knowledge"), even if there persists uncertainties. Decision-makers need then a sound basis for informed decision-making and are asking scientific experts (groups, committees …) for science-based balanced information, including science-based inferences about the risks in the future and science-based information about uncertainties and their potential consequences.

The same is true for affected populations (or patients in medical exposures) which have to take autonomous informed decisions regarding their health and the health of their children.

To take the right decision and take their responsibilities, societal as well as individual decision-makers must be *aware* of "*potential*" harm ("are you sure it is safe?" and, if not, "what may happen?", "what is at stake?"), and of the way uncertainties, including epistemic ones and research needs linked, are *assessed* ("how do you evaluate and balance the available evidence?", "what is the degree of confidence that we avoid false positives and false negatives?", "what is the degree of consensus?", and particularly, "what are the reasons for divergent views?").

Fair communication and information should allow for responsible and autonomous decision-making (as well for decision-makers as for population). In this respect, the uncertainties and assumptions have to be communicated, together with their level of confidence.

Communication heard after Fukushima such as "no detectable (or discernible) effect is expected" is misleading as it is understood as indicating an absence of risk while it in fact just means that there are statistical limitations that would not allow to show a statistically significant effect, ….even if this effect is 100% certain!

The same misleading character is true for statements as "it is safe under 100 mSv". Everybody understands that there is no risk under 100 mSv or that there is a risk threshold at this level, while this statement is just the result of an unbalanced use of the evidence-based approach, looking only to the avoidance of false positives (100% certainty should be necessary before concluding anything). In reality there are a lot of evidences below 100 mSv (or "about" 100 mSv), particularly for radiosensitive sub-populations as young children, embryos or foetus or cancer-prone subgroups with genetic predispositions, and there are solid radiobiological reasons for asking for prudence in the low dose field.

Unbalanced reassuring information is not only misleading but is also counterproductive as it provokes contesting reactions in specialized people, leading to general distrust in all experts and causing finally more anxiety within the population.

The right way to communicate about risks and associated uncertainties should be discussed with human science specialists (not only in communication) but also with the stakeholders, including representatives of the affected population and of NGO's.

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8 SUMMARY

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8.1 Introduction

This document provides the background, summarizes the presentations and the results of the round-table discussion, and tries to emphasize the potential implications of the Scientific Seminar on "Fukushima – Lessons learned and issues", held in Luxembourg on 18 November 2014. It takes into account the discussions that took place during the seminar and during the subsequent meeting of the Article 31 Group of Experts, although it is not intended to report in an exhaustive manner all the opinions that were expressed. The document has been submitted for comments to the lecturers, as far as their contributions were concerned.

8.2 The Article 31 Group of Experts and the rationale of the EU Scientific seminars

The Article 31 Group of Experts is a group of independent scientific experts referred to in Article 31 of the Euratom Treaty, which assists the European Commission in the preparation of the EU Basic Safety Standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. According to the Euratom Treaty and to their Code of Ethics, this group of experts has to give priority to the protection of health, to the safety and to the development of the best available operational radiation protection. For doing so, they have to follow carefully the scientific and technological developments and the new data coming from the world of research, particularly when these could affect the health of the exposed persons.

In this context, a Scientific Seminar is devoted every year to emerging issues in Radiation Protection – generally addressing new research findings with potential policy and/or regulatory implications. On the basis of input from the Directorate General Research of the European Commission and of information provided by individual members of the Article 31 Group of Experts, the Working Party RIHSS proposes relevant themes to the Article 31 Group that could be discussed during a subsequent seminar. After selection of the theme and approval of a draft programme by the Article 31 Group, the Working Party RIHSS deals with the preparation and the follow up of the seminar. Leading scientists are invited to present the status of scientific knowledge in the selected topic. Additional experts, identified by members of the Article 31 Group from their own country, take part in the seminars and act as peer reviewers. The Commission convenes the seminars in conjunction with a meeting of

