APPENDIX E. HEALTH IMPLICATIONS FOR THE PUBLIC AND WORKERS

I. INTRODUCTION

A. Objectives and structure

E1. The objectives of this appendix are to provide a commentary on the immediate and long term health implications of exposures to ionizing radiation resulting from the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS), and to consider the on-going health monitoring programmes.

E2. The phrase "health implications" is used here to express the Committee's interpretation of information on the consequences for health based on its assessment of radiation exposure from the FDNPS accident, specifically *(a)* to provide information on health effects that have been observed in exposed populations within the time frame considered by the Committee (generally about two years after the accident but in some cases longer); *(b)* to provide insight into the magnitude of risks of future health effects from the assessed radiation exposure of these populations; and *(c)* to provide information as to whether it was likely that risks would become manifest and discernible in the future disease statistics covering these populations. In addition to the interpretation of information on health implications of the radiation exposure, some contextual commentary is made on broader health implications, such as the impact on mental health, that are related to the accident and the response to it, as well as to the natural disaster itself.

E3. Section I.B briefly recapitulates current knowledge on the health effects and risks from exposure to ionizing radiation. Consideration is then given separately to the health implications for the public (section II) and for those exposed occupationally or in responding to the FDNPS accident (section III). The commentary on health implications for the public relied upon the Committee's assessment of exposures of different population groups in Japan, as outlined in appendix C. The commentary on health implications for workers was based on the exposures reported to—and to the extent possible independently assessed by—the Committee, and outlined in appendix D. The health risk assessment conducted by the World Health Organization (WHO) based on its preliminary dose assessment was also reviewed. Health effects, irrespective of their cause, that were observed within about the first two years following the accident, and risks of future health effects are discussed. The Committee drew upon the experience from the Chernobyl accident and its implications for the health of the general public and of workers. The radiation exposure resulting from the FDNPS accident is also put into perspective by using some other sources of exposure as a frame of reference, to help provide some context for understanding the overall radiation exposure of the population of Japan.

B. Recapitulation of knowledge on health effects and risks from exposure to ionizing radiation

E4. Exposure of tissues or organs to ionizing radiation can induce the death of cells that can be extensive enough to impair the function of the exposed tissue or organ. Effects of this type, which are called "deterministic effects", are clinically observable in an individual if the absorbed dose to a tissue exceeds a threshold level specific to that tissue. Such effects include the acute radiation syndrome (ARS), skin burns, loss of hair, hypothyroidism and developmental damage to an unborn child. Above the relevant threshold level, the severity of such a deterministic effect increases with the absorbed dose. The International Commission on Radiological Protection (ICRP) has introduced the term, "tissue reaction", which encompasses deterministic effects, circulatory disease and cataracts [I26].

E5. Exposure to radiation can also induce non-lethal changes to cell constituents, including DNA lesions. Different consequences can occur following such an event: the cell is successfully repaired (i.e. it returns to normal); or the cell remains unrepaired or is misrepaired (i.e. it remains abnormal). The human body's immune system is very effective in detecting and destroying abnormal cells. However, any abnormal cells that escape the immune defence over time may proliferate and contribute to carcinogenesis or hereditary effects. Such effects are called "stochastic" effects and are characterized by an increased incidence with increased dose to an exposed population but are indistinguishable from similar effects that occur in the absence of exposure. The Committee has conducted extensive reviews on these effects, most recently in [U7, U8, U9], and has also considered some key issues in this area that require further scientific attention [U10, U15]. Findings from these past reviews related to the most relevant health consequences of radiation from the FDNPS accident are recapitulated below, updated as appropriate with more recent information.

E6. *Solid cancer*. The Committee previously estimated the increased risk of solid cancer for the general populations of China, Japan, Puerto Rico, the United States and the United Kingdom following exposure to low-LET radiation[42] [U9]. The estimated lifetime risk depended on the absorbed dose, the model assumed for describing the risk of cancer following radiation exposure, the baseline cancer rate (i.e. the prevailing cancer rate in the absence of radiation exposure) in the respective country/area, and mortality rates for specific causes of death.

E7. The lifetime baseline risk of solid cancer in the general population of Japan is about 35% on average (males about 41%; females about 29%) [W12]. Following a hypothetical exposure of a group from the same population corresponding to an acute uniform whole-body dose of 1 Sv (equivalent to an absorbed dose of 1 Gy of low-LET radiation to all organs and tissues of the body), the Committee previously estimated the additional lifetime risk of solid cancer due to that exposure to be approximately 13% on average (annex A, table 70 in the Committee's 2006 Report [U9]). Following doses of 0.1 Sv and 0.01 Sv, the additional lifetime risk due to the exposure was estimated to be smaller by factors of about 10 and 100, respectively.

E8. The Committee has evaluated the uncertainty associated with its estimates of risk due to radiation exposure [U14]. For a hypothetical group of male radiation workers in the United Kingdom, the Committee estimated the average additional lifetime risk of solid cancer due to a whole-body dose of 100 mSv to be about 1%, and the 95% subjective confidence interval on this value to be from a factor of 2.5 lower to a factor of 2 higher. These estimates are similar to those made by the United States Committee on the Biological Effects of Ionizing Radiation [N22] and imply that for a population incurring an acute exposure of 100 mSv, the lifetime risk of cancer would increase from about 41% to about 42%. For 10 mSv, the theoretical increase would be from about 41% to 41.1%.

E9. *Leukaemia*. In Japan, the lifetime baseline risk of leukaemia in the general population is about 0.5% on average [W12]. The Committee has previously assessed the risk of mortality from leukaemia due to radiation exposure for the general population of Japan [U9]. Depending on the model applied, the additional lifetime risk after an acute low-LET exposure with an absorbed dose of 1 Gy to the red bone marrow was estimated to be in the range from 0.05% to 0.47% for the general population, and in the range from 0.11% to 0.84% for children exposed between 0 and 9 years of age.

E10. *Exposure during childhood*. The increase in cancer risk due to radiation exposure during childhood is generally greater than that for exposures at older ages (annex A of [U9]). However, the radiosensitivity of children is not the same for all organs and tissues. In annex B to this report to the General Assembly, the Committee describes evidence for children being more likely than adults to develop, for example, breast cancer, thyroid cancer and leukaemia (other than chronic lymphocytic leukaemia, CLL) after radiation exposure [U16]. It also discusses those tumour types for which children have the same or less sensitivity than adults. The increased likelihood for development of certain cancers after exposure during childhood need special recognition in the context of the FDNPS accident.

E11. *Thyroid cancer*. The risk of thyroid cancer following radiation exposure is strongly modified by the age at exposure with young children under age 6 years being at highest risk and risk decreasing with increasing age at exposure [U9]. The Committee estimated lifetime additional absolute risk of thyroid cancer due to irradiation for a hypothetical group of Ukrainians who received an absorbed dose to the thyroid of 0.2 Gy low-LET radiation at age ten years [U14]. For males, the exposure was estimated to add 0.07% (95% confidence interval, CI: 0.01%, 0.21%) to the baseline risk of thyroid cancer of 0.14%. Corresponding values for females were 0.59% (95% CI: 0.11%, 2.1%) and 0.62%.

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[42] As radiation interacts with matter, it loses its energy through interactions with atoms. The Linear Energy Transfer (LET) is a measure of the average amount of energy lost over a defined distance. The same absorbed dose of low-LET radiation (such as beta particles and gamma rays) creates less biological damage than of high-LET radiation (such as alpha particles). The radiation exposure from the FDNPS accident was essentially all from low-LET radiation.

E12. *In utero exposure.* The large and comprehensive Oxford Survey of Childhood Cancers (OSCC) that studied children who had been exposed in utero because of obstetric use of X-rays found a statistically significant increased risk among children of leukaemia and all solid cancers of about 40% relative to the baseline (i.e. a relative risk of 1.4) [W2]. Although no individual dose estimates were available, doses to the foetus were likely to have been of the order of 10 mGy. Similar results have been obtained in a number of other, smaller studies of the effects of obstetric radiography [U7]. However, the causal nature of such low doses following in utero exposure has been debated. Analyses of the survivors of the atomic bombings in Japan who were exposed in utero have only shown a statistically significant increase in incidence of adult-onset cancers at doses higher than about 50 mGy or so [P16]. While the magnitude of the risk of cancer from in utero exposures to diagnostic X-rays remains a matter for discussion [N5], it is possible to estimate upper bounds for any risk.

