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Saving Lives and Preventing Injuries from Unjustified Protective Actions - Method for Developing a Comprehensive Public Protective Action Strategy for a Severe NPP Emergency

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Abstract:	During the response to the Fukushima Daiichi nuclear power plant (FDNPP) emergency about 50 patients died during or shortly after an evacuation when they were not provided with the needed medical support. In addition, during the FDNPP emergency it has been shown that there were increases in mortality rates among the elderly due to long term dislocation as a result of evacuation and relocation orders and an inability to stay in areas advised to shelter for extended periods. These deaths occurred even though the possible radiation exposure to the public was too low to result in radiation induced deaths, injuries or a meaningful increase in the cancer rate, even if no protective actions had been taken. These problems are not unique to the FDNPP emergency and would be expected if the recommendations of many organizations were followed. Neither the International Atomic Energy Agency (IAEA), the International Commission on Radiological Protection (ICRP), the U.S. Nuclear Regulatory Commission (NRC) nor the U.S Environmental Protection Agency (EPA) adequately take into consideration in their recommendations and analysis the non-radiological health impact, such as deaths and injuries, that could result from protective actions. Furthermore, ICRP, NRC, EPA and the Department of Homeland Security (DHS) call for taking protective actions at doses lower than those resulting in meaningful adverse radiation induced health effects and do not state the doses at which such effects would be seen. Consequently, it would be impossible for decision makers and the public to balance all the hazards both from radiation exposure and protective actions when deciding whether a protective action is justified. What is needed, as is presented in this paper, is a method for developing a comprehensive protective action strategy that allows the public, decision makers and others who must work together to balance the radiological with the non-radiological health hazards posed by protective actions, and to counter the exaggerated fear of radiation exposure that could lead to taking unjustified protective actions and adverse

	psychological, sociological and other effects.

Saving Lives and Preventing Injuries from Unjustified Protective Actions – Method for Developing a Comprehensive Public Protective Action Strategy for a Severe NPP Emergency

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Abstract:

During the response to the Fukushima Daiichi nuclear power plant (FDNPP) emergency about 50 patients died during or shortly after an evacuation when they were not provided with the needed medical support. In addition, during the FDNPP emergency it has been shown that there were increases in mortality rates among the elderly due to long term dislocation as a result of evacuation and relocation orders and an inability to stay in areas advised to shelter for extended periods. These deaths occurred even though the possible radiation exposure to the public was too low to result in radiation induced deaths, injuries or a meaningful increase in the cancer rate, even if no protective actions had been taken.

These problems are not unique to the FDNPP emergency and would be expected if the recommendations of many organizations were followed. Neither the International Atomic Energy Agency (IAEA), the International Commission on Radiological Protection (ICRP), the U.S. Nuclear Regulatory Commission (NRC) nor the U.S Environmental Protection Agency (EPA) adequately take into consideration in their recommendations and analysis the non-radiological health impact, such as deaths and injuries, that could result from protective actions. Furthermore, ICRP, NRC, EPA and the Department of Homeland Security (DHS) call for taking protective actions at doses lower than those resulting in meaningful adverse radiation induced health effects and do not state the doses at which such effects would be seen. Consequently, it would be impossible for decision makers and the public to balance all the hazards both from radiation exposure and protective actions when deciding whether a protective action is justified.

What is needed, as is presented in this paper, is a method for developing a comprehensive protective action strategy that allows the public, decision makers and others who must work together to balance the radiological with the non-radiological health hazards posed by protective actions, and to counter the exaggerated fear of radiation exposure that could lead to taking unjustified protective actions and adverse psychological, sociological and other effects.

Introduction

During the FDNPP emergency, evacuations and relocations resulted in deaths and injuries (Hasegawa et al. 2016; Ichiseki 2013; Murakami et al. 2015; Nomura et al. 2013; Saji 2013; Yasumura 2014), but only prevented exposures that were too low to result in meaningfully observable adverse radiation induced health effects‡,§, henceforth referred to as meaningful radiation health effects. Therefore, these protective actions may not have been justified; since they did more harm than good and no process was used to assess whether the protective actions were justified. This occurred because the Japanese emergency arrangements concerning protective actions were not comprehensive as they:

- assumed an exaggerated health risk of radiation exposure,
- did not consider the health impact of taking protective actions, and
- did not consider the impact to health of the psychological, sociological and other effects that were often a result of an exaggerated fear of radiation exposure.

These problems are not unique to the FDNPP emergency and would probably occur during the next severe NPP emergency** if the recommendations of many organizations were followed.

This paper will show how many of the existing recommendations and analysis used for emergency response, for example references: (IAEA 2013a; ICRP 2007; US DHS 2006; US EPA 2017; US NRC and FEMA 2011; US NRC 2012, 2013), can result in actions taken that may not be justified as they can do more harm than good. While the principal of justification is recognized by most of these recommendations as a key concept of radiation protection, no system has been developed to present how this can be realized.

It is necessary to act using a ‘Comprehensive public protective action strategy’ for protection of the public during severe NPP emergencies. This strategy would consider all the hazards encountered by the public and provide the basis for the public response community†† to work together in planning and responding in a way to ensure justified and effective protective actions are taken.

This paper will also describe in Annex 1 and 2 the “COMprehensive Protective Action stRatEgy” method (COMPARE method) for use by the public response community to balance the health hazards of: protective actions, radiation exposure, and NPP emergencies, which would allow the development of a protective action strategy that is justified. The method will also explain how to counter the exaggerated fear of radiation exposure that can be expected during an emergency, which could lead to taking unjustified protective actions. This COMPARE method uses concepts consistent with the ‘risk-informed decision making’ approach (IAEA 2011).

The FDNPP emergency: the response taken consistent with existing recommendations

This section of the paper provides a description of the emergency at the FDNPP, focusing on the limitations of recommendations on protection of the public given in references (IAEA et al. 2007; ICRP 2007; US DHS 2006; US EPA 1992; US NRC and FEMA 1996) that were available at the time of the emergency. In addition, the shortcomings of current recommendations and analysis on the response to severe NPP emergencies, given in references (US DHS 2006; US EPA 2017; US NRC 2013) will be discussed.

Table 1 summarizes the key events during the FDNPP emergency, the protective actions taken that may have been unjustified, why the protective action may have been unjustified and the international and US recommendations in place at the time of the emergency that could lead to taking unjustified protective actions under similar conditions. Fig. 1 shows when and where the protective actions from Table 1 were taken and the projected effective dose [mSv] from external exposure from ground deposition for the first year following the emergency.

Fig. 1 Projected effective dose for the first year from external exposure from ground deposition from the major release of the FDNPP on 15 March, with the protective actions presented in Table 1 (IAEA 2015; NERHQ 2011).

Evacuations implemented before the major release (out to 30 km, (Fig. 1)), were due to concerns raised by the severe conditions at the FDNPP and caused the majority of the > 250 deaths among the elderly (Table 1). Contrary to this experience, the most recent analysis of the risks from a severe NPP emergency performed by the US NRC (2012) and (2013) concluded that there will not be any deaths from severe NPP emergencies, since the public within 10 miles (16 km) would have been evacuated before a major release upon detection of severe conditions at the NPP. This analysis did not recognize the possibility of deaths amongst the elderly as a result of the evacuation.

In addition, as described in Table 1, the public during the FDNPP emergency were relocated from areas where the effective dose from deposition was projected to exceed 20 mSv a^{-1} (IAEA 2015) based on the ICRP reference levels for emergency exposure situations (ICRP 2007). However, this reference level, as with all ICRP reference levels, is below the effective dose at which radiation induced health effects would be meaningful (Table 2). Importantly, these reference levels cannot be used as a basis for justified protective actions since they were developed without considering the impact of the protective actions that would be taken based on these levels (ICRP 2007, 2012). However, ICRP recommendations emphasize optimization and the use of reference levels during emergency situations with limited or no mention of justification (ICRP 2007, 2012). This is highlighted by the ICRP message about the FDNPP emergency

(ICRP 2011; IAEA 2015) issued 10 days after the start of the emergency on 21 March 2011 that recommended the use of optimization and the ICRP reference levels. No mention was made in the message of the principal of justification or that the impact of protective actions needs to be considered. There is no evidence that shows consideration was given to the principal of justification by the Japanese government when establishing the criteria for relocation.

If a projected effective dose of 100 mSv a^{-1}, the dose above which radiation induced health are meaningful (Table 2), had been used as the criterion for relocation during the FDNPP emergency, no relocations would have been required beyond the evacuated 30 km zone (Fig. 1). This would have most likely saved lives (Table 1) among the elderly and other non-radiological health effects due to dislocation from this area.

The US EPA Protective Action Guides (PAGs) (US EPA 2017), which are the projected dose at which evacuations and relocations are recommended, are well below the doses at which any radiation induced health effects (Table 2) would be meaningful. The EPA PAGs were based on LNT assumptions and a cost benefit analysis, which did not take into consideration the adverse health impact of the protective actions triggered by the PAGs, or from the fear of radiation exposure implied by the PAGs. In addition, EPA recommends using conservative assumptions to fill information gaps and this could overestimate the health hazards from radiation exposure (US EPA 2017). Therefore, taking actions based on these PAGs could do more harm than good due to the health impact of the protective actions. Furthermore, the PAGs contained in the Department of Homeland Security (DHS) guidance for the response to a terrorist attack involving a radiological dispersal device or improvised nuclear device (US DHS 2006) are consistent with the EPA's PAG. This means that taking protective actions based on the DHS PAGs may also not be justified and could contribute to adverse psychological, sociological and other effects during a terrorist attack due to the exaggerated fear of radiation exposure portrayed (Orient 2014).