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[2] Besides L. Lebaron-Jacobs (who was acting as rapporteur for the seminar), the following members of the Working Party on Research Implications on Health and Safety Standards of the Article 31 Group of Experts contributed to the preparation of this overview: R. Huiskamp, A. Friedl, S. Risica, P. Smeesters (Chairperson of the WP), and R. Wakeford. They were assisted by S. Mundigl from the European Commission.

the Article 31 Group, in order that members of the Group can discuss the potential implications of the combined scientific results. Based on the outcome of the Scientific Seminar, the Group of Experts referred to in Article 31 of the Euratom Treaty may recommend research, regulatory or legislative initiatives. The European Commission takes into account the conclusions of the Experts when setting up its radiation protection programme. The Experts' conclusions are also valuable input to the process of reviewing and potentially revising European radiation protection legislation.

8.3 Key Highlights of the Presentations at the Scientific Seminar on Fukushima – Lessons learned and issues

Richard Wakeford – *Introduction to the accident at Fukushima Dai-ichi Nuclear Power Station*

Fukushima Dai-ichi NPS is situated on the eastern coast of Japan and consists of six boiling water reactors (BWRs). Three of which (Units 1 to 3) were operating at the time of the earthquake. All three reactors shut-down automatically during the earthquake apparently with no serious damage that would compromise safety. External electrical power to the site was interrupted by the earthquake and the back-up diesel generators started up to provide continuity of electrical supply. However, the large tsunami damaged the reactor cooling water heat exchangers, and drowned the emergency generators. Although the chain reactions in the reactors had been shut down, there was still substantial radioactive decay of fission products generating heat and no effective means of cooling the fuel in the cores. The next days hydrogen explosions occurred in Units 1, 2 and 3 releasing significant quantities of radionuclides into the surroundings.

The Japanese authorities ordered the evacuation of about 100 000 people within an area 20 km-radius around the Fukushima Daiichi site, and sheltering advised within 20-30 km associated to a voluntary evacuation. For the moment there were only non-radiological health consequences due to evacuation.

Activities of radionuclides released to atmosphere, contaminated areas and health effects as a result of the Fukushima and Chernobyl accidents were compared and show significantly more serious consequences for the Chernobyl accident. Finally, lessons have been learnt since Chernobyl and have helped guide the actions taken by Japanese authorities

However the public has lost confidence in nuclear power. A lot of efforts have to be realized to restore trust in operators of nuclear facilities and national regulatory.

Peter Jacob – *Expected influence of the accident on thyroid cancers*

After the Fukushima accident an ultrasonographic screening program has been initiated by Japanese authorities in order to monitor thyroid cancer in people of 18 years old or younger at the time of the accident who live in the Fukushima Prefecture.

Despite some biopsies results of cytology were not yet available as of 30 June 2014 and some people denied fine needle aspiration biopsies, a theoretical prevalence of 0.042% (95% confidence interval: 0.01%; 0.09%) of thyroid cancer has been derived thanks to results from the first screening in the UkrAm cohort after the Chernobyl accident. The same value of prevalence has been observed in three prefectures of Japan not affected by the Fukushima accident. For the moment the latency time is too short to conclude about the possible contribution of radiation exposure to these prevalent cases.

As the age distribution in the UkrAm cohort resembles more to the age distribution of the screened population than other screening studies (Hong Kong), and thyroid cancer incidence rates in Ukraine and Japan are quite similar, an assessment of the impact of the screening in the Fukushima Prefecture on thyroid cancer has been based on data from the UkrAm cohort. The main difference in study protocols is the size of nodules larger than 5 mm for fine needle aspiration biopsies in the Fukushima Prefecture, while in the UkrAm cohort nodules larger than 10 mm were selected.

Compared to risk model for Life Span Study members not participating in Adult Health Study, excess rate calculated after the Fukushima accident differs: it decreases with increasing age at exposure and with increasing age attained. As the number of evacuees is relatively small and despite of their higher thyroid doses a radiation effect on thyroid cancer incidence is not expected to be significantly detectable for them compared to the non-evacuated population. Moreover a radiation effect might become detectable but only after several decades. For an assumed thyroid dose of 10 mGy, the contribution of the radiation exposure to the 50-years thyroid cancer incidence would be about 0.07% (95% 0.003%; 0.2%) with large uncertainty caused by uncertainties in the screening factor.

