Assessment on the 66th day of projected external dose for populations living in the North-West fallout zone of the Fukushima nuclear accident

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Abstract: During the accident that occurred on March 11, 2011 at the Dai-ichi nuclear power plant in Japan, the French Institute for Radiological Protection and Nuclear Safety (IRSN) was strongly committed to perform real-time evaluations of stakes and consequences of the situation based on partially-available information with the objective of responding concerns of French authorities, including French Embassy in Tokyo, and the public. On April 8, IRSN published on its website a first map of doses likely to be received by the population (projected doses) living in the area of the damaged nuclear power plant for the year following the accident. Similar maps were published within the following weeks, notably those of the US DoE/NNSA[1] and of the MEXT[2] of Japan.

The projected doses, adjusted with the caesium deposits maps published by the MEXT on May 6, as well as the geographic and demographic distribution of the Japanese populations living around the nuclear power plant allowed IRSN to assess the impact of evacuation measures (in terms of dose and range of concerned population) depending on reference level adopted for evacuation and the delay of its implementation. The paper will present first the drawing up of projected dose maps based on source term assessments and measurements done around the plant, and also the assessments of range of concerned population. A quick comparison with the Chernobyl accident is then produced, followed by a study about the impact of reference level adopted for the evacuation and the delay of its implementation. Finally, a comparison with the evacuation measures taken by Japanese authorities will conclude.

Key words: Fukushima / deposits / dose / evacuation

1. Introduction

The radiological consequence of the nuclear accident in Fukushima was not estimated in the days following the accident due to the lack of reliable data from Japan about the composition of release, the environmental measurements and the individual monitoring performed in the affected population by the radioactive fallout in the neighbourhood of the nuclear plant.

Airborne dose rate measurements performed by the US DoE/NNSA enabled IRSN to publish on April 8 a first map of doses likely to be received by the population by external exposure during the 1st year following the accident in the fallout zone to the northwest of the plant. Considering the maps published later by the MEXT on April 26 concerning dose rate and external dose 1st year after the accident and on May 6 concerning the mapping of caesium, IRSN improved its source term, and derived a conversion factor between the activity of caesium deposits and the external dose 1st year after the accident. Given demographic data concerning the size of the population located in the different contaminated areas, it was then possible to estimate the external dose likely to be received during 1, 10 or 70 years and the range of people affected, and to assess the impact of evacuation measures according to a prescribed reference level and its implementation time.

The paper, synthesis of the IRSN report DRPH/2011-10[3], will present the drawing up of projected dose maps based on source term assessments and measurements done around the plant, and also the assessments of range of concerned population. A quick comparison with the Chernobyl accident is then produced, followed by a study about the impact of reference level adopted for the evacuation and the delay of its implementation. Finally, a comparison with the evacuation measures taken by Japanese authorities will conclude.

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[1] US Department of Energy, National Nuclear Security Administration

[2] Ministry of Education, Culture, Sports, Science and Technology

[3] Assessment on the 66th day of projected external dose for populations living in the North-West fallout zone of the Fukushima nuclear accident, Rannou A. and *al.*, May 2011, Report DRPH/2011-10, IRSN, 28 p.

2. Drawing up of projected dose maps

2.1 First mapping by IRSN

The first assessment of projected doses[4] from the Fukushima accident published worldwide to IRSN's knowledge, was carried out by IRSN on April 8 from airborne measurements of external dose rates performed between March 30 and April 3 by the NNSA. The American map showed high dose rates in a zone of about 20 km in width and 50 to 70 km in depth in a northwest direction, beyond the 20 km radius area for evacuation and the 20-30 km radius area for sheltering. In this area, deposits of radionuclides seem to have been significantly higher than elsewhere, probably because of precipitation (rain and snow), which fell while the radioactive plume was dispersing.

From this map, IRSN derived a mapping of doses that could be received by the population in the 1st year[5] following the accident, and which result from the external irradiation from deposited radionuclides This map is shown on Figure 1.

