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MEMORANDUM

Radiological protection issues arising during and after the Fukushima nuclear reactor accident

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Abstract
Following the Fukushima accident, the International Commission on Radiological Protection (ICRP) convened a task group to compile lessons learned from the nuclear reactor accident at the Fukushima Daiichi nuclear power plant in Japan, with respect to the ICRP system of radiological protection. In this memorandum the members of the task group express their personal views

[13] The authors are the members of Task Group 84 of the International Commission on Radiological Protection (ICRP), which was convened by the ICRP to collate the lessons learned from the nuclear reactor accident at the Fukushima Daiichi nuclear power plant in Japan. The opinions expressed are those of the authors and do not necessarily reflect the official view of the ICRP.

on issues arising during and after the accident, without explicit endorsement of or approval by the ICRP.

While the affected people were largely protected against radiation exposure and no one incurred a lethal dose of radiation (or a dose sufficiently large to cause radiation sickness), many radiological protection questions were raised. The following issues were identified: inferring radiation risks (and the misunderstanding of nominal risk coefficients); attributing radiation effects from low dose exposures; quantifying radiation exposure; assessing the importance of internal exposures; managing emergency crises; protecting rescuers and volunteers; responding with medical aid; justifying necessary but disruptive protective actions; transiting from an emergency to an existing situation; rehabilitating evacuated areas; restricting individual doses of members of the public; caring for infants and children; categorising public exposures due to an accident; considering pregnant women and their foetuses and embryos; monitoring public protection; dealing with ‘contamination’ of territories, rubble and residues and consumer products; recognising the importance of psychological consequences; and fostering the sharing of information.

Relevant ICRP Recommendations were scrutinised, lessons were collected and suggestions were compiled.

It was concluded that the radiological protection community has an ethical duty to learn from the lessons of Fukushima and resolve any identified challenges. Before another large accident occurs, it should be ensured that *inter alia*: radiation risk coefficients of potential health effects are properly interpreted; the limitations of epidemiological studies for attributing radiation effects following low exposures are understood; any confusion on protection quantities and units is resolved; the potential hazard from the intake of radionuclides into the body is elucidated; rescuers and volunteers are protected with an ad hoc system; clear recommendations on crisis management and medical care and on recovery and rehabilitation are available; recommendations on public protection levels (including infant, children and pregnant women and their expected offspring) and associated issues are consistent and understandable; updated recommendations on public monitoring policy are available; acceptable (or tolerable) ‘contamination’ levels are clearly stated and defined; strategies for mitigating the serious psychological consequences arising from radiological accidents are sought; and, last but not least, failures in fostering information sharing on radiological protection policy after an accident need to be addressed with recommendations to minimise such lapses in communication.

1. Introduction

1.1. The accident

On 11 March 2011, one of the most powerful earthquakes in recorded history set off a cascade of events culminating in the nuclear reactor accident (hereinafter referred to as ‘the accident’) at the Fukushima Daiichi nuclear power plant (NPP) in Japan. The catastrophic 2011 Great East Japan earthquake and subsequent tsunami caused huge devastation in the eastern region of Japan. The United Nations Environment Programme reported that the triple disaster left 15 854 people dead and 3155 missing as at March 2012, according to official Japanese government figures. Hundreds of thousands of houses and other buildings were damaged and more than 400 000 people were displaced. With huge economic damage, this event is considered not only tragic in terms of its human toll; it is the most economically devastating disaster in history (UNEP 2012).

As a consequence of the accident, large amounts of radioactive substances, particularly of volatile elements such as radioisotopes of iodine (^{131}I, ^{132}I, ^{133}I), caesium (^{134}Cs, ^{136}Cs, ^{137}Cs) and tellurium (^{132}Te), and inert gases such as xenon (^{133}Xe), were released into the environment, resulting in relatively high levels of ambient radiation, especially around the plant. Notwithstanding this consequential radiological event, people were mostly protected against radiation exposure and nobody received a lethal dose of radiation or a dose that result in acute radiation sickness of any type. The World Health Organization (WHO) has estimated that people near the damaged power plant received such low doses of radiation that no discernible health effect could be expected (WHO 2012). A more recent WHO report (WHO 2013) suggested that slight increases in lifetime cancer risk might occur in any heavily exposed subgroups of the population, although model estimates where based on conservative (high-sided) assumptions of exposure to hypothetically exposed populations. Despite these generally encouraging assessments of minimal future health effects on the population, many concerns and questions related to radiation protection were raised not only in Japan but also around the world. Addressing these concerns and questions is a main aspiration of this report.

1.2. The ICRP response

The International Commission on Radiological Protection (ICRP) does not normally comment on events in individual countries; however, given the unusual circumstances, it reacted promptly by offering advice and assistance in the hope that its recommendations would prove helpful in dealing with the on-going radiological protection challenges. ICRP Task Group 84 (ICRP-TG84) was established to evaluate the radiological protection lessons from the extraordinary situations created by the accident.

This memorandum reflects the report prepared by the ICRP-TG84 membership for the ICRP Main Commission, a summary of which was posted by the ICRP Secretariat on the ICRP web site (www.icrp.org/docs/ICRP%20TG84%20Summary%20Report.pdf). The authors wish to emphasise that the issues, lessons and suggestions described in this report are their individual assessments and, while based in their report to the ICRP and grounded in ICRP philosophy, are not intended to express the views of the ICRP.

1.3. Aim

The aim of this memorandum is to describe radiological protection issues arising in the aftermath of the accident *vis-à-vis* the ICRP recommendations and guidance. It also attempts to extract lessons learned and to provide suggestions for clarifying and improving existing and future guidance in dealing with a severe radiological event. The memorandum is not intended to be a critique of ICRP recommendations.

It was encouraging to note that measures adopted in a timely manner by the authorities effectively reduced the dose received by people living in the affected area (Kai 2012). However, dealing with the aftermath of the accident has provided suggestions on a number of relevant issues that are addressed herein with a view to improving the effectiveness of radiological protection.

It is not this report's intention to evaluate the causes and consequences of the accident or judge the appropriateness of the protective measures undertaken by the Japanese authorities.

Several assessments on these issues are being developed, including by the government of Japan (GOJ 2011a, 2011b, NDJ 2012), by international intergovernmental organisations (UN 2012, Weiss 2012, van Deventer *et al* 2012, IAEA 2011b, 2012a, MC 2011, Wondergem and Rosenblatt 2012) and by non-nuclear and nuclear organisations (Fitzgerald *et al* 2012, Acton and Hibbs 2012, TEPCO 2011, INPO 2011, ANS 2012, Greenpeace 2011).

The accident reinforced an important reality: nuclear accidents resulting in serious radiological consequences can happen and, moreover, may occur in the future. The accident confirmed that, in addition to the unlikely but foreseeable events that are usually considered when developing measures for preventing nuclear accidents, unpredictable events may also occur and may indeed be dominant for assessing outcomes (Taleb 2007). Preclusion of 'maximum credible accidents', 'design basic accidents' and any other imagined scenarios is a necessary but not sufficient condition for protecting people against radiation. Preventive measures against conceivable accidental conditions will no doubt remain a fundamental nuclear safety objective, but occurrences of unexpected and largely unpreventable events should be considered. The remaining safety tool for such unforeseeable events is the mitigation of radiological consequences, which means: (i) reducing radioactive releases into the public domain by containing radioactive substances as far as feasible and (ii) responding to the emergency with prompt ad hoc radiological protection measures, in order to provide adequate protection to emergency and recovery workers and the affected public.

1.4. Antecedents

A few years before the accident, the ICRP issued a revision and update to its main recommendations (ICRP 2007a). They include renewed radiological protection principles (Cooper 2012) providing the basis for a number of new national and international regulatory instruments. Implementation of these recommendations is still on-going (IAEA 2011a, EC 2011).

Existing international obligations and intergovernmental requirements and guidance documents generally follow ICRP recommendations. The Convention on Early Notification of a Nuclear Accident (IAEA 1986b) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (IAEA 1986c) were adopted in 1986, and place legally binding obligations related to nuclear and radiological accidents on the parties to these conventions and on the International Atomic Energy Agency (IAEA). Article 16 of the Convention on Nuclear Safety (IAEA 1994), and Article 25 of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (IAEA 1997c) establish legally binding obligations related to emergency preparedness for the parties to the conventions. In 2005, the IAEA established an Incident and Emergency Centre (IEC) to serve as a global focal point for preparedness and response to nuclear and radiological incidents and emergencies irrespective of their cause. Under the Early Notification and Assistance Conventions, the IEC coordinates actions of international experts and efforts within the IAEA, and the response with other international organisations and, when necessary, helps to coordinate responses of Member States. Moreover, the IAEA statutorily establishes international safety standards for implementing the ICRP Recommendations. The International Safety Requirement on Preparedness and Response for a Nuclear or Radiological Emergency (IAEA 2002a) incorporates and establishes requirements for emergency preparedness and response so that emergency management can be seen in its entirety by the bodies concerned. It elaborates on, augments and structures all the requirements relating to emergency management established in other IAEA safety standards. The Safety Guide on Arrangements for Preparedness for a Nuclear or Radiological Emergency (IAEA 2007b) and the International Safety Guide on Criteria for use in Preparedness and Response for a Nuclear or Radiological Emergency (IAEA 2011c) (which was adopted after the accident) are intended to assist Member States in the application of the Safety Requirements on Preparedness and Response for a Nuclear or Radiological Emergency (IAEA 2002a) and to help in the fulfilment of the IAEA's obligations under the Assistance Convention. Additionally, over the years the IAEA has issued a number of technical documents providing advice on issues of emergency planning, preparedness and response, including on procedures for determining protective actions following a reactor accident (IAEA 1997b), procedures for assessment and response during a radiological emergency (IAEA 2000c), procedures for monitoring in a nuclear or radiological emergency (IAEA 1999b), methods for developing preparedness for a nuclear or radiological emergency (IAEA 1997a, 2003), medical preparedness and response (IAEA 2002b, 2005c), preparation, conduct and evaluation of exercises to test preparedness for a nuclear or radiological emergency (IAEA 2005b), e-learning tools for first response to a radiological emergency preparedness and response (IAEA 2009a), first response to a radiological emergency (IAEA 2006, 2009b), portable digital assistant for first responders to a radiological emergency (IAEA 2009c), the Joint Radiation Emergency Management Plan of the International Organizations (the so-called JPLAN) (IAEA 2010), cytogenetic dosimetry: applications in preparedness for and response to radiation emergencies (IAEA 2011d), IAEA response and assistance network (IAEA 2011e), and communication with the public in a nuclear or radiological emergency (IAEA 2012b).

The Japanese authorities relied upon ICRP Recommendations in making radiological protection decisions following the accident. Although at the time of the accident specific advice on the application of the Recommendations to emergency situations had been issued by the ICRP, the guidance was relatively new and had not been tested in practice. In fact, around year before the accident, the ICRP had issued specific recommendations for the application of the ICRP Recommendations to the protection of people in emergency exposure situations (ICRP 2009a) and of people living in long-term contaminated areas after a nuclear accident or a radiological emergency (ICRP 2009b). The timeliness of this recent guidance has been recognised (Lochard 2012). The decision by the Japanese authorities to follow ICRP guidance facilitated the retrospective analyses presented in this report.

1.5. Identification and assembly of issues

The issues identified have been assembled in an arbitrary order and are treated in separate sections below:

(1) inferring radiation risks (and the misunderstanding of nominal risk coefficients);
(2) attributing radiation effects from low dose exposures;
(3) quantifying radiation exposure;
(4) assessing the importance of internal exposures;
(5) managing emergency crises;
(6) protecting rescuers and volunteers;
(7) responding with medical aid;
(8) justifying necessary but disruptive protective actions;
(9) transitioning from an emergency to an existing situation;
(10) rehabilitating evacuated areas;
(11) restricting individual doses of members of the public;
(12) categorising public exposures due to an accident;
(13) caring for infants and children;
(14) considering pregnant women and their foetuses and embryos;

(15) monitoring public protection;

(16) dealing with 'contamination' of territories, rubble and residues and consumer products;

(17) recognising the importance of psychological consequences; and

(18) fostering the sharing of information.

Each section will start by describing the major features of the issue and will follow with a full discussion. It is noted that some of the issues were recognisable before the March 2011 accident as they had arisen after other accidents, notably in the aftermath of the 1986 accident at the Chernobyl NPP (IAEA 1986a, 1988a, 1988b, 1991, 1996a, 1996b, 2001, UNSCEAR 2006a, 2006b, WHO 1995).

1.6. Environmental consequences

Radiological protection of the environment is specifically addressed by (ICRP 2003a, 2008, 2009c) and it is touched upon incidentally in this report. Following the accident the immediate priority was the protection of people rather than the environment. It may take time to assess the radiological environmental consequences of the accident. In the meantime, claims of environmental damage will probably arise. For example, it was suggested that the accident and releases of radioactive elements caused physiological and genetic damage to the pale grass blue *Zizeeria maha*, a common lycaenid butterfly in Japan (Hiyama *et al* 2012). Studies will be needed to evaluate the marine environmental impact of the accident because most of the radioactivity released was deposited into the oceans. Increased radioactivity concentrations have been reported in samples of animal plankton in the sea near the accident site (JAIF 2011) and trace levels of radioactive caesium have been found in blue-fin tuna (Madigan *et al* 2012).

The ICRP has provided a framework for assessing the impact of ionising radiation on non-human species (ICRP 2003a, 2003b) and recommendations on the concept and use of reference animals and plants (ICRP 2008) and on the relevant transfer parameters (ICRP 2009c). The ICRP is currently working on a number of environmental protection issues, including: collecting, reviewing and summarising studies that allow the derivation of radiation weighting factors for alpha- and beta-radiation for application in dose assessment for reference animals and plants; compiling a set of transfer factor data for reference animals and plants within an internally consistent, documented format, for the more useful radionuclides with respect to the relevant ICRP exposure situations; realistic dosimetry for non-human species; and integrating a system for the protection of human and non-human species. The results of these activities, which were not available at the time of the accident, should prove useful for preliminary assessments of the potential environmental impacts of the accident.

Non-radiological environmental consequences appear to be surfacing as a result of the accident. For example, all NPPs in Japan, which provide around 30% of the electric energy consumed in the country, were shut down and replaced by fossil fuel generation, therefore increasing significantly the release of greenhouse gases into the environment. Further, the consequences of chemical contamination of the environment which resulted from the widespread damage caused by the tsunami are yet to be determined (Bird and Grossman 2011).

1.7. International cooperation

Japan is a country that is naturally well-prepared to cope with disasters, *inter alia* due to its location in a very active seismic region and its experience in dealing with earthquakes, tsunamis, typhoons and other natural disasters over centuries. However, the consequences of three catastrophic events occurring together (a large earthquake, a huge tsunami and a major nuclear accident) left the country in need of assistance from other countries. This involvement was extremely beneficial but did raise challenging issues.

The European Union responded swiftly with an assistance package to the affected communities (EC 2012). Financial assistance (e.g. Kuwait 2012) and help to affected children (e.g. Pravda 2012) was offered. The USA sent planes over the area to help monitor the radioactive releases, and sent 60 000 military personnel to help with the humanitarian efforts. France, Russia and other countries provided robotics, cranes and expertise. The Assistant Secretary for Preparedness and Response of the US Department of Health and Human Services deployed a five-person advisory team to the US Embassy in Tokyo (Simon *et al* 2012). The US Department of Energy's National Atmospheric Release Advisory Center provided a wide range of predictions and analyses including: daily Japanese weather forecasts and atmospheric transport predictions; estimates of possible doses in Japan based on hypothetical scenarios of the US Nuclear Regulatory Commission; predictions of possible plume arrival times and dose levels at US locations; and source estimation and plume model refinement based on atmospheric dispersion modelling and available monitoring data (Sugiyama *et al* 2012). The US Department of Energy/National Nuclear Security Administration's Aerial Measuring System deployed personnel and equipment to partner with the US forces in Japan (Craig and David 2012). The US Medical Radiobiology Advisory Team, which is the operations arm of the US Armed Forces Radiobiology Research Institute, provided guidance and advice to the US military leaders in Japan aimed at ensuring the safety of US service members, family members and civilians and supported the humanitarian relief in a coordinated effort with the government of Japan (Van Horne-Sealy *et al* 2012). A number of challenges were identified (Miller 2012), particularly at the level of US states which were not always notified of outcomes by the US federal agencies (Salame-Alfie *et al* 2012). The decision to issue an evacuation alert for US citizens within 50 miles of the site by the US Nuclear Regulatory Commission (NRC 2011) was not without controversy; this was based on calculations from a computer model for upper bound radioactive material releases from severe reactor accidents, although its technical basis was not entirely clear (ANS 2012, Musolino *et al* 2012). In one of the countries affected by the fallout from the accident, the Republic of Korea, some over-reactions occurred and it was concluded that significant radioactive contamination of a small country could lead to a severe national crisis, the most important factor being the socio-economic damage caused by stigma, which in turn is caused by a misunderstanding of the radiation risk (Lee 2012a). It is clear that the Fukushima nuclear reactor accident has affected many countries throughout the world and lessons are continually being learned that should be helpful in the event of any future nuclear incident.

A generic lesson is that, while external assistance following a nuclear accident is helpful and appreciated, foreign authorities should be careful and prudent in providing contradictory public recommendations that might be unsuited to a local situation. The unintended consequences of such well-intended advice may add confusion, distraction and even distrust that hinder effective actions.

2. Issues identified

2.1. Inferring radiation risk and nominal risk coefficients

In the aftermath of the accident, claims were made that the risk of radiation-induced health effects is much higher than the nominal risk coefficients recommended by the ICRP for radiation protection. Further, the dose and dose-rate effectiveness factor used by the ICRP and others for estimating radiation risk at low doses was questioned.

This misunderstanding was reinforced during several television shows with a wide viewing audience and added to the existing concern and confusion. The substantial biological and epidemiological data supporting the basic notion of the nominal risk coefficients used for radiological protection purposes were not understood and were misrepresented in the media. A nominal risk coefficient is a sex-averaged and age-at-exposure-averaged lifetime risk estimate for a representative population. Nominal risk coefficients are used in radiation protection to provide an appropriate level of protection for people and the environment. They are based on a substantial compendium of knowledge about radiation health effects accrued over the past 100 years. Following a review of the biological and epidemiological information on the health risks attributable to ionising radiation, the new ICRP Recommendations (ICRP 2007a) reconfirmed the previous estimate of the combined detriment due to excess cancer and heritable effects, which remain unchanged at around 5% per sievert of effective dose. This value is consistent with international estimates of radiation risk. The concept of a dose and dose-rate effectiveness factor (DDREF) also was not understood. This misunderstanding was due in part to its rather convoluted wording, i.e. it is 'a judged factor that generalises the usually lower biological effectiveness (per unit of dose) of radiation exposures at low doses and low dose rates as compared with exposures at high doses and high dose rates'. But the confusion is particularly reinforced when translated into Japanese and other languages. The radiation protection community must do a better job of explaining to the public and the media these concepts of radiation risk used in protection, stressing that they are based on a strong foundation of science that has been synthesised by international committees throughout the world.

2.1.1. Radiation risk coefficients. Radiation risk coefficients are based upon direct human epidemiological data and provide the basis of radiological protection recommendations. Risk is used to mean the probability of occurrence of a radiation-induced effect; it is a prospective concept addressing the chance that an event will occur in the future. Risk coefficients are numerical values that express the expected annual increase in the incidence or mortality rate per unit dose. When multiplied by a specific dose, risk coefficients can be used for inferring risk, namely for estimating the probability that such a dose might produce harm. Risk coefficients are based on the latest epidemiological and biological information on radiation-induced cancer and heritable effects. To estimate these coefficients the ICRP uses *inter alia* the evaluations of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in addition of its own assessments,.

2.1.2. Quantification of risk. Thus, the ICRP uses two fundamental concepts for quantifying risk: (i) the *detriment-adjusted risk*, defined as 'the probability of the occurrence of a stochastic effect, modified to allow for the different components of the detriment in order to express the severity of the consequence(s)'; and (ii) the *nominal risk coefficient*, defined as the 'sex-averaged and age-at-exposure-averaged lifetime risk estimates for a representative population', which is a stated value recommended for radiological protection purposes. The nominal value is taken to be conservatively safe for the protection of the population. It expresses a theoretical value of risk for the protection of populations without any distinctions based on sex or age, as opposed to an actual risk coefficient that is derived from epidemiological studies and is specific to population characteristics (such as age and sex) and the outcome of interest (such as a specific cancer). The real risk coefficients show a distribution of values, which can be presented as a cumulative distribution function, i.e. as a description of the probability that a real-valued coefficient with a given probability distribution will be found at a value less than or equal to it, or as a probability density function, i.e. a description of the relative likelihood for the risk coefficient to take on a given value. The distributions are usually normal, i.e. a continuous probability distribution that has a bell-shaped probability density function that is characterised by the mean risk coefficient (location of the peak) and its variance, i.e. a measure of how far a set of risk coefficients is spread out. When modifier factors are applied to the data, the distribution usually becomes log-normal. From these distributions of 'real' risk coefficients extrapolated from epidemiological studies, the nominal risk coefficients are derived. Nominal risk coefficients are used in radiation protection and are risk-informed, but since they are sex- and age-averaged values for a representative individual or population they should not to be used for inferring risk to an individual or specific population.

2.1.3. The dose–response model. At radiation doses below around 100 mSv in a year, the increase in the incidence of stochastic effects is assumed by the ICRP to occur with a small probability and in proportion to the increase in radiation dose over the background dose. Use of this so-called linear-non-threshold (LNT) model is considered by the ICRP to be a prudent and practical approach to managing risk from radiation exposure. The LNT model is not universally accepted as biological truth, but rather, because we do not actually know what level of risk is associated with very-low-dose exposure, it is considered to be a prudent judgement for public policy aimed at avoiding unnecessary risk from exposure (ICRP 2005a, 2007a).

2.1.4. The dose and dose-rate effectiveness factor. The DDREF is a judged factor introduced by UNSCEAR (2000) that generalises the usually lower biological effectiveness (per unit of dose) of radiation exposures at low doses and low dose rates as compared with exposures at high doses and high dose rates. In general, cancer risk at low doses and low dose rates is not directly apparent from epidemiological studies because the level of excess risk is just too small in comparison with the high natural occurrence of cancer to observe directly. In order to estimate risk in these dose ranges of uncertainty, a DDREF is applied to epidemiological data obtained at higher doses and dose rates to reduce the estimate of risk. The DDREF is based on judgement and considers a broad range of epidemiological, animal and cellular data obtained at high doses and dose rates. In its 1990 Recommendations (ICRP 1991) the ICRP judged that a DDREF of 2 should be applied for the general purposes of radiological protection. In its new 2007 Recommendations, the ICRP continued to use broad judgements in its choice of DDREF based upon dose–response features of experimental data, epidemiological data and the results of probabilistic uncertainty analysis (NCRP 1997, EPA 1999, NCI/CDC 2003, ICRP 2005a). No compelling reason was found to change its 1990 recommendations for a DDREF of 2, emphasising, however, that 'this continues to be a broad whole number judgement for the practical purposes of radiological protection which embodies elements of uncertainty' (ICRP 2007a, section 73). The ICRP considers that the adoption of the LNT dose–response model (combined with a DDREF) provides a prudent basis for the practical purposes of radiological protection, i.e. for the management of risks from low dose radiation exposure (ICRP 2007a, section 65). It is recognised that others have considered lower and higher values for the DDREF and that DRREF evaluations are on-going as new data on radiation effects are accumulating.

2.1.5. The detriment-adjusted nominal risk coefficients. *Detriment* is distinct from risk; it represents the expected total harm to health in an exposed group and its descendants as a result of the group's exposure. Detriment is a multidimensional concept used to quantify future harm. It involves the incidence of radiation-related cancer or heritable effects, the lethality of these conditions, quality of life and years of life lost owing to these conditions.

The ICRP recommends *detriment-adjusted nominal risk coefficients* (usually expressed as % Sv^{-1} or 10^{-2} Sv^{-1}), which are a combination of the notions of nominal risk coefficient and detriment-adjusted risk. They are intended for establishing protection measures to limit stochastic effects (after exposure to radiation at a low dose rate) over an adult population (i.e.

representative of an occupationally exposed population) and also over a whole population (i.e. a generic population that includes adults and children).