Stephanie Haywood – *Exposure and doses – lessons learned*

After a nuclear accident, assessments are undertaken for different reasons: public doses in the early emergency phase, emergency and post-emergency phases to reduce doses from exposure and to engage rapid measures and then longer term measures if required. Retrospective assessment of exposures for dose reconstruction requires spatial and temporal data and combines information from measurements and modelling. In the first few hours of a nuclear accident, the availability of information is severely limited as for Fukushima regarding the data on short-lived iodine and tellurium radionuclides and the early distribution of the noble gases. Moreover as measurements can be considered as photos of the levels in the medium at a particular moment, a subsequent adjustment was needed to consider the intake pathways, the timing of intakes and the decay of short-lived radionuclides up to the time of measurement.

WHO (WHO, 2012) and UNSCEAR (UNSCEAR, 2014) have in particular published dose assessments of the Fukushima accident. These reports conclude that doses delivered in the first days following the accident represented a significant proportion of the first year’s dose with uncertainties due to lack of early measurement data. A geographical variability of the contributing radionuclides to the estimated lifetime effective and thyroid doses for people who were infants at the time of the accident is noticed in all areas. The Japanese authorities implemented countermeasures as evacuation, food restrictions combined with the time of year, which significantly reduced the doses to individuals living close to the Fukushima NPP as demonstrated by the UNSCEAR assessment (UNSCEAR, 2014). Finally the majority of the estimated doses in all areas remain very low.

The lessons learned highlight the necessity to put emphasis on an early measurement programme to inform decisions on countermeasures, to develop a procedure unifying both monitoring and environmental dispersion modelling to provide a projection of dose assessments into the future. In the post-emergency phase, dose assessment may be different regarding to the objective: effectiveness of countermeasures to decrease anxiety of people or usefulness of a long term clean-up. Moreover detailed information as clearly defined populations, ages, time periods or range of organs are needed for a health risk study.

Linda Walsh – *Risk assessment – lessons learned*

In 2013 WHO published a report of two international expert groups: the first responsible for identifying hazard relating to exposure, and the second for assessing health risk (HRA group) as a consequence of the Fukushima nuclear accident.

The HRA group of experts has quantified cancer effects by providing Lifetime Attributable Risk (LAR) estimates of radiation-related cancer incidence risk for different geographical locations and for different age groups, based on either a reference first-year organ/tissue dose or a reference lifetime organ/tissue dose for members of the public and emergency workers. Lifetime Baseline cancer Risk (LBR) has also been evaluated for comparison. Non-cancer effects were assessed but the radiation-related risks were not calculated. Moreover it is interesting to compare reports from WHO (WHO 2013) and UNSCEAR (UNSCEAR 2014): they are generally consistent in terms of dose estimates for population and workers and exposure scenarios for workers. These reports both conclude that in the short term mental and social well-being of persons in the affected area would lead to the most important aspects of health effects related to the nuclear accident.

In future nuclear accidents it could be recommended to involve HRA experts from the beginning of dosimetry assessments, to have precise population data for any ICD grouping of diseases and for any country, to develop a standard program for calculating health risks using a flexible software and considering uncertainties, and to leave it to risk communication specialists to present the results of the health risk assessments to the public within the few months of the accident in order to avoid panic and mental anxiety in persons who live in affected areas and to aid in the reassurance by increasing social well-being.

Jean-René Jourdain – *Worker dose assessment – lessons learned*

After Fukushima accident statistics show that more than 10,000 people have been worked on site as of 30 September 2014. During the emergency phase from 14 March 2011 to 1 November 2011 the exposure dose limit was 250 mSv and 6 of 173 workers on site were exposed to a higher dose. From 1 November 2011 to 30 April 2012 workers were divided into two categories:

- workers engaged in emergency work before 1 November 2011 and those engaged in exempted activities as maintaining functions for cooling reactor systems and spent fuel storage pools, and also functions for suppressing the release of radioactive materials;
- workers engaged in emergency work after 1 November 2011 and not engaged in exempted activities.