E13. *Hereditary effects.* Radiation exposure has never been demonstrated to cause hereditary effects in humans, despite extensive studies of the children of survivors of the atomic bombings in Japan, and of the children of cancer survivors treated with radiotherapy throughout the world. However, experimental studies on plants and animals have demonstrated that radiation can induce hereditary effects, and humans are unlikely to be an exception in that regard. Based on animal experiments, the Committee estimated 3,000 to 4,700 cases of hereditary effects per gray of low-LET radiation per one million progeny of the first generation after the exposed generation [U8]. This is equivalent to an absolute risk of hereditary effects per unit dose of 0.3% to 0.5% per gray. Thus, for a given whole-body exposure, the estimated risk that an individual's offspring will have a hereditary disease is on average less than one tenth of the individual's own risk of cancer.

E14. *Non-cancer somatic effects.* In its 2006 review, the Committee considered the scientific data to be insufficient to derive a causal relationship between radiation exposures and non-cancer somatic diseases for absorbed doses of less than about 1–2 Gy [U9]. In 2012, the ICRP estimated that a dose of 0.5 Gy represented a threshold for developing circulatory diseases as a result of irradiation more than 10 years after exposure [I26]. However, at such a dose it cannot be excluded that the risk of circulatory disease per unit dose is lower [S5] or even non-existent, although the subject remains a matter of much debate [L8].

II. HEALTH IMPLICATIONS OF RADIATION EXPOSURE OF THE PUBLIC RESULTING FROM THE FDNPS ACCIDENT

A. Observed health effects

E15. *Effects of radiation exposure.* In the short term, no deterministic health effects due to radiation exposure after the FDNPS accident were observed among members of the public and none are expected in the long term because the doses were far below the threshold values for such effects [N1, U9, U12].

E16. *Effects from other causes.* The most important and manifest health effects of the nuclear accident in the short term would appear to be on mental and social well-being [B20]. This aspect was exacerbated by the enormous impact of the earthquake and tsunami, the uprooting of thousands of people as a consequence of the evacuation and their displacement to unfamiliar surroundings, and the fear and stigma related to radiation exposure. It is outside of the Committee's mandate to assess the occurrence and severity of such effects. However, they are part of the broad definition of health as used by WHO and such effects may also continue in the long term. Furthermore, the evacuation following the accident caused immediate aggravation of the condition of already vulnerable groups; for example, it was reported that more than 50 hospitalized patients died either during or soon after the evacuation, probably because of hypothermia, dehydration or deterioration of underlying medical problems [T4], and that upwards of 100 elderly people may have died in subsequent months because of a variety of conditions linked to the evacuation [Y6]. Understanding the full health impact of the accident forms an important context for the Committee's commentary on health implications directly related to radiation exposure.

B. Risk assessment conducted by WHO

E17. The WHO published in 2013 a health risk assessment of the FDNPS accident to estimate the potential public health impact so that future health needs could be anticipated and public health actions taken [W12]. It estimated risks based on preliminary estimates of radiation doses using data gathered up until September 2011 [W11]. In contrast, the Committee used more comprehensive and recent data for its scientific assessment of doses, and made more realistic assumptions where data were sparse, particularly for the evacuated areas. Nevertheless, the Committee's dose estimates and the doses estimated by WHO were generally consistent; the ranges of estimates presented by WHO (see appendix C) encompassed the results of the Committee's dose assessment, although the WHO estimates were higher for a number of the evacuated settlements.

E18. The WHO did not expect any deterministic effects in any of the various groups it considered [W12]. It did not expect prenatal exposure to increase "*... the incidence of spontaneous abortion, miscarriages, perinatal mortality, congenital effects or cognitive impairment.*" WHO considered the"*... hereditary risk in the offspring of an exposed person ...* [to] *be much lower ... than the additional cancer risk of that exposed person.*" These statements are consistent with the views of the Committee for exposures typical of those estimated to have been incurred by the public as a result of the FDNPS accident.

E19. The WHO made the following main assumptions in its estimation of cancer risks [W12] (the Committee's remarks on those assumptions follow each one below):

(a) A linear non-threshold (LNT) dose–response model for solid cancer and a linear-quadratic non-threshold dose–response model for leukaemia. While the Committee noted that these models had been used for radiation protection purposes [I21], it also noted that the current state of knowledge on the risk of cancer from doses of the order of 100 mSv or less was quite limited, although some but not all data were compatible with the risks of cancer from such doses not being seriously underestimated by the LNT model. The Committee has previously decided not to use models to project absolute numbers of health effects among populations exposed at such levels, because of large and unavoidable uncertainties in the predictions (annex D to [U12]).

(b) A dose-and-dose-rate effectiveness factor (DDREF) of one. This is not incompatible with the Committee's estimates of cancer risks after doses of 0.01, 0.1 and 1.0 Sv delivered acutely [U9, U11], with recent results for solid cancer in the Life Span Study (LSS) of Japanese survivors exposed as a result of the atomic bombings at Hiroshima and Nagasaki [O8], or with a meta-analysis of low-dose-rate, moderate-dose exposures [J2]. In contrast, experimental evidence indicates values of DDREF greater than one for high-dose exposures at low dose rate [I21, U5].

(c) An onset of increased cancer risk from irradiation after minimum latency periods of 2 years for leukaemia, 3 years for thyroid cancer, and 5 years for breast cancer and all solid cancers combined. WHO assumed values for minimum latency period that are shorter than those from previous reviews of the literature by the Committee [U9] and represent a cautious assumption. Because radiation risks are not expected to be fully expressed already at the presumed minimum

latency period, the WHO assumption, in general, leads to a slight overestimation of the cancer risk for the first decade after exposure. For longer time periods the impact is negligible.

(d) Risk models derived from the LSS cohort of survivors of the atomic bombings in Japan. The WHO justified its choice of risk model by the general consistency of LSS risk estimates (which are themselves based on a Japanese population) with those found in populations exposed to protracted exposures, and with populations exposed during childhood or adolescence to radioiodine released after the Chernobyl accident, although there is inevitably some uncertainty about the level of consistency.

(e) Weights assigned to additive and multiplicative models in the transfer of LSS risk functions to the populations in Fukushima Prefecture. For leukaemia and all solid cancers, WHO gave equal weight to these two models of transfer, because the true interaction of radiation exposure with other causes of cancer is not generally known. For breast cancer, the WHO used an additive model because a pooled study had shown a smaller variability of excess absolute risk estimates than excess relative risk estimates [P14]. The choices made for all solid cancers and breast cancer were broadly consistent with assumptions made by ICRP, BEIR VII and USEPA, although there is less consensus for leukaemia [E2, I21, N22]. However, these organizations have proposed a multiplicative risk transfer model for thyroid cancer. WHO justified their choice of assigning equal weight for additive and multiplicative models by comparing the LSS results with data from studies after the Chernobyl accident. In past reviews, the Committee had applied additive and multiplicative models separately in order to assess the implications of the mode of transfer [U9]. The choice of model, although relevant because the population of Fukushima Prefecture has some different characteristics from the population exposed to radiation from the atomic bombings, was less important because the transfer was from one exposed Japanese population to another, rather than to another population of different ethnicity.

E20. According to WHO's preliminary dose estimation, average lifetime doses due to the accident to the colon, breast and bone marrow of people in the areas with the highest deposition densities of radionuclides (namely Namie Town in Futaba District and Iitate Village in Soma District) were estimated to be up to about 20 mSv [W12]. WHO estimated absorbed doses to the thyroids of adults and young children (delivered mainly within the first year) to be about 50 mGy and 100 mGy, respectively. They estimated that populations in other areas with high deposition densities received doses lower by a factor of at least two.