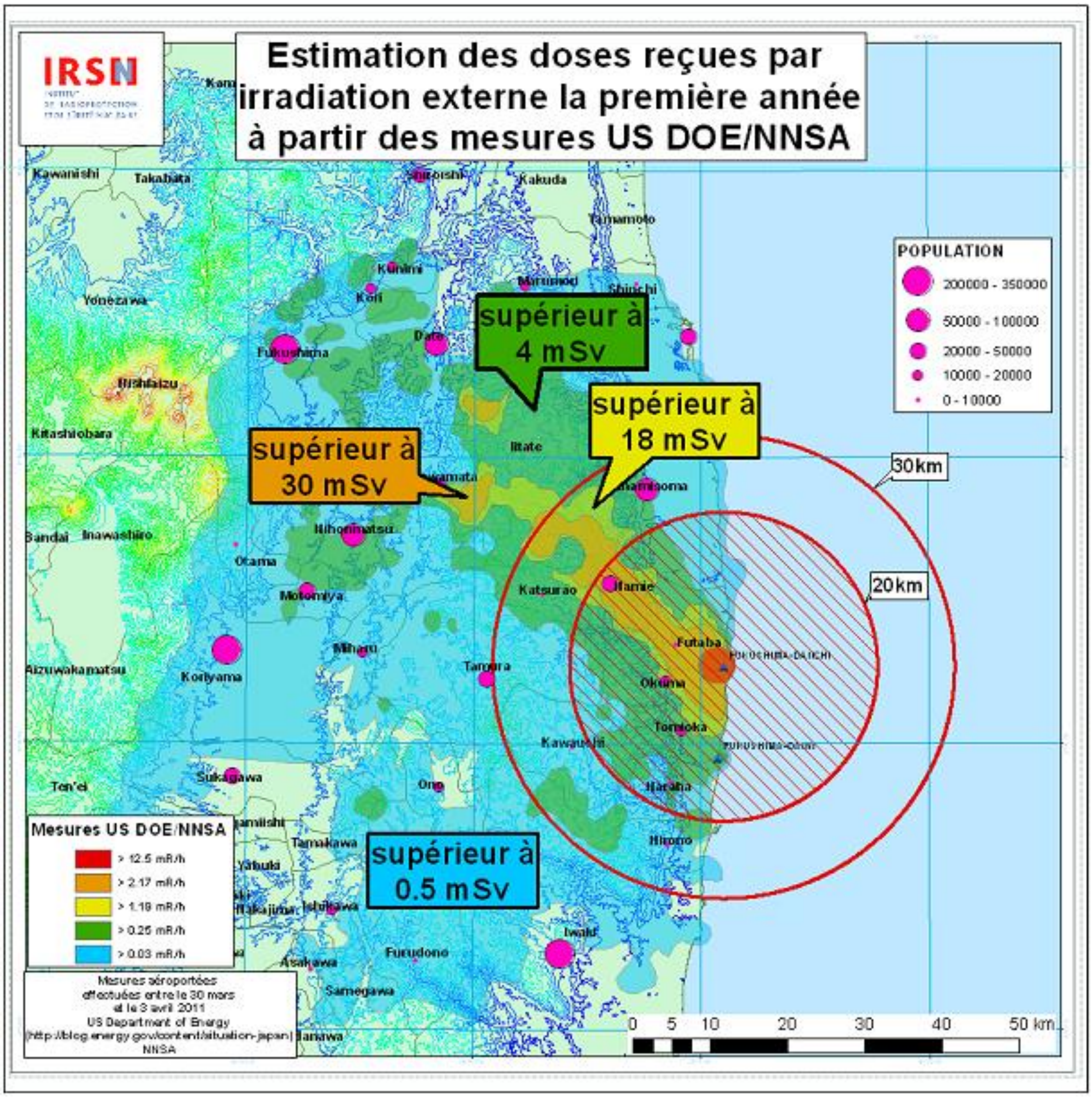

Figure 1: IRSN mapping of external doses received during the 1st year, April 8

[4] The projected dose is defined by the International Commission on Radiological Protection (ICRP) as the dose that would be expected to be incurred if no protective measure(s) were to be taken (ICRP Publication No. 103, 2007)

[5] from 16 March 2011 to 16 March 2012

The methodology used to calculate the projected doses from dose rates have taken into account the following assumptions:

- the radioactive releases occurring between 15 and 16 March are at the main origin of the deposits, as shown by the temporal evolution of dose rates measured by the radiation monitors located in the Fukushima prefecture;
- the projected doses were calculated from the dose rates measured by the U.S. aircraft and have considered also the radioactive decay of these dose rates over time (from March 30 to April 3). The dose received by a person living in a contaminated area for a year has been calculated by integrating the hourly dose rate over the year;
- the relative contributions of the various deposited radionuclides to the measured dose rate have to be known to estimate the dose rate decay over time, because the activity of each radionuclide decreases over time according to its half-life. The relative contributions of different radionuclides to the measured dose rate were estimated based on an assessment of the activity of radionuclides released into the atmosphere by the damaged reactor; this estimation was carried out by the nuclear facility assessment unit of the IRSN emergency response centre. According to this assessment, the dose rates measured 2 weeks after the accident result mainly in the presence of caesium (Cs-137 and Cs-134), iodine-131, tellurium-132/iodine-132, ruthenium-103/rhodium-103, barium-140/lanthanum-140 and niobium-95;
- a shielding factor of 0.3 applied for 12 hours per day was assumed to take into account shielding by buildings, i.e. a dose reduction by a factor of 0.65.

2.1 Mapping by MEXT and IRSN

On April 26, MEXT published the first official Japanese map of projected doses from external irradiation due to deposits for the 1st year following the accident. This assessment assumed a shielding factor of 0.4 for 16 hours per day, i.e. a dose reduction by a factor of 0.6.

A comparison of the first official Japanese map to the first IRSN map showed higher doses on the MEXT map with a factor of 2.5. One reason that might explain this discrepancy between the two assessments could stem from an overestimation of the barium-140/lanthanum-140 ratio initially assessed by IRSN.

On May 6, MEXT published maps of deposits of Cs-134, of Cs-137 and the sum of both activities in the northwest zone. It should be noted that the Cs-134/Cs-137 ratio is equal to 1 in this assessment.

Comparing the maps of MEXT (caesium deposits and external doses potentially received during the 1st year following the accident) enables to derive a conversion factor between the activity of caesium deposits and the projected external dose for the 1st year of living in these contaminated areas.

Deposits of 300,000 to 600,000 Bq/m^2 correspond to the external dose values of 5 to 10 mSv projected for the 1st year. The conversion factor from the surface activity of caesium to the projected external dose for the 1st year is 16.6 mSv/year per MBq/m^2 (Cs-137 + Cs-134).