Following a review of the biological and epidemiological information on the health risks attributable to ionising radiation, the more recent ICRP Recommendations reconfirm its previous estimates of the combined detriment due to excess cancer and heritable effects, which remain unchanged at around 5% Sv^{-1} of effective dose (ICRP 2007a, section e). The ICRP has calculated the detriment-adjusted nominal risk coefficients used for inferring risk for radiological protection purposes through the process described in its recommendations (ICRP 2005a, 2007a). The steps used for the estimations are as follows.

(1) For estimating risk of cancer: (a) *the lifetime risk for radiation-associated incident cancers is estimated*. For 14 organs or tissues, male and female lifetime excess cancer risks are estimated from epidemiological studies by using both the excess relative risk (ERR) and excess absolute risk (EAR) models and these lifetime estimates of risk are then averaged across sexes. (b) *A DDREF is applied*. The lifetime risk estimates are adjusted downward by a factor of 2 to account for the assumed ameliorating effect when radiation is received at a low dose and low dose rate, i.e. a DDREF of 2 is assumed (except for leukaemia, where the linear-quadratic model for risk already accounts for the DDREF). (c) *Risk estimates are transferred across populations*. In order to estimate radiation risk for each cancer site, a weighting of the ERR and EAR lifetime risk estimates is assumed to provide a reasonable basis for generalising across populations with different baseline cancer rates. (d) *Nominal risk coefficients*. These weighted risk estimates, when applied to and averaged across seven western and Asian populations, provided the nominal risk coefficients. (e) *Adjustment for lethality*. The lifetime risks for respective cancer sites, which were based on excess incident cancers, were converted to fatal cancer risks by multiplying by their lethality fractions, as derived from representative national cancer survival data. (f) *Adjustment for quality of life*. A further adjustment was applied to account the morbidity and suffering associated with non-fatal cancers. (g) *Adjustment for years of life lost*. Average years of life lost for a given cause was computed for each sex in each composite population as the average over ages at exposure and subsequent attained ages of the remaining lifetime. The weights were equal to the number of deaths from the cause of interest in each age group. These were converted to relative values by division by the average years of life lost for all cancers. An adjustment for years of life lost was then applied to the result of the previous steps. (h) *Radiation detriment*. The results of the calculations above yielded an estimate of the radiation detriment associated with each type of cancer. These, when normalised to sum to unity, constitute the relative radiation detriments.

    (It should also be underlined that the risk coefficients are mainly based on estimates from epidemiological studies of the population cohorts exposed as a result of the atomic bombing of Japan in 1945, although other populations exposed to medical radiation are incorporated when applicable and available.)

(2) For estimating radiation risk for heritable diseases: (a) the baseline frequencies of human genetic diseases of all classes (a set of values of *P*) is established. (b) The average spontaneous mutation rate per generation for human genes is estimated. (c) Since no human data are available to demonstrate heritable effects following radiation exposure, the average rate of radiation-induced mutations in mice is estimated and it is assumed that radiation-induced mutation rates in mice are similar to those in humans. (d) From (b) and (c) above, the genetic doubling dose (DD) is estimated. The DD is the radiation dose required to produce as many mutations in the next generation as those that arise spontaneously in the exposed generation. (e) The mutation component (MC) for different classes of genetic

diseases is estimated. MC is a relative measure of the relationship between change in mutation rate and increase in disease frequency. (f) The potential recoverability correction factor (PRCF) for different classes of mutation is estimated. The PRCF allows for differing degrees of recoverability of mutations in live births, i.e. the fraction of mutations that is compatible with embryonic/foetal development. (g) For each class of human genetic disease the following equation, which uses the estimates from (a) to (f) above, provides the risk per unit dose for heritable effects: $P \times (1/\mathrm{DD}) \times \mathrm{MC} \times \mathrm{PCRF}$.

In brief, the ICRP recommended that the following nominal coefficients should be used for radiological protection purposes: for detriment-adjusted cancer risk, 5.5×10^{-2} Sv^{-1} for the whole population and 4.1×10^{-2} Sv^{-1} for adult workers; for heritable effects, 0.2×10^{-2} Sv^{-1} for the whole population and 0.1×10^{-2} Sv^{-1} for adult workers.

These values are consistent with current scientific knowledge about radiation risks described in the UNSCEAR reports. UNSCEAR (2006a) estimated that, following radiation exposure of 1 Sv, the excess lifetime risk of death (averaged over both sexes) is: (i) for all solid cancers combined 4.3–7.2% Sv^{-1} for an acute dose of 1 Sv; and (ii) for leukaemia 0.6–1.0 % Sv^{-1} for an acute dose of 1 Sv (UNSCEAR 2006a, 2006b, 2010). Moreover, taking into account available radiobiological information and epidemiological studies in animals, UNSCEAR also estimated the risk of heritable diseases in one generation due to exposure of an absorbed dose of 1 Gy and concluded that the risks in the first generation (per unit low-LET dose) are: (i) for dominant effects (including X-linked diseases) ~750–1500 per million per gray *vis-à-vis* a baseline frequency of 16 500 per million; (ii) for chronic multifactorial diseases ~250–1200 per million per gray *vis-à-vis* a baseline frequency of 650 000 per million; and (iii) for congenital abnormalities ~2000 per million per gray *vis-à-vis* a baseline frequency of 60 000 per million (chromosomal effects were assumed to be subsumed in part under the risk of autosomal dominant and X-linked diseases and in part under that of congenital abnormalities). Thus, as far as radiation-induced heritable diseases is concerned, UNSCEAR concluded that for a population exposed to radiation in one generation only, the risks to the progeny of the first post-radiation generation are estimated to be 3000–4700 cases per gray per million progeny, which constitutes 0.4–0.6% of the baseline frequency of those disorders in the human population (UNSCEAR 2001).

Thus, it can be concluded that the detriment-adjusted nominal risk coefficients recommended by the ICRP for radiological protection purposes are consistent with international estimates of radiation risk, e.g. the estimates of UNSCEAR (2001) and also those of the US Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation (BEIR VII) (National Research Council 2006). It seems therefore that the claims that radiation risks have been underestimated by ICRP and others are not supported by the scientific evidence.

2.1.6. Misunderstanding the coefficients. Notwithstanding the substantial biological, epidemiological and ethical foundations supporting the basic notion of the detriment-adjusted nominal risk coefficients, these coefficients were misunderstood by the public. Granted that trying to explain to the lay public the concept of ‘nominal’, much less ‘detriment-adjusted nominal risk coefficients’, is a daunting challenge, false claims propagated by media coverage that the ICRP intentionally provided low risk estimates because of a pro-nuclear bias contributed to misunderstanding, confusion and anxiety. The concept of a DDREF was notably misunderstood. A serious cause of confusion was the wording used for these concepts, which is somewhat convoluted (even in English), particularly after translation into Japanese and other languages.

2.1.7. Outlook. The radiation protection community should renew its efforts to communicate with the public and press in more easily understood and transparent terms. Perhaps public-friendly and easily understood brochures (and/or websites) should be develop that define and describe the scientific basis, reasonableness and usefulness of the concepts of risk and detriment used for radiological protection, and in particular the detriment-adjusted nominal risk coefficients used for limiting the likelihood of stochastic effects occurring after exposure to radiation at a low dose rate.

2.2. Attributing radiation effects from low dose exposures

Since the accident, hypothetical estimates of future casualties due to the accident have been made. They oscillated between some hundreds of cases in the peer reviewed literature to half a million in reports in the media. These alarmist and misleading theoretical calculations have caused anxiety and emotional distress in the Japanese population.

The inability of epidemiological health research to determine whether there are any health consequences of exposures below about 100 mSv has led to the adoption of the LNT model for the purposes of radiological protection. While prudent for radiological protection, the LNT model is not universally accepted as biological truth, and its influence and inappropriate use to attribute health effects to low dose exposure situations is often ignored. A clear explanation of the limitations of epidemiology is essential for understanding the reasons why collective effective doses aggregated from small notional individual doses should not be used to attribute health effects to radiation exposure situations, neither retrospectively nor prospectively. The ICRP, UNSCEAR, and others strongly urge that this misuse of collective dose should be avoided. It is recognised, however, that collective dose is a very useful concept which decision-making bodies may use to impose radiological protection measures even at low doses, in part for reasons of social duty, responsibility, utility, prudence and precaution. But the distinction between prudent practices for radiological protection and the misuse of protection concepts to attribute adverse health effects is not always clearly enunciated and a much better approach is needed.

2.2.1. Ascribing future deaths. In some low dose radiation exposure situations, particularly after accidents, nominal risk coefficients have been improperly used to ascribe hypothetical future deaths. Speculative, unproven, undetectable and 'phantom' numbers are obtained by multiplying the nominal risk coefficients by an estimate of the collective dose received by a huge number of individuals theoretically incurring very tiny doses that are hypothesised from radioactive substances released into the environment.

The same type of misleading attribution was made after the accident. One attempt purported that total deaths will lie in the range 15–1300, while incident cases will number 24–2500—noting that these are cancers among the public (of the order of a million people exposed) and not among the workers at the NPP (Ten Hoeve and Jacobson 2012a). The estimates were rigorously criticised (Richter 2012), and responses to the critique were made (Ten Hoeve and Jacobson 2012b). It has been noted that the uncertainties surrounding the crisis itself, in addition to the absence of demonstrated risk at the tiny exposures to the population and the uncertain validity of the linear extrapolation of risk down to such tiny doses, raise serious questions about whether these calculations could provide even an order-of-magnitude guess as to possible health consequences (Brumfiel 2012). Further, given the wide range of uncertainties in the risk models used, it is likely that zero effects should be included as a lower bound to the estimates, or even as a central estimate of the likely future effects.

It should be remembered that the exposures from the Fukushima releases are in large part below radiation levels received annually from natural sources of radiation in the environment or from the annual population exposures to medical radiation such as computed tomography (CT) scans.

The media reporting on future cancer cases was dramatic and sensational. For instance, on 20 March 2011 it was predicted that the death toll in the years ahead could exceed 500 000 people (TCNN 2011).

These hypothetical computations of effects are based on assumptions that cannot be validated because the estimated doses are substantially below the level where epidemiology has the ability to detect increases above the natural occurrence. The large number of deaths reported following these theoretical predictions, especially when not contrasted with the normal high occurrence of death, is alarmist and unfounded and has caused severe anxiety and emotional distress in the Japanese population

2.2.2. Previous misattributions. The confusing attribution of health effects was particularly serious after the Chernobyl accident and caused severe mental distress and significant psychological harm to the affected population. A 2006 analysis (Cardis *et al* 2006) concluded that Chernobyl may eventually cause 16 000 thyroid cancers and 25 000 other cancers in Europe by 2065, and that 16 000 of these cancers will be fatal (since thyroid cancer is rarely fatal, most of the cancer deaths will be from other cancers), with the caveat that these estimates do not consider the recovery-operation workers. Moreover, according to a book published in 2009 (NYAS 2010) authored by three Russian scientists including the former director of the Institute of Nuclear Energy of the National Academy of Sciences of Belarus, the Chernobyl death toll amounted to 985 000 people between 1986 and 2004. In the media it was claimed *inter alia* that the Chernobyl nuclear accident caused as many as 170 000 cancer deaths in North America alone (www.huffingtonpost.com/john-rosenthal/level-7-major-nuclear-acc_b_852666.html). The Union of Concerned Scientist (UCS) released a revision to their previous estimates of deaths caused by Chernobyl, which revises them slightly downward from their original posing (7 April 2011), from 70 000/35 000 to 53 000/27 000 (http://allthingsnuclear.org/post/4704112149/how-many-cancers-did-chernobyl-really-cause-updated). In spite of these apocalyptic predictions, the only consistent evidence of harm from the Chernobyl reactor accident to the general population has been the thyroid cancer epidemic that followed the ingestion of radioactive iodine in contaminated milk by children. After 20 years of study, no other cancers have been convincingly linked to Chernobyl radiation, even among the recovery workers (UNSCEAR 2008).

2.2.3. Misuse of the collective dose concept. Part of the confusion is triggered by a misinterpretation of the quantities used by the ICRP, particularly of the quantity *collective dose*, coupled with the previously discussed misunderstanding of the detriment-adjusted nominal risk coefficients. As discussed before, the coefficients are not applicable to actual individuals because they are sex-averaged and age-at-exposure-averaged lifetime risk estimates for a representative population. In fact, these coefficients are termed ‘nominal’ because they relate to the exposure of a hypothetical population of women and men with a typical age distribution and are computed by averaging over age groups and both sexes. They are used to define the main radiological protection quantity, *the effective dose*, which is computed by age- and sex-averaging. There are many assumptions inherent in the definition of nominal factors to assess effective dose and the estimates are defined explicitly for no other intent than radiological protection purposes. These coefficients should not be used to estimate the mathematical expectations of harm in a real population exposed to small radiation doses, much less to attribute prospectively potential deaths in this population.

The ICRP has stressed that effective dose is a prospective protection quantity to be used for the purposes of radiological protection in prospective dose assessments for planning and optimisation of protection, and in demonstration of compliance with dose limits for regulatory purposes. Effective dose is not recommended (and would be inappropriate) for epidemiological evaluations, and should not be used for retrospective investigations of risk or health effects (ICRP 2007a, section j).

The quantity *collective effective dose* is the summation of the individual effective doses calculated for each person in an exposed population, and the ICRP recommends that the collective dose should be used as an instrument for optimisation, for comparing radiological protection options, predominantly in the context of occupational exposure (ICRP 2007a, section k, and annex B, section B.234ff). The ICRP and UNSCEAR have stated that the collective effective dose is not intended as a tool for epidemiological risk assessment, and it is inappropriate to use it in risk projections. The ICRP and UNSCEAR have underlined that the aggregation of very low individual doses over extended time periods is inappropriate, and more importantly the calculation of a theoretical number of cancer deaths based on collective effective doses from trivial individual doses should always be avoided (ICRP 2007a, section k; UNSCEAR 2012).

2.2.4. Inferring risk compared with observing effects. While radiation *risks* and *effects* are both detriment-related concepts, they have a distinct meaning in the ICRP Recommendations. *Risk* is related to the probability (or chance) that an effect will occur, whereas *effect* is the outcome of concern. *Risk* may be inferred, while *effects* should be observed. The distinction is important for low radiation dose situations. Radiation-related cancer risks are inferred using formal quantitative uncertainty analysis that combines the different components of estimated radiation-related cancer risk, accounting for their uncertainties, with and without allowing for an uncertain possibility of a low dose threshold below which no risk is assumed. Conversely, actual cancers in specific cohorts of people may be revealed by epidemiological studies where elevations in cancer occurrence are observed.

While the ICRP Recommendations imply that *risks* may be inferred for any *prospective* assessment of generic radiation exposure situations, such inference of radiation risks should not be automatically interpreted as meaning that *effects*, e.g. cancer deaths of specific individuals, will be revealed by *retrospective* assessment. ICRP Publication 99 (ICRP 2005a, section 47) summarises the dilemma: '*At low and very low radiation doses, statistical and other variations in baseline risk tend to be the dominant sources of error in both epidemiological and experimental carcinogenesis studies, and estimates of radiation-related risk tend to be highly uncertain because of a weak signal-to-noise ratio and because it is difficult to recognise or to control for subtle confounding factors. At such dose levels, and with the absence of bias from uncontrolled variation in baseline rates, positive and negative estimates of radiation-related risk tend to be almost equally likely on statistical grounds, even under the LNT theory*'. Following exposure to low radiation doses below about 100 mSv an increase of cancer has not been convincingly or consistently observed in epidemiological or experimental studies and will probably never be observed because of overwhelming statistical and biasing factors.

In sum, theoretical cancer deaths after low dose radiation exposure situations are obtained by inappropriate calculations based on the LNT model and misuse of the collective dose concept. Any effects—if they occur at all—will be so small that they would fall within the 'noise' (scatter) of the 'spontaneous' cancer of unexposed people (Streffer 2008).

2.2.5. Attribution of health effects. UNSCEAR has addressed the attribution of health effects to different levels of exposure to ionising radiation, and reached the following conclusions (UNSCEAR 2012).

(a) An observed health effect in an individual could be unequivocally attributed to radiation exposure if the individual were to experience tissue reactions (often referred to as 'deterministic' effects), and differential pathological diagnoses were achievable that eliminated possible alternative causes. Such deterministic effects are experienced as a result of high acute absorbed doses (i.e. about 1 Gy or more), such as might arise following exposures in accidents or in radiotherapy.

(b) Other health effects in an individual that are known to be associated with radiation exposure—such as radiation-inducible malignancies (so-called 'stochastic' effects)—cannot be unequivocally attributed to radiation exposure, because radiation exposure is not the only possible cause and there are at present no generally available biomarkers that are specific to radiation exposure. Thus, unequivocal differential pathological diagnosis is not possible in this case. Only if the spontaneous incidence of a particular type of stochastic effect were low and the radiosensitivity for an effect of that type were high (as is the case with some thyroid cancers in children) would the attribution of an effect in a particular individual to radiation exposure be plausible, particularly if that exposure were high. But even then, the effect in an individual cannot be attributed unequivocally to radiation exposure, owing to competing possible causes.

(c) An increased incidence of stochastic effects in a population could be attributed to radiation exposure through epidemiological analysis—provided that, *inter alia*, the increased incidence of cases of the stochastic effect were sufficient to overcome the inherent statistical uncertainties. In this case, an increase in the incidence of stochastic effects in the exposed population could be properly verified and attributed to exposure. If the spontaneous incidence of the effect in a population were low and the radiosensitivity for the relevant stochastic effect were high, an increase in the incidence of stochastic effects could at least be related to radiation, even when the number of cases was small.

(d) Although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure; one reason for this is the large fluctuation in the spontaneous incidence of these effects.

(e) Specialised bioassay specimens (such as some haematological and cytogenetic samples) can be used as biological indicators of radiation exposure even at relatively low levels of radiation exposure. However, the presence of such biological indicators in samples taken from an individual does not necessarily mean that the individual would experience health effects due to the exposure.

(f) In general, increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation. This is because of the uncertainties associated with the assessment of risks at low doses, the current absence of radiation-specific biomarkers for health effects and the insufficient statistical power of epidemiological studies. Therefore, UNSCEAR does not recommend multiplying very low doses by large numbers of individuals to estimate numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels.

(g) UNSCEAR notes that public health bodies need to allocate resources appropriately, and that this may involve making projections of numbers of health effects for comparative purposes. This method, though based upon reasonable but untestable assumptions, could be useful for such purposes provided that it were applied consistently, the uncertainties in the assessments were taken fully into account, and it were not inferred that the projected health effects were other than notional.

2.2.6. Expectations on health effects. There is a general though not universally accepted understanding among scientists that public doses due to the accident are so low that: (i) deterministic health effects have not and will not occur in the general population; and (ii) epidemiological studies will not be able to reveal any stochastic effects. The limitations and robustness of possible epidemiological studies have been recently discussed in the literature. Statistical cancer risk models describing how the radiation-related risks of particular types of cancer vary with the doses of radiation received by specific tissues, which are derived from data gathered in epidemiological studies of exposed groups of people and guided by an incomplete understanding of radiobiological mechanisms gleaned from experimental studies, assume that at low doses or low dose rates the excess risk of cancer is directly proportional to the dose of radiation received, with no threshold dose—the LNT dose–response model—and the inferred summary estimate of the overall average lifetime excess risk of developing a serious cancer is $\sim$5% Sv^{-1} (Wakeford 2012). It is these cancer risk models and this inferred nominal risk estimate that provide the technical basis of radiological protection. A preliminary review of current plans necessary for risk evaluation of cancer and non-cancer diseases from the accident have therefore been described mainly from the view point of inferring health risk using epidemiological approaches rather than for attributing health effects (Akiba 2012). Moreover, it was estimated that apart from the extreme psychological stress caused by the horrific loss of life following the tsunami, the large-scale evacuation from homes and villages and the fear of radiological consequences, such studies have limited to no chance of providing information on possible health risks following low dose exposures received gradually over time—the estimated doses are just too small (Boice 2012). These predictions are consistent with the results of large-scale radiation epidemiological studies of the health effects of the Chernobyl accident, including radiation risks for emergency workers and the affected population (Ivanov 2012, UNSCEAR 2008). Apart from the excess of thyroid cancer among children who drank contaminated milk and the increase in mental disorders following the Chernobyl accident, no other adverse health effects have been convincingly reported despite much higher population doses than at Fukushima (UNSCEAR 2008, Tokonami *et al* 2012).

While even at such low doses, the risk of stochastic health effects can be inferred and used for radiological protection decisions, it should be clear for the Japanese people and authorities that it will not be possible to obtain unequivocal scientific evidence for the expression of such a risk in the future. For this reason, theoretically calculated radiation effects from the low doses expected from the accident should not be used in notional projections of radiation harm. Notwithstanding, it may be necessary for the Japanese decision-making bodies to ascribe nominal radiation risks to prospective exposure situations and impose radiological protection measures even at low doses, *inter alia* for reasons of social duty, responsibility, utility, prudence and precaution.

2.2.7. Epistemological limitations. Epistemology is the branch of philosophy that deals with the nature of knowledge, i.e. ‘how we know what we know’. The epistemological limitations of the sciences of radiobiology and radioepidemiology, and their influence on the attribution of health effects to low dose exposure situations are often ignored. A clear explanation of the epidemiological limitations described above and the more fundamental epistemological limitations are essential for understanding the reasons why collective effective doses aggregated from small notional individual doses should not be used to attribute health effects to radiation exposure situations, neither retrospectively nor prospectively. While there are reasons for the

Japanese authorities to ascribe ‘detriment-adjusted nominal risk coefficients’ to prospective exposure situations involving low radiation doses and impose commensurate radiological protection measures, these coefficients should not be used for attributing prospective health effects to radiation exposure situations at doses below the levels at which increased incidence can be actually observed if they occurred at all. The reporting of theoretical future cancer deaths due to the accident has already become an important ‘detriment’ (and inappropriate measure of harm) to the Japanese people and any future pronouncements should be avoided.

2.2.8. Outcome. The radiation protection community should renew its efforts to communicate to the public and press in more easily understood and transparent terms. Perhaps public-friendly and easily understood brochures (and/or websites) should be develop that define and describe the scientific basis, reasonableness and usefulness of the concepts used for radiological protection, and in particular on the inappropriateness of attributing actual health *effects* to (in contrast to inferring *risk* from) radiation exposure situations involving collective doses that result from summing very low individual doses. The issue of radiation risk and effects will need to be addressed comprehensively for people to understand, after an exposure has occurred, the rationale of the protection levels applied. These suggestions point to the importance of improved risk communication, radiation education and outreach in radiation exposure situations.

2.3. Quantifying radiation exposure

The quantities and units used in radiation science and radiation protection caused considerable communication problems and confusion; these include the following:

- the differences between the quantities (e.g. effective dose and equivalent dose and absorbed dose) are not well explained and are not well understood even by educated audiences;
- the distinction between the quantities used in the radiological protection system (e.g. effective dose) and the operational quantities used for radiation measurement (e.g. personal dose equivalent) are even more difficult to understand;
- the use of the same unit (i.e. sievert) for the quantities equivalent dose of an organ and effective dose without specifying the quantity enhanced the confusion and misunderstanding; and
- it is not understood why there are so many different quantities used in radiation protection, not only the many dosimetric quantities but also the many radiometric quantities (such as activity and activity concentration).

There were great difficulties communicating radiological information to non-experts and the public using the ICRP system and its quantities. This is probably the consequence of the intricate system developed for protecting people which combines physical exposure data to determine equivalent doses to organs and then uses scientific data on radiation risk to specific organs and tissues to compute an effective dose that is used to monitor and control human exposure. Although, the system of protection and its quantities are well suited for operational radiation protection they are not easily understood by non-experts, particularly in emergency situations. It was confusing that the quantities equivalent dose (to an organ or tissue) and effective dose have a common unit, the sievert. The problem was particularly evident in reporting thyroid doses to workers and the public from intakes of radioactive iodine. The equivalent dose is the relevant quantity for reporting organ doses but, if the dose is reported indicating only the unit, it can easily be confused with effective doses. The effective dose is a risk-related quantity for the whole body and can differ appreciably from the equivalent dose to an organ for the same person. For example, the effective dose for workers with a high intake of radioactive iodine would be much lower numerically than the equivalent dose to the thyroid. One solution to minimise confusion is to always add the quantity when the unit sievert is being used. Another solution would be to consider renaming the unit for effective dose, but this would require careful deliberation. (It is noted that while the protection quantities were developed by the ICRP, the operational quantities and the basic radiation quantities and units were developed by the International Commission on Radiation Units and Measurements (ICRU). It seems therefore that a close collaboration between the ICRP and ICRU is essential for improving understanding of the quantification system.)