Only 1 TEPCO worker was added to the 100-150 mSv dose range category before the end of April 2012.

Since 30 April 2012 the situation seems stable. However individual data are needed because tables provided by TEPCO's press releases cannot be used to estimate worker doses above the exposure dose limit.

Several working groups whose worker dose assessment group and health implications group were set up by UNSCEAR to provide the UN General Assembly with an assessment of the levels of exposure and radiation risks due to the Fukushima nuclear accident. A list of questions from the worker dose assessment group were sent to the Japanese government in order to make a selection of workers who were involved in the emergency response and clean-up operations before 31 October 2012, to get data to be able to review reported effective doses and absorbed doses to organs, to assess the reliability of reported doses, to analyse observed health effects and to make a projection of risks to health.

A two-stage approach was used to assess the reliability of reported doses: a review of methodologies for monitoring and dosimetry used in Japan independent and individual dose assessments for selected workers compared with reported doses. Shared dosemeters were used, so the reliability of the external dosimetry performed before 1 April 2011 has to be considered with reservations.

For internal dosimetry all methods and procedures were adequate for conducting *in vivo* measurements and the software used was appropriate. However the most significant issue was the delay in commencing reliable *in vivo* measurements of ^{131}I in the thyroid: for some workers they unfortunately began at mid-April 2011 for most workers at mid- to late-May 2011. This had a significant impact on internal dose assessment because ^{131}I was not measurable in the thyroid of many workers. Two assessment methods were used: an “Environmental ratio” method that had very large uncertainties and a “Minimum Detectable Activity” (MDA) method which finally provided a reliable estimate of the upper limit on ^{131}I intake but without providing a reliable estimate of the true intake. During the period 12–19 March 2011 the estimated additional contribution of workers to dose was in range of 6-45% with a typical value of about 20%, relative to dose from ^{131}I intake. However no significant additional contribution was noticed for workers who began to work on site after 19 March 2011.

The evaluation of reported internal doses shows an agreement between independent assessments and reported values for 12 of the 13 workers with internal doses higher than 100 mSv and largely due to ^{131}I intakes (99%). Moreover sufficient information was available to provide absorbed doses to organs for health risk assessment considering thyroid, red bone marrow and colon. Short-lived radionuclides (^{132}Te, ^{132}I, ^{133}I, and ^{136}Cs) were not included because they would have been undetectable at the time of measurement. Independent assessments for 42 randomly-selected workers with three dose ranges (0-5, 5-20, 20-100 mSv) show that internal doses were largely due to ^{131}I intakes (98%). TEPCO reported values were confirmed as reliable only when a positive measurement of ^{131}I in thyroid was possible. However further information from contractors would be needed to evaluate reliability of values for their workers although some discrepancies were resolved after a 2013 re-assessment of doses reported in Japan. There is very few information about reported doses for other groups of workers (policemen, municipal worker, firefighters and Self Defense Force workers) because they are not radiation workers according to the Japanese government.

Dose ranges and health implications were estimated by WHO. As individual dosimetric data were not available at the time of the WHO assessment, a simple scenario approach was adopted. Risks of leukaemia, thyroid cancer, and “all solid cancers combined” were assessed using organ doses to red bone marrow, thyroid and colon in the first year. Very similar results of organ doses were estimated independently for each scenario by US-DOE and PHE.

Finally according to the data from the Japanese government the highest reported total effective dose for a worker was 679 mSv (590 mSv internal, 89 mSv external). For the workers with the highest internal doses, the major contribution to committed effective dose was the thyroid dose resulting from inhalation of ^{131}I. No radiation-related deaths have been reported among workers since the accident. For 13 workers who received a committed effective dose higher than 100 mSv an additional thyroid cancer risk for a 20 years old worker is around 3.5%. Additional leukaemia risks are about or even below 0.1% for all scenarios. For all solid cancers an excess of cancers is unlikely to be observed because of variability of Life Baseline Risk. Non cancer risks are low.