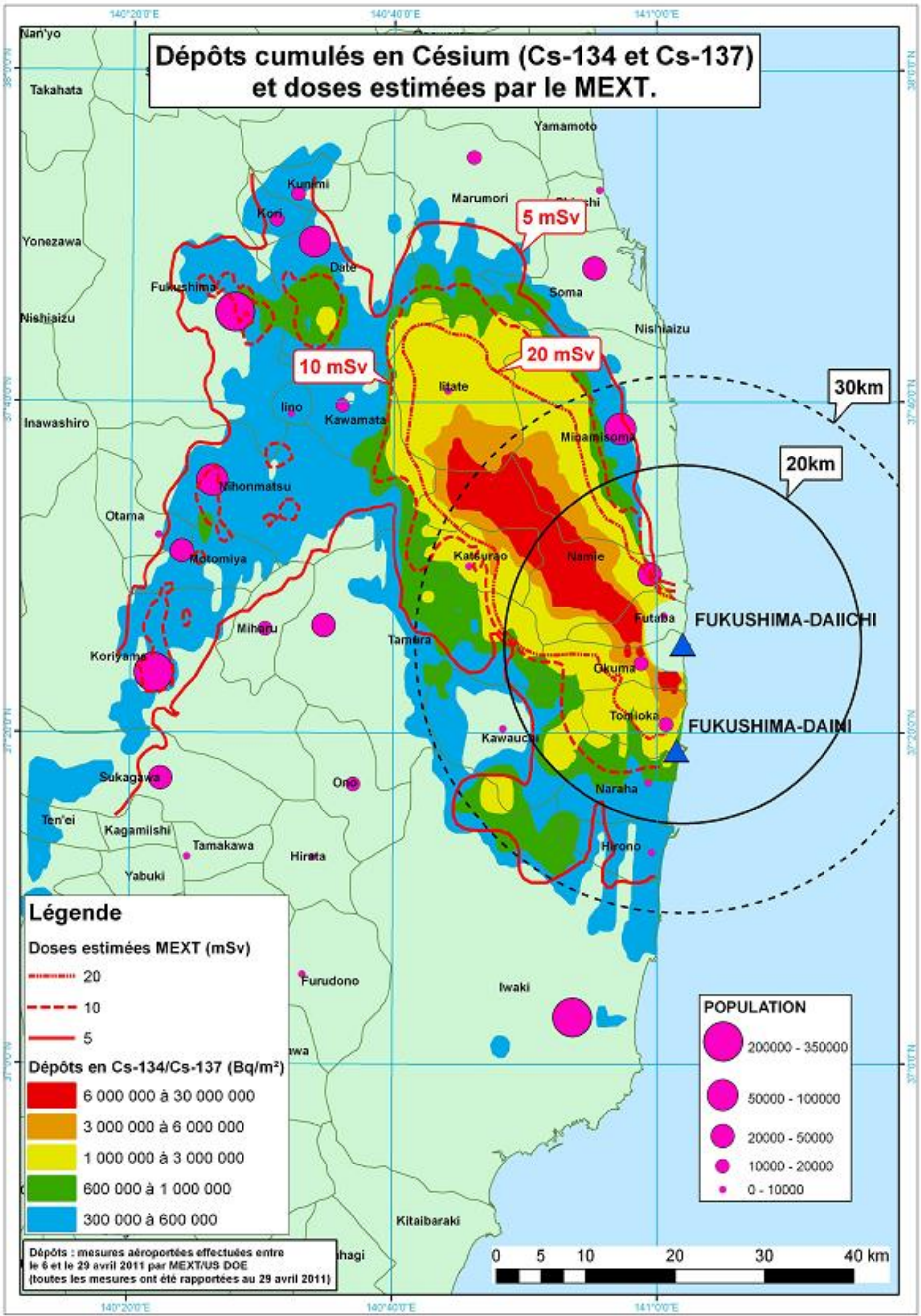

Figure 2: Map of caesium deposits and projected external doses for the 1st year

3. Projected dose and population

In order to appraise the projected doses to be received by population for a long time, IRSN estimated the projected doses for the 10 years and 70 years periods after the accident. The doses were derived from:

- the projected dose for the first year calculated by MEXT;
- the ratios between the projected doses for 10 and 70 years, and the projected dose for the 1st year. These ratios were determined using a new IRSN source term. According to this new source term, the dose rates measured 2 weeks after the accident result from:

- 43% caesium (Cs-137, Cs-136 and Cs-134);
- 17% iodine-131;
- 13% tellurium-132/iodine-132;
- 10.5% ruthenium-103/rhodium-103;
- 9.5% barium-140/lanthanum-140;
- 4% niobium-95.

The conversion factor from the surface activity of caesium to the projected external dose is 70 mSv per MBq/m^2 for the 10 years period, and 160 mSv per MBq/m^2 for the 70 years period (lifetime).

The size of the populations located in the different contaminated areas is given in Table 1. They are based on demographic data of the Fukushima Prefecture from the Statistics Bureau, Ministry of Internal Affairs and Communications, Japan (website http://www.stat.go.jp/).

The number of people in each contaminated zone is assumed to be proportional to the concerned districts surface area and based on an average population density for each district. For Minamisoma and Namie districts where urban areas aren't concerned, the average density used was derived from the rural part of these districts. The administrative limits of the districts used in the calculations of surface areas come from the "Global Administrative Area database" (website www.gadm.org).