Although the quantities and units of the ICRP system of radiation protection have been successfully applied in practical radiation protection, they are not easily explained and could lead to problems for decision-makers in emergency and post-emergency situations. Simplified dose reporting (e.g. organ dose, effective dose) might help to improve the situation in cases of emergencies. The ICRP protection quantities are not to be used for individual or collective risk assessment but rather for planning radiation protection in the low dose range and for verifying compliance with individual dose restrictions.

2.3.1. The radiological protection quantities. There are problems in explaining the quantities and units used in radiation protection. Interestingly, the history of radiation protection reflects the attempts to identify quantities which measure human radiation exposures as well as provide a metric for inferring the risk associated with the exposure.

After many decades, the ICRP converged upon a system of dosimetric protection quantities which are risk related and are now used in the regulatory context to set exposure limits and to enable the implementation of the optimisation of radiological protection (ICRP 1976). The quantities used in the ICRP system of radiological protection and their selected names are as follows.

- The fundamental quantity is the mean *absorbed dose* in specified organs and tissues in the human body, i.e. the mean energy deposited in an organ or tissue divided by its mass, with the unit J kg^{-1} and the special name *gray* (Gy) for this unit.
- To relate the quantity of absorbed dose better to radiation risk, the organ and tissue absorbed doses are weighted by dimensionless *radiation weighting factors* to account for the differences in biological effectiveness of different types of radiations from external and internal sources. The radiation weighting factors are chosen on the basis of experimental values of the relative biological effectiveness (RBE) of various radiation types for various endpoints.
- The radiation-weighted organ and tissue absorbed doses are termed *equivalent doses*. The equivalent dose is the mean absorbed dose from radiation in a tissue or organ weighted by the radiation weighting factors. As radiation weighting factors are dimensionless, the unit of equivalent organ or tissue dose is identical to absorbed dose, i.e. J kg^{-1}. However, to distinguish between absorbed dose, the special name sievert (Sv) is used for the unit equivalent dose.
- The quantity *effective dose* is defined as the risk-related (or risk-informed) dose quantity for the whole body. The effective dose is the sum of the equivalent doses in all specified tissues and organs of the body, each weighted by tissue weighting factors representing the relative contribution of that tissue or organ to the total health detriment. The calculation for effective dose uses age- and sex-independent tissue weighting factors, based on updated risk data applied to a population of both sexes and all ages. The sex-averaged organ equivalent

doses are applied to a reference individual rather than to a specific individual. It is the sum of all (specified) organ and tissue equivalent doses, each weighted by a dimensionless *tissue weighting factor*, the values of which are chosen to represent the relative contribution of that tissue or organ to the total health detriment. As mentioned, the radiation weighting factors are factors to account for the differences in effectiveness of different types of radiation whereas the tissue weighting factors are factors to account for the differences in radiation sensitivity (risk) of different types of organs or tissues. The definition for effective dose uses age- and sex-averaged tissue weighting factors which are based on the most recent human risk data. For a population of both sexes and all ages these tissue weighting factors are applied to the sex-averaged organ equivalent doses of the reference person and not to a specific individual (ICRP 2007a, section i). The values of each tissue weighting factors are less than 1 and the sum of all tissue weighting factors is 1. The values are chosen by the ICRP considering epidemiological studies of organ-specific detriment factors, in particular of Japanese A-bomb survivors. As the tissue weighting factors are also dimensionless, the unit for effective dose is also J kg^{-1}. As effective dose is the (weighted) sum of equivalent organ and tissue doses, the sievert is also used for effective dose.

In summary, quantification in the ICRP system of radiological protection is based on the physical quantity *absorbed dose* and extended to the protection quantities *equivalent dose and effective dose.* Central to the system of radiological protection is the quantity effective dose which is a risk-related whole body quantity that allows for the summing of partial body exposures and intakes of radionuclides. While effective dose is 'risk-informed' and is a quantity used in protection to limit risks, it is not a quantity to be used for risk assessment since it incorporates sex-, age- and tissue-specific averaging for a referent individual and not for specific individuals or populations. The long search for such a dose quantity suitable for setting exposure limits was completed in 1977. It is recognised, however, that the concept and application of effective dose is not easily understood. Effective dose has nonetheless proven to be successful for risk limitation and for risk management, in particular for occupational exposure situations. Effective dose enables the summation of doses due to exposures from external and internal exposures and takes account of scientific information on radiation risks. Effective dose is the dose quantity used in the majority of countries for radiation protection.

2.3.2. The changing names of the radiological protection quantities. The names used for the radiological protection quantities have evolved. ICRP Publication 26 (ICRP 1976) and its amendment issued by the ICRP's 1978 Stockholm statement introduced and defined the quantities 'organ or tissue dose equivalent' and 'effective dose equivalent'. ICRP Publication 60 (ICRP 1991) changed the terms to 'equivalent dose in a tissue or organ' and 'effective dose'. The reason for the change was that '*the weighted dose equivalent (a doubly weighted absorbed dose) has previously been called the effective dose equivalent but this name is unnecessarily cumbersome, especially in more complex combinations such as collective committed effective dose equivalent*'. ICRP Publication 60 also states that '*the Commission has decided to revert to the earlier name of equivalent dose in a tissue or organ*'. However, searching for the name 'equivalent dose' in previous ICRP reports failed to find clear evidence for this statement. For example, in ICRP Publication 2 (ICRP 1959) the name 'RBE dose' was used and in ICRP Publications 6 (ICRP 1962) and 9 (ICRP 1965) the name 'dose equivalent' was used. Therefore, the coexistence of the names of equivalent dose and dose equivalent appears to be due to changes introduced by the ICRP in Publication 60. The coexistence of the two different names for the same quantity has added confusion and misunderstanding within an already complex dosimetric system for radiological protection. Finally, ICRP Publication 103 (ICRP

2007a) uses equivalent dose without the specification 'in a tissue or organ' which can add to misunderstanding with effective dose if the quantity is not clearly specified since the unit, sievert (Sv), is the same.

2.3.3. The operational quantities. Since the quantities *equivalent dose* and *effective dose* cannot be measured directly in body tissues, the ICRP decided to follow the recommendations of the ICRU (1962, 1980), and proposed that the quantity *dose equivalent* be used as the operational quantity for external radiations. Radiation monitors for external radiations are calibrated in terms of the operational quantities derived from the *dose equivalent* (e.g. *ambient dose equivalent* and *personal dose equivalent*). Measurements in terms of dose equivalent are used to estimate effective dose.

Although it did not play a significant role after this Fukushima reactor accident, the use of the operational quantity dose equivalent was another cause for uncertainty and difficulty because it is easily confused with the quantity equivalent dose, i.e. the same words are used but just in reverse order. The names of these quantities provide semantic problems in many languages including Japanese. The usage is grammatically questionable in English because while equivalent can be used as an adjective or noun, dose is a noun (or verb) and its forced use as an adjective should be done with care (e.g. the expression 'dose equivalent' might be more appropriately written as 'equivalent dose'). Not surprisingly, the translation of equivalent dose *vis-à-vis* dose equivalent has been problematic in languages using ideograms such as Japanese. The term dose equivalent is translated to Japanese as 線量当量, while the term equivalent dose is translated as 等価線量. Namely, the character for dose, 線量 (a combination of beam, 線 (here 線 is the short form of 放射線, meaning radiation) and amount, 量), is preserved as an adjective in the first case and as a noun in the second. But the term equivalent is translated as 当量 (a combination of matching, 当, and amount, 量), in the expression dose equivalent; and, as 等価 (a combination of same, 等, and value, 価), in the expression equivalent dose. If you are not versed in Japanese, these explanations may be difficult to understand which in itself may provide an example of the difficulties that language translation and inexact word usage might or does have on understanding and communicating.

Fortunately, the operational quantity dose equivalent is used primarily by dosimetrists whereas the protection quantities, equivalent dose and effective dose, are used in communication with the public and non-experts. Thus, this issue is of less importance than others, although use of the same words to define different quantities remains problematic, and it is not entirely uncommon for dose equivalent to be used incorrectly when equivalent dose is the proper term.

2.3.4. The units of the quantities. The protection quantities *equivalent dose* and *effective dose*, and all the operational quantities derived from the quantity *dose equivalent*, use a common unit—the sievert. The unit of the fundamental quantity *absorbed dose* is the unit corresponding to energy per unit mass, namely joule per kilogram (J kg^{-1}) in SI units. The protection quantities equivalent dose and effective dose and the operational quantities derived from dose equivalent also have the same unit, because both are obtained by multiplying absorbed dose with dimensionless weighting factors. To avoid confusion, within the system of SI units it was internationally agreed to use the special name *gray* for the J kg^{-1} of absorbed dose and the special name *sievert* for the J kg^{-1} of all the other quantities (BIPM 2006); this policy was endorsed by the Consultative Committee for Units (CCU) (Allisy-Roberts 2005).

The same unit, *sievert*, is used for both the radiological protection quantities *equivalent dose* and *effective dose* and for all the operational quantities derived from *dose equivalent*.

Therefore, if the name of the quantity is not specified together with the unit there could be confusion and misunderstanding. Further complicating matters is that the older system of units is used in some countries, expressing energy per unit mass in erg per gram, with the special names *rad* for the absorbed dose and *rem* for the protection and operational quantities.

The confusion in the use of the unit sievert without stating whether it is equivalent dose or effective dose seems to have been particularly evident in reporting of thyroid doses after the accident and was related to the fact that incorporation of radioactive iodine into the body results in radiation exposure almost exclusively to the thyroid. Usually the equivalent dose is the relevant quantity for reporting organ doses but, if the dose is reported indicating only the unit, it can easily be confused with effective doses. There can be a two orders of magnitude difference in the risk to be inferred from the same number of *sieverts* of equivalent dose versus effective dose. For example, a high effective dose might mask a high equivalent dose to the thyroid; but even here, since the adult thyroid gland is less sensitive to the carcinogenic effects of radiation than other organs, this 'dose' may or may not be of major health importance; unless the dose were to children! As seen, this lack of specificity in using the sievert can be a major source of confusion for decision-makers trying to interpret the potential impact of exposures on workers and the public.

There are reasons to keep the same unit for equivalent dose and effective dose, since the latter is just a weighted average of the first, although some have proposed a quick fix by creating yet another name for effective dose. The confusion created by not specifying the dose quantity when giving numerical values in terms of sieverts merits a careful analysis of the possibilities of improving reporting and communication. The practice of not specifying the dose quantity has produced confusion when reporting doses from radioiodine intakes, because whether the number of *sieverts* reported are of thyroid equivalent dose or whole body effective dose makes a difference of a factor of about 25 in terms of radiological protection. This is because the tissue weighting factor for thyroid used in the computation of effective dose is 0.04 (i.e. the dose to the thyroid is reduced by a factor of 0.04).

2.3.5. Radiation-weighted quantities for high doses. A radiation-weighted dose quantity applicable to very high doses is not available, as the equivalent dose is defined only for low doses. Should the doses from the accident have been very high, this deficiency could have caused problems of dose specification. Fortunately, the radiation doses from the Fukushima accident were not high enough to cause any deterministic effects or acute radiation sickness and thus the use of the equivalent dose was appropriate and valid. The problem created by the lack of a formal quantity for a radiation-weighted dose for high doses was identified at the time of the Tokai-Mura accident (Endo 2010) (when a *de facto* neutron weighted dose had to be created to deal with the situation) but remains unsolved.

The dose limits for tissue effects (formally termed deterministic effects) for exposures at higher doses are given in millisievert, usually without explicit specification of the quantity to be used. In situations after accidental high dose exposures, health consequences have to be assessed and decisions have to be made on treatments. The fundamental quantities to be used for quantifying exposure in such situations are organ and tissue absorbed doses (given in Gy). However, if high-LET radiation is also involved, absorbed dose weighted with an appropriate 'relative biological effectiveness (RBE)' is used (NCRP Report 167; NCRP Report 170). Such RBE-weighted absorbed doses are not defined quantities, although they are being used in clinical practice (ICRP 2007a, section B25). For the special situation of astronauts, the gray equivalent (Gy-Eq) is also used (NCRP Reports 132, 142, 167). The ICRU is studying this issue of iso-effective or equi-effective dose in the context of radiation therapy and the outcome of this study could be of interest in addressing accidental exposures.

2.3.6. Outlook. While the system of radiological protection quantities has been used successfully for more than 30 years in controlling occupational exposure and public exposure in normal situations (prospectively in the design of facilities and planning of operations and retrospectively for demonstrating compliance with regulations), the experience in the aftermath of the Fukushima reactor accident revealed great difficulties in communicating radiological information to non-experts and the public. These difficulties in understanding the units and quantities appeared to be a consequence of the complexity of the system which uses more than one quantity (organ doses and whole body dose) and combines physical exposure data with scientific data on radiation risk for organs and tissues. Although the system and the quantities have shown to be well suited for operational radiation protection, they is less suited for communication with non-experts, particularly in emergency situations. The quantities used internationally for radiological protection purposes and for measurement purposes are somewhat sophisticated and their application requires professional knowledge. However, radiological protection practitioners are not alone in using these quantities, as emergency decision-makers—who do not necessarily know the details—rely on them for their choices of intervention. Misunderstandings about the quantities in the aftermath of an accident may lead to untoward difficulties, incorrect interpretations of potential consequences and incorrect decisions.

There are a number of possibilities for improving the situation in the short term. For instance: (i) avoiding the use of equivalent dose without specification of the organ or tissue concerned, e.g. a thyroid equivalent dose; and (ii) using the shorter and simpler term 'organ dose' for organ equivalent dose in communications, e.g. thyroid dose, which is already usual in many radiological protection practices.

As always, ways to improve and foster information exchange and education and to develop 'easy-to-read' material on the system of radiological protection quantities and units are sorely needed.

2.4. Assessing the importance of internal exposures

Internal exposures come from the inhalation or ingestion of radionuclides in the body. Radiation doses from internal exposures have been incorrectly perceived as being more dangerous than the same dose from external sources. There is compelling and consistent scientific evidence that radiation effects depend on the amount of dose received by specific organs and tissues, and not on whether the dose is received from internal or external sources. The ICRP and other scientific committees conclude that for a given radiation dose the same radiation risk should be expected, and the risk does not depend on whether the source of radiation comes from outside or inside the body. The ICRP system of protection is somewhat more conservative for internal than for external exposures because the limits for internal sources are based on the committed dose (which could be delivered over a 50 year or longer period) rather than on the dose actually incurred.

2.4.1. Perception. The perception that internal exposures were particularly dangerous was a recurring misunderstanding after the accident. A legal case related to the atomic bomb survivors of Hiroshima and Nagasaki may have contributed to this confusion. Plaintiffs alleged that the survivors had been exposed to radioactive fallout, so-called 'black rain', immediately after the bombs exploded and that this internal exposure was not taken into account by the Radiation Effects Research Foundation (RERF) that has provided quantitative estimates of health effects for nearly 60 years (Ozasa *et al* 2012) . It was claimed that the effects of internal exposures from intakes of tiny radioactive particles are more severe than those from external exposures and that internal exposures were ignored in the RERF studies that form the basis of the ICRP Recommendations (Sawada 2007). Despite decades of comprehensive dosimetry programmes there remains little to no evidence that fallout contributed measurably to the radiation dose received by survivors (Young and Kerr 2005). Nonetheless, the allegations of possible missed dose from internal exposures among atomic bomb survivors have raised anxiety and stress levels which will likely cause more harm to the population than conceivable from any exposure to intakes of radionuclides which appear to be miniscule based on large-scale measurements of children and adults (Hayano *et al* 2013). Further, any contribution of fallout from the atomic bombs could not have had much of an impact on future cancer risk, since the total number of excess cancers in the population is of the order of 600 deaths (Ozasa *et al* 2012).

There were also misrepresentations of the conclusions of the United Kingdom Committee Examining Radiation Risks of Internal Emitters (CERRIE) (NRPB 2004), which have been discussed elsewhere (Wakeford 2004). The CERRIE committee in fact concluded 'To the extent that ionising radiations from both internal emitters and external sources generate similar physical and chemical interactions in living matter, there are no fundamental differences between the two sources of radiation that suggest that their effects cannot be combined for radiological protection purposes.'

2.4.2. The protection policy for internal exposures. The protection against internal exposure, namely against exposure delivered by radioactive substances incorporated into the body, is based on the concept of *committed dose*. The committed dose from an incorporated radionuclide is defined as the total dose expected to be delivered within a specified time period, typically taken to be at least 50 or more years and often longer than the life expectancy of the person exposed. The need to regulate exposures to radionuclides that remain in the body for extended periods of time led to the recommendation that limits be based on committed dose, i.e. the dose committed to be incurred over 50 or more years, rather than on the doses incurred in a given period of time, usually in 1 year (as is the case for external exposures) .

For a given radiation dose the same radiation risk should be expected, whether irradiation is from outside or inside the body, implying that the system for internal exposures is more protective than that for external exposure. This intrinsic conservatism of the system of protection against internal exposures is not generally appreciated (Mobbs *et al* 2011).

2.4.3. Outlook. While the protection system for internal exposures is well established and globally accepted, there is widespread misunderstanding of the potential effects of internal emitters and of the concept of committed dose, which takes into account that internal radiation exposure is persistent for an extended period of time. The current scientific evidence from human, animal and cellular studies indicates that radiation risk depends on the amount of dose received and not on whether the dose is delivered from outside or inside the body. There is a need, however, to address comprehensively the radiation risks from internal exposure compared with the radiation risks from external exposure. It is encouraging that UNSCEAR is currently discussing the biological effects of exposure to selected internal emitters (UNSCEAR 2012). In addition, the perceived importance of internal exposure over external exposure points once again to the importance of improved risk communication, radiation education and outreach in radiation exposure situations.

2.5. Managing the emergency

Available international guidance to manage an emergency crisis involving large releases of radioactive materials into the environment could be improved. Issues to be addressed include:

- the management of an emergency radiological incident involving a prolonged release of radioactive substances from multiple units rather than by an acute or brief release from a single unit;
- guidance on extending emergency planning zones to effectively manage changing exposure situations and changing exposure scenarios;
- prioritising the emergency protective measures that could be taken;
- planning when and how to lift the emergency protective measures that were taken; and
- deciding when, why and how an emergency radiological incident should become an existing exposure situation.

2.5.1. Difficulties in managing. International guidance available for managing a radiological incident that involved protracted and episodic releases of radiation into the environment over a period of days and potentially longer periods of time was not adequate. Difficulties included the need to extend the emergency planning zones to account for changing exposure scenarios during the emergency response phase. However, this may not be a matter of radiological protection per se, but rather of regulatory policy. Prioritising emergency protective measures arose as an issue where guidance would have been welcomed. There was a need for clear recommendations for when and how to lift the emergency protective measures that were taken in response to the accident.

2.5.2. International guidance. Guidance on how to implement protective actions and on the concept of emergency planning zones are available from IAEA (1997a, 1997b, 2002a, 2002b, 2003, 2011c). These were developed in the light of ICRP Recommendations which advise that response actions should be planned because some potential emergency radiological incidents can be assessed in advance depending upon the type of installation or situation being considered; however, because actual emergency exposure situations are inherently unpredictable, the exact nature of the necessary protection measures cannot be known in advance but must flexibly evolve to meet actual circumstances (ICRP 2007a, section 274). As discussed in Publication 96 (ICRP 2005b), three phases of an emergency are considered: the early phase (which may be divided into a warning and possible release phase), the intermediate phase (which starts with the cessation of any release and regaining control of the source of releases) and the late phase. At any stage, decision-makers will have an incomplete understanding of the future impact of the effectiveness of protective measures taken, and of the concerns of those affected by the decisions made. An effective response must also include a regular review of impact and effectiveness and make modifications accordingly (ICRP 2007a, (283)).

The ICRP has issued specific recommendations for the protection of people in emergency exposure situations (ICRP 2009a), which are applicable to manage the emergency crisis arising after a serious nuclear accident. The recommendations provide advice on the preparedness for, and response to, radiological emergency situations, recognising that these situations may evolve, in time, into an existing exposure situation. The ICRP recommends that reference levels for emergency exposure situations should be set in the band of 20–100 mSv effective dose (acute or per year), indicating that a dose rising towards 100 mSv will almost always justify protective measures. The ICRP also recommends that an overall protection strategy must be justified, resulting in more good than harm, and that, in order to optimise protective measures, it is necessary to identify the dominant exposure pathways, the timescales over which components of the dose will be received and the potential effectiveness of individual protective options. Knowledge of the dominant exposure pathways will guide decisions on the allocation of resources. Resource allocation should be commensurate with the expected benefits, of which averted dose is an important component but not the only consideration. Other factors of importance when managing resource allocation include individual and social disruption, anxiety and reassurance and indirect economic consequences. Knowledge of the time periods over which exposures will be received informs decisions about the lead times available to organise the implementation of protective measures once an emergency exposure situation has been recognised. The protection strategy takes into account the dose which an individual has already received during an emergency when determining what constitutes optimum protection in later response actions.

For the ICRP, decisions to remove protective measures should have due regard for the appropriate reference level. The change from an emergency radiological incident to an existing exposure situation will be based on a decision by the authority responsible for the overall response. This transition may happen at any time during an emergency situation, and may take place at different geographical locations at different times. Such a decision may be accompanied by the setting of a radiological protection criterion above which it is mandatory to relocate the population, and below which inhabitants are allowed to stay subject to certain conditions. The transition should be undertaken in a coordinated and fully transparent manner, and should be understood by all parties involved. Assessments based solely on potential future health effects would be inadequate and due considerations should be given to societal, economic and stakeholder desires among other consequences (ICRP 2007a, section 277).

2.5.3. Outlook. Several issues for crisis management following a serious radiological incident are not clearly covered by international guidance. Specific issues to address include:

- managing an emergency exposure situation created by a prolonged (rather than a brief) release of radiation into the environment;
- extending emergency planning zones in the light of changing exposure scenarios over time;
- prioritising emergency protective measures;
- continuing assessment and modification as needed of the emergency protective measures taken; and
- lifting emergency protective measures and deciding when a radiological incident transitions into an existing exposure situation.

2.6. Protecting rescuers and volunteers

The adequacy of occupational radiological protection recommendations for workers who are not usually classified as 'radiation' workers needs to be addressed. Such workers include:

- rescuers, often the first responders to an emergency situation whose aim is to rescue people from dangerous and life-threatening situations, recognising that their own well-being will be at risk (e.g. fire-fighters, local police and members of the defence forces); and
- volunteers, often people who freely offer to help in the aftermath of an accident rather than in the early phase.

The dose restrictions for rescuers had to be increased by the authorities above the limits set for occupationally exposed 'normal' workers in order to maintain control of a potentially catastrophic situation. Nonetheless, there was confusion as to why this was being done and whether it resulted in a meaningful increase in health risk. For the volunteers, there was confusion on what type of dose restriction should be applied, and how to address the fact that some volunteers lived in proximity to the Fukushima plant and thus were already subjected to increased doses due to the accident. Other volunteers came from outside the proximal area with additional doses that were potentially very different.

The ICRP system of occupational protection is not specifically tailored to workers who may be exposed to radiation only in special circumstances. The system of protection was not conceived for people who willingly take high risks in order to save lives or control potentially catastrophic situations. The system is even less tailored to volunteer workers, namely the casual helpers in an emergency.

2.6.1. Emergency response personnel. As with other human-made or natural catastrophes, the Fukushima accident involved people who by profession engage in emergency response activities as well as people who are usually classified as occupationally exposed workers and controlled by occupational protection regulations. Some ad hoc helpers were professional *rescuers* and others were *volunteers*.

2.6.2. Rescuers. Rescuers are distinct from the normal occupationally exposed workers. A rescuer is a specialised worker, usually employed by emergency organisations (e.g. fire-fighting organisations) that are called upon after a disaster to save people from a dangerous or distressing situation. They take risks that would be unacceptable in any other profession. Usually, they are not employees of an employer engaged in activities that involve radiation exposure, because radiation is rare in the daily disasters in which rescuers are engaged.

The differences between normal 'radiation' workers and rescuers were evident in the recovery operations following the Chernobyl accident, where the rescuers received the enigmatic name of 'liquidators'. For Fukushima Daiichi, the combination of the improbable events leading to the severe nuclear accident, plus the disruption caused by the accident aftermath, resulted in an extreme state of affairs requiring an unexpected number of responding rescuers working under extreme circumstances. They are the heroes of the situation, risking their lives to undertake protective actions that could benefit millions of people. The prevailing circumstances, both at Chernobyl and Fukushima Daiichi, were exceptional and the criteria to be used for the protection of these rescuers are not easily delineated.