E21. WHO [W12] estimated, for the areas with the highest deposition densities of radionuclides, the mean lifetime risk of all solid cancer due to radiation exposure during infancy to be about 0.6% and 1.2% for males and females, respectively (table E1). This would be in addition to a baseline risk expected in the absence of radiation exposure from the accident of 41% and 29% of males and females, respectively. This estimated increase in risk due to radiation exposure was small compared with the temporal and regional variability of cancer incidence [C3]. For females, about 20% of the increase in cancer risk was estimated to be due to the risk of breast cancer. For exposure during infancy, nearly 40% of the estimated increase in risk of cancer for females was due to the risk of thyroid cancer; this was because the absorbed dose to the thyroid was significantly higher than that to other organs, and the excess relative risk of thyroid cancer per unit dose for this population group was high. However, because of the very low baseline lifetime incidence of thyroid cancer, WHO expected the additional absolute lifetime thyroid cancer risk due to radiation exposure to be small. The WHO estimates of risk per unit dose were compatible with estimates of the Committee in its earlier reports (see section I.B of this appendix).

Table E1. WHO's estimates of lifetime baseline risk, LBR, and lifetime attributable risk, LAR for areas within Fukushima Prefecture with effective doses of 12–25 mSv in the first year [W12]

The calculations were based on absorbed doses to the colon, bone marrow and breast of 20 mGy for the whole population, and absorbed doses to the thyroid of about 100, 75 and 50 mGy for an age at exposure of 1, 10 and 20, respectively The values calculated by WHO were quoted to two significant figures and have been reproduced here. The use of such precision should not imply that the numbers are accurately known. For example, consideration of the uncertainty associated with the LAR estimates would suggest that the actual values likely lie within bounds that are perhaps 2–3 times higher or lower. The LBR are also associated with uncertainty and variability between different years

Age at exposure (y)	*Sex*	*Risk quantity*	*All solid cancer[a]*	*Leukaemia*	*Breast cancer*	*Thyroid cancer*
1	Male	LAR LBR	0.6% 41%	0.03% 0.60%	–	0.10% 0.21%
	Female	LAR LBR	1.2% 29%	0.02% 0.43%	0.26% 5.5%	0.43% 0.77%
10	Male	LAR LBR	0.5% 41%	0.02% 0.58%	–	0.04% 0.21%
	Female	LAR LBR	0.8% 29%	0.01% 0.41%	0.17% 5.5%	0.19% 0.77%
20	Male	LAR LBR	0.3% 41%	0.01% 0.57%	–	0.01% 0.21%
	Female	LAR LBR	0.5% 29%	0.01% 0.40%	0.11% 5.6%	0.07% 0.76%

[a] *Includes the risk of thyroid cancer taking into account the relatively high absorbed dose to the thyroid, while the WHO report calculated the risk of all solid cancer assuming that the absorbed dose to all organs was equal to the dose to the colon.*

E22. The WHO remarked that the "ultrasound screening for thyroid disease is likely to lead to an increase in the [reported] incidence of thyroid diseases due to earlier detection of non-symptomatic cases (screening effect)" (see section D below). In its calculations, WHO did not consider explicitly the effect that the ultrasound screening programme in Fukushima Prefecture would have on detection rates and therefore on the observed/reported prevalence and incidence rates of thyroid disease. Nevertheless, the survey was expected to lead to an increase in the detection of cases of thyroid cancer, both of baseline ones and those that may be related to radiation exposure, which are currently indistinguishable.

C. The Committee's commentary on health implications for the public

E23. The Committee based its commentary on *(a)* its own dose estimates for subsets of the Japanese population as reported in appendix C and relevant attachments; *(b)* its estimates of disease risks from exposures to ionizing radiation including new estimates of the risk of thyroid cancer as summarized in section I.B; and *(c)* results of the WHO report [W12] as reviewed in section II.B (but modified by considering the risk of solid cancer including the full risk of thyroid cancer, whereas the WHO estimates for the risk of solid cancer were based on doses to the colon not taking into account that doses to the thyroid were in general higher). The Committee's commentary considers quantitative and qualitative estimates of potential disease outcomes among the exposed populations that may or may not be observable in future disease statistics. For the purpose of this study, the Committee has used the phrase "no discernible increase" where, although a disease risk in the longer term can be theoretically inferred on the basis of existing risk models, an increased incidence of effects is unlikely in practice to be observed in future disease statistics using currently available methods, because of the combination of the limited size of population exposed and low exposures, i.e. consequences that are small relative to the baseline risk and their uncertainties. To gain insight as to whether increased incidence might be discernible, the Committee considered some indicative numbers of individuals within doses bands, based on the population and dose information in appendix C and associated attachments.

1. Population of Japan and of Fukushima Prefecture

E24. For the general public of Japan, inhabiting areas where exposures from the FDNPS accident in the first year were of the order of or below annual background exposure to natural sources of radiation (and lifetime exposures are expected to be much below those incurred from background radiation), the Committee estimated that risks over their lifetimes were so low that no discernible increase in the future incidence of health effects due to radiation exposure would be expected among the population or their descendants. Disease risks for people who were evacuated and for people in districts of Fukushima Prefecture that were not evacuated (who received, in the first year, doses from the accident that exceeded the annual background exposure to natural sources) are discussed in detail below.

E25. The radiation exposure of the population resulting from the FDNPS accident had two main components: *(a)* doses due to external exposure and to internal exposure from incorporated radiocaesium, both of which are relatively homogeneous in the body. For such homogeneous whole-body exposures of adults with effective doses spanning up to about 100 mSv, the value of effective dose could be used to estimate absorbed doses to particular organs and qualitatively evaluate the exposure to explore whether a more sophisticated risk analysis was necessary; and *(b)* absorbed doses to the thyroid due to incorporation of radioiodine, which is discussed separately below.

E26. The quantity effective dose is itself not suited for quantitative risk estimations, having been developed for radiation protection and for demonstrating compliance with regulatory limits. It does allow partial body exposures as well as exposures due to intakes of radionuclides to be combined into an aggregate quantity that is useful in radiation protection, but not quantitative risk assessment. It includes judgements on values for tissue weighting and radiation weighting factors, and averages over all ages and both sexes. It thus does not represent risk to an individual or groups of similar individuals with the same characteristics, and is not useful for quantitative risk estimation. Therefore, the Committee based its estimates of risk from exposure during childhood on estimates of absorbed doses to specific organs.

E27. *All cancer*. The Committee estimated settlement averages of effective doses to adult evacuees to be less than 10 mSv in the first year after the accident (table C11). In the most affected districts of the areas that were not evacuated, average lifetime effective doses to adults were up to just over 10 mSv above natural background (table C14). Individual doses could be lower or higher by a factor of about 2 to 3. The Committee estimated that perhaps 15,000 people in the highest dose bands might have received average lifetime effective doses of about 25 mSv.

E28. Definite evidence for an increase in the incidence of some cancers from acute (weighted colon) doses of 100 mSv or more has been reported for population groups such as the survivors of the atomic bombings in Hiroshima and Nagasaki (see section I.B in this appendix and [U9]). While there is little or no direct evidence for an increase in the incidence of cancer as a whole in adult populations from homogeneous whole-body exposures with effective doses of 100 mSv or less, risks can be inferred at such levels (e.g. using a linear dose–response model). However the values of inferred risks are so small that in general no discernible radiation-related increase of overall cancer incidence would be expected among exposed members of the general public. However, separate consideration of certain malignancies has been made for particular groups (see below).

E29. *Thyroid cancer*. During the first year, incorporated radioiodine from the accident led to higher absorbed doses to the thyroid than to other organs and tissues. For adults in areas that were not evacuated, the district-average absorbed doses to the thyroid were less than 20 mGy in the first year after the accident (table C10). Available evidence indicates that the thyroid is not particularly sensitive to such doses during adulthood.

E30. In contrast, for 1-year-old infants who were evacuated after the accident, the Committee estimated settlement-average absorbed doses to the thyroid to be up to about 80 mGy (table C12). In the areas that were not evacuated, district-average doses to the thyroid were up to about 50 mGy (table C10). For example, the Committee estimated that about 35,000 children in the age range of 0–5 years lived in districts where the average absorbed dose to the thyroid was between 45 and 55 mGy.