In the event of a nuclear accident monitoring systems and equipment should be resilient to a major accident, individual monitoring of workers should be carried out promptly and provided to evaluate the reliability of the dose assessment. Moreover in case of a capacity severely reduced, monitoring of a limited number of workers should be better than no monitoring. The maintenance of capabilities for urine monitoring in the event of an accident (e.g. for ^{90}Sr or Pu intakes) should be considered.

Capabilities for radiation monitoring and dose assessments for other ("non-radiation") categories of personnel involved should be thought in advance and set up promptly. At the end an access to clear and comprehensive information about the activities carried out by the first hours/days would be highly interesting.

Ulrike Welte – *Emergency preparedness – discussions on a review of the current strategy*

The SSK (Strahlenschutzkommission = German commission on radiation protection) reviewed the insights of emergency response and emergency preparedness planning in Germany in light of the Fukushima accident. Some lessons were learnt from discussions about the German current strategy. As even nuclear accidents of the INES Level 7 happen a detailed and adapted planning of emergency response is necessary. Moreover the reference source terms are required as a basis for detailed planning. While the „Level 7 Source Term" was already used to determine extended planning areas, it should not be done only for the worst accidents. For the moment the implementation of Level 6 and Level 5 source terms and source terms for long-lasting releases is discussed. Furthermore the lack of information on the nature, course, and extent of the release of radioactive substances can complicate the crisis management a lot. Consequently the methods for determining the source term were reviewed in Germany.

By the Fukushima accident the SSK noticed that the area in which protective measures (in particular evacuation) were implemented immediately after the accident was much larger than the current planning zones in place in Germany. Consequently Emergency Preparedness Planning Areas were changed in Germany. New planning areas for emergency response in the vicinity of nuclear power plants can be consulted on SSK website (www.ssk.de). The German Commission on Radiological Protection recommends a basis for emergency planning "NPP-Scenarios" covered up by regulations because plans for measures to be taken in case of accidents outside of Europe are not available.

Then it is very important to improve a planning for all phases of an accident. During the post-accident-phase in particular it is essential to normalize lives of people as quickly as possible: lots of people lost their life because they are not informed. When only few facts are available a tool which supports the situation judgment is also needed. The SSK recommends enlarging the planning to all phases of accidents and provides a phase model for a nuclear accident.

In case of an emergency there is not enough time to develop optimal protection strategies for all phases of the accident. So prepared protection strategies are needed for all types and phases of nuclear accidents. Is there any country where there are prepared protection strategies? In Germany it is currently discussed whether the elaboration of a guideline is reasonable and whether the computer code RODOS can be used for the development and further optimization of protection strategies. However the German Commission on Radiological Protection recommends preparing protection strategies in advance for all types and phases of nuclear accidents, a further optimization of these strategies in an emergency situation and a tool.

A good quality of planning is important especially during build-up of the crisis organization, during the evacuation and also in the post-accident phase, so the methods for quality assurance and quality assurance monitoring in Germany were reviewed. Finally there are sufficient regulations on quality assurance and monitoring for the NPP-internal emergency preparedness and response. However quality assurance and quality monitoring of the competent authorities for emergency preparedness and response are not sufficiently ensured. The SSK discusses the need of special rules for quality assurance and quality monitoring, the implementation of reviews by independent institutions and the improvement of quality by implementation of a certification eventually on a European level.

The SSK concluded that more harmonization is needed not only among neighbouring states but in Europa and even worldwide and the Council Directive 2013/59/Euratom seems to be a good basis for a new European approach.

Patrick Smeesters – *Ethical issues debated after Fukushima*

Since the Fukushima accident, a lot of meetings and workshops have been conducted throughout the world. All of them nearly constantly highlighted one or another aspect of this accident having an ethical component. One of the most frequently highlighted issues was the need of a global approach, not limited to radiological protection but enlarged to all public health aspects and to societal aspects. The need for taking better into account long term issues, including return to "normality", has also been frequently underlined.