2.6.3. Volunteers. In the aftermath of the accident, people with charitable and humanitarian intentions volunteered to perform remediation activities. International guidance is basically silent in relation to 'occupational' protection of *volunteers*. Moreover, terming the exposure from volunteer activities 'occupational' is somewhat questionable or at best unclear. The approach to protecting such volunteers, however, may be similar to the approach for the protection of health-care providers and comforters of patients who are diagnosed or treated with nuclear medicine techniques. The ICRP recommends that for individuals directly involved in comforting and caring for patients who are 'radioactive' because of nuclear medicine procedures, other than young children and infants, a dose constraint of 5 mSv per episode is acceptable (ICRP 2007a, section 351). On the other hand, given that informed consent is obtained from the volunteers involved with remediation activities, there seems to be no reason for not considering them as temporary occupational workers, e.g. they can be regarded as temporary workers whose employer is the operation's management. Should this be the case, the dose constraint of 5 mSv imposed for health-care providers and comforters, except for those from whom informed consent is not obtainable (e.g. children), may be considered over restrictive.

2.6.4. Occupational exposures. The ICRP distinguishes occupational exposures from public exposures and medical exposures of patients, and also of comforters and carers of medically treated patients, and volunteers in research. Occupational exposure refers to all exposure incurred by workers during their work with the exception of: excluded exposures or exposures from exempt activities; any medical exposure; and the normal local natural background radiation. A worker is defined by the ICRP as any person who is employed, whether full time, part time or temporarily, by an employer and who has recognised rights and duties in relation to occupational radiological protection (a self-employed person is regarded as having the duties of both an employer and a worker).

The ICRP recommendations on occupational protection refer to the classification of working areas but they do not introduce any explicit classification of workers. It is nonetheless implicit that the recommendations are aimed at workers whose activities customarily involve exposure to radiation sources. In some countries, these occupationally exposed workers are called 'radiation workers'. However, because duration of employment is not a criterion for classifying an employee as an occupationally exposed worker from the view point of protection, temporary workers are not excluded from occupationally exposed individuals.

The ICRP suggests that occupational and public dose limits for planned exposures situation should not be applied in emergency radiological incidents, where an informed individual is engaged in volunteered life-saving actions or is attempting to prevent a catastrophic situation. For informed workers undertaking urgent rescue operations, the normal dose restriction may be relaxed. However, workers undertaking recovery and restoration operations after the initial crisis situation has passed should be considered occupationally exposed workers and should be protected according to normal occupational radiological protection standards (ICRP 2007a, section 247). This can be construed to imply that the exposure situation of these workers is a planned exposure situation.

The absence of ad hoc recommendations for handling the emergency exposures of workers has been recognised for over three decades (ICRP 1978). The distinction between 'normal' workers, whether working in normal or in emergency conditions, and 'rescuers' is not apparent. This issue resurfaced when the ICRP issued recommendations for protecting people against radiation exposure in the event of a radiological attack (ICRP 2005b). At that time, the ICRP recommended that responders involved in recovery, remediation and eventual restoration should be subject to the usual international standards for occupational radiological protection, but that restrictions may be relaxed for informed rescuers.

2.6.5. International regulation. Occupational protection is regulated by national laws, some of them under the International Labour Organization (ILO) Convention 105 (ILO 1960) and its code of practice (ILO 1987), which are based on ICRP Recommendations. These legal undertakings are often based on the 1990 ICRP Recommendations issued as ICRP Publication 60 (ICRP 1991). Therefore, many national regulations, including the Japanese regulations, establish the dose limit for radiation workers in 'normal' circumstances at an effective dose of 100 mSv over 5 years and no more than 50 mSv in a single year. The dose limit for women may be regulated separately, e.g. in Japan, as 5 mSv over 3 months. These international standards (co-sponsored *inter alia* by the ILO) (IAEA 1996c), consider occupational exposure outside 'normal' circumstances in two ways: workers occupationally exposed in special circumstances and workers who are involved in emergency situations. For special circumstances the Regulatory Authority may approve a temporary change in a dose limitation requirement if appropriate consultation with the workers has taken place. For emergencies, the standards specify that no worker undertaking an intervention shall be exposed in excess of the maximum single-year dose limit for occupational exposure except: for the purpose of saving life or preventing serious injury; if undertaking actions intended to avert a large collective dose; or if undertaking actions to prevent the development of catastrophic conditions. When undertaking intervention under these circumstances, all reasonable efforts shall be made to keep doses to workers below twice the maximum single-year dose limit (i.e. below 100 mSv), except for life-saving actions, in which every effort shall be made to keep doses below ten times the maximum single-year dose limit (i.e. below 500 mSv) in order to avoid deterministic effects on health.

The IAEA had addressed the issue of regulating occupational exposure after an accident in a technical document on emergency response criteria (IAEA 2005d, p. 20, table 3, Guidance levels for emergency workers), and in its *Manual for First Responders to a Radiological Emergency* (IAEA 2006, p. 41, table 5). The latter provided dose guidance for those who will be on the scene as emergency workers such as fire-fighters and law enforcement officers. Dose guidance is different for different types of actions (e.g. life-saving actions that include rescue from immediate threats to life; providing first aid for life-threatening injuries; and preventing/mitigating any conditions that could be life threatening). Moreover, it was clarified that the guidance is for '*…emergency service personnel who would initially respond at the local level…*'. In other words, emergency workers are not considered typical radiation workers. This guidance was developed further (IAEA 2011c (GSG-2); IAEA 2002a (GSR), part 3), in which it was concluded that '*…emergency workers may include workers employed by registrants and licensees as well as personnel of responding organisations, such as police officers, fire-fighters, medical personnel, and drivers and crews of evacuation vehicles*'. While there is still room for improving the guidance provided for emergency workers who are not typical radiation workers and who perform rescue operations, it is noted that existing international documents provide a good foundation to do so.

2.6.6. Unresolved issues. Nonetheless, there was confusion on how best to deal with rescuers and volunteers. The dose limits for the emergency workers had to be increased from 100 to 500 mSv by the authorities *after* the accident, which created anxiety among workers and questions of appropriateness. It was seen as a relaxation of dose limits which, while necessary, was considered by many as something the authorities should not do. In contrast there is rarely an outcry when dose limits are lowered, even when unnecessary. For volunteers, there was confusion on what type of dose restriction should be applied; moreover, it was not clear how to address the fact that, while some volunteers lived in close proximity to the Fukushima plant, and thus were already subjected to increased doses due to the accident, other volunteers came from outside the proximal area where there was not a significant increase of the extant doses.

The main lesson learned is that the international system of occupational protection is not specifically tailored to people who are not typical 'radiation' workers but who nevertheless may be involved in radiation protection operations after an accident. The most obvious example is presented by the 'rescuers' and 'volunteers' intervening in the aftermath of an accident. The current system of radiation protection was not conceived for people who willingly take risks in order to save lives and the system is even less tailored for volunteers helping in an emergency.

General guidance exists for workers in an emergency, but not for rescuers, and the guidance provided in international codes of practice seems to be not well-focused for severe situations. The absence of guidance on these issues was apparent during the Chernobyl accident in 1986, and in subsequent efforts dealing with planning in the event of a terrorist attack involving radioactive or nuclear materials. It comes as no surprise that the absence of clear guidance for rescuers and volunteers was also a problem during the Fukushima accident.

2.6.7. Outlook. It might be appropriate to consider developing specific recommendations for the protection of *rescuers* and of *volunteers* in the event of a serious radiological incident or accident, distinct from the existing recommendations for the protection of workers who are normally engaged in work involving occupational exposure to radiation.

A special category might be considered for people who are willing to engage in highly dangerous work that threatens their own lives and safety (similar, perhaps, to soldiers who willingly go into battle for their country and loved ones). Such an exposure category might be for 'heroic' (intolerable) exposure. Volunteers from the public might also be 'heroic' in the sense of self-sacrifice. A rigid dose restriction for this category of people is not relevant, although every effort to reduce doses should be made.

Volunteers could therefore include many occupations such as plant employees, fire-fighters, health professionals or compassionate citizens. Conceptually, all such volunteers should be considered in one category. The current guidance sets 100 mSv as the upper bound of a reference level while volunteer doses exceeding 100 mSv might still be tolerable. Hence, it might be appropriate to have two sub-categories for volunteers: the first would include volunteers planned to be exposed below 100 mSv and the other would include volunteers planned to be exposed above 100 mSv but below an upper bound (e.g. about or even above around 500 mSv).

2.7. Responding with medical aid

A number of medical management issues arose in the aftermath of the Fukushima accident. These included:

- coping with a radiological accident in parallel with a tragic natural disaster that caused tens of thousands of deaths and countless disrupted lives;
- personnel involved in emergency medicine and their understanding of radiation and radioactive elements;
- dealing with people's contamination, including the selection of a screening level for decontamination and the consequences of removing clothing;
- the role of experts in health physics during emergencies;
- the appropriate core curriculum in medical schools for training in radiological science;
- risk communication and education; and
- medical preparedness, including drills and exercises.

Some of the more relevant lessons are the following:

- the complexity of the disaster that included damage to nuclear or radiological facilities in addition to the damage and health consequences caused by the earthquake, increased the need for *multidisciplinary* measures in the medical response;
- drills and exercises for medical radiological emergency professionals should be carried out using scenarios that include a radiological/nuclear event caused by extreme natural events such as earthquakes and tsunamis;
- medical professionals should have a basic understanding of radioactivity and radiation, of their potential health effects and, particularly, of contamination with radionuclides;
- a basic understanding of radiation and its potential health effects is extremely important for physicians, nurses, radiation technologists and first medical responders, because all of these professionals might be called upon to respond to a radiological emergency; and
- the potential damage to community infrastructure such as water supplies and electrical generators, as well as the monitoring and/or calculation system for radiation after an earthquake or natural disaster, requires intense focus and vigilance.

2.7.1. A combined disaster. Some medical management issues have been addressed and guidance provided (IAEA 2005c, 2006). However, the accident was a complex combined disaster of a nuclear accident associated with a destructive earthquake and a calamitous tsunami. This combination of catastrophes seriously affected the medical management of people who were adversely affected. Earthquakes have a tremendous impact on the infrastructure of public facilities, including hospitals, and public intercommunication. Indeed, telecommunications infrastructures collapsed at the time of the accident, cutting off communication between the local and general headquarters of health services. Essential lifelines, such as water and electricity supplies, were also severely affected and impaired medical management. The natural disaster resulted in deaths and serious injuries that required immediate health care that was obstructed by damage to the basic infrastructure of the prefecture.

In Japan, NPPs have been built on the coast in part because of the need for cooling systems. Since primary medical facilities were located near the nuclear facilities, medical staff at these facilities were also asked to evacuate. Thus, primary-level hospitals were unable to function, and medical facilities not designated as radiological emergency hospitals had to replace them. Unfortunately, these medical facilities did not or were not able to accept contaminated patients. Some local ambulance services refused to transport injured workers because of the concern that such workers were contaminated with radioactive materials and thus dangerous to others.

The local headquarters, located 5 km from the plant, were not able to function adequately because community infrastructures such as water supplies and electricity generators were severely damaged by the earthquake and tsunami. Therefore, even simple countermeasures for decontamination, such as removing clothes and wiping the skin with wet towels, could not be performed for evacuees at the shelters. Further, the local hospital system was dysfunctional; hospitals designated as radiological emergency facilities lost their function because the earthquake and tsunami caused severe structural damage, and they were also located in the evacuation areas and the personnel left. Local fire departments were also asked to evacuate, and a lack of knowledge prevented these personnel from transporting contaminated workers from the plant. In addition, hospitals not designated for or trained in radiological measures could not or would not receive patients from the plant because of concerns about health effects of radiation on staff and other patients (Akashi *et al* 2013).

The evacuation itself also was not without severe consequences. The accident was in the winter, and the evacuation of 840 patients or elderly people in nursing homes and health-care facilities apparently resulted in 60 immediate deaths due to hypothermia, dehydration, trauma and deterioration of serious medical conditions (Tanigawa *et al* 2012) and upwards of 100 deaths in subsequent months (Yasumura *et al* 2013).

2.7.2. Radioactive contamination of people. Dealing with people's contamination was an important aspect of the nuclear reactor accident. Local officials had criteria for identifying members of the public who should be decontaminated and were aware of the criteria for contamination of skin and clothing. The cut-off criterion for screening of the public below which decontamination was not deemed necessary was 40 Bq cm^{-2} for beta/gamma contamination. On 12 March 2011, however, the levels of body surface contamination on some evacuees in shelters exceeded this level (Akashi *et al* 2013). Eleven workers were injured at the Fukushima Daiichi NPP on 14 March 2011 and seven of them were transferred to the Daini NPP by a TEPCO vehicle and a public ambulance. However, a worker needed treatment for his injury at a hospital. At the Daini NPP, however, the local ambulance personnel refused to transport the worker to a hospital, the reason stated was their belief that the worker was significantly contaminated and, more importantly, that no hospitals could be found to receive him. After extensive efforts, the worker was eventually admitted to the Fukushima Medical University (FMU) Hospital, a second level hospital for radiation emergency, in Fukushima City. The journey of the worker by ambulance was nearly 120 km from the accident site to the hospital that accepted him. On 19 March, the Nuclear Safety Commission of Japan (NSC) agreed to revise the screening level. According to the IAEA's *Manual for First Responders to a Radiological Emergency*, a dose rate of 1 μSv h^{-1} at a distance of 10 cm or a contamination level of 10 000 Bq cm^{-2} is a standard for decontamination in the case of contamination on the surface of the body for general residents (Akashi *et al* 2013).

Removal of the outer clothing has been shown to remove approximately 90% of a person's contamination. Unfortunately, residents were evacuated to shelters with only personal items and did not have clothes to change into. The earthquake resulted in substantial damage, not only to the nuclear facilities but also on the infrastructures of public facilities. The near complete collapse of telecommunications infrastructures occurred, resulting in the inability of health professionals and administrators to communicate between the local and general headquarters. Moreover, public infrastructures such as water and electricity supplies were severely compromised. People living or staying in the vicinity of the NPPs evacuated to shelters immediately after being asked to do so. In the shelters, examinations for radiation contamination showed elevated levels of contamination with radionuclides on the body surface and hair. When contamination is found in residents, it should be removed with wet towels as soon as possible. However, only drinking water was available and the supply of tap water was shut down in most shelters, so decontamination was not possible. Moreover, the residents could not stay in the shelters for long periods of time without warmer clothes and overcoats, because the temperature was low and the heating systems were inadequate. Thus, the pre-accident guidelines had to be revised by necessity (Akashi *et al* 2013).

2.7.3. Role of health physicists. The role of health physics professionals during emergencies was another important aspect of the nuclear reactor accident. These experts are in a unique position to assist first responders and medical personnel and to provide information as well as to evaluate the true extent and potential impact of any contamination present. If these procedures can be carried out properly, appropriate medical activities will occur in a timely manner consistent with the safety of these personnel. From the experience gained after an accident at Tokai-mura, Japan, in 1999, the NSC described the role of experts for radiation safety in an emergency in the Medical Guidelines for Radiation Emergency issued in 2001 and revised in 2008. According to the guidelines, for smooth transportation and acceptance of patients in hospitals, experts in radiation safety of NPPs or related companies should accompany patients to hospitals. Moreover, they should be trained for emergencies (Akashi *et al* 2013).

A hydrogen explosion occurred at the reactor building of Unit 3 on 14 March 2011, and workers and JSDF personnel were injured. The JSDF members were brought to the local headquarters by other JSDF personnel, but without experts in radiation safety; all of them showed heavy contamination on their protective gear. After removal of their protective gear, decontamination and showering, residual contamination was observed on their faces. One JSDF member was transferred to the Fukushima Medical University Hospital, a secondary emergency hospital in Fukushima prefecture, by ambulance. The patient had a contaminated wound on his right thigh. He was then transferred to the National Institute of Radiological Science by a JSDF helicopter. However, no expert on radiation safety accompanied the patient. Fortunately, his fracture of the lumbar transverse process was not serious, although he was internally contaminated with radioactive iodine and caesium (Akashi *et al* 2013).

2.7.4. Medical school curricula. Another related issue was the appropriate core curriculum in medical schools. Education and training are critical for physicians, nurses, radiation technologists and first responders, because all of these professionals might be involved in medical response activities after a radiation emergency. The Fukushima accident uncovered the need for all medical professionals to have a basic knowledge of radiation exposure and contamination from radionuclides. Such knowledge has not been provided in medical schools. In March 2001, the model core curriculum for medical education, Guideline for Medical Education, was published by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). The guideline presents what should be learned in medical schools and is a reference for making up the curriculum; this was revised on 31 March 2011, just after the earthquake. In this revision, the guideline recommended that the following topics should be included in the curriculum: radiation, radioactivity, their characteristics, radiation measurement and units; effects of radiation on humans (including the foetus) (acute and late effects); radiation sensitivity in various tissues; and effects of radiation on genes, interaction with cells, mechanisms of cell death due to radiation, local and whole body injuries. The reason for this revision was to ensure that medical doctors know that people are continually being exposed to natural sources of radiation and also the benefits of radiation used for medical purposes (Akashi *et al* 2013).

2.7.5. Communication of health risks. Public communication is one of the most important challenges for medical emergency management, and communicating effectively with the public about radiation effects is a key to its success. Radiation accidents can cause medical, environmental, psychological and economic problems. Scientifically correct information about health issues is critical for the prevention of psychological consequences, and explanation of radiation risks and any countermeasures in plain language is a vital part of an effective risk communication process. There are many ways to communicate today, including TV, radio, newspapers, the internet, hot-lines, leaflets, social media (such as twitter) and public meetings. There are also many ‘experts’ on radiation. Using these multiple sources of communication, knowledgeable professionals can provide helpful information. Members of the general public did not have sufficient knowledge about radiation and its effects before the Fukushima accident. After the accident, an enormous amount of information, often conflicting, was suddenly provided, and the public was not able to filter effectively which information was correct and which was wrong and thus became confused and worried. There are some patients who refuse medical tests using x-rays at hospitals, for the simple reason that radiation increases the risk of cancer mortality. It is critical that scientifically correct information concerning radiation be understood by the public, not just after a radiological incident has occurred but beforehand. Accordingly, MEXT provided an auxiliary textbook for education on radiation and its effects in primary, junior and senior high schools on 14 October 2011 (Akashi *et al* 2013).

2.7.6. Medical preparedness. Medical preparedness, including training, drills and exercises, was another important issue. Central and/or local governments have performed annual radiation emergency drills in Japan. However, drills using the scenario of a radiation/nuclear event caused by an earthquake have never been performed in Japan. This earthquake caused not only deaths and life-threatening injuries, but also had a tremendous impact on public infrastructure and the NPP. An earthquake measuring 6.8 on the Richter scale struck the Niigata-Chuetsu region of Japan on 16 July 2007. The earthquake affected the Kashiwazaki-Kariwa NPPs, the biggest NPP site in the world. The earthquake caused damage to the NPPs, resulting in a small amount of radioactive material being released into the air and the sea. Fortunately, no significant effects were observed in the public and the environment, and no damage was caused to the monitoring system of the NPPs, although infrastructure such as water supplies and roads were affected. Similar to Fukushima, most of the members of the disaster medical assistance team (DMAT) members who were sent to hospitals and first-aid care centres at the NPP site had concerns about the effects of radiation, since adequate information about the problems at the NPPs was not communicated to them (Akashi *et al* 2010). Although experiences associated with this previous earthquake indicated the urgent need for an all-hazards approach to address the complexity of medical issues, they were not incorporated into the planning and response for future 'combined disasters' such as the one in 2011. The complexity of disasters that include damage to nuclear or radiation facilities has increased the need for multidisciplinary medical experts, and improved strategies to plan and respond to future disasters.

In response to a radiation emergency, the level of contamination from radionuclides has to be evaluated for the public, patients, responders and medical staff. However, fixed screening criteria set in advance are not applicable to everyone for all incidents and flexibility is required to cope with the unique circumstances of each radiological incident. For example, when this criterion was applied to a seriously injured but also contaminated patient with radionuclide levels above the designated criteria, the patient could not be transported or admitted to a hospital. For contamination with radioactive materials, unlike for chemical or biological contamination, there is a general consensus that the first priority for medical response should always be life-saving and that the main priorities of disaster rescue teams should be rescue and the provision of emergency care for physical trauma. There are no reports showing significant effects of radiation exposure upon receiving contaminated patients. Planning should be done in advance, with some room for flexibility, and first responders have to have clear instructions to follow on the basis of decisions by headquarters under specific circumstances (Akashi *et al* 2013).

2.7.7. International guidance. International guidance on medical management in emergency exposure situations is limited but can be found in several IAEA documents co-sponsored by the WHO dealing with medical surveillance issues (IAEA 2005c, 2005d), which preceded the general system of protective and other actions established in IAEA standards (IAEA 2011c) and the long-term health surveillance programmes recommended by the WHO (WHO 2006). In its guidance for the protection of people in emergency exposure situations, the ICRP recommended that where prompt medical intervention has the potential to avert injuries, procedures and measures should be included in the emergency response plan to enable those individuals who may have received high exposures to be identified promptly and receive appropriate medical treatment (ICRP 2009a, section e).

The ICRP guidance on the protection of people living in long-term contaminated areas after a nuclear accident or a radiological emergency (ICRP 2009b) addresses health surveillance. Following a serious nuclear accident or radiological emergency, the exposed population should have an initial medical evaluation, the first step being a census of the affected individuals, possibly with an early dose assessment. It also recommends that, in addition, and regardless of the level of dose, the affected population should also receive accurate and appropriate information regarding their level of exposure and potential future health risks. If the level of dose is sufficiently low, and below levels associated with natural background radiation, there may be discussions as to the extent to which these recommendations are implemented. The ICRP has also made recommendations on medical management in the event of a radiological attack (ICRP 2005b). Action taken to avert exposures is a much more effective protective measure than those taken after exposure has occurred.

A handbook on triage, monitoring and treatment of people exposed to ionising radiation following a malevolent act is also available (Rojas-Palma *et al* 2009). European national emergency response plans have long been focused on accidents at NPPs and other nuclear installations. Recently, possible threats by disaffected groups have shifted the focus to being prepared for malevolent use of ionising radiation aimed at creating disruption and panic in society. Although some countries may have adequate national plans for response, there is a need for European guidelines on how to act in the event of malevolent use of radioactive material.

Moreover, some of the issues raised have been recognised previously, and some recommendations incorporated in international standards (IAEA 2002a). Descriptions have been provided (IAEA 2005a) as well as explanatory materials (leaflets and posters), and training materials are available on the IAEA website (IAEA 2002b, 2009a, 2009b, 2009c).

Finally, the US National Council on Radiation Protection and Measurements (NCRP) has also published a series of reports that are relevant to medical response, radionuclide decontamination and emergency response during radiological incidents and emergencies (NCRP 2001, 2004, 2005, 2006, 2008, 2010).

2.7.8. Outlook. Many issues concerning medical management were raised as a result of the Fukushima accident, as follows.

- It was fortunate that no workers from the plant or residents around the site incurred doses that would have required medical treatment. That is, there were no severe tissue reactions (deterministic effects) because the radiation exposures were far below the threshold doses necessary to produce such effects.
- The complexity of disasters that involve not only damage to nuclear or radiological facilities but also damage caused by natural forces such as earthquakes and ensuing tsunamis increases the need for multidisciplinary measures in the medical response. Planning operations after a complex disaster require an all-hazard approach.
- Training, drills and exercises for a medical radiological emergency should be carried out using scenarios of a radiological/nuclear event caused by natural events such as earthquakes and tsunamis.
- Medical professionals should have an understanding of radiation, radioactivity, radionuclides, internal and external sources of radiation and their potential for causing future health effects in the individuals exposed. Such training in medical and other professional schools needs to be improved.
- Education and training in radiation-related issues is critical for physicians, nurses, radiation technologists and first medical responders. All types of professionals are likely to be involved during medical response to a radiological emergency. Basic knowledge of radiation and its effects is extremely important for health-care providers, to provide understanding, guidance and assurance as appropriate. Such professionals are on the front line with the public and their opinions are highly valued.
- A system should be encouraged to improve, foster and educate health physics professionals in radiation safety to assist first responders and medical personnel and to provide real-time information and guidance as to the extent and potential impact of any contamination present.
- The potential to disrupt the infrastructure of society, such as electricity generation, sewers, water supplies, hospitals, fire departments, as well as the monitoring and/or calculation system for radiation necessitates an intense focus and vigilance to cope with the ensuing myriad of unexpected consequences. There is an urgent need for a 'combined disaster' medical response strategy, which should be emphasised for current disaster planning and response.