E31. The Committee previously evaluated the risk of thyroid cancer from an absorbed dose to the thyroid of 200 mGy at age of ten years [U14]: the lifetime risk of thyroid cancer was estimated to be approximately doubled by the exposure. However, even for a hypothetical exposure of 10,000 children with such a dose to the thyroid, the uncertainty of the risk estimate is large, ranging from a relative risk of about 1.15 to about 4.0. The WHO estimates of the risk of thyroid cancer due to radiation exposure [W12] were consistent with those of the Committee, if the risk dependence on dose to the thyroid were assumed to be linear from several hundred milligrays down to the levels of dose received after the accident.

E32. From an estimate of absorbed dose of 50 mGy to the thyroid of infants, and assuming that the risk of thyroid cancer could be extrapolated down to these dose ranges using a linear dose–response function, a relative lifetime risk of thyroid cancer due to the exposure over the baseline risk could be inferred to be about 1.3. Such an increase in principle ought to be discernible if the effect of increased detection rate due to sensitive screening and other factors could be isolated, although most of the increased incidence would be expected to appear several decades after the exposure. Furthermore, direct measurements of radioiodine content in the thyroid have suggested that actual doses to the thyroid for some individuals might be lower than the average doses estimated by the Committee using environmental measurements and modelling, although there are some questions about how representative the thyroid measurements generally were. A detailed re-evaluation of the absorbed doses to the thyroid taking into account all available information relevant to thyroid exposure including the thyroid measurements, their quality assurance and information on individual protective measures is highly desirable.

E33. The Committee estimated that the doses to the thyroid varied considerably among individuals, indicatively from about 2 to 3 times higher or lower than the average for a district. It considered that fewer than a thousand children might have received absorbed doses to the thyroid that exceeded 100 mGy and ranged up to about 150 mGy. The risk of thyroid cancer for this group could be expected to be increased. However, it would be difficult, if not impossible, to identify precisely those individuals with the highest exposure, and risks at these low doses have not been convincingly demonstrated; moreover, as noted above, the lower dose values suggested by direct thyroid measurements on some populations should be reviewed, as well as their associated uncertainties. Information on dose distribution and uncertainties was not sufficient for the Committee to draw firm conclusions as to whether any potential increased incidence of thyroid cancer would be discernible among those exposed to higher thyroid doses during infancy and childhood.

E34. *Leukaemia*. The Committee estimated settlement-average absorbed doses to the red bone marrow of 1-year-old evacuees before and during their evacuation to be up to 10 mGy (appendix C, section III.A.6). In the areas not evacuated, district-average doses in the first year were estimated to be up to about 5 mGy (appendix C, section III.A.5). For example, about 18,000 children in the age range of 0–5 years were estimated to live in districts where the average absorbed doses to the red bone marrow were 4 to 6 mGy. The Committee has previously assessed the risk of mortality from leukaemia due to radiation exposure for the general population of Japan [U9]. Depending on the model applied, the lifetime risk from an absorbed dose of 1 Gy to the red bone marrow in children aged 0 to 9 years at exposure was estimated to be in the range from 0.11% to 0.84%. The risk estimates were mainly based on the LSS. In the past, (e.g. at the time when childhood leukaemia could be observed in the LSS), mortality rates of the disease were very high. Therefore, the risk function for mortality from childhood leukaemia is now often used to represent the risk function for incidence of childhood leukaemia as well. For the accident at FDNPS, the WHO estimates of the risks of leukaemia due to radiation exposure [W12] were consistent with those of the Committee.

E35. Most of the radiation-induced leukaemia risk after exposure during infancy would be expressed during childhood. WHO estimated the risk of leukaemia for the first 15 years after exposure during infancy. An absorbed dose of 26 mGy to the red bone marrow was estimated to increase the risk from a baseline of 0.03% to 0.05% [W12]. This is slightly lower but broadly consistent with some recent studies of childhood leukaemia after radiation exposure [W5]. The Committee's estimates of exposure were lower than those of WHO. Considering the exposures and risks, and the size of the exposed group, any increase in childhood leukaemia is not expected to be discernible.

E36. *Breast cancer*. The Committee estimated settlement-average absorbed doses to the breast of girls before and during their evacuation to be up to 10 mGy. In areas that were not evacuated, district-averages of lifetime doses to the breast were up to 20 mGy. The Committee previously calculated a lifetime risk of breast cancer of about 0.3% for the general female population of Japan from an absorbed dose to the breast of 100 mGy [U9]. The difference in risk due to exposure as a child compared to as an adult depends on the assessment model used [U16]. However, in some studies the risk of breast cancer from exposure as a child was estimated to be higher by a factor of three to five than the risk from exposure as an adult [U16]. Compared to a baseline risk for breast cancer of about 5.5% [W12], the Committee does not expect that any increase in future incidence of breast cancer due to radiation exposure would be discernible.

E37. *Childhood cancer after exposure in utero*. Absorbed doses in utero may increase the relative risk of childhood cancer including leukaemia [U7] (see section I.B above). The Committee estimated settlement-average doses to the uterus of pregnant women who were evacuated to districts with high deposition densities to be up to 9 mGy. It could not exclude the possibility that a small number of pregnant women may have received absorbed doses to the uterus of up to about 20 mGy. However, because of the small numbers of pregnant women and foetuses exposed at such levels, it is not expected that any increase in the incidence of childhood leukaemia or other childhood cancers would be discernible. Further, low-dose prenatal exposure at these levels would not be expected to increase the incidence of spontaneous abortion, miscarriages, perinatal mortality, congenital effects or cognitive impairment.

2. Experience from the Chernobyl accident and comparison with other sources of exposure

(a) *Experience from the Chernobyl accident relevant to the public health implications of the accident at FDNPS*

E38. The doses received by the public due to the March 2011 FDNPS accident are in general much less than those received by the population residing near Chernobyl due to the April 1986 accident. There were no deterministic effects reported among the general population after the Chernobyl accident, and accordingly none are expected after the Fukushima accident, where the doses were considerably lower. The highest doses from the Chernobyl accident were to the thyroid as a result of the intake of ^{131}I into the body [U12]. The largest doses resulted from the failure to restrict the consumption of foodstuffs containing high concentrations of ^{131}I, in particular of milk; millions of children were exposed through ingestion with tens of thousands of them receiving doses to the thyroid exceeding 1,000 mGy [U12]. After the FDNPS accident, transfer to foodstuffs was more limited because the accident occurred earlier in the growing season. Moreover, restrictions on the sale of foodstuffs with radionuclide concentrations exceeding regulatory levels were implemented relatively promptly (the first instructions on restrictions were introduced on 17 March); this greatly reduced and constrained exposures from ingestion [N1].

E39. An increase in the incidence of thyroid cancer associated with the Chernobyl accident was first identified about four years after the accident [K4]. By 2005, approximately 6,000 people, under age 18 years at the time of the accident, had been diagnosed with thyroid cancer [I2, U9, U12, W3]. It has been estimated that about 30% in Ukraine and about 60% in Belarus of the incidence of diagnosed thyroid cancer could be attributed to the radiation exposure [J1]. In comparison, doses to the thyroid for the general public following the FDNPS accident were lower.

E40. No convincing increase in the incidence of childhood leukaemia or of solid cancer (except cancer of the thyroid) was reported as a result of exposures received from the Chernobyl accident, which is not unexpected given the levels of exposure that occurred [B13, U12]. No significant increases in the incidence of birth anomalies or foetal deaths were identified that could be attributed to radiation exposure resulting from the accident [W9].

E41. Reports about survivors of the atomic bombings of Hiroshima and Nagasaki indicated a psychological aftermath that included stigma, economic and social discrimination, anxiety, depression, and post-traumatic stresses that were long term [H8, K14, L6]; these were independent of any resulting physical sicknesses [Y1] and were associated with perceptions of disease risks [K14, O4]. The psychological impact of the accidents at Three Mile Island and Chernobyl followed a similar pattern as that of the atomic bombings [B19, B20, H4]. Two studies, conducted 6–7 years after the Chernobyl accident [H3, V2], found that the exposed population had significantly poorer mental health than controls. In Gomel Oblast, mothers with young children were found to be a particularly high risk group. Both studies found that the perception of harmful levels of exposure to radiation, as opposed to the actual levels of exposure, was the key risk factor. Similarly, an increase in the incidence of psychological effects has already been observed among the general population after the FDNPS accident [Y4, Y5]. Such long-term psychological effects can be expected to occur in the population of Fukushima Prefecture.