Other more challenging ethical issues have also been highlighted, as the lack of independency of safety agencies, collusions between authorities and companies and the frequent reluctance of authorities to disclose information, as for example on doses or contaminations or one dose distributions. More touchy issues were also sometimes underlined, such as potential conflicts of interest of some involved experts or organizations working in the field (due to their explicit mandates or to conventions).

May be the most touchy ethical issue concerned the fairness, quality and adequacy of risk communication to the affected populations and to people in general. Downplaying of the risk of health effects or even denying such risks by some experts or national authorities as well by some international organizations has been frequently denounced, not only by the media but also by other experts and organizations. On the other hand, experts asking for more fair risk communication were sometimes accused to be “anxiety-provoking experts“, while as well “reassuring“ experts or organizations as these “anxiety-provoking“ experts all claimed following only ”science” .

There are political reasons that can explain these discrepancies regarding judgment and evaluation of risks but there are also deep and somewhat hidden epistemological and ethical issues at stake in risk evaluation and communication. These fundamental issues are essentially the misuses of the evidence-based approach and the questioning of the adequacy and legitimacy of the precautionary attitude within the scientific work.

The basic concern of the evidence-based approach is to avoid concluding that a causal relationship exists before it is strongly proved (hard evidence is required). In other words, the main concern is avoiding the “false positives”. The problem is that, particularly in the current world, new things (or situations) are introduced rapidly but have possibly long term consequences, unknown by definition, asking for vigilance and responsiveness for early indications of health effects. But decisions most frequently are to be made about these new introduced things (or situations), while strong evidence or certainty is lacking. Such decisions must be based on “available evidence” (evidence, here not in the sense of “certainty”, but in the sense of ”indications” or “corpus of knowledge”), even if there persists uncertainties.

This very fundamental conceptual issue lies at the root of the discussions at the level of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) that, as a committee, tends these last years to give overwhelming importance to the avoidance of false positives, by highlighting all possible bias for an association between effect and exposure, in comparison with the avoidance of false negatives, while possible dismissal of real health effect of radiation is a major concern for responsible decision-makers.

This attitude of giving overwhelming importance to the avoidance of false positives is at the origin of the comeback of the 100 mSv “magic number”, used as a kind of pseudo-scientific general threshold for all radiation-induced health effects.

This problem makes part of the more global issue of the adequacy and legitimacy of the precautionary attitude within the scientific work. Precaution is relatively largely accepted regarding decision-making processes in situations of uncertainty. The point here is that the precautionary approach is also relevant and appropriate within science. As underlined in the COMEST report from UNESCO, the precaution approach in science includes:

- a focus on risk plausibility rather than on hard evidence
- a responsiveness to the first signals (“early warnings”)
- a systematic search for surprises (“thinking the unthinkable”), particularly for possible long term effects

Recent developments regarding the late recognized radiation effects of low to moderate doses on the lens of the eye and on the circulatory system are good illustrations of a lack of vigilance and responsiveness regarding early warnings that were described many years ago.

Recent UNSCEAR reports (Fukushima, children) are based quasi exclusively on the “hard” evidence approach and generally fail to consider and discuss epistemic uncertainties (i.e. lack of knowledge or data), such as about long term hereditary effects, long term Nervous Central System effects of exposure in utero or effects of prolonged internal exposure on children.

Decision-makers need a sound basis for informed decision-making and are asking scientific experts for science-based *balanced* information, including science-based inferences about the risks in the future and science-based information about uncertainties and their potential consequences.

The same is true for affected populations (or patients in medical exposures) which have to take autonomous informed decisions regarding their health and the health of their children.

Communication heard after Fukushima such as “no detectable (or discernible) effect is expected” is misleading as it is understood as indicating an absence of risk while it in fact just means that there are statistical limitations that would not allow to show a statistically significant effect.

The same misleading character is true for statements as “it is safe under 100 mSv”. Everybody understands that there is no risk under 100 mSv or that there is a risk threshold at this level, while this statement is just the result of an unbalanced use of the evidence-based approach, looking only to the avoidance of false positives (100% certainty should be necessary before concluding anything). In reality there are evidences below 100 mSv (or “about” 100 mSv), particularly for radiosensitive sub-populations as young children, embryos or foetus or cancer-prone subgroups with genetic predispositions, and there are solid radiobiological reasons for asking for prudence in the low dose field.