Table 1: Deposits, external doses projected at 1, 10 and 70 years and affected populations

<table>
<tr><th>Deposits of caesium[a] (Bq/m^2)</th><th>> 300,000</th><th>> 600,000</th><th>> 1 million</th><th>> 3 millions</th><th>6 - 30 millions</th></tr>
<tr><td>External dose (mSv) at 1 year</td><td>> 5</td><td>> 10</td><td>> 16</td><td>> 50</td><td>100 – 500</td></tr>
<tr><td>External dose (mSv) at 10 years</td><td>> 19</td><td>> 38</td><td>> 63</td><td>> 190</td><td>380 – 1,900</td></tr>
<tr><td>External dose (mSv) at 70 years</td><td>> 41</td><td>> 82</td><td>> 136</td><td>> 408</td><td>816 – 4,080</td></tr>
<tr><td rowspan="3">Affected population
(excluded the no-entry zone)</td><td rowspan="3">292,000</td><td colspan="4">69,400</td></tr>
<tr><td rowspan="2">43,000</td><td colspan="3">26,400</td></tr>
<tr><td>21,100</td><td>3,100</td><td>2,200</td></tr>
</table>

a : Cs-137 + Cs-134; source MEXT

Projected external doses for the people living lifetime in contaminated areas show significant values, even beyond values of low doses according to UNSCEAR[6] definition, i.e. less than around 200 mSv. The number of people affected could also be high, around 70,000 including 9,500 children from 0-14 years, assuming that children represent 13.7% of the total Japanese population in 2005.

These dose levels do not take into account other exposure pathways such as external exposure by immersion within the plume and internal contamination resulting from inhalation of particles in the plume, and internal doses already received or to be received as a result of ingestion of contaminated food.

The total effective doses (external + internal) could be increased considerably according to the type of deposit (dry or wet), diet and source of food.

4. Comparison with the Chernobyl accident

First-year external dose estimates, surface areas and populations in the heavily contaminated zones impacted by the accident in Fukushima can be put into perspective with those of the Chernobyl accident.

[6] United Nations Scientific Committee on the Effects of Atomic Radiation

Table 2: Comparison between Chernobyl (1986) and Fukushima (2011)

CHERNOBYL								
	Less contaminated areas			**Most contaminated areas**				
				« STRICTLY CONTROLLED ZONES (SCZs) »				**INITIAL EVACUATION ZONE** 30 km
	Control Zone	**Voluntary Evacuation Zone**		**EVACUATION**	**OBLIGATORY EVACUATION**			
Cs-137 deposits (Bq/m²)	37,000	185,000	370,000	555,000	1,5 million	3,7 millions	7,4 millions	up to 37 millions
Cs-137 deposits (Ci/km²)	*1*	*5*	*10*	*15*	*40*	*80*	*200*	*1,000*
1st year dose (mSv)	> 0,5	> 2,4	> 5	> 7	> 20	> 50	> 100	
Surface (km²)	116,000	19,000		7,200	3,100			2,830
Population Size	5,281,000 *(1995)*	1,300,000 *(1995)*		270,000 *(1986)*				135,000
FUKUSHIMA Dai-ichi								
Cs-137 deposits (Bq/m²)			> 150,000	> 300,000	> 500,000	> 1,5 million	3 -15 million	**INITIAL EVACUATION ZONE** 20 km
1st year dose (mSv)			> 5	> 10	> 16	> 50	100 - 500	
Surface[a] (km²)	?	?	1,241	320	384	91	79	628
Population[a] Size	?	?	292,000	69,400				85,000
				43,000	26,400			
					21,100	3,100	2,200	

a : outside of the evacuation zone

In case of Chernobyl accident, the conversion factor from the surface activity to the projected external dose for the 1st year is 13 mSv/year per MBq/m² of Cs-137.

Heavily contaminated territories located outside the initial evacuation zone of 20 km around the Fukushima plant were 8.5% in surface of those in Chernobyl (874 km² compared to 10,300 km²) and the order of magnitude of the affected population size would be 26% of that of Chernobyl (69,400 compared to 270,000).

5. Impact of evacuation measures

Lessons learnt from the Chernobyl accident led ICRP[7] to develop a doctrine for the protection of population in emergency situations, which was introduced in its publication 103[8] (2007) and described in more details in its publication 109[9] (2009).

5.1 Impact of evacuation measures on population sizes according to prescribed reference levels

The implementation of any protection action shall be justified, i.e. should maximise the margin of benefit over harm (individual or societal benefit should be sufficient to offset the detriment it causes), and shall be optimized to ensure that the magnitude of individual doses, the number of individuals subject to exposure are as low as reasonably achievable, economic and social factors being taken into account.