The underlying problem, as highlighted in Table 1, is that the most important radiation protection principle, justification, was forgotten in the development of the recommendations that were available at the time of the FDNPP emergency and has also been forgotten in the development of the recommendations that have been published since then.

Adverse radiation health hazards for a severe NPP emergency release

As demonstrated above, protective actions have been taken during severe NPP emergences to avert exposures that were not meaningful since the hazards of radiation exposure were not placed in perspective by the existing guidance. Consequently, a color-coded system to place in perspective the meaningful radiation health hazards for a severe NPP release has been developed (McKenna et al. 2015) in order to help decision makers and the public make informed decisions on protective actions. The system is presented in Table 2 and was designed recognizing that dose estimates by themselves are meaningless and are only useful as an indicator of the possible health effects if compared to doses calculated for a specific set of circumstances (IAEA 2013a)‡‡. This color-coded system will be used as part of the COMPARE method (Annex 1 and 2) in order to allow all hazards to be compared on an equal ground to facilitate balancing the meaningful radiation health effects (Table 2) against the meaningful health hazards of protective actions.

In addition to exposure related health effects, nuclear and radiological emergencies have resulted in adverse economic, social, and psychological effects (IAEA et al. 2005; WHO 2013, 2016) and the public, decision makers and others (e.g. medical staff) have taken inappropriate and damaging actions that are not justified based on the radiological health hazard, often in the misguided belief that they were protecting themselves and their families (IAEA 2013a; ICRP 2012; McKenna et al. 2015). This was due in part to the failure to communicate the health hazards of radiation exposure clearly and compounded by a complex system of radiation protection concepts and units (IAEA 2013a; ICRP 2012; McKenna et al. 2015) that does not provide information on when radiation induced health effects would be meaningful.

For example, it is often considered prudent to use the linear no-threshold model (LNT) as a basis for the criteria for taking protective actions (US EPA 2017; ICRP 2007). This is assumed even though the LNT assumption is questionable§§, does not help define what levels of exposure are meaningful in terms of health effects and its use often exaggerates the health hazards from radiation exposure (Cuttler 2016; Orient 2014; Rithidech 2016; Sacks et al. 2016; Siege et al. 2012). As documented in reference (Brooks et al. 2016), a general finding of the 2015 Health Physics Society symposium, health risks from low doses and low dose-rates of ionizing radiation, was: "A decision to implement protective actions for public health (e.g., evacuations) in the event of low dose exposure must be carefully justified to ensure that the actions provide public benefit and do not result in harm. In the case of any radiation exposure, the serious fear and stigma can lead to highly detrimental mental and social suffering". Thus the use of LNT during emergencies, rather than being prudent, can result in taking protective actions that do more harm than good when the impact of the protective action is considered.

In addition, the LNT assumption is often misused to estimate deaths from very low exposures, such as half a million deaths from the FDNPP and Chernobyl NPP emergencies (ICRP 2012). This is done even though ICRP clearly states that this is inappropriate (ICRP 2007; 2012) and it is not recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2015). However, this is often done by the media and 'experts' during emergencies, in peer reviewed articles (e.g. Hoffman et al. 2011) and assessments (e.g. WHO 2013). The result is often mixed messages being provided to the public not to worry about the low doses, while at the same time being told that these low doses will cause excess cancers. These unfounded death estimates and mixed messages caused emotional distress and confusion among the public (ICRP 2012). Some assessments (e.g. Tsuda et al. 2017) of the possible health consequences of severe NPP emergencies focus almost exclusively on the possible effects of radiation exposures at very low levels where these effects, if any, would not be meaningful. This is done without considering the adverse psychological and other effects of not putting the health risk in perspective or considering the health impact of protective actions that would be taken to avert these exposures.

Another example is that during the FDNPP emergency the public could not understand why higher public doses were permitted during the emergency (i.e. ICRP 20 mSv a^{-1} effective dose reference level) than before the emergency, when the 'annual limit' for public exposure was 1 mSv a^{-1}***. This gave the public the impression they were being less protected during the emergency than before, and logically that doses above 1 mSv -a^{-1} effective dose were dangerous (ICRP 2012). The same could be expected if a severe emergency occurred in the US, since the US EPA and US NRC have established dose limits for the general public of between 0.04 and 1 mSv a^{-1}effective dose (HPS 2016).

The system of concepts and units that has been successfully used for radiation protection during normal situations is not suited for emergencies (ICRP 2012) and can be the basis for unjustified actions being taken. The various limits and levels are not explained in terms of the possible meaningful health effects and present an exaggerated impression of the health risk of exposure when compared to any action taken to reduce exposures. This shows the importance of being able to place calculated doses or measured quantities (e.g. dose rates, food concentrations) into perspective relative to meaningful health effects from radiation exposure. This would allow the public to make informed decisions concerning the actions to take and would help to relieve their anxiety.

There is a need for a new system of radiation protection for emergency response with the objective of taking justified protective actions in the event of an emergency. This system would be designed for use by the public and other members of the public response community who must work together when planning for and responding to a severe NPP emergency. The system should provide a graded approach that can be used as a basis for balancing the meaningful health hazards of radiation exposure against those of the protective actions that might be taken to avert exposure. The system would be based on meaningful health effects presented in a way that is understandable for the public. The system would provide a basis for countering the exaggerated fear and concerns resulting from the use of LNT assumptions that could lead to taking unjustified protective actions. In applying the system, the best estimate of the hazards is used, rather than conservative estimates. This is because a conservative estimate of the radiological hazards, i.e. assuming the worst effects theorized, can result in an increased hazard from the protective actions that are implemented.

Conclusion

Over the last 40 years protective action strategies have been developed to protect the public from NPP emergencies that focus principally on the radiological effects, without fully considering the health impact of the protective actions, and have been predominantly based on the LNT theory projections of radiation induced health effects and assumptions (conservative assumptions) that overestimate the doses. The result, as has been observed during past emergencies, is that often the most severe health effects are those caused by protective actions or by the exaggerated fear of radiation exposure. Consequently, the protective action strategies developed to date are, in many cases, not justified as they have done more harm than good.

Clearly much of the recommendations and analysis (IAEA 2013a; ICRP 2007; US DHS 2006; US EPA 2017; US NRC 2012, 2013) concerning protection of the public in the event of severe NPP emergency needs to be re-examined considering the full impact of protective actions, the meaningful health effects of radiation exposure and the exaggerated fear of radiation exposure. The public, decision makers and other members of the public response community need to understand when the risk of taking protective actions outweighs the risks from radiation exposure. This is to ensure they can work together during the preparedness and response to a severe NPP emergency to most effectively protect the public. Therefore, the authors support a petition for rulemaking to the NRC and EPA requesting these issues to be addressed.

In support of these needs, the COMPARE method is presented in this paper (Annex 1 and 2) to allow the existing recommendations to be re-examined and revised accordingly to ensure that actions taken to protect the public do more good than harm.

Annex 1

The solution – the COMPARE method

This section presents a method for developing a ‘comprehensive protective action strategy’ for protecting the public, hereinafter referred to as the COMPARE††† method, as a solution to help facilitate urgent and early‡‡‡ protective actions being taken during a severe emergency at an NPP that are justified.

The COMPARE method would need to be integrated into the emergency preparedness and response arrangements, and training on its use provided. Further details of the arrangements that need to be in place in order to respond effectively to a severe nuclear or radiological emergency can be found in references (FAO et al. 2015; IAEA 2013a). The majority of the concepts used in the method have been tested in several IAEA workshops and were revised following comments and feedback from the emergency preparedness and response community. However, the newly developed approach of the COMPARE method has not been tested in workshops and the authors recommend that this is done before the method is integrated into emergency preparedness and response arrangements.

The fundamental concept of the COMPARE method is shown in Fig. 2 and the application of the method is presented in Fig. 3.

The COMPARE method is based on best estimates of the meaningful health effects presented in a way that is understandable to all members of the public response community, with the goal of promoting informed decision making:

- during planning to balance the health hazards of possible radiation exposure and the possible health hazards from protective actions to determine the protective action strategy that is most likely to do more good than harm and therefore is justified in the event of a severe NPP emergency,
- during response to provide a sound, understandable basis on which to compare the hazards and make informed decisions based on the information being provided, and
- during planning and response to counter the exaggerated projections of the health hazards of radiation exposure which could lead to taking unjustified protective actions.

Fig. 2 Fundamental concepts of the COMPARE method – how to attain justification for a severe NPP emergency

Fig. 3 Application of the COMPARE method

The protective action strategies must be developed by the public response community working together to take effective and justified protective actions during a severe NPP emergency based on a common understanding of the key elements summarized in Table 3. In order to facilitate this common understanding and to allow all of the hazards to be compared and balanced, all the meaningful health hazards are presented in a color-coded system for different hazard situations:

- calculated doses (Table 2),
- NPP conditions (Table 4),
- environmental measurements (Table 5) and,
- protective actions (Table 6).