Unbalanced information is not only misleading but is also counterproductive as it provokes contesting reactions in specialized people, leading to general distrust in all experts and causing finally more anxiety within the population.

8.4 Summary of the Roundtable discussion

Hans Van Marcke, Maria del Rosario Perez, Wolfgang Weiss, Richard Wakeford, Peter Jacob, Stephanie Haywood, Linda Walsh, Jean-René Jourdain, Ulrike Welte, Patrick Smeesters, Frank Hardeman (Moderator)

Hans Van Marcke – How people's perception can be influenced – Examples from UNSCEAR

By the choice of the data and the way they are presented, perception of people about the consequences of a nuclear accident can be influenced. Three examples from UNSCEAR reports can be analysed: population exposure from normal operation versus reactor accidents, population exposure in the contaminated areas versus the Chernobyl red forest contamination and considering the protection of the environment: routine discharges versus accidental discharges.

Regarding the UNSCEAR 2008 report the effective dose to members of the public from the nuclear fuel cycle in normal operation is very low: 200 manSv (evaluation period 1998-2002). Finally if major nuclear accidents are considered Chernobyl is equal to 1800 years of normal operation and Fukushima 240 years! Moreover the total effective dose accumulated during the first 10 years by the 5 million people living in the most contaminated areas around Chernobyl was not very high (excluding thyroid dose): the exposure is less than the difference in exposure between the Ardennes and the Campine region of Belgium. Reactor accidents are the biggest threat but these small risks with far-reaching consequences are not included in the UNSCEAR figures.

How many of the 49 000 inhabitants would have survived the initial dose rate of about 1 Gy/h if the wind blew to Pripyat instead of to the red forest?

UNSCEAR report on Fukushima accident concludes that beyond a geographically very restricted area the potential for effects on biota may be considered insignificant. Why dealing with protection of the environment if MBq/m² of soil contamination with ^{137}Cs has no effect on the ecosystem while the contamination levels during normal operation are many orders of magnitude lower?

Maria del Rosario Perez – Fukushima

Regarding WHO Constitution (1948) "health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". Moreover health is a human right. Health promotion is the process of enabling people to increase control over, and to improve, their health. It includes improvement of individual behavior, as well as a wide range of environmental and social interventions to promote and sustain health such as radiation safety.

Immediately after the Fukushima accident WHO activated its emergency response plan. WHO has set up short-term actions as monitoring the situation, activating relevant expert networks, implementing inter-agency coordination plan, assessing health risks, providing technical advice to national authorities, providing information to the public to inform decision-making*,* prevent risky reactions*,* allay unnecessary fears*, and* advocate healthy behaviours. WHO has also set up long-term actions considering exposures that are likely to occur, the resulting dose to humans and the estimated health risk in the exposed population. WHO has identified research needs to reduce uncertainties of exposure data (public, workers), calculation of lifetime dose, health statistics data, adjusted survival curves or international classification of diseases. Furthermore risk models are needed for cancer incidence risk assessment (low doses, DDREF, exposure and attained age, gender, attributable risk, risk transfer weights…) and non-cancer risk assessment (thyroid nodules, thyroid dysfunction, visual impairment, circulatory diseases, reproductive dysfunctions, risk to embryo and fetus). A tool is also required to establish the framework of cancer risk assessment. Thyroid cancer screening is a key issue and research is needed on screening effect, magnitude, factors influencing its impact, how to deal with it…

There is a need of a multidisciplinary approach when planning and implementing response strategies considering radiation-related health risks, the psychological impact and the social and economic impact. The psychosocial impact is one of the major consequences of nuclear emergencies and may outweigh other health consequences. This still remains as a challenge that may have an impact at all levels of society.