It would be worthwhile to consider ad hoc recommendations addressing the issues raised concerning the medical needs following a significant radiological incident that includes compromised society infrastructures.

2.8. Justifying necessary but disruptive protective actions

Some of the decisions taken after the accident to protect the public were extremely disruptive and caused significant social distress. For instance, evacuating people from their homes obviously results in serious disturbance to normal life. Not all decisions were as clearly justified and it is unclear whether they really produced more good than harm.

While the radiological protection principle of justification is usually applied to the introduction of new sources of radiation, which are expected to increase exposure of people, the principle is equally applicable to the introduction of disruptive protective actions, which are expected to decrease the exposure of people. In the immediate emergency situation and in the long-term existing exposure situation, decision-makers need to justify disruptive protective actions from the perspective of the benefit obtained.

Applying justification in and after an emergency situation is particularly difficult. For instance, decisions on whether to evacuate people from areas of elevated but not high doses (or to allow them to return to such areas after evacuation) can present dilemmas. If people remain they will incur some radiation doses and increase their theoretical chance of developing radiation-induced harm in the future; if they are evacuated such a plausibility will disappear but they will incur the immediate detriments associated with the evacuation itself.

Further guidance on the application of the justification principle in these challenging situations would be welcomed. It should be recognised, however, that 'balancing' good and harm is not confined to issues associated with radiation exposure. Other non-radiation-related benefits and detriments arising from the protective action must also be considered, thus going far beyond the scope of radiological protection.

2.8.1. The justification principle. The justification principle, namely the justification of actions that may change the radiation exposure of people, has always been and continues to be a fundamental ethical principle of the ICRP (ICRP 2007a, section 5). It is founded on teleological ethics (from the Greek τέλος, 'end, purpose'), which is usually referred to as consequentialism because it holds that the consequences of a particular action form the basis for any valid moral judgement about that action, and argues that decision-makers ought to be consequentialists. Protection-related consequentialism would therefore hold that the ends or consequences of a protection-related action should determine whether such action is good or evil. Thus, it is concerned with the overall outcomes or consequences of protection-related actions, which would be morally right if they produce a good outcome or consequence—namely, they turn out to have more absolute good than absolute harm for society.

The ICRP principle of justification simply states that 'any decision that alters the radiation exposure situation should do more good than harm' (ICRP 2007a, section 203). In relation to accidents, justification is precisely defined by the ICRP as the process of determining whether a proposed remedial action in an emergency or existing exposure situation is likely, overall, to be beneficial, i.e. whether the benefits to individuals and to society (including the reduction in radiation detriment) from introducing or continuing the remedial action outweigh its cost and any harm or damage it causes. The ICRP considers (ICRP 2009a) that more complete protection is offered by simultaneously considering all exposure pathways and all relevant protection options when deciding on the optimum course of action. While each individual protective measure must be justified by itself in the context of an overall protection strategy, the full protection strategy must also be justified, resulting in more good than harm.

2.8.2. Approaches to justification. There are two different approaches to applying the principle of justification in exposure situations. The first approach is used in the introduction of new activities where radiological protection is planned in advance. Application of the justification principle to these situations requires that no planned exposure situation should be introduced unless it produces sufficient net benefit to the exposed individuals or to society to offset the radiation detriment it causes. The second approach is used where exposures can be controlled mainly by action to modify the pathways of exposure and not by acting directly on the source. The main examples are existing exposure situations and emergency exposure situations such as those resulting from the accident. In these circumstances, the principle of justification is applied in making the decision as to whether to take action to avert further exposure. Any decision taken to reduce doses, which always have some disadvantages, should be justified in the sense that it should do more good than harm.

2.8.3. Justification after the accident. Following the accident, justification was theoretically applicable to the protective actions to decrease exposure but surfaced as a relevant issue of uncertainty. While the benefit of introducing new sources can be positive, the benefit of introducing protective actions is indirectly gained by reducing harm. So the characteristics of benefit (good versus harm) are different in these situations. It could be conceived that when introducing a NPP, this process inherently includes the justification of decisions on protective actions during emergency and existing exposure situations potentially caused by accidents. However, once an accident occurs, in other words in the immediate emergency situation and in the long-term existing exposure situation, people can only justify disruptive protective actions from the perspective of the benefit obtained from the protective action.

In relation to accidents, the ICRP recommends that, when activities aiming at decreasing the level of radiation exposure are being considered, the expected change in radiation detriment should be explicitly included in the decision-making process (ICRP 2007a, section 205). The consequences to be considered are not confined to those associated with the radiation—they include other risks and the costs and benefits of the activity. Sometimes, the radiation detriment will be a small part of the total. Justification thus goes far beyond the scope of radiological protection. It is for these reasons that the ICRP only recommends that justification require that the net benefit be positive. To search for the best of all the available alternatives is a task beyond the responsibility of radiological protection authorities.

According to the ICRP the approach to justification of dose reduction should be used where exposures can be controlled mainly by action to modify the pathways of exposure and not by acting directly on the source, as was the case in the aftermath of the accident (ICRP 2007a, section 207). In these circumstances, the principle of justification is applied in making the decision about whether to take action to avert further exposure. Any decision taken to reduce doses, which always have some disadvantages, should be justified in the sense that it should do more good than harm.

The ICRP also recommends that every practicable effort should be made to avoid the occurrence of severe deterministic injuries in an emergency exposure situation. This means that it will be justified to expend significant resources, both at the planning stage and during the response, if this is required, in order to reduce expected exposures to below the thresholds for these effects.

The ICRP has recognised that: (i) except for the case of medical exposure of patients, the responsibility for judging the justification falls on governments or national authorities to ensure an overall benefit in the broadest sense to society and thus not necessarily to each individual; (ii) input to the justification decision may include many aspects that could be informed by users or other organisations or persons outside of government, and justification decisions may be informed by a process of public consultation; and (iii) there are many aspects of justification, and different organisations may be involved and responsible (ICRP 2007a, section 208). However, no clear guidance is available to governments and national authorities on exercising their duties or whether other institutions should participate in the process.

2.8.4. Difficulties in the practical application of justification. Applying justification in the emergency situation triggered by the accident is particularly difficult. For instance, decisions on whether or not to evacuate people from areas of elevated but not high doses can present difficult dilemmas. If people remain they will incur some radiation dose and increase the possibility of radiation-induced harm in the future; if they are evacuated such a possibility will disappear but they will certainly incur the actual detriments associated with the evacuation itself. Thus, applying justification to decide about actions to change the radiation exposure situation of people in the aftermath of large radiological accidents should be done within a self-critical attitude. This is the result of the extremely demanding nature of justification. As there is no realm of moral permission, no realm of going beyond one's moral duty (supererogation), no realm of moral indifference, all actions are seemingly either required or forbidden, and the approach might be deemed profoundly alienating. Justification seemingly permits (or, more accurately, requires) difficult choices. If wrongly interpreted, it might be seen to demand (and thus, of course, permit) that innocents be killed because of lack of protection, or deprived of material goods because of excessive protection that may produce greater benefits for others. Consequences stemming from decisions altering the radiation exposure situation can conceivably justify any kind of act, no matter how harmful it is to some. Moreover, the concept of justification gives little or no guidance for the decision-makers' practical reasoning, because the consequences (positive and negative) of any protective action, such as evacuation or resettlement, stretch into the distant future, making them essentially unknowable. It should be noted that the cultural situations of the country where justification is being applied have to be considered (ICRP 2007a, section 284).

2.8.5. Outlook. Further guidance on the application of the principle of justification in the demanding situations created by a major accident would be welcomed and are needed. One problem, however, is that there are often non-radiation-related benefits and detriments to deal with that arise from the protective actions taken, i.e. the issues go far beyond the scope of radiological protection. The search for the best of all the available alternatives is a task beyond the responsibility of radiological protection professionals; their remit should be confined to ensuring a positive net radiation-related benefit. In addition, it should be kept in mind that the principle of optimisation of protection calls us to seek the best protection option among those available, which is perhaps the most important task of radiological protection professionals and it is a challenge.

2.9. Transitioning from an emergency situation to an existing situation

Deciding when to transition from an emergency radiological incident to an existing exposure situation that will remain for many years to come is not always straightforward. One difficulty is how to define and decide when the emergency situation has in fact ended and, accordingly, when the existing exposure situation begins.

The process of transitioning from the emergency situation to an existing exposure situation raised doubts about the credibility of the relevant authorities. Although there were engineering guidelines as to when the reactors could be considered 'safe' and in cold shutdown, the demarcation between the emergency crisis and an existing exposure situation was more difficult. More quantitative guidance may have been helpful in making this judgement.

2.9.1. The exposure situation. In addition to traditional *planned exposure situations* (namely situations involving the planned introduction and operation of sources), the ICRP has made a distinction between what it termed *emergency exposure situations* and *existing exposure situations*. Emergency exposure situations are defined as those that may occur during the operation of a planned situation, or from any other unexpected situation, and require urgent action in order to avoid or reduce undesirable consequences (ICRP 2007a, section 176). Existing exposure situations are defined as those that already exist when a decision on control has to be taken, including prolonged exposure situations after emergencies (ICRP 2007a, section 176).

These definitions may influence the difficulties experienced in transitioning from the emergency exposure situation to an existing exposure situation. The definition of an emergency exposure situation might be unnecessarily detailed and could have been clearer without the initial qualifiers, e.g. simply stating that emergency exposure situations are those require urgent action in order to avoid or reduce undesirable consequences (still a question would remain: whether an emergency exposure situation requires urgent actions or urgent actions create an emergency exposure situation). Furthermore, the differences between the common understanding of 'emergency' and the connotation given to the qualifier 'emergency' in the term 'emergency exposure situation' could have been another cause of confusion. For instance, some questionable descriptions were made regarding all the exposure situations related to the accident as emergency exposure situations: for example, many emergency responders to the accident who participated in certain works at places distant from the plant, such as workers restoring roads damaged by the earthquake, were certainly not subjected to an emergency exposure situation.

It has also to be noted (Homma 2013) that what transitions is the radiological condition rather than the exposure situation. In fact, as defined, the three exposure situations recommended by the ICRP are mutually exclusive; hence an emergency exposure situation cannot become an existing exposure situation. (As an example, a teenager will eventually become an adult, but this does not mean that teenager becomes adult as long as the definition of the both teenager and adult are kept; what becomes an adult is the person considered, not the category itself.) Thus what changes is the radiological condition, from variable and quasi-uncontrollable into steady and basically controllable, rather than the defined situation.

2.9.2. Difficulties experienced in the aftermath of the accident. While most exposure situations created by the accident are tailored to the definition of an emergency exposure situation, questions were raised on when the emergency condition could be considered terminated.

For the emergency workers and rescuers, the termination of the emergency situation is self-evident: the emergency exposure situation is terminated when the assigned work expected to cause doses exceeding the normal dose limits is over. This could be construed to mean that an emergency exposure situation may be specific to the situations of the individuals being subjected to the situation.

For the public, however, the concept of transition is unclear. Questions have been raised on whether the concept of an emergency exposure situation is applicable to the public at all, and it has even been suggested that the exposure of members of the public under an accident may fit better to an existing exposure situation (Lee 2012b, 2013). Under this assumption the issue of a transition point naturally vanishes.

The radiological conditions of members of the public residing in the affected area are characterised by a measurable and prolonged incremental dose, which is higher than the existing pre-accident background dose. This situation can be categorised as an 'existing' (or even clearer, an 'extant') exposure situation. In fact the ICRP underlines that the management of long-term contamination resulting from an emergency situation should be treated as an existing exposure situation (ICRP 2007a, section 283).

Transiting from the emergency exposure situation into an existing exposure situation, defined by the ICRP, caused doubts among the Japanese authorities. On 30 March 2012, the NSC judged that the reason for evacuation no longer existed in part of the evacuated area within a 20 km radius of the Daiichi NPP, designated as 'restricted area' (警戒区域 or 'caution zone', and termed 1F), because of *inter alia* the stabilisation of the nuclear reactor. The removal of the designation 'restricted area' could be understood as a case where the emergency exposure situation shifted to an existing exposure situation.

It is felt in Japan that the transition would be easier and clearer to judge if clearer and more quantitative guidance were available.

2.9.3. International guidance. The ICRP provides some recommendations on the transition from an emergency exposure situations to an existing exposure situation (ICRP 2009a). Moreover, the ICRP noticed the commonalities between emergency and existing exposure situations (and their differences from planned exposure situations), which could make it difficult to define the transition. In its recommendations on protection of the public in situations of prolonged radiation exposure (ICRP 1999) the ICRP recognised that, while in planned exposure situations control was exercised over the *additional* doses that were expected to be delivered due to the planned introduction of a source, the other possible exposure situations (which are now described as emergency and existing exposure situation) were 'interventional' in the sense that control was aimed at reducing doses that originated in retrospective causes rather than restricting *additional* doses that are inferred prospectively. The ICRP has recognised that the concept of 'intervention' has become widely used in radiological protection and has been incorporated into national and international standards to describe situations where actions are taken to reduce exposures, but in its recent recommendations it stated that it believes that it is more appropriate to limit the use of this term to describe protective actions that reduce exposure, while the terms 'emergency exposure' or 'existing exposure' should be used to describe the radiological exposure situations where such protective actions to reduce exposures are required (ICRP 2007a, section 50).

In both emergency and existing exposure situations the system of radiological protection could be conceived as follows: (i) the principle of justification is implemented by judging whether any intervention that alters the doses (e.g. evacuating people) is justified, namely would it produce more good than harm; (ii) the principle of optimisation of protection, which aims at the best protection under the prevailing circumstances by maximising the margin of benefit over harm, is achieved by averting the largest dose that is reasonably achievable, social and economic considerations being taken into account; and (iii) the restriction of individual doses is achieved through comparison with *reference levels* of dose. (Establishing prospective limits, such as the dose limits, is not appropriate under these circumstances, because the real exposure situation is not fully predictable and can be very variable. The prevailing circumstances, particularly the protection efforts and undesirable consequences from protective actions, are also variable and furthermore may play a dominating role. In sum, limiting *prospective additional* doses can be realistically exercised at the planning stage of the introduction of a source, where doses can be forecast with reasonably certainty so as to ensure that these restrictions will not be exceeded.)

However, as indicated previously, there have been difficulties in deciding when and on what grounds the transition from emergency to existing exposure situations should occur. The ICRP expresses the time frame of transition as a grey area where the uncertainty in dose rates decreases significantly, and leaves the decision on transition to the relevant authority (ICRP 2009a). The responsible authority may experience difficulties in deciding on transition because of such ambiguities.

Another issue related to difficulties in the transition to an existing situation is the difference between existing exposure situations created by an accident and existing exposure situations created by nature (see the next section on the different public perception of these situations). A distinction in control between these situations is implicitly recognised by the ICRP. While reference levels in 'natural' existing exposure situations are conventionally expressed as an annual effective dose (e.g. mSv in a year), in existing exposure situations remaining after an emergency the reference levels are expressed as the total residual dose to an individual as a result of the emergency that the regulator would plan not to exceed, either acute (and not expected to be repeated) or, in case of protracted exposure, on an annual basis (ICRP 2007a, section (238)).

2.9.4. Public perception. The public seems to perceive an important distinction between two distinctive existing exposure situations, namely an existing exposure situation due to high levels of natural radiation and an existing exposure situation remaining in the aftermath of an accident. The long-term dose level in the aftermath of an accident will necessarily be higher than the background dose level existing before the accident, which would however be taken by the public as a reference for comparison. In this sense, people consider the difference between both these levels as an *additional* dose and, unsurprisingly, expect that this additional dose be controlled with the same criteria and levels used in planned exposure situations (see below on the issue of categorising public exposure). This public perception is a major element in the difficulties experienced by the authorities for transiting from an exposure situation that is considered 'emergency' to a situation that is considered 'existing'.

Recommendations for using the dose limit for planned exposure situation as a desired objective during an existing exposure situation have increased the public's misunderstanding. People usually ignore the fact that millions of people are living in regions of elevated background doses, which is an archetypal case of an existing exposure situation. In such regions the public is exposed continuously to doses of tens of mSv year^{-1}, far exceeding the annual dose limit for the public of 1 mSv year^{-1}, which is only applicable to the expected additional doses resulting from a planned exposure situation. The crucial difference in the public perception is that natural radiation exposure is imposed by nature while the exposure remaining after the accident is imposed by a human act, i.e. there is someone responsible and imputable for the exposure. This difference may be reflected in the course of selecting the reference level value and in eventual legal actions, but does not alter the basic protection concept of optimising protection under the prevailing circumstances. However, it is a major component in the usual public claim that the dose limits for a planned exposure situation be used for the additional dose (over the pre-existing background dose) in the existing exposure situations remaining in the aftermath of the accident; this is not an issue in 'natural' existing exposure situations because such a 'previous' levels does not exist.

2.9.5. Outlook. The crisis created by the accident has been managed according to the currently recommended characterisation of exposure situations, but it was noted by the public and the authorities that the demarcation between planned, emergency and existing exposure situations is subtle and its practical purpose not fully understood.

The protection paradigm for dealing with emergency and existing exposure situations could be revisited. Consideration could be given as to whether the differentiation between these situations should be more than conceptual or whether the concept of emergency exposure situations fits the exposure of members of the public. A comprehensive practical approach common to all interventional situations could be sought.

2.10. Rehabilitating evacuated areas

The Chernobyl accident vividly demonstrated how extremely difficult it is to rehabilitate an area evacuated as a result of a nuclear accident. A large intergovernmental project was required to tackle this problem after that accident. Rehabilitating and re-inhabiting areas in the Fukushima Prefecture that were evacuated due to the accident are posing similar challenges.

Rehabilitating evacuated areas, for example allowing people who were evacuated to return to their homes and constructing residential areas for both returning evacuees and new residents, has proved to be extremely difficult. Evacuees from specific regions designated by the Japanese government as ‘difficult to return’ (because of the levels of environmental contamination) will be unable to return to their homes for some years to come. Some people do not wish to return, either for economic reasons or because of concerns about potential health risks for their families, or both, while others are not as concerned about living in areas where the radiation exposure levels are just somewhat elevated and wish to return promptly. Issues being addressed include how to characterise and classify the exposure situation, determining the type of exposure, and deciding how the exposure situation should be remediated and controlled.

Existing recommendations have produced confusion among members of the public who were evacuated, in large part to a misunderstanding the difference between a planned exposure situation and an existing exposure situation. The ICRP recommended 1 mSv $year^{-1}$ as the dose limit for a planned exposure situation. However, the reference level for existing exposure situations can be higher where people are allowed to return to their homes and then optimisation continues to lower the exposure levels. Depending on the circumstances and view point, however, rehabilitation can be interpreted differently: as an existing exposure, as a planned exposure of informed individuals or even as an exposure to background radiation that is excluded from control if the residual dose is low enough. While ICRP Recommendations are not explicit on how to handle this type of situation, it is generally, though not unambiguously, understood that returning from a temporary evacuation changes the pre-existing status of the affected areas and that the contaminated regions then become existing exposure areas.

2.10.1. The challenge of rehabilitation. Rehabilitating evacuated areas following a large accident involving huge releases of radioactive materials into the environment continues to be a serious test for the radiological protection profession. How to control the prospective exposure of residents returning to rehabilitated areas is a major challenge.

2.10.2. International guidance. The ICRP Recommendations for the protection of people living in long-term contaminated areas after a nuclear accident or a radiological emergency (ICRP 2009b) provide guidance for the protection of people living in those areas. They consider the pathways of human exposure, the types of exposed populations and the characteristics of exposures. Although the focus is on radiological protection considerations, the recommendations also recognise the complexity of post-accident situations, which cannot be managed without addressing all the affected domains of daily life, i.e. environmental, health, economic, social, psychological, cultural, ethical and political aspects. The recommendations emphasise the effectiveness of directly involving the affected population and local professionals in the management of the situation, and the responsibility of authorities at both national and local levels to create the conditions and provide the means to favour the involvement and empowerment of the population.

In these recommendations the ICRP considers that the situation at the rehabilitation stage is an existing exposure situation. For existing exposure situations, the ICRP states that as the long-term objective for existing exposure situations is 'to reduce exposures to levels that are close or similar to situations considered as normal', it recommends that the reference level for the optimisation of protection of people living in contaminated areas should be selected from the lower part of the 1–20 mSv year^{-1} band recommended in Publication 103 for the management of this category of exposure situation (ICRP 2009b, section 50).

However, the recommendations also indicate that past experience has demonstrated that a typical value used for constraining the optimisation process in long-term post-accident situations is 1 mSv year^{-1}. The recommendations encourage national authorities to take into account the prevailing circumstances and use the timing of the overall rehabilitation programme to adopt intermediate reference levels to improve the situation progressively. In addition, they state that the principles of protection for planned situations also apply to planned work in connection with existing and emergency exposure situations, once the emergency has been brought under control (ICRP 2007a, section 253).

2.10.3. Confusion about dose limits. These recommendations appear to have produced some confusion among members of the public subjected to evacuation. It seems that they interpret that returning to their homes is a planned exposure situation rather than a return to an existing exposure situation. Therefore, they consider that they should be subjected to the ICRP recommended dose limit of 1 mSv year^{-1} for planned exposure situations, a level that was suggested by the ICRP in Publication 111.

While rehabilitation is not yet an imminent issue in the severely affected areas in Japan, a question with no clear answer is already on the agenda: whether the exposure at the forthcoming rehabilitation stage should be categorised as an existing exposure situation. The exposure situation during rehabilitation is somewhat different from exposure in existing situations. Rehabilitation is not a matter of coping with a given extant exposure situation, but it is viewed as an intentional introduction of exposure by moving people into the area with elevated exposure potential and hence formally regarded as a planned exposure situation of informed individuals.

Thus, the public has doubts about what type of exposure the inhabitants of the rehabilitated area will be subject to when the rehabilitation starts. If these people are regarded as members of the public and if the exposure situation is regarded as a planned one, the dose limit of 1 mSv year^{-1} and the corresponding dose constraint could in principle be considered as applicable, therefore requiring annual doses to the residents to be kept below a few tenths of a millisievert, a restriction that might be considered unrealistic and furthermore rather strange and unreasonable. Conversely, it could be assumed that the inhabitants returning to their homes are to be subjected to a very special type of public exposure, namely exposure of people willing to live in the area and who made their decision with informed consent.

2.10.4. Outlook. It seems advisable to explore the feasibility of issuing additional ad hoc guidance for rehabilitating evacuated areas after an accident, including clear numerical criteria as appropriate. The categorisation of exposure situations involved in rehabilitation of the relocated areas could also be revisited. While current international guidelines are not explicit on how to handle this type of situation, it might be considered implicit that returning from a temporary evacuation leads to an existing exposure situation rather than a planned exposure situation. Notwithstanding, it would be appropriate to provide ad hoc recommendations on the protection of the inhabitants' children, including those unborn.

2.11. Restricting individual doses to members of the public

The nuclear reactor accident released large amounts of radioactive materials into the environment. As such, the potential for members of the public to be exposed was greatly increased and ways to restrict their exposures became critically important. The authorities acted appropriately with 'sheltering in place' instructions, evacuation and food restrictions that effectively reduced to low levels the dose received by people living in the affected area. The Japanese authorities tried to follow the situation-based approach recommended by the ICRP and naturally regarded the situation as an emergency exposure situation. The regulatory authority selected a reference level of 20 mSv year^{-1}, whereas the dose limit to members of the public for planned exposure situations is (and continues to be) 1 mSv year^{-1}.

Unfortunately, people living in the affected areas were confused by the logic behind the restrictions applied to individual doses, in what was perceived as a mixture of the pre-emergency, emergency and post-emergency protection policies. The fact that the reactor conditions did not come under reasonable control for nine months after the accident did add challenges and communication problems. Uncertainty and confusion arose among the public, and even among some authorities, on the individual dose restrictions recommended for public protection, particularly between the dose limit of 1 mSv year^{-1} for a planned situation and the various reference levels going up to 100 mSv for an emergency situation.

There was a particular misunderstanding about the appropriate use and application of the dose value of 1 mSv year^{-1}. The public tended to regard a dose above this value as dangerous, which created challenges in coping with the aftermath of the accident. The fact that there is little convincing evidence for human health effects below 100 mSv year^{-1} (or 100 times the dose limit) appeared to hold little sway over the level of concern.