It should be noted that while the same color and category (e.g. red and 'possibly dangerous to health') are used for each of the hazardous situations, the criteria listed in each table defining the category are different depending on the nature of the hazard. Each hazard situation has an associated pictograph: radiation symbol (Table 2) for the hazard indicated by calculated doses, NPP with core melt and plume symbol (Table 4) indicating the hazard of a core melt and possible release from an NPP, environmental monitoring symbol for the hazard indicated by monitoring results (Table 5) and a family under an umbrella (Table 6) for the hazard associated with protective actions. All of the hazards must be balanced at each point at which protective action decisions are made during a severe emergency:

1) *Upon detection of plant conditions indicating actual or projected severe damage to fuel in the reactor.*
   At this decision point protective actions are initiated that must be taken before or shortly after a release (i.e. before monitoring) to be effective. The possible meaningful radiation induced health hazards indicated by severe emergency conditions at the NPP, as a function of distance, and possible effective protective actions are shown in Table 4, with the basis discussed later.

2) *Following a major release based on environmental measurements.*
   At this decision point protective actions are taken to prevent meaningful radiation induced health

effects principally from longer-term exposures due to deposition and ingestion. The meaningful radiation induced health hazards indicated for selected environmental measurements and exposure situations are summarized in Table 5. The basis for these hazards is described in (IAEA 2013a; McKenna et al. 2015)§§§.

If dose projection models are to be used in the decision-making process it is crucial that all those involved in the decision making process understand the significant difficulties of using such models as an effective basis for protective actions due to the inability to predict the timing, magnitude, composition, effective height and duration of severe releases as demonstrated during the FDNPP and Chernobyl NPP emergencies (IAEA 2013a, 2015).

It is assumed that in applying the COMPARE method the necessary elements of emergency preparedness are in place, such as arrangements for:

- initiation of safe protective actions promptly (i.e. within 30 min.) of detection of severe conditions at the NPP,
- initiation of safe protective actions promptly following a release based on environmental measurements, to include default operational intervention levels (OILs) (IAEA 2013a; McKenna et al. 2013),
- effective implementation of protective actions, such as: (1) pre-distribution of iodine thyroid blocking to allow it to be taken immediately, (2) consideration of the local conditions (e.g. location of hospitals) that could affect implementation of protective actions, (3) providing medical care for hospital and nursing care facilities to allow safe longer term operations in areas that will be advised to shelter, and (4) recognizing that families will, if possible, evacuate or shelter together during an emergency, and
- effective communication with the public during the emergency, placing the health hazards of exposures and protective actions into perspective, and countering assessments that may result in an exaggerated fear of radiation exposure.

Reference (FAO et al. 2015) has comprehensive recommendations concerning emergency response arrangements.

Table 4 presents the meaningful radiation health hazards when conditions at the facility are detected that indicate a severe NPP emergency, along with the effective protective actions. This table is used in the COMPARE method to balance the possible health hazard of protective actions (Table 6) and radiation exposure at the first decision point, which is when protective actions need to be taken based on conditions at the NPP to be effective. Table 4 is based on the examination of years of analysis and experience of severe reactor emergencies, such as that presented in references (IAEA 1991, 1997, 2013a, 2015; McKenna 2000; US NRC 1975, 1978, 1990, 2002, 2007, 2010, 2012, 2013).

This table considered certain characteristics of severe NPP emergencies that need to be understood when developing a protective action strategy. This includes: what could cause a major release, when a major release could be expected to occur, how long a major release could last, and how to characterize the resulting off-site health effects. Decision makers would also need to understand what information will be available during an emergency that can be used as a basis for taking protective actions. The most important insights are summarized in reference (IAEA 2013a)****, along with the effectiveness of protective actions for a severe NPP emergency at a light water reactor.

Table 5 presents the meaningful radiation health hazards indicated by selected environmental measurements for realistic exposure scenarios for a release of radioactive material from a light water reactor. This table is used in the COMPARE method to balance the possible health hazard of protective actions (Table 6) and radiation exposure at the second decision point, which is when protective actions need to be taken following a release based on environmental measurements. References (McKenna et al. 2013, 2015; IAEA 2013a, 2013b, 2017) provide comprehensive recommendations and tools on taking justified protective actions and on putting the radiation health hazards in perspective based on environmental measurements.

Table 6 presents the possible hazards to health from taking protective actions. This is used in the COMPARE method to balance the health hazards at both decision points – *upon detection of plant conditions* and *based on environmental measurements*. The basis for the hazards is discussed in Annex 2.

In developing the protective action strategy it will be necessary optimize the strategy by determining where protective actions can be taken most effectively when considering both the hazard to health from radiation exposure and from protective actions. For example, the boundary of where evacuations would be recommended upon detection of severe condition in the NPP (e.g. somewhere between 3 to 5 km) (Table 4) should be established such that those at greatest risk are most effectively protected, but also ensuring that the protective actions will, overall, do more good than harm. This may involve, for example, establishing the boundary to exclude a hospital or nursing care home (Fig. 4) in order to aid fast evacuation of those closer to the NPP and reduce the possibility of increased mortality and morbidity rates among the elderly, or those with severe underlying medical conditions.

Fig. 4 Evacuation zone boundary adjusted to exclude hospital or nursing care home

An example of the results of the application of the COMPARE method for a severe NPP emergency is presented in Table 7, which lists the protective action to be implemented, the distance, and the considerations when balancing all of the hazards. This table is for exemplary purposes only; it is important to emphasize that the COMPARE method should be adapted and applied to local conditions, and coordinated among all members of the public response community.

Possible health effects that could result from using the example COMPARE method

This section will briefly discuss the possible health effects, including both the positive and negative impacts, from using the example COMPARE method (Table 7). This discussion will include the FDNPP emergency and an NPP emergency involving the most severe release considered reasonable.

The health impact of the protective actions would be expected to be much lower if the COMPARE method (Table 7) had been applied during the FDNPP emergency. About 18,000 people would be dislocated under the COMPARE example versus 140,000 during the FDNPP emergency. The dislocations under the COMPARE method include evacuation of 6,000 people living within 3 km (IAEA 2015) upon detection of severe conditions at the facility (Table 4), along with relocation of about 12,000†††† people from areas where the environmental measurements indicate health concerns due to external exposure from deposition projected in excess of an effective dose of 100 mSv a^{-1} (Table 5).

Deaths due to unsafe movement of those needing ongoing care would not be expected to occur because evacuations close to the NPP would only be performed when it was safe to do so. In addition, the psychological and other health effects due to an exaggerated fear of radiation exposure would probably be reduced as tools would be used to place the health hazards of radiation exposure into perspective (McKenna et al. 2015).

The most severe release considered reasonable‡‡‡‡ is much larger than the FDNPP release and occurs about 8 hours after core damage and lasts for several hours, possibly resulting in exposures off-site that could:

- be dangerous to health for the approximately 6,000 people within the first few kilometers, as well as a very small possibility of radiation induced deaths among those sheltered in houses within 1 to 2 km in the event of rain,
- cause health concerns, primarily within 15 km, but also among those in small heavily affected areas out to about 30 km primarily due to radio-iodine inhalation and longer term exposure due to deposition,
- cause health concerns from ingestion of directly contaminated food or rainwater at distances greater than 100 km from the NPP, as occurred in the Chernobyl emergency.

If the example response strategy developed based on the COMPARE method (Table 7) was applied for an emergency with the most severe release considered reasonable, there should not be a detectable increase in radiation induced health effects among the public.

Annex 2

Basis for the health hazards of protective actions presented in Table 6

This section presents the basis for the health hazards of the protective actions§§§§ presented in Table 6.

Possibly dangerous to health:

Evacuation of the elderly or patients needing medical care without providing such care. During the FDNPP emergency about 50 people died (as of April 2011) during or shortly after the evacuation of elderly people from hospitals and nursing homes (Hasegawa et al. 2016; IAEA 2015). These evacuations were carried out without the necessary medical and other support and conditions were imposed for accepting evacuees to shelters (the patients had to be monitored and decontaminated) when priority should have been given to ensuring necessary medical care was provided (IAEA 2015; NAIIC 2012). Radioactive material deposited on the skin or clothing during such an emergency would not be a significant danger to the health of anyone located off site and universal precautions against infection (gloves, mask etc.) provide sufficient protection from handling possibly contaminated patients (Callen and Homma 2017; IAEA 2013a). The deaths were due to factors such as hypothermia, dehydration, deterioration of underlying medical problems and lack of medical support (Hasegawa et al. 2016; Tanigawa et al. 2012).

Evacuation (movement) under life threatening conditions (e.g. dangerous road/weather conditions). Under most conditions, the movement of the general population***** during evacuations is safe as was observed after the FDNPP emergency (IAEA 2015). Furthermore, during the FDNPP emergency elderly people were safely moved during the evacuation of hospitals and nursing care facilities when medical and other support was provided (Hasegawa et al. 2016). In the United States, evacuations of more than 1,000 people occur about three times a month and deaths are rare (US NRC 2008). Studies (US NRC 2005, 2008) of 60 evacuations†††††, within the USA, involving 15 million people, identified only 5 deaths occurring during the evacuations. This death rate appears to be similar to those during normal travel in the US (NHSA 2016). However, during the response to Hurricane Rita in 2005 there were about 100 deaths related to the mass evacuation of more than 1 million people. This evacuation, in some cases, lasted more than 24 hours in temperatures above 38°C (100 F), during which evacuees turned off car air conditioners to conserve fuel or to keep engines from overheating. The deaths resulted from hyperthermia, dehydration, lack of access to necessary medical care and an accident involving 23 nursing home evacuees in a bus fire (Carpender et al. 2006; Zachria et al. 2006).