E42. In summary, the radiation exposures resulting from the FDNPS accident are substantially lower than those after the Chernobyl accident. This suggests that any increase in the incidence of health effects among the general public resulting from radiation exposure from the FDNPS accident will likely not be discernible.

(b) *Comparison with other sources of exposure*

E43. Background exposure to natural sources of radiation results in a global average effective dose of about 2.4 mSv annually, with wide variation about this value depending on geographical location (indicatively in a range of about 1–13 mSv) [U11]. The average annual effective dose in Japan is about 2.1 mSv [N23]. The effective dose over a lifetime from naturally-occurring sources of radiation in Japan (about 170 mSv) is significantly higher than that estimated as a result of the accident for an average person living in Fukushima Prefecture (see appendix C). In contrast, the annual absorbed dose to the thyroid from natural sources of radiation is about 1 mGy, and thus the lifetime dose to the thyroid is about 80 mGy.

D. Long-term medical monitoring

E44. The Fukushima Health Management Survey [A4, Y4, Y5] was launched to "evaluate radiation doses of citizens and [record] their health conditions, with the intention of utilizing the results for prevention, early detection and treatment of possible illness". It includes a basic survey to estimate doses from external exposure to radiation of all 2.05 million residents of Fukushima Prefecture at the time of the accident, and the following detailed surveys for selected population groups: a thyroid ultrasound examination of children, a health check, a mental health and lifestyle survey, and a pregnancies and birth survey. The investigation is planned to continue for 30 years [Y5].

E45. The basic survey started in June 2011. A questionnaire was distributed to collect information on the activities and locations of residents during the period 11 March to 11 July 2011. The response rate to the questionnaire was low, less than 30% [Y5]. Individual doses from external exposure were estimated based on a respondent's location, using a system for assessing external doses developed by NIRS in Japan [N10]. Doses from internal exposure were measured using whole-body counting. Many measurements were performed a considerable time after the accident, making it difficult to estimate doses from internal exposure for those radionuclides with short physical or biological half-lives.

E46. Improvements in the sensitivity of diagnostic techniques for thyroid cancer, such as the advent of ultrasound and fine-needle aspiration, have enabled the detection of subclinical disease. To ensure the early identification and treatment of any thyroid cancer in the child population, and their lifelong follow-up, ultrasound examinations of the thyroid were being performed on all individuals in Fukushima Prefecture who were aged 18 years or younger on 11 March 2011. Assessment of the current thyroid status of some 360,000 eligible subjects was expected to be completed within 3 years (by March 2014). Thereafter, individuals would undergo thyroid examinations every 2 years until age 20 and every 5 years thereafter [Y5]. As of 31 July 2013, in total 41,296 children living in 13 municipalities were selected for ultrasound examinations of the thyroid before April 2012, and 135,586 children in another 13 municipalities were selected for the period April 2012 to March 2013 (table E2) [F3]. The remaining 34 municipalities of Fukushima Prefecture were selected for ultrasonographic examinations in the period April 2013 to March 2014. The participation rate was about 82%. Nodules were detected in about 1% of the surveyed persons. The rate of cysts increased from 36% among persons from the municipalities examined in 2011/2012 to 45% among persons from the municipalities examined in 2012/2013. It should be noted that these examinations were made with modern, sensitive ultrasound equipment which could detect very small cysts and nodules. Similar equipment was used from November 2012 to January 2013 in an ultrasound survey of 4,365 children and adolescents (aged between 3 and 18 years) in the prefectures of Aomori, Nagasaki and Yamanashi [T5]. These prefectures were far from FDNPS and were not significantly affected by the accident. Thyroid nodules were detected in 1.6% of the children and cysts in about 57%, rates that were even higher than those found in Fukushima Prefecture. The Committee considered that the detected prevalence in the more distant prefectures represented the normal baseline risks under intensive screening conditions and were not related to radiation exposure.

E47. Children and adolescents with cysts with a diameter larger than 20 mm or with nodules larger than 5 mm were selected for secondary examination. About 0.5% of the children surveyed in the municipalities of Fukushima Prefecture before April 2012 met these criteria (table E2) [F3]. Again, this rate was somewhat higher for children of the municipalities examined in the period April 2012 to March 2013. In the unaffected prefectures of Aomori, Yamanashi and Nagasaki, the rate was slightly higher at 1.0%, which might be due to regional variability [T5].

Table E2. Numbers of persons participating in thyroid examinations, or having a specified diagnosis

Districts of Fukushima Prefecture were selected targeted for the first ultrasonography examinations in three time periods. Results for the first two groups given here are as of 31 July 2013 [F3]. Districts of Fukushima Prefecture with very low deposition densities were to be targeted for 2013/2014. Data for three prefectures with insignificant deposition densities were as of May 2013 [T5]

Examination / diagnosis	*Municipalities in Fukushima Prefecture targeted before April 2012*[a]	*Municipalities in Fukushima Prefecture targeted April 2012 to March 2013*[b]	*Prefectures of Aomori, Nagasaki and Yamanashi*
Ultrasonography	41 296	135 586	4 365
With nodules	438 (1.0%)	1 623 (1.2%)	72 (1.6%)
With cysts	14 728 (36%)	60 382 (45%)	2 483 (57%)
Required secondary examination	214 (0.5%)	953 (0.7%)	44 (1%)

[a] *Date, Futaba, Hirono, Iitate, Katsurao, Kawamata, Kawauchi, Minamisoma, Namie, Naraha, Okuma, Tamura, and Tomioka.*

[b] *Fukushima, Hisanohama of Iwaki, Izumizaki, Kori, Koriyama, Kunimi, Miharu, Motomiya, Nihomatsu, Nishigo, Otama, Shirakawa, and Tenei.*

E48. In the municipalities of Fukushima Prefecture with examinations before April 2012, 76% (165 persons) of those selected for secondary examination had been examined by 31 July 2013 (table E3). This enabled a preliminary estimation to be made of the frequency of malignancies in this population group. Cytological analysis of thyroid tissue taken from biopsies by fine-needle aspiration classified fourteen of the nodules to be malignant. Surgery had been performed for ten of these patients. In nine cases papillary carcinoma had been confirmed. One nodule turned out to be benign; the remaining thirteen cases of suspected or confirmed malignancy corresponded to a prevalence of 13/41,296, or about 0.03%. The increased prevalence of thyroid cancer may reflect the identification of previously undetected disease with these improved diagnostic techniques and increased screening rates, rather than a true increase in the prevalence of thyroid cancer [J8]. The prevalence of clinically occult small papillary thyroid cancers (i.e. asymptomatic tumours that would remain latent, but detectable) could be as high as 35% in many parts of the world, according to findings from autopsies of young people from the general population [R4]. A fraction of these would be detected by any ultrasound screening programme. Following treatment, the 10-year survival from those types of cancer that are radiation-induced is high (about 90%) [H14].