Finally the assumptions used in the WHO HRA assessment were deliberately chosen to minimize the possibility of underestimating health risks. The HRA framework may be used to refine risk estimates as more precise dose estimations become available. This HRA provides information for setting priorities for population health monitoring, as has already begun with the *Fukushima Health Management Survey.*

Wolfgang Weiss

The major problem is the mistrust of public in front of scientists. There are some weaknesses of the radiation protection existing system: public health in decision-making about emergency preparedness and response, the application of principle of justification concerning the evacuation, available communication concepts. Actions are consequently needed to extent protective measures beyond emergency planning zones, to harmonize criteria for the implementation of these protective measures and to optimize cross-border arrangements in the preparedness response and post-emergency phases.

The most important health effect of the tsunami, the earthquake and the nuclear accident is on mental and social well-being. So including the realities of modern societies in the concepts of involvement and communication is a key issue.

Some priorities have been listed to improve preparedness arrangements and to better define good practice, as the development of a methodology for the definition of national reference levels considering both individual radiation protection and societal criteria and for the prompt identification and assessment of the emergency conditions, of a strategy based on scientific grounds of the assessment of the radiological situation, of operational concepts including ethical and social values, of criteria and strategies for long-term protective measures, also as the evaluation of the reliability of key ICRP biokinetics models and of dosimetric models, and the development of concepts to evaluate radiation quality and RBE.

Round table

In regards to health consequences of the Fukushima accident a necessary expertise in social science is needed. So a WHO group of experts specifically works on social consequences of the Fukushima accident. The perception of the Fukushima accident by the public has evolved because at the beginning it was not considered as a nuclear accident. Are we enough prepared for reactions from the public? It is urgent to develop a framework considering social aspects of a nuclear accident involving stakeholders and scientists in order to be more understandable, traceable with the information. Although monitoring is under the responsibility of the industrial, national regulators have to be more involved in the medical follow-up of workers.

There is a need in harmonization and collaboration between countries to correctly protect people and communicate. The issues of the Fukushima accident are complex to understand however experts have to explain all the consequences to public simplifying the principles of radiation protection. Because of its psychological impact, education is important in case of a nuclear accident.

For example how to deal with the uncertainties when evacuation is decided? After the Chernobyl accident the lesson to be learned was the inaction, however screening has to be done with caution especially if doses are low. The screening of people can be very stressful for population as after the Fukushima accident because people want to forget and stress is at its highest level when people are waiting for their results. And also how to deal with workers who still work on Chernobyl or Fukushima site? The long-term post accidental phase has to be better considered in terms of mental and social consequences.

9 CONCLUSIONS

Working Party on Research Implications on Health and Safety Standards of the Article 31 Group of Experts[3]

From the presentations and discussions, the members of the Working Group identified the following important issues. In order to improve future preparedness for and handling of nuclear accidents and exposure situations, there is a

- Need for strong and independent regulations/regulators and a need for mechanisms trying to guarantee independency of actors, including experts
- Need for ad hoc emergency plans also for INES level 7 accidents, but without forgetting that each accident may be different; need for maintaining flexible expertise
- Need for disease registries and software for rapid health assessments, including estimation of uncertainties
- Need to address the following main issues for dose assessments:
  - large uncertainties;
  - main doses occur in the first days where quality of measurements may be low;
  - geographical variability
- Need for harmonization/cooperation between states
- Need to address the following main issues for workers:
  - access to data;
  - sharing of responsibilities;
  - information about contractors and rescuers
- Need for evaluation of advantages/disadvantages of screening
- Need for involvement of stakeholders/public and scientists representing the humanities and social sciences in communication strategies and emergency preparation
- Need for science-based balanced information (both for decision makers and for the general population); avoidance of the 100 mSv “magic number”, which is scientifically not justified, misleading and creating distrust
- Need for global approaches, not limited to radiation protection but enlarged to all public health aspects, including societal aspects
- Need for taking better into account the long term exposure situation, waste management, and return to "normality"

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[3] The following members of the Working Party on Research Implications on Health and Safety Standards of the Article 31 Group of Experts contributed to the preparation of these conclusions: A. Friedl, L. Lebaron-Jacobs, R. Huiskamp, S. Risica, P. Smeesters (Chairperson of the WP), and R. Wakeford. They were assisted by S. Mundigl from the European Commission.

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