Dislocation of the elderly who require medical support. Dislocation of the elderly who require medical support has resulted in increased mortality and morbidity rates among the elderly over 60 to 65 years old

(Dosa 2012; Hasegawa et al. 2016; Ichiseki 2013, Yasumura 2014). Analysis of deaths rates before and after the dislocations showed death rates of the elderly moved from nursing facilities and hospitals increased from about 1% per month to 2 to 3% per month for the first few months before returning to the rates before dislocation (Hasegawa et al. 2016; Nomura et al. 2013) resulting in about 200 deaths within the first year (Yasumura 2014). Similar increases in the death rates were observed during evacuations of hospitalized elderly in the US due to Hurricane Katrina even though adequate medical care was provided during and after the evacuations (Dosa 2012). In this regard about 6% of the population in the US are elderly (over 65) living at home but needing help with personal care (CDC 2015). This raises the concern that deaths among this cohort may also be seen if the whole population is dislocated. Many authors (e.g. Saji 2013, WNA 2017), the media and others have stated that over 1,000 died due to dislocations of the whole population during the FDNPP. However, these estimates were based on 'disaster-related premature deaths' (DRD) reported by the local Japanese government (municipal offices) that were not supported by analysis of death rates before and after the dislocations.

Sheltering resulting in dislocation of the elderly. Sheltering may be dangerous, as observed during the FDNPP emergency, if it results in dislocation of the elderly.

Causing health concerns:

Dislocation of the general population and the elderly. Dislocation can result in increased cardiovascular and other chronic diseases, diseases related to lifestyle (e.g. alcohol abuse) and adverse psychiatric and psychosocial issues (e.g. stigma) (Hasegawa et al. 2016; Nomura et al. 2013, 2016; Suzuki et al. 2015).

Footnotes

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‡ Severe deterministic effects and radiation induced cancers that are meaningfully observable in the sense that the rate of occurrence is large enough that any action taken to reduce the rate may do more good than harm when the impact on the overall health of those affected is considered. This would not include small (relative to the background rate) increases, in theory, shown at low doses.

§ The maximum effective dose averted by evacuation was 50 mSv effective dose and by relocation it was 20 mSv effective dose to adults. Between 750 and 200 mGy absorbed dose to the 1 year infant thyroids was averted by evacuation in a relatively small number of people living within a few kilometers of the FDNPP (UNSCEAR 2014); however, these thyroid doses could have been averted by timely application of iodine thyroid blocking (ITB) agent. ITB agent needs to be pre-distributed to ensure it can be taken immediately when instructed. Taking an ITB agent is safe provided it is taken according to WHO recommendations (WHO 2011).

** Emergencies that can result in meaningful radiation induced health effects off the site. This would involve severe overheating (> 1,200°C) and damage to the fuel in the core or spent fuel pool (US NRC 2002).

†† The public, decision makers, physicians, the radiation protection community and others who must work together to balance the radiological with the non-radiological health hazards posed by protective actions, and to counter the exaggerated fear of radiation exposure that could lead to taking unjustified protective actions.

Table 1:

[a] A major release occurred on 15 March that resulted in significant deposition due to rain (IAEA 2015).
[b] Assumed to be effective dose, but not clearly stated as such in official reports.
[c] Estimates of >1,000 deaths due to the dislocation have been made; however, these estimates need to be viewed with caution, as discussed in Annex 2.

‡‡ Such as dose rates in an inhabited area or conditions at an NPP.

Table 2:

[a] RBE weighted absorbed dose to the red marrow to the most highly exposed individual for the exposure situation (representative person, in accordance with reference (ICRP 2007)).
[b] Equivalent dose to the fetus is derived as the sum of the dose from external exposure and the maximum committed equivalent dose to any organ of the embryo or fetus from intake to the embryo or fetus for different chemical compounds and different times relative to conception (FAO et al. 2015).
[c] The hazard applies to anyone affected during a particular exposure scenario when the fetal dose is exceeded; the fetal dose is used as a surrogate to account for the hazard from intake (inhalation or ingestion) in any exposed person.
[d] Total effective dose to the most highly exposed individual for the exposure situation (representative person, in accordance with reference (ICRP 2007)).

[e] The original definition of safe presented in (McKenna et.al 2015) has been revised from below 'observable' health effects to below 'meaningfully observable' health effects to address criticism (e.g. Tsuda et al. 2017) by those that say studies, in theory, have observed health effects at very low doses. Within the text of the paper 'meaningfully observable' is shortened to 'meaningful' for simplicity and ease of reading.

§§ The LNT model is not universally accepted nor scientifically verified and the level of risk is associated with very-low-dose exposure is unknown (ICRP 2007; Siege et al. 2012). There is growing evidence the LNT model may be wrong (Cuttler 2016; Rithidech 2016; Sacks et al. 2016).

*** Consistent with the ICRP limit for an existing exposure situation (ICRP 2007).

††† COMprehensive Protective Action stRatEgy.

‡‡‡ Urgent protective actions need to be taken promptly (normally within hours) in order to be effective; their effectiveness will be markedly reduced if they are delayed. Early protective actions can be implemented within days to weeks and still be effective (IAEA 2007).

§§§ Note that the radiation hazards indicated by measurements in Table 5 are for short-term exposures of a year or less. For long-term exposure situations (involving many years) the criteria need to be adjusted to ensure that the total dose of the longer-term exposure periods are still safe, as indicated in Table 2.

Table 3:

[a] References (IAEA 2013a, 2013b, 2017; McKenna et al. 2015) provide further information.

**** The protective actions described in this reference may not be justified, since the health hazards of the protective actions were not fully considered.

Table 4:

[a] There is a small possibility, for the very unlikely worst postulated release, of exposures resulting in health concerns out to about 30 km principally if an ITB agent is not taken before or shortly after plume arrival.
[b] A release that could result in off-site health concerns indicated by predetermined criteria such as measuring an ambient dose equivalent dose rate >1 mSv h^{-1} (IAEA 1997) near the NPP.

Table 5:

[a] Meaningful radiation health hazards from Table 2 indicated by selected environmental measurements for realistic exposure situations for a release of radioactive material from a light water reactor based on references (IAEA 2013a, 2017; McKenna et al. 2013).
[b] The measured quantities indicating health concerns are also used as the OILs, which if exceeded, protective or other response actions would be taken (IAEA 2013a, 2017; McKenna et al. 2013).
[c] Measured within the first 10 days of reactor shutdown.
[d] Measured 10 days after reactor shutdown.

Table 6:

[a] Due to the inability to provide needed support in the sheltered area.

Table 7:

[a] Distance from the NPP, the actual boundary would be established considering local conditions (as shown in Fig. 4).

[b] The latest studies of severe NPP emergencies (US NRC 2013) indicate, as occurred at the FDNPP (IAEA 2015) and Chernobyl emergencies (IAEA 1991), the major release will probably last only a few days.

†††† 12,000 was estimated as the number of people to be relocated based on Fig. 1 assuming the area and population density are directly related.

‡‡‡‡ Consistent with the largest releases projected by the latest analysis of severe NPP emergencies, as presented in reference (US NRC 2013) and examined in reference (IAEA 2013a).

§§§§ Restrictions of food/water that are life threatening is not included as it is considered self-explanatory.

***** Not including those requiring continuous medical support.

††††† Involving hurricanes, chemical fires, wildfires, an earthquake, malevolent acts, wildfires, railroad and truck accidents, pipeline ruptures and floods.

References

Brooks A., Morgan W, and Feinendegen L. Introduction 2015 Health Physics Society Symposium, 13–14 July 2015, Health risks from low doses and low dose-rates of ionizing radiation. Health Phys 110:241–248; 2016.

Callen J and Homma T. Lessons Learned in Protection of the Public for the Accident at the Fukushima Daiichi Nuclear Power Plant. Health Phys 112:550–559; 2017.

Carpender K, Campbell P H, Quiram B J, Frances J, Artzberger J J. Urban evacuations and rural America: lessons learned from hurricane Rita S, Public Health Reports / November–December / Vol.121, 2006.

Centers for Disease Control and Prevention. Early release of selected estimates based on data, National Health Interview Survey. Available at: https://www.cdc.gov/nchs/nhis/releases/released201605.htm Accessed 29 June 2017.

Cuttler J. Urgent change needed to radiation protection policy. Health Phys 110: 267–270; 2016.

Dosa D. To evacuate or shelter in place: implications of universal hurricane evacuation policies on nursing home residents. J Am Med Dir Assoc February; 13: 190.e1–190.e7. doi:10.1016/j.jamda.2011.07.011; 2012.

Food and Agriculture Organization of the United Nations, International Atomic Energy Agency, International Civil Aviation Organization, International Labour Organization, International Maritime Organization, Interpol, OECD Nuclear Energy Agency, Pan American Health Organization, Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, United Nations Environment Programme, United Nations Office for the Coordination of Humanitarian Affairs, World Health Organization, World Meteorological Organization. Preparedness and response for a nuclear or radiological emergency. Safety Standards Series No. GSR Part 7. Vienna: IAEA; 2015.

Hasegawa A, Ohira T, Maeda M, Yasumura S, Tanigawa. K. Emergency responses and health consequences after the Fukushima accident; evacuation and relocation. Clinical Oncology 28; 237-244; 2016.