Table E3. Persons in areas of Fukushima Prefecture participating in thyroid examinations, or having a specified diagnosis, as of 31 July 2013 [F3]

Examination	*Persons in municipalities examined before April 2012*[a]	*Persons in municipalities examined from April 2012 to March 2013*[b]
Primary ultrasonography	41 296	135 586
Required secondary examination	214 (0.5%)	953 (0.7%)
Completed secondary examination	165	431
Malignancy according to biopsy cytology	14	30
Surgery	10	9
Confirmation of papillary carcinoma	9	9

[a] *Date, Futaba, Hirono, Iitate, Katsurao, Kawamata, Kawauchi, Minamisoma, Namie, Naraha, Okuma, Tamura, Tomioka.*

[b] *Fukushima, Hisanohama of Iwaki, Izumizaki, Kori, Koriyama, Kunimi, Miharu, Motomiya, Nihomatsu, Nishigo, Otama, Shirakawa, Tenei.*

E49. This is consistent with results from a study of a cohort of Ukrainians (the "UkrAm cohort") who had been exposed during childhood or adolescence to ^{131}I from the Chernobyl accident, where an ultrasound screening programme detected higher prevalence and incidence rates of thyroid cancer than previously reported [T23]. During the first screening of the cohort between 1998 and 2000, forty-five cases of thyroid cancer were observed among 13,127 individuals. Part of the apparent increase could be attributed to the increased detection rate due to the programme of ultrasound screening of the cohort. It was estimated that about eleven of these cases would have been detected even if there had been no radiation exposure from the accident. The component of the incidence observed after the screening but not associated with radiation exposure was estimated to be considerably higher than the normal cancer rate for the whole of Ukraine [B16, F2]. The results corresponded to a prevalence of thyroid cancer cases not related to the accidental radiation exposure of about 0.09%, a value considerably larger than that observed in Fukushima Prefecture. (The difference between screenings of the UkrAm cohort and of people in Fukushima Prefecture could be explained, in part, by differences in the average age at first screening. The UkrAm cohort was first screened at an average age of about 21 years, which was older than the average age for the Fukushima screenings. Because the incidence rate of thyroid cancer increases strongly with increasing age during adolescence and early adulthood, the prevalence in the UkrAm cohort was higher than among those screened after the FDNPS accident.)

E50. A comprehensive health check (involving measurements of height, weight, body mass index, blood pressure, blood cell counts, blood chemistry, and urine testing) was being performed for people who lived in the precautionary evacuation areas (radius 20 km from FDNPS) and in Yamakiya District in Kawamata Town, Namie Town, and Iitate Village. A survey on mental health and lifestyle was asking parents to evaluate their children using the Strength and Difficulties Questionnaire [M7]. A self-administered questionnaire was provided to those 16 years or older [K9, W6]. Clinical psychologists and other mental health specialists offered telephone counselling and psychiatric referral based on answers to the questionnaires. The size of the selected population for the health check and the mental health and lifestyle survey was 210,189 people [Y5].

E51. The pregnancy and birth survey aimed to collect data on all pregnancies and births among all women in Fukushima Prefecture who were pregnant on 11 March 2011. Survey questionnaires included antenatal health, delivery records and mental health. Telephone and e-mail hotlines had been set up and midwives or public health nurses were providing consultation services and medical referral if necessary. The total number of women targeted was 15,954 [Y5].

III. HEALTH IMPLICATIONS OF RADIATION EXPOSURE OF WORKERS RESULTING FROM THE FDNPS ACCIDENT

A. Observed health effects

E52. As of November 2012, seven deaths had been reported since 11 March 2011 among FDNPS workers (i.e. workers of TEPCO and contractors) [T11]:

(a) Two workers, aged 21 and 24, died on 11 March 2011, directly as a result of the earthquake and tsunami. They were performing inspections in the turbine building of Unit 4 of FDNPS when the tsunami inundated the site and flooded the building [I29].

(b) Three contractors died from acute myocardial infarctions while at work on 14 May 2011, 9 January 2012, and 22 August 2012, respectively. All three workers had received effective doses

from external exposure of 0.7, 6.7 and 25 mSv, respectively. Whole-body counting of two of the workers carried out a few weeks prior to their deaths showed that they had received minimal doses from internal exposure. No effect attributable to radiation exposure on the mortality from myocardial infarction has been observed among the survivors of the atomic bombings of Hiroshima and Nagasaki, who received much higher doses [S9].

(c) On 16 August 2011, a contractor died from acute leukaemia. He received an effective dose from external exposure following the accident that was recorded as 0.5 mSv; whole-body counting carried out on 7 August 2011 showed minimal dose from internal exposure. Given the very low level of exposure and the minimal latency period of 2 years for leukaemia, this death could not be attributed to radiation exposure resulting from the accident.

(d) On 6 October 2011, a contractor died from septic shock owing to a retroperitoneal abscess. He received an effective dose of 5 mSv from external exposure following the accident. Whole-body counting carried out on 9 September 2011 showed that he had received minimal dose from internal exposure. The retroperitoneal abscess could not be attributed to radiation exposure resulting from the accident.

Acute radiation syndrome was neither reported nor expected because whole-body doses were below the threshold levels for such effects.

E53. On 24 March 2011, the feet of three contractors were reportedly exposed to radioactive water in a turbine building. The absorbed doses to the skin from the radioactive water were subsequently estimated to be about 450 mGy for two of the contractors and for the third essentially no dose to the skin from the radioactive water was estimated. However, in addition, during the same day the workers' skin was also exposed to gamma radiation in the air. Conservative estimates of the dose from this route of exposure were added to the dose to the skin from the radioactive water to give total absorbed doses to the skin of the feet, specifically about 650 mGy for two of the contractors and about 170 mGy for the third [T10]. After four days of hospitalization they were released with a prognosis of no likelihood of significant long-term harm [I6]. Assuming the dose estimates were correct, the Committee agreed with this prognosis. Further, no radiation-induced health effects were ever observed from this exposure; the estimated doses were far lower than the threshold values for skin damage [I13].

E54. On 29 October 2011, an accident occurred in which two workers were struck by the release of retaining wires on a crane. One worker had both of his legs broken and the other sustained injuries to his shoulders and other areas of his body. The worker with broken legs had surgery at Fukushima Medical University Hospital and was transferred to an Intensive Care Unit. The other worker was transported to Sogo Iwaki Kyoritsu Hospital after first receiving treatment at the medical unit at J-Village, which was a facility used as a base for FDNPS workers following the accident [I4].

E55. Approximately 17,500 stable iodine tablets (50 mg as potassium iodide) were distributed to about 2,000 workers involved in the emergency response [K11]. No immediate side effects, such as anaphylaxis with iodine hypersensitivity, were observed. Approximately 230 workers received health check-ups (from 13 March 2011 to 3 October 2011) because either they took stable iodine continually for more than 14 days, or received more than 20 tablets. Health check-ups were performed by J-Village Medical Centre or the Health Management Group of TEPCO Head Office. Blood tests were performed. Three workers had transient changes in the thyroid hormones TSH and FT_4. Four workers had TSH levels greater than 5.0 μIU/mL and normal FT_4 levels. This was not acknowledged as an increased rate of hypothyroidism attributable to distribution of stable iodine for thyroid blocking, because between 1% and 3.5% of males in the population normally has potential hypothyroidism.

B. Risk assessment conducted by WHO

E56. WHO conducted a health risk assessment [W12] that considered FDNPS workers employed by TEPCO and contractors exposed during the emergency phase. A preliminary dose estimation had been performed based on data provided by the Japanese government and TEPCO by mid-September 2011. The WHO assessment addressed 23,172 workers assigned to one or other of the following four exposure scenarios:

- Scenario 1: workers with very low doses to all tissues (absorbed doses to bone marrow, colon and thyroid: 5 mGy);
- Scenario 2: workers who received moderate doses to the thyroid and low doses to other tissues (dose to bone marrow and colon: 24 mGy; dose to thyroid: 140 mGy);
- Scenario 3: workers who received moderate doses to tissues (dose to bone marrow and colon: 200 mGy; dose to thyroid: 200 mGy);
- Scenario 4: twelve workers who received high doses to the thyroid and low to moderate doses to other tissues (dose to bone marrow and colon: 100 mGy; dose to thyroid: 11,800 mGy).

About 99% of the workforce involved with the emergency and subsequent mitigation were covered by Scenarios 1 and 2; the remaining 1% of workers assigned to Scenarios 3 and 4 comprised those at the upper bounds of internal and external exposure. These scenarios had been developed as part of the WHO study before individual dosimetric and bioassay data were available. They are, however, broadly consistent with the individual dosimetric data that were made available to the Committee (see section V and appendix D).

E57. More recent data have indicated that the doses from internal exposure for the majority of workers included in Scenario 1 were predominantly due to ^{131}I rather than $^{134/137}$Cs alone as assumed by WHO; this would have resulted in higher estimates of doses to the thyroid but lower estimates of effective doses. Data made available to the Committee also showed that there were 173 workers who had received effective doses greater than 100 mSv, rather than the 87 identified by WHO in specifying Scenarios 3 and 4.