To do this, ICRP recommends the use of reference levels. These reference levels represent the level of residual dose or risk:

- above which exposure is judged unacceptable and requires the implementation of protective actions;
- below which protection should be optimized, by taking into account all exposure pathways.

[7] International Commission on Radiological Protection
[8] 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4)
[9] Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations. ICRP Publication 109. Ann. ICRP 39 (1)

ICRP suggested reference levels in terms of effective dose in a range from 20 to 100 mSv received in one year for radiation emergency situations. The selection of the reference level value should be adapted to the situation and to the protection strategy.

The recommendations of the ICRP publication 103 for the Fukushima situation would entail different number of people to evacuate according to the reference level selected by the Japanese authorities.

Table 3, an excerpt from Table 2, exhibits the number of people to evacuate, for a range of reference levels from 20 to 100 mSv.

Table 3: External doses at 1 year, affected populations, and reference level recommended

ICRP 103 and 109
20 – 100 mSv

External dose (mSv) at 1 year	> 5	> 10	> 16	> 50	100 – 500
Affected population (excluded the no-entry zone)	292,000	43,000	69,400		
				26,400	
			21,100	3,100	2,200

Table 3 shows that 2,200 people whose external dose would exceed 100 mSv for the 1st year should be evacuated. Depending on the level selected between 20 and 100 mSv the number of people to evacuate could range between 2,200 and about 15,000 to 20,000. These data prove the need to evacuate at least 2,200 people that would likely receive doses above 100 mSv the 1st year.

5.2 Impact of evacuation measures on projected doses according to implementation times

The Fukushima population living in the northwest fallout zone and likely to exceed external dose of 10 mSv for the 1st year (distributed in the subgroups presented in Table 1) has been represented on Figure 3 (blue lines), according to the evacuation time : 4 years, 1 year or 3 months after the accident.

The comparison with Chernobyl in terms of external doses puts the radiological impact of the Fukushima accident into perspective compared to that of Chernobyl (red line on Figure 3).

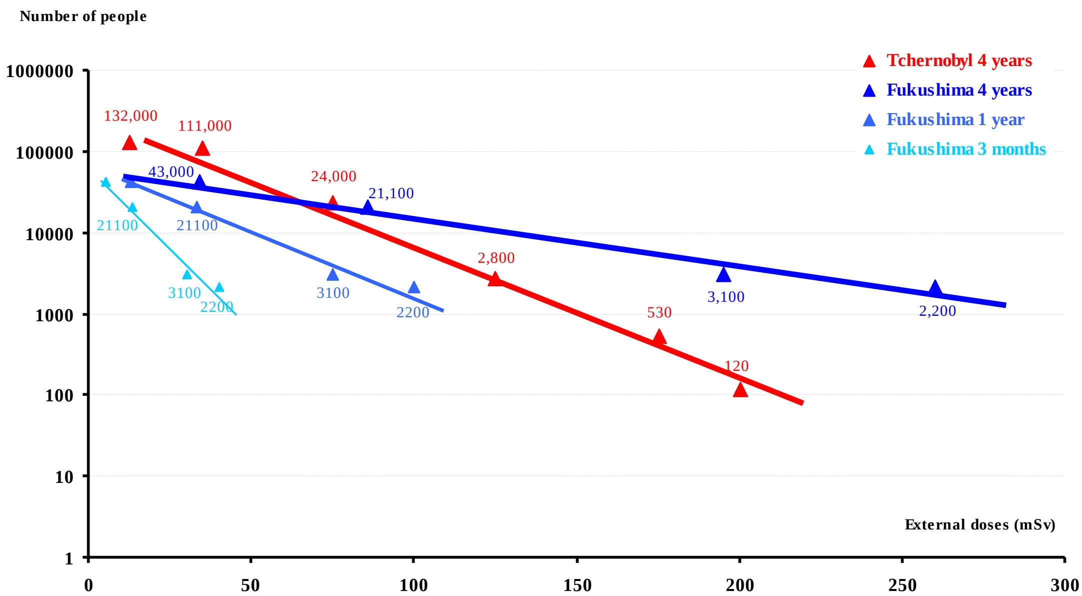

Figure 3: Population and projected external doses according to evacuation time

The distribution of the 270,000 people who lived in the most contaminated areas by the Chernobyl fallout[10] (> 555,000 Bq/m^2) in subgroups according to the external dose received in 4 years also decreases exponentially as illustrated by the red line in logarithmic scale in Figure 3.