Health Physics Society. Regulatory Dose Limits, Available at: http://hps.org/publicinformation/ate/faqs/regdoselimits.html Accessed 29 June 2017.

Hoffman O, Kocher D, Apostoaei A. Beyond dose assessment: Using risk with full disclosure of uncertainty in public and scientific communication. Health Phys 101:591– 600; 2011

International Atomic Energy Agency. The international Chernobyl project, technical report. Vienna: IAEA; 1991.

International Atomic Energy Agency. Generic assessment procedures for determining protective actions during a reactor accident. Technical Document Series No. 955. Vienna: IAEA; 1997.

International Atomic Energy Agency. Safety glossary terminology used in nuclear safety and radiation protection. Vienna: IAEA; 2007.

International Atomic Energy Agency. A framework for an integrated risk informed decision making process. INSAG-25. Vienna: IAEA; 2011.

International Atomic Energy Agency. Actions to protect the public in an emergency due to severe conditions at a light water reactor. EPR-NPP Public Protective Actions. Vienna: IAEA; 2013.

International Atomic Energy Agency. Placing the radiological health hazard in perspective in an emergency due to severe conditions at a light water reactor. Vienna: IAEA; 2013. Available at: http://www-ns.iaea.org/downloads/iec/health-hazard-perspec-charts2013.pdf Accessed 29 June 2017.

International Atomic Energy Agency. The Fukushima Daiichi accident technical volume 3 emergency preparedness and response. Vienna: IAEA; 2015.

International Atomic Energy Agency. Operational intervention levels for reactor emergencies and methodology for their derivation. EPR-NPP-OILs. Vienna: IAEA; 2017.

International Atomic Energy Agency, Food and Agriculture Organization of the United Nations, International Labour Organization, OECD Nuclear Energy Agency, Pan American Health Organization, United Nations Office for the Coordination of Humanitarian Affairs, World Health Organization. Preparedness and response for a nuclear or radiological emergency. Safety Standards Series No. GS-R-2. Vienna: IAEA; 2002.

International Atomic Energy Agency, World Health Organization, Food and Agriculture Organization of the United Nations, United Nations Development Programme, United Nations Environment Programme, United Nations Office for the Coordination of Humanitarian Affairs, United Nations Scientific Committee on the Effects of Atomic Radiation, World Bank Group, Government of Belarus, Government of the Russian Federation, Government of Ukraine. Chernobyl's legacy: Health, environmental and socio-economic impacts and recommendations to the Governments of Belarus, the Russian Federation and Ukraine. The Chernobyl Forum. Vienna: IAEA; 2005.

International Atomic Energy Agency, Food and Agriculture Organization of the United Nations, International Labour Organization, Pan American Health Organization, United Nations Office for the Coordination of Humanitarian Affairs, World Health Organization. Arrangements for preparedness for a nuclear or radiological emergency. Safety Standard Series No. GS-G-2.1. Vienna: IAEA; 2007.

Ichiseki H. Features of disaster related deaths after the Great East Japan Earthquake. The Lancet, Vol. 381, 19 January 2013.

International Commission on Radiological Protection. Pregnancy and medical radiation. Oxford: Pergamon Press; ICRP Publication 84; Ann ICRP 30(1); 2000.

International Commission on Radiological Protection. Protecting people against radiation exposure in the event of a radiological attack. ICRP Publication 96; Ann. ICRP 35 (1); 2005.

International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. Oxford: Pergamon Press; ICRP Publication 103; Ann ICRP 37 (2/3); 2007.

International Commission on Radiological Protection. Fukushima Nuclear Power Plant Accident, official communication; ICRP ref: 4847-5603-4313, 2011. Available at: http://www.icrp.org/docs/Fukushima%20Nuclear%20Power%20Plant%20Accident.pdf. Accessed 29 June 2017.

International Commission on Radiological Protection. Lessons learned from the accident at the Fukushima Daiichi NPP vis-à-vis the ICRP system of radiological protection, Report prepared by ICRP Task Group 84 for the ICRP Main Commission. Oxford: Pergamon Press; ICRP ref 4817- 7814- 8113; 2012.

Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company. Final Report, Tokyo, Investigation Committee. 2012.

McKenna T. Protective action recommendations based upon plant conditions. Journal of Hazardous Materials 75. 145–164. 2000.

McKenna T, Kutkov V, Vilar Welter P, Dodd B, Buglova E. Default operational intervention levels (OILs) for severe nuclear power plant or spent fuel pool emergencies. Health Phys 104:459–470; 2013.

McKenna T, Vilar Welter P, Callen J, Martincic R, Dodd B, Kutkov V. Tools for placing the radiological health hazard in perspective following a severe emergency at a light water reactor (LWR) or its spent fuel pool. Health Phys 108:15–31; 2015.

Murakami M, Ono K, Tsubokura M, Nomura S, Oikawa T, Oka T, Kam M. Was the Risk from Nursing-Home Evacuation after the Fukushima Accident Higher than the Radiation Risk? PLoS ONE 10: e0137906, https://doi.org/10.1371/journal.pone.0137906; 2015.

NAIIC National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission. The official report of The Fukushima Nuclear Accident Independent Investigations Commission. Tokyo: The National Diet of Japan; 2012.

NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety: The Accident at TEPCO's Fukushima Nuclear Power Stations, Government of Japan; 2011.

U.S. National Highway Traffic Safety Administration. NCSA data resource website. Available at: https://www-fars.nhtsa.dot.gov/Main/index.aspx Accessed 29 June 2017.

Nomura S, Gilmour S, Tsubokura M, Yoneoka D, Sugimoto A. Mortality risk amongst nursing home residents evacuated after the Fukushima nuclear accident: A retrospective cohort study. PLoS ONE 8(3): e60192, https://doi.org/10.1371/journal.pone.0060192; 2013.

Nomura S, Blangiardo M, Tsubokura M, Ozaki A, Morita T, Hodgson S. Post nuclear disaster evacuation and chronic health in adults in Fukushima, Japan: a long-term retrospective analysis. BMJ Open, Vol. 6, https://doi:10.1136/bmjopen-2015-010080; 2016.

Orient J. Fukushima and reflections on radiation as a terror weapon. Journal of American Physicians and Surgeons, Vol. 19 summer; 2014.

Rithidech R. Health benefits of exposure to low-dose radiation. Health Phys 110:293–295; 2016.

Sacks B, Meyerson G, Siegel J. Epidemiology without biology: false paradigms, unfounded assumptions, and specious statistics in radiation science (with commentaries by Inge Schmitz-Feuerhake and Christopher Busby and a reply by the authors). Biol Theory 11:69–101; 2016.

Saji G. A post accident safety analysis report of the Fukushima accident — future direction of evacuation: lessons learned Proceedings of the 21st International Conference on Nuclear Engineering, July 29 - August 2, 2013, Chengdu, China. DOI: 10.1115/ICONE21-16526, Available at: https://www.researchgate.net/publication/267581914_A_Post_Accident_Safety_Analysis_Report_of_the_Fukushima_Accident_-_Future_Direction_of_Evacuation_Lessons_Learned Accessed 29 June 2017.

Siegel J, Stabin M. Radar commentary: Use of linear no-threshold hypothesis in radiation protection regulation in the United States. Health Phys 102:90 –99; 2012.

Suzuki Y, Yabe H, Yasumura S, Ohira T, Niwa S, Ohtsuru A, Mashiko H, Maeda M, Abe M. Psychological distress and the perception of radiation risks: the Fukushima health management survey. Bulletin of the World Health Organization, 93:598-605, doi: https://dx.doi.org/10.2471/BLT.14.146498; 2015.

Tanigawa, K, Hosoi, Y, Hirohashi N, Iwasaki Y, Kamiya, K. Loss of life after evacuation: lessons learned from the Fukushima accident. www.thelancet.com Vol 379 March 10, 2012 p 889-890,

Tsuda T, Lindahl L, Tokinobu A. Ethical issues related to the promotion of a “100 mSv threshold assumption” in Japan after the Fukushima nuclear accident in 2011: background and consequences, Curr Envir Health Rpt 4:119–129; 2017.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, effects and risks of ionizing radiation, UNSCEAR 2013 Report to the General Assembly. United Nations, Volume I, Scientific Annex A, New York; UN; 2014.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, effects and risks of ionizing radiation, UNSCEAR 2012 Report to the General Assembly, Scientific Annex A. New York; UN; 2015.

U.S. Department of Homeland Security, Preparedness Directorate. Protective action guides for radiological dispersal device (RDD) and improvised nuclear device (IED) incidents; Preparedness Directorate, Department of Homeland Security. Federal Register Vol. 71, No. 1, pp. 174-196, 3 January, 2006.

Environmental Protection Agency. Manual of protective action guides and protective actions for nuclear incidents. EPA 400-R-92-001, Washington, D.C: U.S. Environmental Protection Agency; 1992.

U.S. Environmental Protection Agency. Protective action guides and planning for radiological incidents. EPA-400/R-17/001, Washington, DC: US Environmental Protection Agency; 2017.

U.S. Nuclear Regulatory Commission. Reactor safety study: An assessment of the accident risks in U.S. commercial nuclear power plants. WASH-1400, NUREG-75/014, Washington, DC: U.S. NRC; 1975.

U.S. Nuclear Regulatory Commission. Examination of the off-site radiological emergency measures for nuclear reactor accidents involving core melt. Washington, DC: U.S.NRC; NUREG/CR -1131; 1978.