E58. Lifetime attributable risk (LAR) of cancer occurring as a result of radiation exposure was calculated using the same method as was used for the general population (see section II.B of this appendix). According to the WHO report, about 50% of the workers were in the age range from 30 to 49 years at 31 January 2012. Estimated risks for workers exposed at age 40 are summarized in table E4; the LAR for exposure at age 20 was estimated to be higher by about 70%, and that at age 60 to be lower by about 50%.

E59. The WHO also assessed risks of effects other than cancer for the emergency and mitigation workers [W12]. They did not expect any deterministic effects, apart from possible thyroid disorders among the twelve workers of Scenario 4. They identified that there might be an increase in the risk of long-term circulatory disease among the workers of Scenario 3. They stated that any risk of hereditary effects among the offspring of workers involved in the emergency and subsequent mitigation would be much lower than the additional cancer risk for these workers.

Table E4. WHO estimates for FDNPS workers of lifetime attributable risks of leukaemia, thyroid cancer and all solid cancer, and percentage increase over lifetime baseline risk [W12]

Results are given for age 40 years at exposure and rounded

Exposure scenario	*Cancer type*	*Assumed dose (mGy or mSv)[a]*	*Lifetime risk (%) attributable to radiation exposure*	*Percentage increase over the lifetime baseline risk*
3	Leukaemia	200	0.12	23
	Thyroid cancer	200	0.02	8
	All solid cancer	200	2.0	5
4	Leukaemia	100	0.06	11
	Thyroid cancer	11 800	0.9	480
	All solid cancer[c]	100[b]	1.9	5

[a] *Dose to bone marrow for leukaemia, dose to thyroid for thyroid cancer, and dose to colon for all solid cancer combined.*

[b] *Dose to all organs except to the thyroid, which was assumed to be 11,800 mGy.*

[c] *Includes the risk of thyroid cancer taking into account the relatively high absorbed dose to the thyroid, while the WHO report calculated the risk of all solid cancer assuming that the absorbed dose to all organs except the thyroid was equal to the dose to the colon.*

C. The Committee's commentary on health implications for workers

E60. The Committee based its commentary on the same assumptions as for members of the public, modified as appropriate to match the worker population, and on the doses to workers reported in appendix D. Similar to its commentary on health implications for the public, qualitative estimates were made of disease outcomes, where the Committee has used the phrase "no discernible increase" where, although a disease risk in the longer term can be theoretically inferred on the basis of existing risk models, an increased incidence of effects is unlikely in practice to be observed in future disease statistics using currently available methods, because of the combination of the limited size of population exposed and low exposures, i.e. consequences that are small relative to the baseline risk and their uncertainties.

1. FDNPS workers

E61. The effective doses received by most of the FDNPS workers (99.3%) as a result of the accident were estimated to be less than 100 mSv with an average of about 10 mSv. The risk of these workers developing radiation-induced cancer is low (cf. the WHO estimates [W12]). There are distinct groups of more highly exposed workers; an assessment of the health implications for these groups is made below.

E62. *Cancer among workers receiving the highest effective doses.* A group of 160 workers received an effective dose equal to or in excess of 100 mSv, predominantly from external irradiation. The average effective dose in this group was about 130 mSv. If the group of 13 workers with high doses to the thyroid were included, the average effective dose would increase to about 140 mSv among a group of 173 workers (see below). Based on current understanding of risks, about two to three additional cases of cancer could on average occur in this group in addition to about seventy baseline cancers expected to occur in the absence of exposure (see table E1), although the uncertainties in such estimates are substantial. Such an increase occurring during the lifetime of the exposed individuals would not, however, be discernible because fluctuations of cancer incidence in groups of this size are considerably larger. The statistical power of detecting such an increase would be about 10%; for conducting a meaningful epidemiological study, a statistical power of 80% would usually be required.

E63. About one baseline leukaemia case would be expected to occur among a group of 173 male adult Japanese workers during their lifetime (noting the uncertainties associated with such estimates). A whole-body exposure of an adult male with an effective dose of about 140 mSv has been assessed to lead to a relative risk of about 1.2 for exposure at age of 20 years, and lower for exposure at older ages [W12]. Because of the small numbers involved, it is not expected that any potential increase in leukaemia incidence would be discernible.

E64. *Thyroid disease and disorder*. Approximately 2,000 workers (as of June 2013) received thyroid doses exceeding 100 mGy [M16], with an average dose of the order of 400 mGy. The question of whether the risk of thyroid cancer is elevated following exposure during adulthood in the interval 100 mGy to 1,000 mGy is under debate [M1, R5]. WHO estimated the risk at different ages at exposure: for a thyroid dose of 400 mGy at an age of 40 years, they estimated the relative increase of lifetime thyroid cancer risk to be 16% [W12]. Ultrasound surveys of these workers will increase the detection rate of baseline and potential radiation-induced thyroid cancer cases; the number expected to be detected will exceed considerably the number expected on the basis of reported incidence of thyroid cancer among population groups that do not undergo such surveys. Although there are very large uncertainties in estimating the risk of radiation-induced thyroid cancer, any increase in the incidence due to radiation exposure is not expected to be discernible.

E65. Thirteen TEPCO workers were estimated to have received committed absorbed doses to the thyroid in the range of 2 to 12 Gy, with an average of about 5 Gy. The two TEPCO operators in the control rooms for Units 3 and 4 who received the highest total effective doses (679 and 646 mSv, respectively), the highest cumulative effective doses from internal exposure (590 and 540 mSv, respectively), and who had not taken potassium iodine for thyroid blocking prior to their exposures, had no early deterministic health effects as a result of their exposures [I29]. The probability of occurrence of excess thyroid cancer cases during the lifetimes of the thirteen workers is small, because thyroid cancer is a rare disease even after high exposures (see the WHO estimate as outlined in table E4).

E66. Hypothyroidism (i.e. transient elevation of TSH) is a late deterministic effect observed after external radiotherapy of the neck and following nuclear medicine procedures using radioactive isotopes of iodine that deliver several grays [H2, H15, L2, M9, M10, O6, P5]. It has also been observed following heavy fallout from nuclear weapons testing in 1954 [C10]. Excess incidence of thyroid nodules have also been reported following external irradiation resulting from medical procedures or high levels of radioactive fallout [C10, N4, R7] and following protracted exposure to radioactive iodine [H1, L1, L2, Z1]. Given the magnitude of inherent uncertainties in the dose estimates, the Committee could not preclude the possibility of hypothyroidism among the more exposed workers. A particular issue is the suggestion that ionizing radiation induces Hashimoto thyroiditis (autoimmune thyroiditis). In its 2008 Report, the Committee stated that there had been few studies of significant size that had addressed the relationship between this disease and exposure to radiation, and that the largest study could not demonstrate any conclusive evidence of a relationship [U12].

E67. *Other diseases and health effects*. There is little likelihood of an excess incidence of circulatory diseases at the dose levels incurred by the group of workers with the highest effective doses [I26, S5, U9]. Beta particles may have contributed substantially to the dose to the eye lens of the workers. No direct information on beta-radiation fields at FDNPS was available to the Committee. For workers involved in response and recovery after the Chernobyl accident, the contribution of beta particles to the dose of the eye lens ranged between 0% and 350% of the dose from gamma irradiation (see annex D [U12]). Recently, ICRP published a statement on tissue reactions and considered a threshold level of absorbed dose to the lens of the eye of 500 mGy for tissue reaction effects [I26]. If the relative contribution of beta particles to the dose to the eye lens of workers at FDNPS were not higher than after the Chernobyl accident where posterior subcapsular cataracts have been detected, then no discernible excess incidence of cataracts due to the FDNPS accident would be expected. However, uncertainties remain about the doses to the eye lens and the dose–response relationship for cataracts.

E68. After technological disasters, the prevalence of post-traumatic stress disorder (PTSD), characterized by symptoms such as flashbacks, nightmares, hyper-vigilance and avoidance of reminders of the event, ranges from 15% to 75% [N9], depending on the gravity, severity and level of threat from the disaster, the population affected and the timing of the study.