Decisions on the levels used for restricting public doses are often debatable because by necessity they involve judgements on possible future risk and individual acceptance of these risks. The issue becomes exceptionally difficult in a radiological emergency, where doses are difficult to control but people expect to be particularly well protected. The logic behind different levels of restrictions according to the prevailing circumstances is difficult to grasp and accept, not only by the public but also by professionals and competent authorities.

While the current ICRP Recommendations take account of most of the difficulties surrounding issues on individual dose restrictions, they may not adequately convey clearly the assurance for protection under all circumstances requested by the public. For instance, it is not entirely clear to the public that the reference levels recommended for dealing with emergencies, while higher than the limits used for planned situations, still provide sufficient protection to members of the public. Similarly, the rationale behind the numerical limits recommended by the ICRP is also not entirely understood.

2.11.1. Dose restrictions at the time of the accident. At the time of the accident, the intergovernmental International Basic Safety Standards (or BSS) (IAEA 1996a, 1996b, 1996c) were was being revised to take account of the new ICRP Recommendations in Publications 103, 109 and 111. The revision had reached a very advanced state but was not yet adopted (it was finalised on 21 March 2011 and the new BSS was endorsed by the IAEA Commission on Safety Standards (CSS) at its meeting from 25 to 27 May 2011). The relevant IAEA Safety Guide GSG-2 which takes into account the most recent recommendations of the ICRP and provides generic criteria for protective actions and other response actions in the case of a nuclear or radiological emergency, including numerical values of these criteria, was published in May 2007 (IAEA 2007b). In essence this means that at the time of the accident the old BSS, which was based on ICRP Publications 60 and 63, was still in force, while new approaches were under way.

Therefore, while confronting the emergency crisis immediately after the accident, the Japanese authorities had to apply the dose restrictions recommended in the former ICRP Recommendations in ICRP Publication 60 (ICRP 1991) and 63 (ICRP 1992), which were internationally established as the global norm by the BSS and are still used in many national standards. This implied, *inter alia*, the use of an intervention level of 50 mSv for deciding on evacuation. It should also be noted that the protection of the public during emergencies is still handled in many places following the recommendations of the ICRP in its Publication 63 (ICRP 1992), namely, the emergency is managed through decisions on intervention with protective measures, following action levels, which are based on criteria of averted dose for each protective action.

It seems, however, that the intervention criteria in terms of averted dose as recommended in Publication 63 (ICRP 1992) and the BSS have not been so useful in implementing the protective actions such as evacuation and shelter. In order to reduce potential radiation exposure to the public, the Japanese authorities took the precautionary action of advising those within the first 3 km, then 10 km, and finally 20 km of the plant to evacuate and those between 20 and 30 km to stay indoors and get ready to evacuate. In fact, this advice were given mainly on the basis of the conditions at the Fukushima NPP at the time of the decisions.

Over time these criteria were adjusted to the newly recommended ICRP approach (ICRP 2007a) for restricting doses to the public by the use of reference levels with the selection of a reference level of 20 mSv year^{-1}, the bottom value of the recommended band for reference levels for emergency exposure situations, for intervention with protective measures. In selecting the reference level, the authorities tried to follow the situation-based approach recommended by the ICRP. It is to be noted that the regulatory public dose *limit* (emphasis added) for planned exposure situations was and continues to be 1 mSv year^{-1} in Japan.

The Japanese authorities applied the new recommendations to the decision to introduce temporary relocation of people outside the 20 km zone. At this time it was also very difficult to implement this protective action during the response phase because no operational criteria had been enforced. When Japanese authorities had evaluated the monitoring data at the contaminated area, the IAEA advised the Japanese government to carefully assess the situation because one of the IAEA's operational criteria for evacuation (temporary relocation) was exceeded in the village of Iitate. The IAEA published this operational concept in GSG-2 just after the accident in May of 2011. There was some confusion in moving from intervention action levels to reference levels for the emergency situation, which may be caused by generic statements in ICRP Publication 103 (ICRP 2007a, section 275). However, there is general advice on how to use intervention levels described in Publication 103 (ICRP 2007a, table 8, section g): '*Intervention levels remain valuable for optimisation of individual countermeasures when planning a protection strategy, as a supplement to reference levels for evaluation of protection strategies; these refer to residual dose*'. The intervention level may be useful as an inputs to the planning and development of the overall response strategy in the optimisation process. A detailed recommendation on how to use the intervention level is also described in Publication 109 (ICRP 2009a, section 7.2.5). As described in Publication 109 (ICRP 2009a, section 9), it is necessary to determine, in advance, a set of internally consistent criteria for taking prompt actions, and based on these criteria to derive appropriate triggers expressed as measurable quantities or observables for initiating them (see (IAEA 2002a and 2007a)). In the accident, the triggers for initiating precautionary protective actions were the conditions at the plant as measurable quantities or observables.

The real problem was that the Japanese authorities did not have enough time or experience to issue emergency preparedness and response on the basis of the new ICRP Recommendations. It is noted, however, that some confusion was caused by recommendations indicating that the intervention levels are valuable for use as triggers for consideration of relevant protective measures. The differences between the old and new approaches are significant, particularly for emergency exposure situations and members of the public, and they have been summarised in ICRP Publication 103 (ICRP 2007a, table 8).

2.11.2. Recommended dose restrictions. The ICRP distinguish public exposures from other exposures and recommends specific individual restrictions on the dose expected to be incurred by members of the public. It terms as public exposure any exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure and the normal local natural background radiation. It also recognises that public exposure should be controlled coherently and consistently, although necessarily differently, under different exposure situations, namely planned, emergency or existing exposure situations, by a combination of three basic principles: justifying any decision that can change exposures; optimising protection measures; and restricting individual doses. In planned exposure situations, individual dose restriction is achieved through dose limits, expressed as the value of the (additional) effective dose or the equivalent dose to individuals (from all regulated sources that are able to generate planned exposure situations) that shall not be exceeded. The ICRP also recommends the use of dose constraints, a prospective and source-related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a particular source, and serves as an upper bound on the dose in optimisation of protection for that source, being an upper bound on the annual doses that members of the public should receive from the planned operation of any controlled source. For emergency situations, such as that caused by the accident, the source is not under control and dose cannot be 'limited', either *sensu stricto*, *sensu lato* or *sensu amplo*. Therefore, individual dose restrictions are achieved on a case-by-case basis using reference levels as guidance, which are recommended for planning and responding with radiological protection measures. The reference levels represent the level of dose above which it is judged to be inappropriate to plan to allow exposures to occur, and below and above which optimisation of protection should be implemented, the chosen value depending upon the prevailing circumstances of the exposure under consideration.

The ICRP Recommendations for public protection are based on the concept of optimisation of protection, namely selecting the best protection option under the prevailing circumstances, but under restrictions on the expected individual doses. Three types of individual restrictions are recognised: dose limits, dose constraints and reference levels. *Dose limits* are values of the effective dose or the equivalent dose to individuals from (all controlled sources in) *planned exposure situations* (emphasis added) that shall not be exceeded. *Dose constraints* are upper bounds on the annual doses that members of the public receive from the *planned operation of any controlled source* (emphasis added). *Reference levels in emergency and existing exposure situations* (emphasis added) are levels of dose above which it is judged to be inappropriate to plan to allow exposures to occur, the chosen value depending upon the prevailing circumstances. While for public exposure in a *planned exposure*, the ICRP recommends a dose limit of 1 mSv year^{-1} (although in special circumstances a higher value could be allowed in a single year, provided that the average over defined 5-year periods does not exceed 1 mSv year^{-1}), a framework for dose constraints and reference levels for all situations is recommended with three bands: greater than 20–100 mSv year^{-1}, for situations where individuals are exposed to sources that are not controllable, or where actions to reduce doses would be disproportionately disruptive; greater than 1–20 mSv year^{-1}, for situations where individuals will usually receive benefit from the exposure situation but not necessarily from the exposure itself; and 1 mSv year^{-1} or less, for situations where individuals are exposed to a source that gives them little or no individual benefit but benefits society in general.

In its previous recommendations (ICRP 1991), the ICRP had calculated the cumulative risk due to continuous lifetime exposure from birth at certain low dose rates and compared the resulting maximum annual risk with a risk level considered to be acceptable to society i.e. 10^{-4} year^{-1}. From this comparison, the annual dose limit for members of the public, i.e. 1 mSv year^{-1}, was derived and recommended. At the time of preparing the new ICRP Recommendations, new information on radiation risk was taken into account in the re-assessment of radiation risk. The dose limits were left unchanged because the changes in radiation risk coefficients were minor so that a resetting of dose limits was not justifiable when the inconvenience following the reset is considered. Perhaps the rationale behind the dose limit of 1 mSv year^{-1} was not sufficiently considered in the course of revising the recommendations. In the previous recommendations, the unacceptable risk for the public, i.e. 10^{-4} year^{-1}, related to 'practices', namely the introduction of human activities increasing radiation exposure. For 'interventions', the concept of unacceptable risk and consequently of the dose limit was not relevant because intervention only reduces doses. In the formulation of the new system of protection where dose restriction is based on the exposure situations, there is not a distinction between intervention and practices but the dose limit, 1 mSv year^{-1} for members of the public is kept, without necessarily linking it to an acceptable risk.

2.11.3. Confusion among the stakeholders. There seems to be a considerable discrepancy in understanding the dose limit of 1 mSv year^{-1}, which is used worldwide as a public dose limit for planned exposure situations. The general public and society at large tend to regard a dose above this value dangerous and this consequently creates many complications when coping with emergencies. The public (and to some extent the non-specialist authorities) became confused on a fundamental issue: why they were permitted to receive during the emergency situation higher doses than those that they were informed were a '*limit*' before the accident occurred? Thus, doubts arose on the coherence and consistency of the numerical restrictions recommended for individual doses, namely the numerical values of dose limits, constraints and reference levels. This issue created uncertainties in members of the public and their representatives. They cannot understand why the dose limit of 1 mSv year^{-1}, which was valid before the accident, could be exceeded after the accident—at a time when people expect to be better protected. They are confused about the rationale for tolerating individual doses based on reference levels of 20–100 mSv year^{-1} after the accident when doses above 1 mSv year^{-1} (for the sum of all regulated practices!) were unacceptable before the accident. In sum the relevant issue for stakeholders was the rationality of the regulated values (e.g. a dose limit of 1 mSv year^{-1} *vis-à-vis* a reference level of, for example, 20 mSv year^{-1}) and, consequently, the perception that double standards were being recommended (e.g. those suffering the accident being less protected than neighbours of unaffected NPPs).

In addition there are semantic problems in the definitions of the levels of restriction, which in turn create communication problems. An obvious semantic communication problem occurred when the already confusing English terminology denoting the various individual dose restrictions is translated into Japanese. The terms used for the individual restrictions applied to dose (線量) are blurred in English and, unsurprisingly, unclear in Japanese: sophisticated explanations are required for understanding the concepts of dose limit, 線量限度, dose constraint 線量拘束値 and reference level, 参考レベル . The Japanese expression for dose limit, 線量限度, seems to be less ambiguous than its English version: 線量 means dose, used as an adjective, and 限度, which is used as the substantive, means limit, bound, boundary, end, border, brim, edge, verge, etc. Namely, 線量限度 means a level of dose that shall not be exceeded under any circumstance; it is therefore unsurprising that the population was perplexed with the use of dose restrictions higher than the dose limits. Moreover, the descriptors of dose (線量) are also unclear, both in English and in Japanese: dose (線量) can be an extant dose (現存線量) in the habitat, which is usually a total dose (総線量), and it can also be an additional dose (追加線量) added by a given source. In an emergency exposure situation, it is possible to deal with projected dose (予測線量), avertable dose (回避線量) and residual dose (残存線量).

Part of the confusion is perhaps attributable to the fact that the differentiation between additional doses (追加線量) and extant doses (現存線量) is somehow blurred. The semantics of these concepts is not clear in English and could be more confusing in other languages, including Japanese. To the understanding of some, extant dose means the total dose that is there and is incurred for whatever cause. To the understanding of others, it means 'real' dose, a counter concept of hypothetical (or conceptual) dose, and under this understanding an extant dose should not necessarily encompass all dose components including the natural background. In this understanding, an occupational dose of a worker in a year is a kind of extant dose. Equally, the natural background dose to the worker can constitute an extant dose. The extent to which doses are summed into a total dose (総線量) might be dependent on the purpose. The radiological protection recommendations imply as obvious that the level of 1 mSv year^{-1} is not applied to a total dose incurred by individuals but rather to the additional doses (追加線量) added by the introduction of (all) regulated sources. But this perception is not necessarily apparent to the recipients.

An additional problem is that the 'dose limit' is not a factual 'limit' (despite this, unfortunately, it is termed a limit, namely a point beyond which doses shall not pass), but rather a restriction suggested that the regulatory authorities should take into account when they set the authorised levels of individual dose for a given regulated source. This individual dose from each specific regulated source is supposed to be restricted by dose constraints (線量拘束値) to be established by the regulatory authority. It should be noted that the concept of dose constraint also applies to the additional dose (追加線量) expected from the source, rather than to total doses. Namely, it applies to the dose expected to be added by the planned introduction of a specific controlled source to the already existing extant dose.

It might be possible that in the Japanese situation, people and their representatives did not necessarily realise the subtle differences between additional doses and extant doses in planned exposure situations. Even if planned exposure situations in Japan and elsewhere are controlled, so that the additional dose they deliver to individuals is below 1 mSv year^{-1}, the exposed individuals may still be incurring a much higher total dose due to the existence of an extant dose caused by natural radiation, past human practices and releases into the environment from other sources. They may not even be aware that the extant dose may vary by more than two orders of magnitude: its minimum value is around 1 mSv year^{-1} (in very few isolated places of the world); its global average is well above 2 mSv year^{-1}; its typical high value is around 10 mSv year^{-1} (which is incurred by many people in many areas of the world); and, in some few cases, its value may be as high as 100 mSv year^{-1} or more. It is obvious, but not explicit, that the rationale of the 1 mSv year^{-1} restriction for all the additional doses from regulated practices is base on the premise that the introduction of such practices should not change substantially the *de facto* extant dose that individuals are incurring.

For emergency exposure situations, the scenario is necessarily different. At the stage of emergency planning and preparedness it is still feasible to use the concepts of additional dose (in this case it would be the additional dose expected to be delivered should the emergency actually occur). When an emergency does in fact occur, like the accident in Japan, it is no longer feasible to plan for controlling the additional doses due to the accident. At that stage, the relevant dose quantity is the extant dose in the aftermath of the accident—such doses that already exist or are being delivered when control measures are decided—and they have a pivotal role in deciding the justification for intervening with disruptive protective measures or not. Another relevant quantity is the fraction of the extant dose which can be avoided by the application of a protective measure or set of protective measures, namely the avertable dose (回避線量), which has a pivotal role in optimising the protection strategies. For the ICRP the more important quantity for restricting individual doses is the dose that would be expected to be incurred if no protective measure(s) were taken, namely the projected dose (予測線量) and the dose expected to be incurred after protective measure(s) have been fully implemented (or a decision has been taken not to implement any protective measures), namely the residual dose (残存線量) 109 (ICRP 2009a).

The current framework for source-related dose restrictions, with examples for workers and the public, does not indicate explicitly whether it refers to additional doses or extant doses. The reader might suspect that the lower band around 1 mSv year^{-1} refers to additional doses and that the upper band towards 100 mSv year^{-1} refers to extant doses, but this is not clear, and potentially could be a source of confusion. Thus, the numerical values of annual limits *vis-à-vis* the numerical values of reference levels (e.g. 1 mSv *vis-à-vis* 20–100 mSv) are not easily to convey to a sceptical public. Furthermore, in addition to the conceptual confusion about the quantities themselves, there may also be a lack of understanding of the epistemological basis of the recommended levels.

2.11.4. Controversies and questions. Decisions on the levels used for restricting public doses are naturally controversial because they involve judgements on individual acceptability of risks. The issue becomes exceptionally difficult in a radiological emergency, where doses are difficult to control but people expect to be particularly well protected. The logic behind different levels of restrictions according to the prevailing circumstances is difficult to grasp and accept, not only by the public at large but also by the competent authorities. After an accident occurs, people hold a natural but equivocal expectation of being better protected than before the accident. It is difficult for them to recognise that, because an accident has unfortunately occurred, they will obviously be subjected to higher risks. Whatever good the wishes of the authorities, better protection might simply be unfeasible: while in planned exposure situations authorities may be very conservative in their protection strategies, during the aftermath of an unplanned emergency they have to deal with the situation as it is and apply the best protection they can under the prevailing circumstances.

The current system of protection does take account of most of the problems described for individual dose restrictions, but it perhaps fails to convey clearly the assurance for protection under any circumstance demanded by the public. For instance, it is not clear to the public that the reference levels recommended for dealing with emergencies, while being levels of dose higher than the limits used for planned situations, still provide sufficient public protection. It is also not clear what the rationale is for the recommended numbers.

There are many questions related to exposure of people living in 'contaminated areas'. Questions are raised about the tentative reference level, 20 mSv in the first year, asking if the level is not too high when the annual dose limit of 1 mSv year^{-1} and especially exposures to children are considered. Furthermore, many people believe that bearing a child in the area where the projected dose exceeds 1 mSv year^{-1} is inappropriate because the dose limit to an embryo or foetus is only 1 mSv. This belief reflects a misinterpretation of the dose limit recommended for members of the public or unborn children. The dose limit 1 mSv year^{-1} is for planned exposure situations. In existing exposure situations, people, residents in high background areas for instance, are living with elevated doses much exceeding 1 mSv year^{-1}. There is no question that the exposure of current residents in an area with elevated residual radioactivity due to the accident belongs to an existing exposure situation, and hence the concept of dose limit does not apply. Instead, reference levels suitable for the prevailing circumstances are applied.

Contrary to this, '1 mSv year^{-1}' is referred to in almost every situation involving exposure of the public, not only in planned exposure situations but also existing situations related to a radiological event and even related to naturally occurring radioactive materials (NORMs). The new criteria set for control of foodstuff in Japan, enforced on 1 April 2012, are also calculated on the basis of 1 mSv year^{-1} despite the situation not being a planned one.

The somewhat ambiguous presentation of the dose restriction of 1 mSv year^{-1} may have been partly due to misinterpretation. As described, the reference level for an existing exposure situation can be selected in the dose band of 1–20 mSv year^{-1}, with a long-term objective of around 1 mSv year^{-1}. While it is not explicitly indicated, it is implicit that the boundary doses, 20 mSv year^{-1} and 1 mSv year^{-1}, correspond to the dose limits for workers and the public, respectively. Actually, the value of 1 mSv is explained as two orders of magnitude lower than the maximum value for a reference level. However, they should mean the dose limits because, for planned exposure situations, the dose constraints selected in the band should not exceed the dose limits. The upper bound of the first band (<1 mSv) cannot have another value, for example 3 mSv, because a dose constraint for members of the public should be set in this first band and cannot exceed 1 mSv (the dose limit). This means that the upper bound should match the dose limit for the public. This numerical link of 1 mSv year^{-1} to the dose limit for the public leads to confusion about the underlying concept and people believe that their dose should be below 1 mSv year^{-1} whatever the situation.

This problem of interpretation may have been caused by the fact that both occupational and public exposures fall into a single set of bands. In reality, there are no obvious reasons why the boundaries should be 20 and 1 mSv year^{-1} for the reference levels. The second boundary could well be a few mSv year^{-1} for existing exposure situations of the public. The levels 20 and 1 mSv year^{-1} are only appropriate for the dose constraints in planned exposure situations.

2.11.5. Outlook. An important lesson learned from the accident in Japan is to the need for better communication of the rationale behind the judgement as to whether and how an individual dose should be averted. The current recommendations are to select a reference level between 100 and 20 mSv year^{-1} for emergency exposure situations and between 20 and 1 mSv year^{-1} for existing exposure situations. The concepts of additional doses and extant (existing) doses are misunderstood. The public and others do not completely understand the reasons why different dose levels are recommended for different exposure situations, in large part because they believe, incorrectly, that a 'safe' dose is below 1 mSv year^{-1}, independent of the exposure situation.

It would be worthwhile clarifying further the rationale and ethical foundations behind the intended use of individual dose restrictions (dose limits, constraints and reference levels) for protection of the public. The recommendations for the protection of the public in situations of prolonged radiation exposure might sure as a useful guide in this regard (ICRP 1999).

2.11.6. Categorising public exposures due to an accident. From the issues reviewed in the previous sections, it can be concluded that some of the problems found in transitioning from the emergency to an existing situation, in rehabilitating areas and in limiting public doses might all be related to some confusion about the current characterisation of public exposure during an accident. For such categorisation reference should be made to the relevant definitions of exposure and situation. Public exposure is defined as exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure and the normal local natural background radiation; emergency exposure situations are defined as situations that may occur during the operation of a planned exposure situation, or from a malicious act, or from any other unexpected situation, and require urgent action in order to avoid or reduce undesirable consequences. Therefore, according to the definitions, the accident has clearly created an emergency exposure situation and all non-occupational, non-medical and non-background exposure incurred during such an emergency should be treated as an emergency exposure situation for members of the public and therefore restricted with the use of reference levels rather than dose limits. Implicit to this situation is the fact that restrictions on doses that were in place in the planned exposure situation before the accident, specifically the relevant regulations on dose limitations, are 'suspended' or 'relaxed' to make certain important and unavoidable actions possible, or to allow people to stay in the affected areas with exposure above the 'normal' dose limits without violating the principles of protection, i.e. to prevent the occurrence of deterministic effects and to reduce the risk of occurrence of stochastic effects to as low as reasonably achievable taking into account the prevailing circumstances.

It could be (and was) argued that the exposure of the public being delivered during an emergency could conceptually be treated as an existing exposure situation from the beginning, and consequently no concepts such as transition from an emergency exposure situation to an existing one would really be needed. However, the time frame and the controllability of the source differ between emergency and existing exposure situations. Protective actions must be implemented urgently and in a timely manner to maximise effectiveness in an emergency exposure situation, generally on the basis of estimated doses. In the existing exposure situation, planning protective actions can only be done on the basis of good knowledge of the actual conditions of exposure to control the pathways, and is often based on measured individual doses.

The definition of public exposure puts together very different conditions of exposure, namely those resulting from planned situations, from emergency situations and from existing situations. This concoction created some confusion among members of the public and authorities. The uncertainty created might not have much to do with the recommended system of radiological protection but it was perhaps mainly fuelled by the public perception of radiation being serious health hazard, an idea which has been successfully promoted by many. The radiation protection community faced and failed to handle this misconception of the public and authorities alike on the use of reference levels rather than dose limits for the public exposure during the emergency.

The confusion created by the characterisation of public exposure during accidents suggests that it should be reviewed to improve its comprehensibility. The restriction of individual public doses based on dose limit and two reference level bands (one for emergencies and another one for existing situations) confuses people because they think that there must be only one line separating safe and unsafe or dangerous while the recommended restrictions offers multiple numbers. The radiation protection community has failed to convey a clear message that these numbers are just benchmarks and that, moreover, they apply to different quantities, namely to a differential dose, the limit, and to a total extant dose, the reference level. Moreover, the radiation protection system does not give much advice to authorities on how to choose an exact numerical reference level. An explanation of the philosophy behind the numbers would have been very helpful for authorities trying to make the best decisions under the circumstances. Crucially there seems to have been a failure to convey such a philosophy to the Japanese authorities before and after the accident. The use of crude numbers without the philosophy behind them unsurprisingly resulted in disastrous confusion.

2.11.7. Diverse public exposures. The definition of public exposure does make any distinction between members of the public who may not even be aware that a planned exposure situation is being arranged, members of the public who are well aware that an accident has occurred, that they may be exposed to enhanced levels of radiation and that they should take immediate protective actions to avoid exposures, and members of the public who are subject to the informed-consent decision to leave an area that will necessarily have some residual dose or to accept to live under a new existing exposure situation. In the first and second cases the exposure could not be considered voluntary and consented, while in the third there is a case of informed consent in deciding whether to stay, and therefore incur the exposure, or to depart, remain outside the area or come back.