The comparison of external doses received during the 4 first years by 270,000 people who lived in the heavily contaminated territories by the Chernobyl accident with those who are likely to be delivered, for the same period, to 70,000 people residing in the northwest zone of the Fukushima Daiichi plant, shows that a fraction of the Japanese population would be more impacted than those for Chernobyl (main blue line of Figure 3). For the highest doses (above 100 mSv over 4 years), the size of population impacted in Fukushima (3,100+2,200 = 5,300) is higher than that of Chernobyl (2,800+530+120 = 3,450).

The other blue lines of Figure 3 illustrate the distributions of 1st year and 3 months external dose estimates following the accident in Fukushima. These distributions have shifted towards lower doses as time of evacuation reduces, compared to the dose distribution of Chernobyl (1986-1989).

A risk indicator that takes into account both the radiological impact and the size of the population is the collective dose (in person.Sv), product of the dose multiplied by the number of affected people.

The external collective dose received over 4 years by the population of 270,000 people in Chernobyl was 7,300 person.Sv.

The projected external collective dose over 4 years for the 70,000 people in Fukushima is 4,400 person.Sv. Therefore, without evacuation during the 4 years after the accident, the radiological consequence of the Fukushima accident from external exposure would reach 60% of that of Chernobyl and could be in the same order of magnitude.

The evacuation of Japanese population one year after the accident would significantly reduce this radiological consequence as shown in Figure 3. The collective dose would decrease to 1,800 person.Sv, i.e. a reduction of 59% of the accident's dosimetric consequence.

The evacuation of Japanese populations 3 months after the accident would drastically reduce the radiological consequence. The new collective dose would be 800 person.Sv, i.e. a reduction of 82% of the accident's dosimetric consequence.

Thus, in case of total evacuation of the population 1 year and especially 3 months after the accident in Fukushima, the long-term risk of developing leukaemia and radiation-induced cancer for the Japanese population would be very much lower than in Chernobyl.

6. Conclusion

Since the accident in Fukushima has occurred several dose assessments have been carried out by IRSN, US DoE and Japan MEXT. The results are of the same order of magnitude; a high degree of consistency between these radiological assessments and the magnitude of caesium-137 and caesium-134 deposits is observed.

Projected external doses for the people living lifetime in contaminated areas include significant values, even beyond low doses according to UNSCEAR definition, i.e. less than around 200 mSv. The number of people involved could also be high, around 70,000 including 9,500 children of 0-14 years in age. The projected doses do not take into account other exposure pathways, such as immersion within the plume and internal contamination resulting from inhalation of particles in the plume, as well as internal doses already received or to be received from contaminated food ingestion. The total effective doses (external + internal) could be increased considerably according to the type of deposit (dry or wet), diet and source of food.

The level of external doses projected in upcoming years — up to 4 Sv lifetime in the most contaminated areas (30 million Bq/m^2 of caesium-137 + caesium-134) — requires the implementation of protective actions such as evacuation of population. According to the ICRP recommendations in radiation emergency situations, the selection of the highest protective reference level, i.e. 20 mSv, would avert external doses above this level for 15,000 to 20,000 people. If the Japanese authorities

[10] Chernobyl: Assessment of Health and Radiological Impact. 2002 Update of Chernobyl Ten Years On, for OECD Nuclear Energy Agency Table 11 p. 73

decide to take an even more protective reference level, for example 10 mSv for the 1st year, the averted external doses for the affected populations (70,000 people) would be much higher if the evacuation is quickly prescribed. An evacuation one year after the accident would result in a 59% decrease of the projected external dose for this population; evacuation three months after the accident would result in an 82% decrease.