E69. Initial observations have identified severe psychological effects following the earthquake, tsunami and FDNPS accident among emergency workers [M8, S7, S8, W1]. An initial voluntary self-reported questionnaire on the psychological status of workers at TEPCO's Fukushima Daiichi and Daini nuclear power stations was conducted 2 to 3 months after the disaster [S7]. Psychological distress and PTSD were observed among radiation workers. They reported intrusive flashbacks, avoidance of the plant, hyper-vigilance toward aftershocks, fear of irradiation and dissociative episodes. These health implications should not be attributed to radiation exposure itself, because they have been evoked by many other causes. Some workers suffered public harassment and were severely discriminated against as a result of TEPCO's negative image. In addition, many of them lived within the 20-km radius of the FDNPS while their families had been evacuated; they had experienced first-hand deaths from the tsunami, were placed in temporary housing with poor living conditions, and had been working long hours. Occupational health physicians and nurses provided mental health checks and consultations for the workers; however, there is a lack of trained psychiatrists for primary prevention of stress [S7, W1].

2. Experience from the Chernobyl accident relevant to the health implications of the FDNPS accident for workers

E70. In terms of health implications for workers, the Chernobyl accident differed from the FDNPS accident in many ways. The average effective dose received by the 530,000 Chernobyl recovery workers between 1986 and 1990, mainly from external exposure, was estimated to have been about 120 mSv. Some recovery workers received very high doses; for example, for 51 Russian Federation and 168 Ukraine recovery operation workers each receiving an effective dose in excess of 1 Sv, their average dose was as high as 9.4 Sv and 6.9 Sv, respectively [U12].

E71. In comparison, there were only 3,973 workers on-site at FDNPS during the first month after the accident and they received an effective dose during this period of about 21 mSv on average (see table D3). The highest effective doses (250–679 mSv) occurred among 6 TEPCO workers in the first month. During the first 19 months, 99.3% of 24,832 TEPCO and contractor workers were recorded as having an effective dose lower than 100 mSv and on average about 10 mSv; the remaining 173 workers received doses in excess of 100 mSv with an average of about 140 mSv. For all these workers, recorded doses over this period ranged from less than 10 mSv to 679 mSv. Although the periods of exposure differ significantly, these levels are far below those experienced by the Chernobyl recovery workers. Only doses to the thyroid of the six TEPCO workers with the highest effective doses reached levels received by the most exposed Chernobyl recovery workers.

E72. After the Chernobyl accident, acute radiation sickness (ARS) was diagnosed for 134 of the first responders and firefighters, 28 of whom died of ARS within a few months [U12]. In contrast, the FDNPS accident did not result in any cases of ARS.

E73. A radiation-related increase in the incidence of all solid cancers has been reported for the Russian Chernobyl recovery workers [I37], although not in another, albeit much smaller, study of recovery workers from Estonia [R2]. Owing to the much smaller number of workers exposed and their lower exposures, it is not expected that there will be an observable radiation-related general increase in the incidence of solid cancer among the FDNPS workers [P15, U11, U12].

E74. Elevated rates of thyroid cancer among the Chernobyl recovery workers compared with the general population have been reported; but no clear association with radiation dose has been found [I36, K8, M1, U12]. Similar results might be expected for the FDNPS workers, as a result of intensive thyroid screening, although substantially fewer workers were involved and they received lower doses.

E75. Studies of the Chernobyl recovery workers suggest an increase in the incidence of leukaemia. The limitations of these studies include uncertainties in dose reconstruction, potential biases and confounding factors [I38, K7, R6, U12]. A recent article reported statistically significant effects [Z2], however exposure estimates were based on proxy interviews, which implies a high uncertainty and potential for bias. The workers at FDNPS who incurred the highest external exposure received doses to the bone marrow of at most 200 mSv. Owing to the small number of workers involved, no discernible effect of the radiation exposure on leukaemia incidence is expected.

E76. Few studies assessed circulatory disease among the Chernobyl workers. More evidence is needed to conclude whether or not radiation exposure at doses below 500 mGy increases the risk of circulatory disease. Radiation doses of FDNPS workers were too low to expect an observable excess incidence of radiation-induced circulatory disease in the future. However, there may be secondary effects due to psychological stress that confound any relationship with radiation exposure.

E77. There have been two lines of research on the psychological impact of the Chernobyl accident on recovery workers: *(a)* potential radiation-related cognitive impairment; and *(b)* the psychiatric effects of exposure-related stress [B18].

(a) Four studies conducted in Kiev provide suggestive evidence of measurable cognitive or neuro-psychiatric effects of radiation exposure among highly exposed recovery workers [G1, L11, L12, P11]. Although consistent and suggestive, methodological limitations of the studies prevent general conclusions being drawn [B17, B19, W7].

(b) Significant long-term psychiatric effects are well documented among recovery workers following the Chernobyl accident [L10, R1, R3, V1]. Initial observations have identified psychological effects among FDNPS radiation workers following the earthquake, tsunami and nuclear accident [M8, S7, S8, W1].

D. Long-term medical monitoring

E78. On 3 August 2011, the Japanese Ministry of Health, Labour and Welfare (MHLW) announced the "grand design of a long-term health management of all the emergency operations workers at TEPCO's No. 1 Fukushima Nuclear Power Plant" [M14]. The database would be constructed to contain radiation dose records that are systematically collected, and information about long-term health conditions of emergency operations workers. Health management would be provided by employers while workers were employed, and contact points located throughout Japan would be determined to provide appropriate long-term health management, consultation and regular health examinations of workers after leaving their workplace. Periodic health examinations would be given to workers to monitor for potential late radiation-related health effects. Special health examinations would be given to workers with the highest exposures, including annual eye check-ups (for lens opacity), and monitoring of the thyroid, stomach, large intestine and lung for cancer.

E79. Ultrasonography was planned to be performed for all emergency workers with absorbed doses to the thyroid exceeding 100 mGy. The eligible group consisted of about 2,000 workers. Modern ultrasonography is able to detect very small tumours; however the probability of occurrence of thyroid cancer due to radiation exposure in adulthood is small and would be unlikely to manifest as a discernible increase in statistics on cancer incidence [D2, F6].

E80. Three studies of cancer mortality among Japanese workers exposed occupationally in the nuclear industry have been previously conducted [A7, H11, I39]. The average cumulative effective dose ranged from about 12 to 15 mSv in these studies; this is similar to the dose received by most FDNPS workers as a result of the accident (average about 12 mSv from the accident until October 2012, see table D4). In one of the three analyses [I39], 4,161 workers had received doses over 100 mSv, with a mean dose of 154 mSv. This compares to only 173 FDNPS workers with doses greater than 100 mSv and an average dose of about 140 mSv. Because no change in the mortality rates due to cancer was detected among Japanese nuclear industry workers with follow-up from 1986 to 2002, it is unlikely that a study of the FDNPS workers would discern a difference in the mortality rate from that of the general population, or that a significant relationship between radiation dose and cancer mortality be any different from that found among other Japanese nuclear industry workers. Studies would lack sufficient statistical power to assess the risk of cancer due to irradiation; the doses would be too low and the population size too small [B13, W4]. Likewise, excess screening and diagnostic suspicion may bias studies of FDNPS workers, in particular detecting a greater incidence of small tumours, unrelated to radiation exposure, than would otherwise have been detected.

E81. Despite these scientific limitations, it is important that FDNPS workers be included in the existing Japanese nuclear worker cohort, and that long-term cohort studies of these workers be conducted. Finally, studies of the mental and physical health of workers exposed after the Chernobyl accident were conducted separately instead of integrating cohort studies of cancer and other disease outcomes with mental health research. If mental health measures were embedded in the Japanese nuclear worker cohort, the combined approach would track mental health effects and provide a unique opportunity to advance understanding of risk factors, such as perceptions about the health impact of radiation exposure and synergistic psychological effects of stress with radiation exposure [B19, B20]. Indeed, future studies of the FDNPS workers could improve understanding of the association of PTSD and depression with circulatory risk and recovery [K26] and other medical conditions [V5].