U.S. Nuclear Regulatory Commission. Severe accident risks: An assessment for five U.S. nuclear power plants. NUREG-1150, Washington, DC: U.S. NRC; 1990.

U.S. Nuclear Regulatory Commission. Perspectives on reactor safety. NUREG/CR-6042, SAND93-0971, Rev. 2, Washington, DC: U.S. NRC; 2002.

U.S. Nuclear Regulatory Commission. Identification and analysis of factors affecting emergency evacuations. NUREG/CR-6864, Vol. 1, Washington, DC: U.S. NRC; 2005.

U.S. Nuclear Regulatory Commission. Review of NUREG-0654, Supplement 3, "Criteria for Protective Action Recommendations for Severe Accidents". NUREG/CR-6953, Vol. 1 SAND2007-5448P; Washington, DC: U.S. NRC; 2007.

U.S. Nuclear Regulatory Commission. Assessment of emergency response planning and implementation for large scale evacuation. NUREG/CR-698, Washington, DC: U.S. NRC; 2008.

U.S. Nuclear Regulatory Commission. Review of NUREG-0654, Supplement 3, "Criteria for Protective Action Recommendations for Severe Accidents" Technical basis for protective action strategies. NUREG/CR 6953 Vol 3, Washington, DC: U.S. NRC; 2010.

U.S. Nuclear Regulatory Commission. Modeling potential reactor accident consequences. NUREG/BR-0359, Revision 1, Washington, DC: U.S. NRC; 2012.

U.S. Nuclear Regulatory Commission. State-of-the-art reactor consequence analyses, Volume 1: Peach Bottom integrated analyses, and Volume 2: Surry integrated analyses. NUREG/CR-7110, Washington, DC: U.S. NRC; 2013.

U.S. Nuclear Regulatory Commission, U.S. Federal Emergency Management Agency. Criteria for preparation and evaluation of radiological emergency response plans and preparedness in support of nuclear power plants. NUREG-0654/FEMA-REP-1, Rev 1, Supplement 3, Washington, DC: U.S. NRC; 1996.

U.S. Nuclear Regulatory Commission and U.S. Federal Emergency Management Agency. Criteria for preparation and evaluation of radiological emergency response plans and preparedness in support of nuclear power plants. NUREG-0654/FEMA-REP-1, Rev. 1, Supplement 3, Washington, DC: U.S. NRC; 2011.

World Health Organization. Use of potassium iodide for thyroid protection during nuclear or radiological emergencies, technical brief, Revised 31 March 2011 (originally published on 29 March 2011) [online] 2011. Available at: http://www.who.int/ionizing_radiation/pub_meet/tech_briefings/potassium_iodide/en/; Accessed 29 June 2017.

World Health Organization. Health risk assessment from the nuclear accident after the 2011 Great East Japan earthquake and tsunami, based on a preliminary dose estimation. Geneva: WHO Press; 2013.

World Health Organization. FAQs: Fukushima Five Years On, Ionizing Radiation, Radiation Emergencies, Japan Nuclear Concerns, Geneva: WHO; 2016. Available at: http://www.who.int/ionizing_radiation/a_e/fukushima/faqs-fukushima/en/ Accessed 29 June 2017.

World Nuclear Association. Fukushima Accident. (2017) Available at: http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx Accessed 29 June 2017.

Yasumura S. Evacuation effect on excess mortality among institutionalized elderly after the Fukushima Daiichi nuclear power plant accident. Fukushima J Med Sci Vol 60:192-195; 2014.

Zachria A., and Patel B., Deaths related to hurricane Rita and mass evacuation. University of Texas Health Science Center-Houston, Houston, TX Chest. 130 (4_MeetingAbstracts) 124S. doi:10.1378/chest.130.4_MeetingAbstracts.124S-c 2006.

Table

Table 1. Protective actions that may have been unjustified during the FDNPP emergency and relevant recommendations in place at the time of the emergency

Protective actions that may have been unjustified	Why protective actions may have been unjustified	International and US recommendations available at the time of the emergency that could lead to unjustified actions under similar conditions
Protective actions were recommended before a major release of radioactive material due to the hazard indicated by severe emergency conditions at the NPP. These actions included: • 11 to 12 March evacuation of about 80,000 people out to 20 km. • 25 March voluntary evacuation of about 60,000 people within the 20 to 30 km radius being sheltered. This was due to difficulties caused by prolonged sheltering (NAIIC 2012; NERHQ 2011; Investigation Committee 2012).	The risk of fatal exposures from deterministic effects and cancers off the site from a future release at this point in the emergency was almost totally confined to within a few kilometers of the FDNPP (IAEA 2013a). However, evacuations were carried out to 30 km and resulted in: • About 50 deaths (as of April 2011) from the unsafe movement of patients from some hospitals and nursing care homes that may have been preventable (IAEA 2015; NAIIC 2012; Tanigawa et al. 2012) • An increase in mortality rates amongst the elderly who had been dislocated (Hasegawa et al. 2016; Ichiseki 2013; Murakami et al. 2015; Nomura et al. 2013) has been shown to result in about 200 deaths (Yasumura 2014) and may have resulted in more[c].	The evacuations and sheltering by Japan were broadly in line with the IAEA and US recommendations at the time (IAEA et al. 2007; US NRC and FEMA 1996). These recommendations did not adequately consider the possible health effects of the protective actions, such as deaths and injuries among the elderly, or other health concerns among the general population.
Following the major release[a] additional protective actions were taken based on environmental monitoring to include relocation of about 10,000 people starting on 15 May onwards (NAIIC 2012) from areas where the dose from the 15 March deposition was projected to exceed 20 mSv[b] in a year.	The dose criterion for relocation was well below that at which there would be any meaningful radiation induced health effects. These relocations could have resulted in a small number of deaths among the elderly.	The criterion used by Japan for relocation was established at 20 mSv effective dose based on ICRP recommendations (ICRP 2007; NAIIC 2012) which is a dose below which there would be no meaningful radiation induced health effects (Table 2). This criterion was consistent with the recommendations of many organizations at the time of the emergency (ICRP 2007; US EPA 1992) which did not adequately consider the possible health effects of the protective actions.

Table

Table 2 Adverse radiation health hazards for a severe NPP emergency

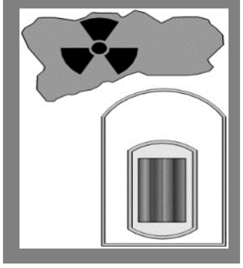
Radiation health hazard	Explanation	Calculated dose
(Red) Possibly dangerous to health	Possibility of observing radiation induced health effects that: • are life threatening, or • can result in a permanent injury that reduces the quality of life to include: (1) permanently suppressed ovulation and sperm counts, (2) hypothyroidism, and (3) severe effects to the fetus (e.g. reduction in IQ). Possibility of detecting an increase in the cancer rate by careful medical follow-up, spanning many years, if more than a few hundred people are exposed (ICRP 2005).	$\geq AD_{red\ marrow}{}^{a}$ 1 Gy **or** $\geq H_{fetus}{}^{b,\ c}$ 1 Sv
(Orange) Health concerns	Possibility of: • exposures to pregnant women (fetus) warranting consultation with medical experts (ICRP 2000), and • detecting an increase in the cancer rate by careful medical follow-up, spanning many years, if more than 10,000 people are exposed (ICRP 2005). Taking protective actions that are possibly dangerous to health (Table 6) may not be justified to avoid this level of hazard since the actions may do more harm than good.	$\geq H_{fetus}{}^{b,\ c}$ 100 mSv **or** $\geq E^{d}$ 100 mSv
(Green) Safe	Safe for all members of the public including the most sensitive (i.e. children and pregnant women), since: • any radiation induced injuries or increase in the cancer rate, if at all, are too small to be meaningfully observable[e] in the sense that any protective action taken to reduce them may do more harm than good when the impact on the overall health of those affected is considered. • the international generic criteria (FAO et al. 2015) at which protective actions and other response actions are considered justified are not exceeded. Taking protective actions that are possibly dangerous to health or that could result in health concerns (Table 6) may not be justified to avoid this level of hazard since the actions may do more harm than good.	$< H_{fetus}{}^{b,\ c}$ 100 mSv **and** $< E^{d}$ 100 mSv

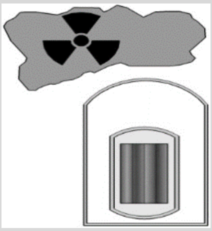
Table 3. Key elements of the COMPARE method and where to get more information

Key elements of the COMPARE method	Where to get more information
The health hazards for radiation exposure (dose projections)	Table 2
The health hazards for severe NPP emergencies	Table 4
The health hazards indicated by environmental measurements	Table 5[a]
The health hazards of protective actions	Table 6
How to recognize and counter assessments by the media and 'experts' that exaggerate the health hazard of radiation exposure that could cause the public to take unjustified protective actions	(IAEA 2013a) (McKenna et al. 2015)

Table

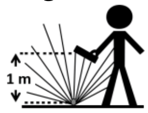
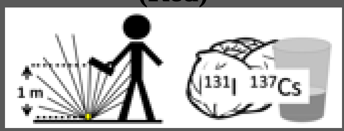
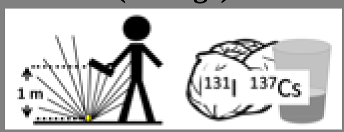
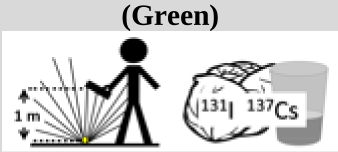
Table 4. Radiation health hazard for a severe NPP emergency and effective protective actions