This policy for preventing the risk of developing long-term leukaemia and radiation-induced cancer has been clearly understood by the Japanese authorities as shown in the map of population evacuation beyond the initial zone of exclusion of 20 km reported to the IRSN knowledge on May 16, i.e. the 66th day after the accident (Figure 4). The prescribed evacuation area seems to meet the 20 mSv reference level — the most protective dose value within the range recommended by the ICRP in an emergency situation.

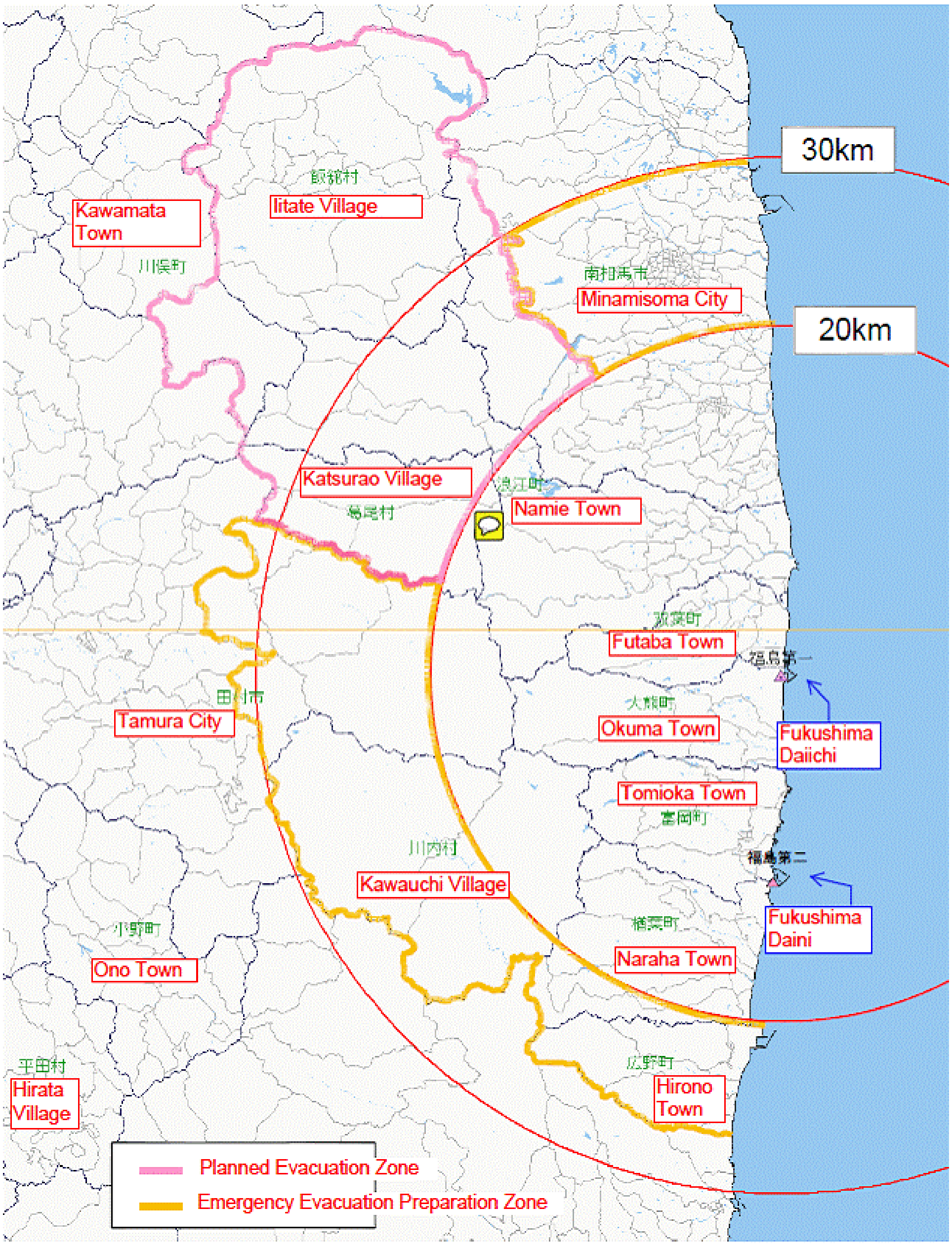

Figure 4: Planned evacuation zones or evacuation zones by the Japanese authorities