The principles of justification of actions that may change the exposure and of optimisation of protection would apply to all cases. However, individual dose restrictions are very different in these cases. It is recommended that the first case should be controlled with individual dose restrictions exercised via dose limits and constraints over the additional dose expected from the introduction of the new source; assurance of compliance will be provided via source- and environment-related monitoring rather than via individual monitoring. For the second case it is recommended that control will be exercised via reference levels to be decided from a higher band of extant doses extending for around one order of magnitude; individual monitoring is difficult, probably unfeasible, and checking compliance would probably require theoretical modelling. In the third case, restrictions are also recommended to be based on reference levels but selected from a band one order of magnitude lower (it is not clear whether these are extant or differential doses), with the caveat that in the long term such a reference level should numerically coincide with the dose limits; for this third case, individual monitoring is feasible and will usually be implemented.

These conditions of exposure are crucially dissimilar but the definition of public exposure does not differentiate them. *Mutatis mutandi* the problem is similar to that discussed for occupational exposure; within a category of exposure many conditions are assembled and this creates confusion.

2.11.8. Outlook. It is suggested that the tangled problems related to the categorisation of public exposure in an accident should be analysed. The current dose bands and the logic behind the recommended values need to be clarified. The logic behind the upper bound and lower bound for emergency and existing exposure situations and, in particular, the rationale for the 20 mSv transition require clarification.

2.12. Caring for infants and children

The protection of children in the aftermath of an accident has been of particular concern in Japan and parents remain extremely worried about protecting their offspring. They are concerned that the levels of dose applied to the protection of the population as a whole do not provide sufficient safety for the younger members of the population and their children in particular. There is the belief that the reference level of 20 mSv year^{-1} is unacceptably high for children since 1 mSv year^{-1} is the established dose limit for the public for planned situations.

No definitive document with recommendations and guidance specifically dedicated to the protection of children and infants is available. The relatively small difference between the detriment-adjusted nominal risk coefficient for the population as a whole, which includes children, and those for the adult population, i.e. around 30%, merits clearer explanations, particularly in light of the forthcoming UNSCEAR document (UNSCEAR 2013) that comprehensively addresses radiation risks following childhood exposures.

2.12.1. Worrying about the protection of the children. Parents are extremely worried and concerned about the protection of children in the aftermath of an accident. Information on the internet has accelerated the concern about internal exposure to children and the related health effects. In addition to the natural emotional reasons for this preoccupation, there appear to be ostensible facts supporting the concern. The international scientific literature on the issue has produced apprehension. The 2006 UNSCEAR report to the UN General Assembly clearly states that '*lifetime cancer risk estimates for those exposed as children might be a factor of 2–3 times higher than the estimates for a population exposed at all ages*' (UNSCEAR 2006b). It is assumed that the longer life expectancy of children is one factor that may contribute to a higher risk for children than for adults. A higher sensitivity of children to radiation has been reported in a number of epidemiological studies (e.g. Pierce *et al* 1996) but other studies, notably those in high background areas, do not report significant differences. It is to be noted that UNSCEAR and other organisations are completing extensive reviews on the effects of radiation exposure during childhood.

2.12.2. The protection approach. As discussed before the ICRP protection approach is based on the concept of detriment-adjusted *nominal* (emphasis added) radiation risk coefficients. For occupational protection these coefficients are assessed for an 'adult' population; conversely, for public protection the coefficients are assessed for a 'whole' population, namely a population that includes infants and children. As infants and children are generally more sensitive to radiation, the coefficients for a 'whole' population are higher than those for an 'adult' population. The ICRP has recommended that the difference for detriment-adjusted cancer risk of the population that includes children and that excludes children is from 5.5×10^{-2} to 4.1×10^{-2} Sv^{-1}, namely around 30%. For heritable effects, such difference is from 0.2×10^{-2} to 0.1×10^{-2} Sv^{-1}, namely a factor of 2, but the heritable effect coefficients are one order of magnitude smaller than the cancer coefficients and do not weight significantly in the total detriment-adjusted nominal risk coefficient. However, the ICRP risk model without children means it lacks an age group of 0–20, and it has been noticed that the age group in question is 0–10 or less, those of newborn to primary school ages. As indicated before, the lifetime radiation risk for this age group is much higher.

The ICRP makes a further differentiation for children in the calculation of committed effective dose, namely the sum of the products of the committed organ or tissue equivalent doses and the appropriate tissue weighting factors, integrated over time following the intake, where the commitment period is taken to be 50 years for adults, but to age 70 years for children. For instance: for an adult at age 40 the committed effective dose due to a given intake is integrated up to age 90, but the same intake is integrated only up to age 70 for children in spite of the higher sensitivity of children.

It has been noted, however, that dose coefficients for internal exposures are tabulated for age groups while dose conversion coefficients for external exposures are presented for adults. It is speculated that the reason would be that anatomical differences are not significant in external exposures and that the operational quantities are adequate for the protection of infants and as well as adults, but should this be the case the explanation is absent in current recommendations (Chino 2013).

The ICRP Recommendations are rather mute on special protection measures for children in the aftermath of an accident. However, they state that after an emergency situation has occurred, planned protection measures should evolve to best address the actual conditions of all exposed populations being considered with particular attention being given to pregnant women and children (ICRP 2007a, section 280). Moreover, in ICRP Publication 109 (ICRP 2009a), the ICRP has stated that it would be expected that where children and other sensitive groups are likely to be present in an affected area, the consequences and protection strategy for these groups would be explicitly considered as deemed appropriate in the planning arrangements. These general indications may not be sufficient in relation to the proved higher sensitivity of children to radiation exposure, as shown in the epidemic of thyroid cancer in the population affected by the Chernobyl accident. No ICRP document with recommendations specifically dedicated to the protection of children and infants is available.

In international standards, the issue of protection of infants and children (as well as pregnant women) while applying protective actions is tackled by the IAEA in a technical report (IAEA 2005d) and completed as a concept in a safety guide (IAEA 2011c).

2.12.3. Outlook. There are some merits in a re-assessment of the relatively small difference between the recommended nominal risk coefficient for the population as a whole, which includes children, and those for the adult population. The new reviews on radiation risks of children will be especially relevant in this regard.

2.13. Considering pregnant women and their foetuses and embryos

Pregnant women are extremely concerned about the health effects of radiation exposure due to the accident on themselves and their unborn children. Affording proper protection to foetuses and embryos has not been entirely clear or understood, even among medical professionals. Concerns were notably high with respect to exposures after uptake of radioactive material.

While the ICRP's and other recommendations for the protection of pregnant women, foetuses and embryos are detailed and available, they pertain in large part to pregnant female workers and patients. Specific recommendations for female members of the public are not readily available. Guidance for exposures after emergency and existing exposure situations is notably absent. In these situations the biokinetic specificities of individual radionuclides have to be considered, including the different exposure potentials during the different stages of development of embryos and foetuses.

2.13.1. Concerns about pregnancy. In the aftermath of the accident, as in the case of parents and the protection of their children, pregnant women were extremely concerned about the protection of their foetuses and embryos and of themselves and their pregnancy. While no specific data have been reported, this situation could lead to undesired abortions, as was the case in the aftermath of the Chernobyl accident.

2.13.2. International guidance. As indicated before, the ICRP Recommendations clearly indicate that after an emergency situation has occurred particular attention should be given to pregnant women. Some limited advice is provided regarding special dose restrictions for pregnant members of the public, foetuses and embryos. The new ICRP recommendations validate previous recommendations in Publication 82 (ICRP 1999), where it was concluded that prenatal exposure would not require protective actions other than those aimed at the general population. Practical recommendations concerning *in utero* exposures were also provided. Dose coefficients for the embryo/foetus due to intake of radionuclides by the mother were provided in ICRP Publication 88 (ICRP 2001) and, in Publication 90 (ICRP 2003a) it was concluded that newly available information on *in utero* risk at low doses (up to a few tens of mSv) supported in general the advice developed in Publications 60, 82, 84 and 88 (ICRP 1991, 1999, 2000, 2001). The ICRP has also indicated that reference computational phantoms are being developed for children of different ages and for pregnant women and foetuses (ICRP 2007a, section 131).

It is to be noted that the ICRP recommendations for the protection of pregnant women and their embryos and foetuses seems to have focused on pregnant or breast-feeding workers (ICRP 2007a, section 5.4.1) and patients (ICRP 2007a, chapter 7.4), but no specific recommendations are provided for members of the public. The recommendations for pregnant or breast-feeding workers (ICRP 2007a, section 186 *et seq.*), clearly indicate that if a female worker has declared that she is pregnant, additional controls have to be considered in order to attain a level of protection for the embryo and foetus broadly similar to that provided for members of the public (ICRP 2007a, section o), namely that exposures of the embryo and foetus of a pregnant worker are considered and regulated as public exposures (ICRP 2007a, section 180). Furthermore, the ICRP has recommended that female workers who are pregnant or breast-feeding an infant should not be employed as first responders undertaking life-saving or other urgent actions, taking account of the unavoidable uncertainties surrounding early response measures in the event of an emergency exposure situation (ICRP 2007a, section 247).

2.13.3. Outlook. Specific guidance for pregnant women is not readily available. This absence of guidelines is especially notable for exposures associated with emergency and existing exposure situations. Furthermore, the biokinetic specificities of individual radionuclides have to be taken into account.

It might be worth developing specific and comprehensive recommendations for protecting pregnant women who are members of the public and their foetuses and embryos in emergency and existing exposure situations. Specific protection criteria for pregnant and nursing mothers might come from existing recommendations for the protection of pregnant workers and patients.

2.14. Monitoring the public

Two important questions on monitoring the public arose in the aftermath of the accident:

- what should be the general policy of environmental monitoring after an accident; and
- why are members of the public not individually monitored while radiation workers are individually monitored?

While recommendations are available on radiation monitoring for the protection of people living in areas that remain contaminated for years after a nuclear accident, there is no comparable guidance on monitoring the radiological protection of the public in the more immediate aftermath of an accident. This deficiency creates unnecessary public anxiety.

2.14.1. Public monitoring after an accident. Requirements regarding public monitoring after an accident are available in international standards (IAEA 2002a), and there are specific technical documents (IAEA 1999b) and relevant procedures (IAEA 2006) on the subject. But these were not sufficient to avoid some confusion about the general policy of environmental monitoring after the accident.

At the beginning of the accident, emergency radiation monitoring in response to the massive release of radioactive materials into the atmosphere was conducted in particular by MEXT. In the aftermath of the accident, the NSC issued a basic policy on the process of radiation monitoring. The declared objective was to provide a detailed situation of radiation dose distribution in inhabited areas. The NSC indicated a number of items and points of concern about the radiation monitoring to be conducted, including: evaluation of the radiation dose (both the external and internal doses) of the surrounding population exposed up to now from the onset of the accident, and estimation of the future radiation dose, monitoring of chronological change, monitoring of medium- to long-term change in radiation dose, planning and decision on measures to reduce exposure doses, detailed monitoring at locations with exceptionally high dose rates in comparison with the surrounding areas, monitoring of radiation sources causing external exposure in various activities, reviewing and judgement on lifting/modification of evacuation areas, investigation to understand the dynamics of the radioactive materials in the environment, health care for the surrounding population, matching check between the individual dose data and the environmental monitoring data, monitoring of food circulating in the market, assessment of the environmental fate of radioactive materials released, monitoring of medium- to long-term changes in the amount of radioactive materials, monitoring to understand the trend of diffusion in the ocean, monitoring to understand the transition parameters of radioactive materials, etc.

A relevant issue arose due to the fact that members of the public were not individually monitored while workers received that benefit. While some indirect individual monitoring of members of the public has been going on, particularly in public halls (LNERH 2012), and is increasing, it seems that the individual monitoring might have been insufficient.

2.14.2. International guidance. The ICRP Recommendations on monitoring for the protection of the public have been limited to recommendations for monitoring the sources and monitoring the environment (ICRP 1966 and 1985). These recommendations are not new and they are not necessarily tailored to extreme situations such as that caused by the accident. In fact, the recommendations recognise that although both normal and emergency situations are considered, the emphasis is on normal monitoring programmes.

In general, the monitoring of members of the public subject to planned exposure situations is considered unnecessary and impractical. The doses expected in these situations are extremely low and individual monitors would be unusable. For this situation the preferred practice is to monitor the actual release of radioactive substances into the environment. Therefore, taking account of the guidance of the ICRP on radiation monitoring, the IAEA issued international safety standards on environmental and source monitoring for the purposes of radiological protection (IAEA 2005a), which elaborate relevant requirements established by IAEA (1999a, 2000a, 2000b, 2002a, 2002b). These accompany an international standard on regulatory control of radioactive discharges to the environment (IAEA 2000b), which is mainly concerned with the considerations and the procedures to be followed in establishing authorisations for the discharge of radioactive material.

No international standards exist for the individual monitoring of members of the public for cases where the doses could be measurable, such as in post-accident situations. Emergency exposure situations may require a different approach from planned exposure situations. Doses may be higher than those for planned exposure situations and members of the public may feel more reassured if they are individually monitored. This was already recognised at the time of the Chernobyl accident. The International Chernobyl Project (IAEA 1991) was launched several years after the accident (when the authorities of the former USSR allowed an international evaluation of the situation). As part of this project more than 10 000 residents were provided with individual monitoring of both external radiation and internal contamination. Also methods of retrospective dose reconstruction using solid state materials (electron paramagnetic resonance on tooth enamel, luminescence dosimetry with bricks, tiles of inhabited houses) as well as methods using biological indicators, partly together with returned questionnaires, have been used to assess individual doses. Individual monitoring of members of the public provides invaluable data on the actual situation and, more importantly, reassurance to the affected population.

The ICRP Recommendations on individual monitoring have been restricted to workers. The ICRP has issued detailed recommendations on the monitoring of occupationally exposed people (ICRP 1982), which have been translated into international standards that make such monitoring internationally mandatory, and even detailed recommendations for the monitoring of intakes by workers (ICRP 1989). However, neither ICRP Recommendations nor international standards have been issued for the individual monitoring of members of the public.

2.14.3. Outlook. The international guidance on monitoring the radiological protection of the public in the aftermath of an accident appears insufficient. This deficiency creates unnecessary public anxiety (Rojas-Palma *et al* 2009).

It might be worthwhile to consider developing recommendations to deal with monitoring the environment and whether individual monitoring of members of the public is warranted in the event of a large release of radioactive substances into the environment with high potential for public exposures.

2.15. Dealing with 'contamination'

(Of territories, rubble and residues and consumer products)

Following the accident, radioactive substances originating from the accident were present in the public domain, including the surrounding environment, consumer products and foodstuffs. Understandably, the population was concerned and authorities were under pressure to act quickly.

The releases from the accident deposited radioactive substances over large areas, equivalent to the size of the state of Connecticut in the USA. The issues facing the authorities are to determine whether these territories are 'contaminated' and, if so, whether they have to be 'remediated' in order to allow habitation. Unfortunately, the concepts of 'contamination', 'remediation' and 'habitability' have been misunderstood. For members of the public, the question is simply: is it safe for me and my family to live in this area?

The disposal of 'contaminated' rubble, including the 'cleaned up dirt' is arguably one of the most serious challenges faced in the aftermath of the accident. A small fraction of the 'contaminated' rubble may contain levels of radioactive substances that require treatment as radioactive waste with the regulations set by relevant international conventions. The main problem, however, is that most of the rubble is not 'contaminated' as normally considered for radioactive waste but nonetheless will be so perceived by the public, raising its disposal as a serious issue way beyond its actual significance.

Following significant releases of radioactive substances into the environment, products used or consumed by the public, such as foodstuffs, water and non-edible consumer products, may contain elevated levels of radioactive substances attributable to the accident. While radionuclides are present in all foods and consumer products because of natural processes, the additional radionuclides from a nuclear accident can be a serious issue, as it was after Chernobyl for radioactive iodine in milk. The regulation of radioactive substances in food, water and consumer products has not been straightforward. In fact, the control of contaminated consumer products is one of the major unresolved issues in practical radiological protection.

In Japan, the authorities initially issued guidelines restricting the levels of radioactivity in ingested food and drink, which differed from both the WHO guidelines (which were lower) and from the Codex Alimentarius (which were higher). The guidelines were then modified over time and the different values apparently increased the level of concern and confusion.

Some intergovernmental agreements have been reached for dealing with the contamination of foodstuffs, drinking water and non-edible consumer products. However, these agreements remain incoherent and inconsistent. Moreover, there are different guidelines for consumer products under accident conditions and under normal situations and also between domestic versus international control.

The absence of clear quantitative international guidance for dealing with ‘contamination’ in the public domain, for example for remediating ‘contaminated’ territories, disposing of ‘contaminated’ debris and rubble or controlling ‘contaminated’ consumer products, has caused many problems for the authorities. In aftermath of the accident, this is one of the more important issues to deal with.

2.15.1. The issue of ‘contamination’. The presence of radioactive substances in the public domain, including the environment and consumer products, is confusedly termed ‘contamination’. Most languages have derived the term from the Latin *contaminare*, which means ‘made impure’, having a primeval religious meaning. A typical example of the religious understanding of contamination is non-kosher food, namely food not satisfying the requirements of religious law with regard to its origin and preparation. In Japanese, the term is translated as 汚染, which is a combination of the ideograms for dirtiness and dyed. However, in the radiation protection profession, the term contamination is used to denote the presence of radioactivity, even if its amount is small. This subtlety is missed by most people. The public connotation of contamination is different, and to most people it conveys the message of a serious danger of radiation exposure. People usually perceive contamination as a yes/no situation, namely either there is contamination, and therefore some danger, or there is not. The concept of ‘low’ ‘contamination’ is incomprehensible to most people. These undertones cause anxiety and concern to people and confusion to the authorities when handling situations involving contamination.

Perhaps the religious nuance of contamination is one of the reasons why the term may have reached a connotation that was not intended when introduced by radiological protection specialists. The experts’ original intention was to refer only to the presence of any (radioactive) materials expressed by the quantity *activity*, namely describing an amount or concentration of radionuclides in a given energy state at a given time; they did not intend to give any indication of impurity, dirtiness or pollution, nor even of the magnitude of the hazard involved. However, in the public mind, ‘contamination’ became a quasi-synonym for dangerously undesirable radioactivity. In sum, while the term is commonly used by experts to quantify the presence and distribution of radioactive material in a given medium, it became widely misinterpreted as a measure of radiation-related danger. As a result, after the accident, the issue of contamination became loosely related to the protection of individuals and developed into an issue of perception of harm having a social dimension.

The term ‘contamination’ is rarely used in ICRP recommendations. It is used in relation to ‘controlled’ and ‘supervised’ areas in occupational protection. It is also used in relation to terrorist events, which have the potential for exposing people to radiation and causing significant environmental contamination, which would require specific radiological protection measures (ICRP 103, section 273).

Notwithstanding, the ICRP Recommendations include a full section dedicated to the concepts of ‘exclusion’ and ‘exemption’, which are indirectly linked to the concept of contamination (ICRP 103, Section 2.4). The ICRP clearly states that some exposure situations may be excluded from radiological protection legislation, usually on the basis that they are not amenable to control with regulatory instruments, and some exposure situations may be exempted from some or all radiological protection regulatory requirements where ‘such controls are regarded as unwarranted (ICRP 103, section d).

Moreover, the ICRP has issued recommendations about the scope of radiological protection control measures (ICRP 2007b), where it recommends approaches to national authorities for their definition of the scope of radiological protection control measures through regulations, by using its principles of justification and optimisation. The recommendations provide advice for deciding the radiation exposure situations that should be covered by the relevant regulations because their regulatory control can be justified, and, conversely, those that may be considered for exclusion from the regulations because their regulatory control is deemed to be unjustified. It also provides advice on the situations resulting from regulated circumstances but which may be considered by regulators for exemption from complying with specific requirements because the application of these requirements is unwarranted and exemption is the optimum option. The recommendations also address specific exposure situations. The quantitative criteria in the recommendations are intended only as generic suggestions to regulators for defining the regulatory scope, in the understanding that the definitive boundaries for establishing the situations that can be or need to be regulated will depend on national approaches.

The issue of 'contamination' became particularly critical in Japan in territories where some of the radioactive releases from the accident were deposited in rubble and other residues left after the accident and in consumer products. However, these issues are distinct and they are described separately later.

2.15.2. Radioactivity in territories. The fallout of some of the releases from the accident deposited radioactive substances over large territories. The issues for the authorities are whether these territories are 'contaminated' and whether they have to be 'remediated' in order to allow their habitation (it is noted that remediation relates not only to relocated areas but also inhabited areas at lower contamination levels). It seems therefore that there is a strong connection between the misunderstandings about the concepts of 'contamination', 'remediation' and 'habitability'. In simple terms, remediation should be expected if there is contamination and there will be contamination if and only if the levels of radioactivity per unit area are above given values considered unsafe for living in. Ambiguity in understanding has been part of the problem in solving this controversial issue. Practical solutions for the conundrum of whether or not a 'contaminated' territory needs 'remediation' for its 'habitability' have been unconvincing for a growingly sceptical public, *inter alia* because the arguments were unimpressive and puzzling. There have been basic common misunderstandings on the basic concepts, not only by the public but also among experts.

The so-called 'remediation' of territories, experiencing so-called 'contamination' with radioactive substances, and requiring 'rehabilitation', has been one of the more elusive issues for the radiological protection community to tackle and regulate. Following the presence of radioactive residues over a territory, radiological protection experts have generally been unable to respond to a simple and straightforward question from anxious members of the general public: is it safe for me and my family to live in this territory? Providing confusing answers to such a simple enquiry is most unhelpful. Experts try to explain that, while the territory was in fact 'contaminated', 'remediation' had to be 'optimised', and depending on many factors (generally incomprehensible to common souls) they might or might not remain there. Moreover, sometimes members of the public are implicitly advised that it is ultimately their decision to leave or to remain in a 'contaminated' territory. The meaning of the term 'remediation' is as vague as the meaning of the term 'contamination' already discussed. Thus 'remediation' became closely associated with the misinterpretations of 'contamination', as the former is a consequence of the latter. The term may be used in a variety of contexts and, as a result, it can be badly misunderstood. In common parlance, it means providing a remedy, namely a pharmaceutical product, cure or treatment, for a medical condition. Not surprisingly, members of the public became extremely anxious when informed that the place were they are living will be subject to remediation because of a radiation-related contamination!

As indicated before, however, environmental radiological protection specialists use the term remediation to mean the removal of radioactive substances from environmental media such as soil, groundwater, sediment or surface water. The ultimate purpose of ‘remediation’ is protecting human health and the environment against potential detrimental effects from radiation exposure, rather than eliminating ‘contamination’ *per se*. In international standards (IAEA 2007a) the term remediation has been formally defined as any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans. Notably, the formal definition underlines that the term does not imply ‘*complete removal of the contamination*’ (*sic*), a key concept that is usually forgotten.

The untranslatable and more informal English term ‘cleanup’ has been used as a synonym for ‘remediation’ and this usage added to the misunderstanding. (It is to be noted that English substantives resulting from the combination of verbs and prepositions are particularly obscure in their precise meaning and difficult to translate.) The term implies making a place ‘clean’, and is taken to mean making it absolutely free from any foreign substance. The confusion arise because a decision to shrink a given level of radioactive ‘contamination’ may be taken simply because the radioactivity is measurable and not because is ’dirty’ or ‘harmful’. Moreover, the term ‘clean’ can also be tacitly equated to ‘morally pure’, which again has religious implications. This combined with the misinterpretations of the term ‘contamination’ already described may be playing an important role in the misunderstanding.

The terms ‘rehabilitation’ and ‘restoration’ have also been used within the context of ‘remediation’. And, again, their usage has been confusing. These terms may be taken to imply restoring the conditions that prevailed before the ‘contamination’, presuming that such restoration is feasible, which is not normally the case (e.g. owing to the effects of the remedial actions themselves). For this and other reasons, the use of these terms as alternatives to remediation has been discouraged.

2.15.3. Radioactivity in rubble and other residues from the accident. The disposal of ‘contaminated’ rubble (and more so ‘cleaned up dirt’) is probably one of the most serious issues in the aftermath of the accident. A fraction of the ‘contaminated’ rubble may contain substantial amounts of radioactive substances, which may require that it be treated as radioactive waste with the regulations required by relevant international conventions. The main problem, however, is that most of the rubble is not really ‘contaminated’ but will be so perceived by the public, making its disposal an artificially serious issue. Thus, a main issue with the disposal of most of the ‘contaminated’ rubble becomes again the misunderstanding of the term ‘contamination’. This misinterpretation is not surprising, as it was similar during the accidents in Goiânia (IAEA 1988a) and Chernobyl (IAEA 1991), but may have enormous effects on the relevant radiological protection strategies.