Radiation health hazard	Distance from NPP (radius)	Description of the radiation health hazards and effective protective actions
Possibly dangerous to health (Red) 	For living within a minimum of 3 km and possibly out to 5 km	Upon detection of severe NPP emergency conditions the greatest risk of exposures dangerous to health is within: • 1.5 km for those sheltering in a large building, • 3 km for those sheltering in a house, • 5 km within days for all those sheltered after a release due to exposure from deposition, especially if it rains. If an ITB agent is not taken it could be dangerous to health beyond 5 km. The hazard to health is from inhalation of radio-iodine in the plume and early external exposure from deposited material, particularly if it rains during plume passage. The most effective protective actions for reducing the health hazards of radiation exposure are ITB combined with safe evacuation within a few hours. The second most effective is large building sheltering combined with ITB followed by safe evacuation as soon as possible.
Health concerns (Orange)	For living beyond 3 to 5 km and possibly out to 15 to 30 km	The greatest risk of exposure resulting in health concerns are confined to within about 15 km[a]. Health concerns are due to inhalation of radio-iodine in the plume and early exposure to deposited material, particularly if it rains during plume passage. The most effective protective actions are safe evacuation within a few hours combined with ITB or large building sheltering combined with ITB. Sheltering in a typical house combined with ITB is less effective, but can greatly reduce the risks. Within 15 to 30 km ITB may be needed to prevent health concerns from inhalation of radio-iodine.
	For living within a minimum of 50 km and possibly out to 100 km	Following a major release[b] there may be health concerns (Table 2) from long term exposure due to radioactive material deposited on the ground, principally by rain. Therefore, affected areas need to be monitored within days to identify and safely evacuate areas where the criteria listed in Table 5 indicate health concerns.

	For ingestion - within a minimum of 100 km and possibly out to 300 km	Following a major release[b] there may be health concerns within hours due to ingestion of rainwater, milk from grazing animals and vegetables affected by deposition of radioactive material principally by rain. Restrictions should be promptly placed on ingestion of rainwater and milk from grazing animals or vegetables grown out in the open following detection of a major release[b]. This would allow restrictions to be implemented within hours, and remain in place until monitoring can be performed and the results assessed using the criteria given in Table 5.
Safe (Green) 		It is safe off the site: - Beyond the distances stated above for living in the area and ingestion until conditions at the facility indicate there is a very low probability of a major release (e.g. fuel of the reactor is being cooled long term and the containment is not threatened and will be protected long term). **and** - Environmental monitoring confirms that living in the area and ingesting food is safe.

Table

Table 5. Radiation health hazards indicated by selected environmental measurements

Radiation health hazard[a]	Ambient dose equivalent at 1 m above ground level  Living normally in a frame house in the affected area for 1 year	^{131}I and ^{137}Cs concentrations  1 year consumption of 10% contaminated food, milk and water
Possibly dangerous to health (Red) 	≥500 $\mu Sv\ h^{-1}$	≥ ^{137}Cs 50,000 Bq kg^{-1} **or** ≥ ^{131}I 500,000 Bq kg^{-1}
Health concerns[b] (Orange) 	≥100 $\mu Sv\ h^{-1}$ [c] ≥25 $\mu Sv\ h^{-1}$ [d]	≥ ^{137}Cs 2,000 Bq kg^{-1} **or** ≥ ^{131}I 10,000 Bq kg^{-1}
Safe (Green) 	< 25$\mu Sv\ h^{-1}$ [d]	< ^{137}Cs 2,000 Bq kg^{-1} **and** < ^{131}I 10,000 Bq kg^{-1}

Table

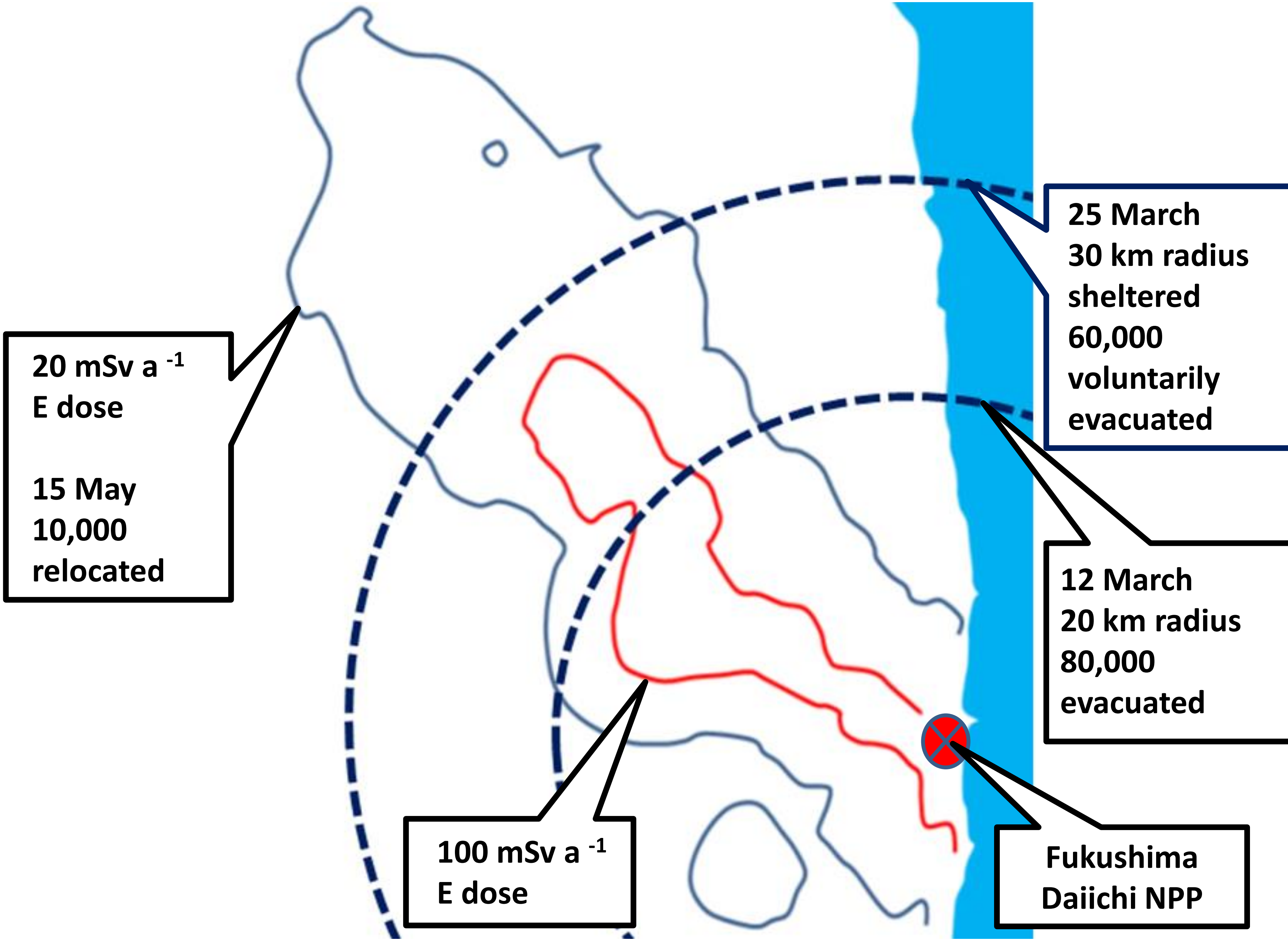
Table 6. Health hazards from taking protective actions

Protective action health hazards	Protective actions
Possibly dangerous to health (Red) 	Protective actions that may result in a detectable increase in mortality or injuries that reduce the quality of life, such as: • Evacuation of patients needing medical care without providing such care. • Evacuation under life threating conditions (e.g. dangerous road/weather conditions). • Dislocation of the elderly requiring support, even if needed support is provided. • Sheltering resulting in dislocation[a] of the elderly. • Restrictions of food/water that are life threatening.
Health concerns (Orange) 	Protective actions that result in health effects or lifestyle changes that may, over time, result in a detectable increase in mortality or injuries that reduce the quality of life, such as dislocation of the general population.
Safe (Green) 	Protective actions are safe if they will **not** result in: • detectable increase in mortalities or injuries that reduce the quality of life, **or** • health effects or lifestyle changes that may, over time, result in increased mortality or injuries that reduce the quality of life.

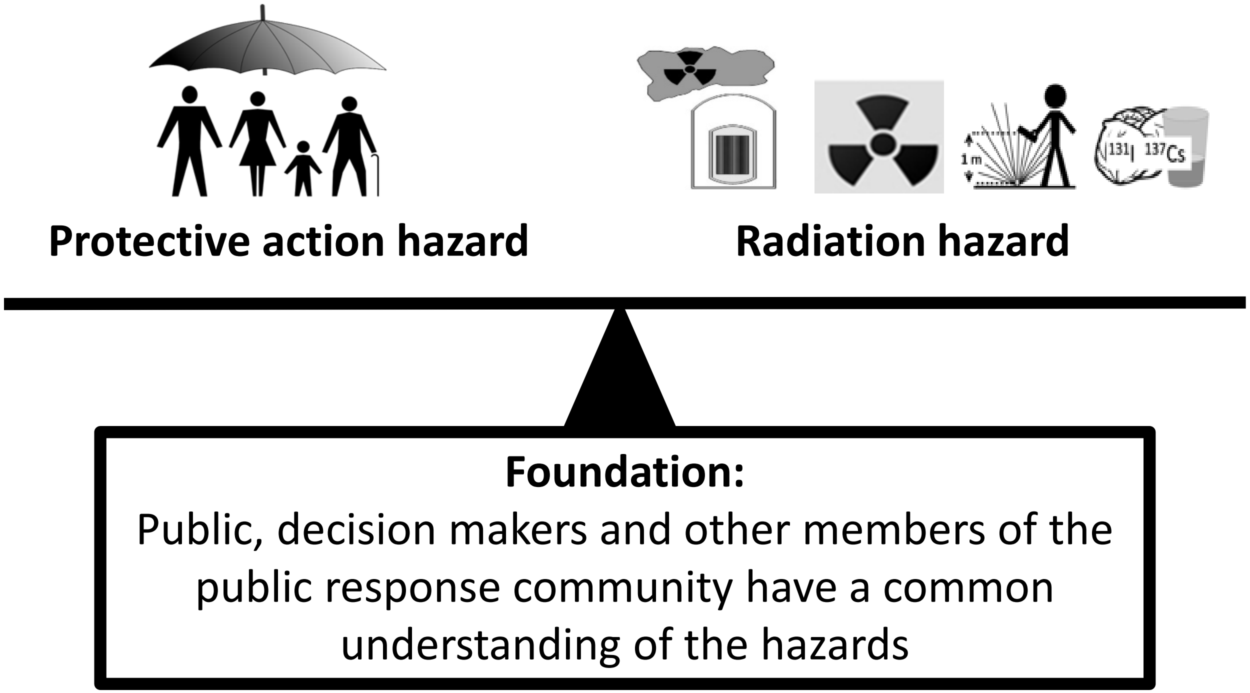
Table 7. Example of applying the COMPARE method

Distance[a] [km]	Protective actions for the public	Considerations in balancing the hazards
Within 3 km	Upon detection of severe emergency conditions at the NPP in all directions: - safe and prompt evacuation combined with ITB - if safe and prompt evacuation is not possible, use best possible sheltering combined with ITB followed by evacuation when possible.	There is a possibility of radiation exposure dangerous to health to all those within this distance (Table 4). This is considered to be greater hazard than the hazard from dislocation due to evacuation of a relatively limited number of elderly people (Table 6).
Between 3 and 15 km	Upon detection of severe emergency conditions at the NPP in all directions prepare to shelter and to take ITB if instructed. Upon detection of a major release in all directions take ITB and shelter.	Upon detection of a major release, sheltering, as opposed to evacuation, was selected because dislocation of the elderly due to evacuation is possibly dangerous to health, whereas at this distance there would most likely only be health concerns among the general population sheltered (Table 4 and Table 6). It is assumed sheltering could be lifted within days[b] after the major release and thus dislocation due to long term sheltering would not be necessary.
Between 15 and 30 km	Upon detection of severe emergency conditions at the NPP in all directions prepare to take ITB if instructed. Upon detection of a major release in all directions take ITB.	At this distance the risk is dominated by inhalation of radio-iodine which is averted by ITB and ITB is considered safe.
Between 3 and 100 km	Upon detection of a major release conduct monitoring within days to identify and evacuate areas where predetermined OILs indicate health concerns (Table 5).	Following a major release evacuation is carried out for the entire population where monitoring results indicate health concerns (Table 5). This is considered to be greater hazard than the hazard from dislocation due to evacuation of a relatively limited number of elderly people (Table 6).
Within 300 km	Upon detection of the major release restrict, in all directions, consumption of food and water that can be ingested immediately and conduct monitoring within days to identify where the OILs (Table 5) indicate health concerns from food products and extend or lift restrictions. Restrictions are only applied if they do not result in health hazards due to starvation or dehydration, or interruption of sanitary systems.	Food and water restrictions are justified because they would only be taken if they would not result in any health hazards.

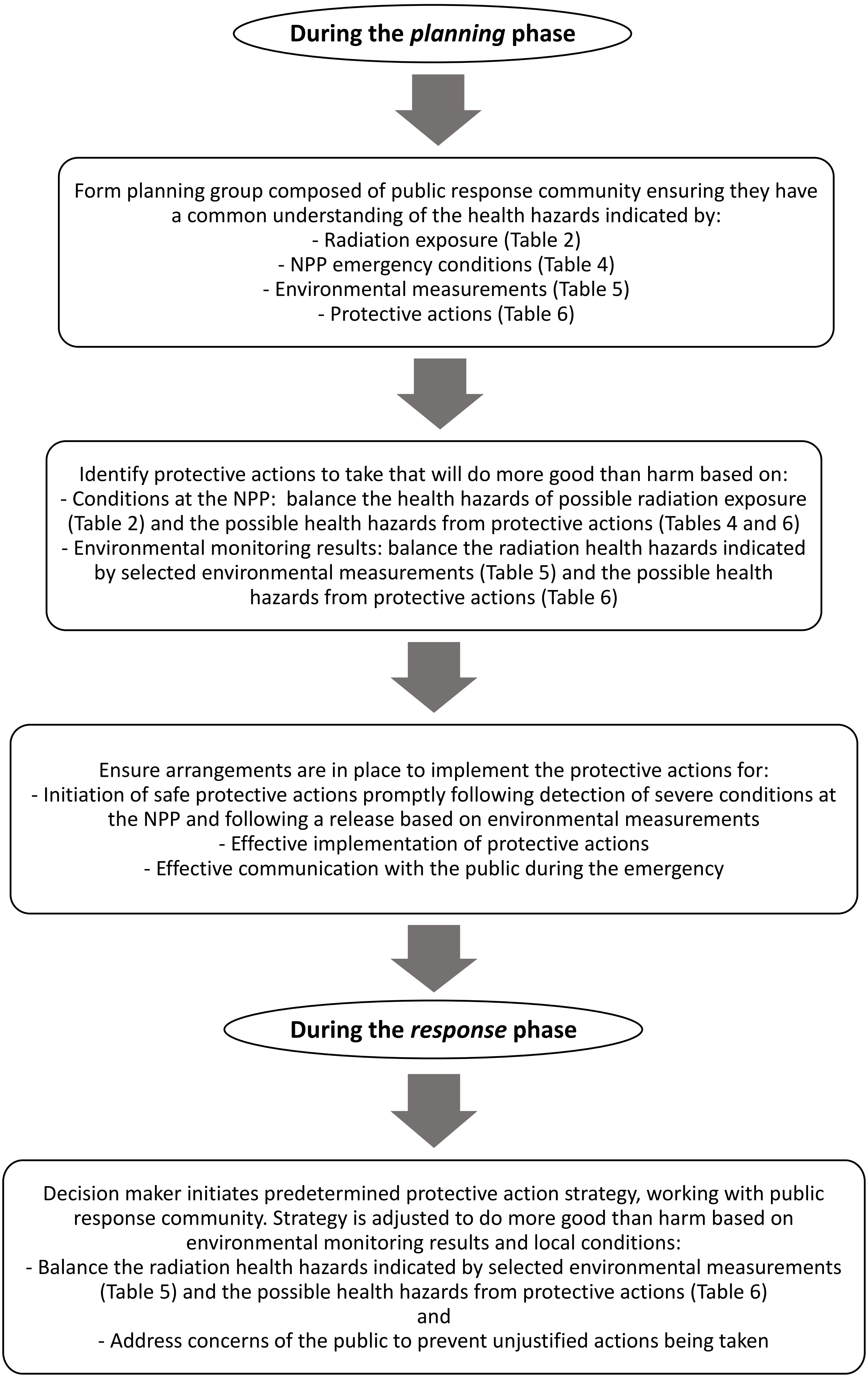
Figure


25 March
30 km radius
sheltered
60,000
voluntarily
evacuated
20 mSv a -1
E dose
15 May
10,000
relocated
12 March
20 km radius
80,000
evacuated
100 mSv a -1
E dose
Fukushima
Daiichi NPP

Figure


Protective action hazard
Radiation hazard
Foundation:
Public, decision makers and other members of the public response community have a common understanding of the hazards

Figure


During the *planning* phase
Form planning group composed of public response community ensuring they have a common understanding of the health hazards indicated by:
- Radiation exposure (Table 2)
- NPP emergency conditions (Table 4)
- Environmental measurements (Table 5)
- Protective actions (Table 6)
Identify protective actions to take that will do more good than harm based on:
- Conditions at the NPP: balance the health hazards of possible radiation exposure (Table 2) and the possible health hazards from protective actions (Tables 4 and 6)
- Environmental monitoring results: balance the radiation health hazards indicated by selected environmental measurements (Table 5) and the possible health hazards from protective actions (Table 6)
Ensure arrangements are in place to implement the protective actions for:
- Initiation of safe protective actions promptly following detection of severe conditions at the NPP and following a release based on environmental measurements
- Effective implementation of protective actions
- Effective communication with the public during the emergency
During the *response* phase
Decision maker initiates predetermined protective action strategy, working with public response community. Strategy is adjusted to do more good than harm based on environmental monitoring results and local conditions:
- Balance the radiation health hazards indicated by selected environmental measurements (Table 5) and the possible health hazards from protective actions (Table 6)
and
- Address concerns of the public to prevent unjustified actions being taken

Figure