2.15.4. Radioactivity in consumer products. It is natural that, following significant releases of radioactive substances into the environment, like those from the accident, products used or consumed by the public, such as foodstuffs, water and non-edible consumer products, may present elevated levels of radioactive substances attributable to the accident. While natural radionuclides are present in consumer products because of natural processes, the inclusion of artificial radionuclides following accidents is a serious issue because it is perceived as a more pervasive process of incorporation of radioactivity. Its regulation has been controversial and not straightforward. In fact, the control of these consumer products is one of the main unresolved issues of practical radiological protection. It has created (and continues to create) many problems for Japan in general and for the Fukushima region in particular.

While the exposure conditions in Japan following the accident represent an emergency exposure situation, the exposures from consumer products could be characterised as planned, emergency or existing, depending on the circumstances of incorporation of the relevant radionuclides. Therefore, in theory, control measures could conceptually be implemented following the ICRP Recommendations for each type of situation. However, mainly due to the increasing globalisation of markets, regulation of radioactivity in consumer products cannot be established on a case-by-case basis but needs to be standardised, which in this case makes the characterisation of exposure situations futile.

Perhaps due to these difficulties the ICRP recognised that the radiological protection regulation of consumer products was an international challenge (ICRP 2007b). The ICRP had been following with interest the development of standardised radiological criteria for consumer products being implemented under the aegis of international intergovernmental organisations. Furthermore, it considered that a good basis for generic and universal radiological protection criteria could be provided by existing international intergovernmental agreements, such as those established by the Codex Alimentarius Commission for foodstuffs, by the WHO for drinking water and by the IAEA for non-edible consumer products.

The specific guidance levels for radionuclides in drinking water have been incorporated into the third edition of the WHO's *Guidelines for Drinking-water Quality* (WHO 2008). The guideline levels for radionuclides in foods following accidental nuclear contamination for use in international trade were adopted by the Codex Alimentarius Commission of FAO/WHO, and are published in Schedule I, Radionuclides, of the Codex General Standard for Contaminants and Toxins in Foods (CAC 2006). The levels for non-edible commodities were issued as an international Safety Guide on the Application of the Concepts of Exclusion, Exemption and Clearance (IAEA 2004), which provides values of activity concentrations of radionuclides in bulk amounts of materials in public use. However, the situation is far from being resolved. In fact, these intergovernmental agreements are incoherent and inconsistent among themselves. For instance, under the WHO guidelines it would not be acceptable for drinking water to contain more than 10 Bq of ^{137}Cs per litre of water; however, if the affected people decide to drink fruit juice rather than water, then this would supposedly be regulated by the Codex Alimentarius, which accept up to 1000 Bq of ^{137}Cs per kilogram of product, i.e. per litre of juice. There are caveats that try to explain this inexplicable two orders of magnitude difference for essentially the same consumer product: the WHO guidelines are explicit in that the numbers are valid for 'normal' situations. But how can any member of the public accept that after an accident, when they are expected to be better protected, the limits can be relaxed by two orders of magnitude? Another even more shocking example is that it would be possible to eat foodstuffs that could not be used as a non-edible product. For instance, according to the Codex Alimentarius it is possible to consume rice (a critical product in the Japanese diet) containing up to 1000 Bq of ^{137}Cs per kilogram; however, if the rice is used to make rice-paper (a common non-edible product in Japan), then, according to the IAEA guideline for non-edible products, it should not contain more than 100 Bq of ^{137}Cs per kilogram of product!

International recommendations for generic and operational criteria to restrict consumption of contaminated food and drinking water in an emergency are contained in IAEA guidance (IAEA 2011c). These generic criteria are based on the reference levels in an emergency exposure situation recommended by the ICRP (ICRP 2007a). Criteria for the international trade (e.g. the Codex Alimentarius) are based on the annual dose limit of 1 mSv, hence the values for international trade cannot be the same as the values for restricting consumption of contaminated food in an emergency. These values are not the same, as they apply for different purposes. There was a similar experience after the accident at Chernobyl, when criteria for restricting of food consumption in the affected countries were different (higher) from introduced levels for trade between different countries in the world. The difference between criteria for restriction of consumption of contaminated food (IAEA 2011c) and criteria for international trade (Codex Alimentarius) is continuously explained by the IAEA and FAO, but much confusion remain among members of the public and the authorities alike.

The Japanese authorities initially issued specific guidelines for restrictions on food and drink intake, which were aimed at restricting consumption of contaminated food within the country and differed from both the WHO guidelines (which are lower) and the Codex Alimentarius (which are higher). They were reduced over time, and these differences and changes were not necessarily helpful in reducing the level of confusion. On 27 October 2011 the Food Safety Commission (FSC) under the Cabinet Office of the Japanese government answered requests for an assessment of the health effects of contaminated food from the Ministry of Health, Labour and Welfare (MHLW), the agency that is responsible for risk management of food. The FSC recognised that provisional regulation values on nuclides were adopted immediately after the accident without an assessment of the health effects of food. The philosophy of the FSC implies that the regulatory food limits even for radioactive materials should be decided independently of the exposure situation, since there is no difference in the criteria for protecting health effects between emergency and planned situations. The risk assessment by the FSC would have an impact on the decision regarding a new limitation in place of the current food restrictions adopted for the emergency. Serious attention is paid to this issue by the public in terms of controlling internal exposure in the existing exposure situation as it transfers from being an emergency exposure situation. Furthermore, this probably implies that the risk-based philosophy of radiological protection has not prevailed even in the academic field of chemical toxicity with non-radiation experts who seem unlikely to take a risk-informed approach. The situation-based approach in addition to the risk-informed approach needs to be disseminated in order to clearly select the level of protection that should be the best possible under the prevailing circumstances. It seems that a dialogue between radiation and other risk experts such as chemists is needed.

The ICRP has recognised the difference in management for consumer products produced and consumed in the region (or country) affected by the accident and those subject to interregional or international trade. The ICRP has recommended that (ICRP 1999, section 131):

- If the restrictions on commodities produced in the area affected by an accident have not been lifted, production of the restricted commodities should not be restarted; conversely, if the restrictions have been lifted, production can be restarted. If an increase in production is proposed, it could proceed subject to appropriate justification.
- In circumstances where restrictions have been lifted as part of a decision to return to 'normal' living, the resumption and potential increase in production in the affected area should have been considered as part of that decision and should not require further consideration.

2.15.5. Outlook. The absence of clear quantitative international guidance for dealing with 'contamination' in the public domain, for example for remediating 'contaminated' territories, disposing of 'contaminated' debris and rubble or controlling 'contaminated' consumer products, has caused many problems for the authorities and has become one of the more important issues to deal with in the aftermath of the accident.

While recognising that the ultimate responsibility for establishing standards on 'acceptable' levels of 'contamination' in the public domain rests with national authorities and relevant international intergovernmental organisations, it might be worthwhile to consider developing ad hoc international consensus guidelines for dealing with this challenging issue.

Some intergovernmental agreements have been reached for dealing with the contamination of foodstuffs, drinking water and non-edible consumer products, but they are incoherent and inconsistent and could not be applied in Japan. Moreover, the differences in allowable levels for consumer products under accident conditions and under normal situations and also between domestic versus international control need to be addressed.

It might be worthwhile to consider developing a set of universal values for the regulation of consumer products containing radioactive substances (e.g. by further elaborating ICRP Publication 104), therefore facilitating the adoption of such values by agreements to be reached under the aegis of relevant intergovernmental agencies. The ultimate target will be consensus regulations from intergovernmental international organisations for: levels of radioactive substances in territories that would need no further 'remediation'; levels of radioactive substances in rubble and other residues that would allow them to be managed normally; and, levels of radioactive substances in consumer products, such as foodstuffs, drinking water and non-edible products, that permit their universal use without restrictions.

2.16. Recognising the importance of psychological consequences

The radiation exposure situations created by the accident, combined with the disruption to lives caused by the preceding catastrophic earthquake and tsunami, produced serious psychological consequences in the affected population. The psychological consequences include depression, grieving, post-traumatic stress disorder (PTSD), chronic anxiety, sleep disturbances, severe headaches and increased smoking and alcohol use. In many areas dysfunctional behaviours included intense anger, despair, extreme anxiety about health and health of children and, in particular, concern over stigma and discrimination.

A recently published report by Japan's Reconstruction Agency indicates that the stresses of personal involvement in the evacuation, management and clean-up related to the Fukushima accident have emerged as the biggest factor in ill-health for Japanese people.

The accident reconfirmed that psychological consequences are a major outcome following major radiation accidents. While they are important, consequential and observable health effects in their own right, they are ignored in radiological protection recommendations and standards. Advance planning for emergencies should recognise the need to deal with psychological consequences and the concerns that may be engendered for decades following an accident. Responding to the mental health needs of the community as a whole raises many challenges of preparation and of providing adequate care.

2.16.1. A recurrent issue. The importance of the psychological consequences of catastrophic radiological events has been a recurrent topic in radiological protection. However, it receives little if any mention in radiological protection guidance. Serious psychological health effects are common consequences of radiation-related accidents involving vast numbers of people. It was present in the radiological accident in Goiânia, Brazil (IAEA 1988a, 1988b), and in the Chernobyl accident (IAEA 1996b), and the resulting psychological effects could be considered one of the more serious penalties of these events. Mental disorders were a relevant consequence of the Chernobyl accident (Drottz-Sjoberg *et al* 1993, Lee 1996, Bromet and Havenaar 2007). They were also a serious issue in the aftermath of the 1945 atomic bombings of Japan: a recent publication (Kim *et al* 2011) covers the persistent psychological distress after exposure to the Nagasaki atomic bomb explosion in 1945, concluding that having been in the vicinity of the atomic bomb explosion, even without any radiological exposure, continued to be associated with poor mental health more than half a century later. Fear, even if unfounded, about the potential hazard of being exposed to radiation and lack of knowledge about radiological risk appears to be responsible for long-lasting and debilitating health conditions.

It is therefore unsurprising that psychological consequences may be the dominant health effect in the aftermath of the Fukushima accident (Bromet 2012). In fact, the accident has reconfirmed that psychological consequences are a major outcome of major radiation accidents. Psychological consequences are dominant in the accident aftermath and they are health effects in their own right. These situations have shown that profound and scientifically solid information about radiation exposure and its effects is necessary to prevent or mitigate psychological outcomes. While such information should already be provided before accidents happen, it becomes absolutely necessary during emergency situations and the related evacuation and eventual rehabilitation.

2.16.2. The experience of Chernobyl. People in the area of the Chernobyl plant were exposed not only to radiation but also to multiple psychological stressors, including displacement, separation from families, misinformation and stigmatisation. Comparisons of adult populations exposed to radiation with demographically matched comparison groups who were not exposed showed that after two decades the exposed populations had significantly poorer mental health. The analyses indicated that perceived (rather than actual) exposure to harmful levels of radiation was the key risk factor and that mothers of young children were at particularly high risk. In another study, clean-up workers (called liquidators) were found to have higher rates of suicide, depression, PTSD and severe headache compared with a matched comparison group. Studies of the long-term effects of exposure on the psychological and cognitive development of children yielded ambiguous results, partly because the researchers did not have direct access to data on exposure. The Chernobyl Forum concluded that the greatest impact of the Chernobyl disaster, in terms of the number of people affected and its implications for public health, was its impact on mental health.

It has been pointed out (Bromet *et al* 2011) that findings on the psychological consequences of the Chernobyl accident suggest the importance of monitoring of mental health in the routine surveillance of populations affected by the accident at Fukushima, of providing credible information to disaster victims and of training physicians to recognise and treat common mental health problems, while keeping in mind the significance of perceived, rather than measured, effects.

2.16.3. Observed psychological outcomes. The psychological consequences of the accident are evolving into the same type of outcome observed in other similar situations (Bromet 2012), such as:

- depression,
- grieving,
- PTSD,
- chronic anxiety,
- sleep disturbances,
- severe headaches, and
- increased smoking and alcohol use.

Moreover, some other psychological outcomes are observable, such as:

- intense anger,
- despair,
- long-term anxiety about health and health of children and, in particular,
- stigma.

The accident has caused these various psychological effects to various degrees, resulting in many undesired outcomes such as consideration of unnecessary abortions by pregnant women. Stigma seems to be a particularly important consequence of the accident. Within this context, stigma can be defined as a mark of disgrace associated with being a victim of the accident and might be related to the general issue of communication. While stigma had been observed in other accidents, it might be particularly significant in this accident due to the different subtly related concepts in Japanese culture. Stigma can be understood in Japanese as similar concepts such as: 汚名, polluted name; 烙印, mark; 恥, shame; 不名誉, dishonour; 不面目, humiliation; and, fundamentally, 被差別, discrimination.

A recently published report by Japan's Reconstruction Agency (Reconstruction Agency 2012) indicates that the stresses of personal involvement in the evacuation, management and clean-up related to the Fukushima accident have emerged as the biggest factor in ill-health for Japanese people. The mental or physical burden of the forced move from their homes because of the Fukushima accident was the cause of 34 early deaths. The figure compares with 1916 people from Fukushima, Iwate and Miyagi prefectures who died during evacuation from areas hit only by the tsunami and the earthquake. The leading causes of the majority of those early deaths were disruption to the smooth operation of hospitals, the exacerbation of pre-existing health problems and the general 'mental fatigue' from dramatic changes in life situations. A cross-section of all people who died during their evacuation showed that the vast majority were elderly: only 4% were below 60 years of age, while 67% were over 80. Some 18% of these fatalities came within 1 week of the natural disasters and nuclear accident; 48% within 1 month; and 78% within 3 months.

Regarding the health risks attributed to nuclear evacuation, the Reconstruction Agency said that information was key. In a nuclear accident situation it is essential for the authorities to understand and communicate the direction in which contamination is travelling and where it may be deposited on land. Given this information, as well as 'basic knowledge' of the risks of radiation, residents would not 'feel anxiety unnecessarily'.

While the Japanese authorities were effective in protecting the population, there were serious multiple failures in official communication resulting in widespread exaggerated fears of the risks posed by the accident.

2.16.4. International guidance. In its recommendations for protecting people against radiation exposure in the event of a radiological attack (ICRP 2005b), the ICRP had recognised the major psychological impact to be expected from the combination of a radiological catastrophe with the fear of radiation, stating that it will be necessary to provide the public with timely and accurate information. Some of these ICRP Recommendations are *mutatis mutandi* applicable to the psychological consequences of the accident. They deal with psychological health effects, including distress and fear of cancer and other health effects attributable to radiation, and also with psychological triage and disposition, and contain a full description of psychological issues.

The ICRP fundamentally recommends that:

- The response must essentially institute a process for returning to normality, while dealing with psychological issues such as distress and misattribution and fear of illness, which will be major concerns.
- The perceived risk is a major contributor to the anxiety and fear that may be induced by a radiological catastrophe—an extra dimension presenting additional challenges to those who will have to manage the health consequences of such an event.

- Psychological impacts are likely to pose a significant challenge, and these issues need to be addressed in planning the response, because following a serious radiological accident, health-care providers, offices, medical clinics and hospitals will be deluged with symptomatic and asymptomatic people seeking evaluation, care and guidance for possible radiation exposure or contamination.
- A well-organised, effective medical response will instil hope and confidence, reduce anxiety and support the continuity of basic community functions.
- Health-care providers will need appropriate training in advance, as they may also be subject to fear and anxiety.
- Ensuring clear communications and the availability of advance information are key elements in the successful preparation for managing radiological consequences of a radiological accident.

Furthermore, ICRP Publication 109 (ICRP 2009a) states that the results of an analysis of the lessons learned from the responses to the Chernobyl, Goiânia and other emergencies over the past years lead to the conclusion that while the nature and extent of past emergencies are dissimilar, the lessons concerning their outcome are very similar: psychological consequences may become more important than the radiological consequences. This might be *inter alia* due to a lack of pre-established guidance that is understandable to the public and officials and because of the nature of the actual prevailing circumstances. Thus, it recommends that during an emergency exposure situation other measures are also likely to be considered, including comprehensive psychological counselling, which should not be construed as suggesting that people are experiencing mental disorders (e.g. (radio) phobias) but rather the need to contextualise their psychological experiences.

2.16.5. Outlook. Advance planning for emergencies should recognise the need to deal with physiological consequences, and with the concerns that may be engendered for decades following an accident. Responding to the mental health needs of the community as a whole raises many challenges of preparation. In addition to dedicated facilities, staffing, contact registry and intensified primary care follow-up efforts, intervention for people concerned with unexplained symptoms should involve brochures, fact sheets and literature about self-management approaches to medically unexplained symptoms. The use of an on-site advocate who can help people with unexplained symptoms to overcome perceived barriers to care helps to defuse people's notions that no one cares and affords clinicians a way to reduce the pressure to meet these people's needs.

It might be worthwhile to consider developing international recommendations on protection against the psychological consequences of radiological accidents, perhaps elaborating upon the recommendations already available for protecting people against radiation exposure in the event of a radiological attack.

2.17. Fostering the sharing of information

Communication between radiological protection experts and the authorities and between the authorities and the public at large presented difficulties and was far from optimal.

The accident confirmed the importance of communication during a serious accident involving radiation exposure of the public. Mistakes in communicating radiation risk and protection measures to members of the public and the media were unfortunate and raised concerns as well as issues of credibility.

A number of lessons were reconfirmed:

- the important role of the media in a serious accident;
- the importance of sharing information with the media regularly;
- the important role of social networks, a new but ubiquitous way of communicating facts and events almost instantaneously;
- the importance of involving non-radiation experts in the sharing of information; and
- the importance of sharing information with the medical profession and with teachers.

2.17.1. A candid description. The complicated issue of communication after a nuclear or radiological accident is candidly described in the Japanese government reports on the accident (GOJ 2011a, 2011b). Some basic and profound ideas on communicating radiation risk were ignored. Firstly it was essential that the communicators learn the meaning of the sophisticated issues of radiation risk they wished to communicate, and then proceed with the communication. Many communicators, particularly politicians, did not know about the issues they wanted to communicate. The communicators should have recognised from the start that the single biggest problem in communicating radiation risk is the illusion that proper understanding has been conveyed. If communicators wish to converse understandably with the public, they should have first properly defined the terms being used (www.iaea.org/newscenter/focus/fukushima/japan-report.pdf.)

2.17.2. International guidance. The issue of communication was not addressed by the ICRP in its latest general recommendations which are rather mute on how to communicate with members of the public and the media in the aftermath of emergency exposure situations, communication being referred to only in the context of occupational exposures. However, in its recommendations protecting people against radiation exposure in the event of a radiological attack (ICRP 2005b), the ICRP had addressed the issue of reliable and accurate communication and dissemination of information as a key element for successful radiological protection efforts in the aftermath of an extreme event. Many recommendations are available in the open literature for this purpose and the ICRP recommended that national authorities to refer to the available reference material in establishing their communication strategies.

The ICRP has therefore recognised the importance of communication, indicating *inter alia* that:

- Justifiable radiological protection efforts without proper communication with the public can themselves become a contributor to anxiety and fear as people can misinterpret them as an indication that they are subject to a high risk.
- Ensuring clear communications and the availability of advance information are key elements in the successful preparation for managing radiological consequences.
- Clear, understandable and empathetic communications are needed, both immediately following a catastrophic event such as the accident, and repeatedly and consistently for extended periods of time after the event. This is especially important for the phase when the planning of the rehabilitation has to be discussed.
- A credible and successful communications programme for consequence management should begin with the fundamental objectives of reducing risk to the public, and enables those affected to comprehend its scope and make informed decisions

The accident experience reiterated how important communication is in the aftermath of a serious accident involving exposure of the public to radiation. Mistakes in communicating radiation risk and protection measures to members of the public and the media have been made during previous accidents and were repeated in this accident.

If the communicators had been strong in their understanding, their strength would have spoken for itself, but if they were weak, words would have been of no help. ‘White lies’, or kind lies’, which are benign or trivial lies aimed at helping people not to become anxious, are unhelpful for communication (in the long run by his own mouth does the liar expose himself). It was important for the communicators to see the forest behind the trees, too much detailed information on the accident was provided but a comprehensive picture was absent. People have certain levels of knowledge on radiation risk, usually very limited levels, and the communicators should have honoured those limits.

Since misunderstanding of radiation risk seems to be nested on top of the psychological consequences of the accident and vice versa, and considering the unequal power of bad news and good news in social amplification and the endeavours of activist groups and their propaganda power of in contemporary society, the ICRP should not just sit back and recommend principles and scientific facts. The ICRP may consider actions to overwhelm negative communications or at least to proportionate them. The ICRP should do all it can do to reach the minds of people. Thus the ICRP may take the initiative of constructive actions, addressing concerned international organisations including UNSCEAR, the International Agency for Research on Cancer, the International Radiation Protection Association, the IAEA and the WHO. In this sense, a good example is the recent development by the IAEA on communication with the public in a nuclear or radiological emergency (IAEA 2012b).

In fact the ICRP should be involved in the issue of communicating with accuracy and clarity issues such as the risk of radiation exposure and the logic and ethical foundations of protective measures. The ICRP may wish to elaborate further its guidance on this problem issued with the ICRP recommendations on protecting people against radiation exposure in the event of a radiological attack. Especially during the phase of discussion about rehabilitation a clear communication of radiation risk is necessary. The possible external and internal radiation exposures and the following radiation effects have to be communicated in order to achieve acceptance for the procedures. This has to be performed on the basis of free choices. Alternatives have to be explained. The radiosensitivity of infants, embryos/foetuses as well as future generations should be considered. Distributive justice is another important criterion in these considerations. Risk management has to reduce the risk to an acceptable level and to show the plausibility of the procedure. To achieve credibility is another important issue for risk communication (Streffer *et al* 2004).

It is apparent that communication was a key issue driving a lot of the public and media (and decision-maker) reactions to the accident. It is well known that clear communication is essential in this type of situation, which has been expressed in ICRP Publications 109 and 111. In any case, however, it could be useful for the ICRP to be clearer with its key accident-related recommendations. A possibility would be to develop a *short ICRP accident primer* to present in clear language what the ICRP is recommending and why. This would be a first in the ICRP’s history, aiming a recommendation at the non-radiological protection community. This would be a ‘communication tool’ that could cover radiation risks, the ICRP’s principles (justification, optimisation, limitation) and their application in specific situations (planned, emergency and existing). ICRP-TG84 notes that the recent ICRP symposium in Bethesda, USA (ICRP 2011) was a good example of a first step towards better communication among radiological protection professionals. The group also emphasise that in order to improve communication further ICRP publications should be more readable.

3. Overall recommendations

This memorandum has attempted to identify a number of issues related to radiological protection arising in the aftermath of the Fukushima accident, to compare these issues *vis-à-vis* ICRP Recommendations, to derive some lessons learned and, subsequently, to suggest possible corrective actions. While substantive international guidance is available for tackling many of the issues addressed in this report, many lessons can be extracted from the accident experience. The radiological protection community has the responsibility, if not the ethical duty, to learn from the Fukushima accident and suggest improvements in the system of protection. Accordingly, it should be ensured *inter alia* that:

- radiation risk coefficients of potential health effects be properly explained to enhance proper interpretation;
- the limitations of epidemiological studies for attributing radiation effects following low exposures be clearly explained;
- protection quantities and units should be more clearly explained to minimise confusions;
- the potential hazard from the intake of radionuclides into the body should be explained and placed in proper perspective with regard to external exposures;
- rescuers and volunteers should be protected with an ad hoc system;
- clearer recommendations on crisis management and medical care and on recovery and rehabilitation should be developed and made readily available;
- recommendations on public protection levels (including infants, children and pregnant women and their expected offspring) and on related issues (such as, categorising public exposures due to an accident, transitioning from an emergency to an existing situation and rehabilitating evacuated areas) should be consistent and understandable;
- updated recommendations on public monitoring policy should be developed;
- acceptable (or tolerable) 'contamination' levels need to be clearly stated and defined;
- strategies for mitigating the serious psychological consequences arising from radiological accidents have to be sought; and
- ways to foster information sharing on radiological protection policy after an accident must be developed with recommendations to minimise the disruption caused by communication lapses.

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areas; radiobiology and radioepidemiology; lessons learned from the Chernobyl accident (including psychological lessons); and radiation safety and guidelines regarding health risks. The Symposium concluded *inter alia* that Japan has considerable expertise in radiation-related issues, which should be called upon to help those affected by the Fukushima nuclear accident, recognising the responsibility of the authorities to learn as much as possible from the information obtained (Sasakawa *et al* 2011, Sasakawa 2012). A summary of the main issues being considered by the ICRP-TG84 has already been given at the Fukushima International Expert Symposium (González 2012).

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