REPORT

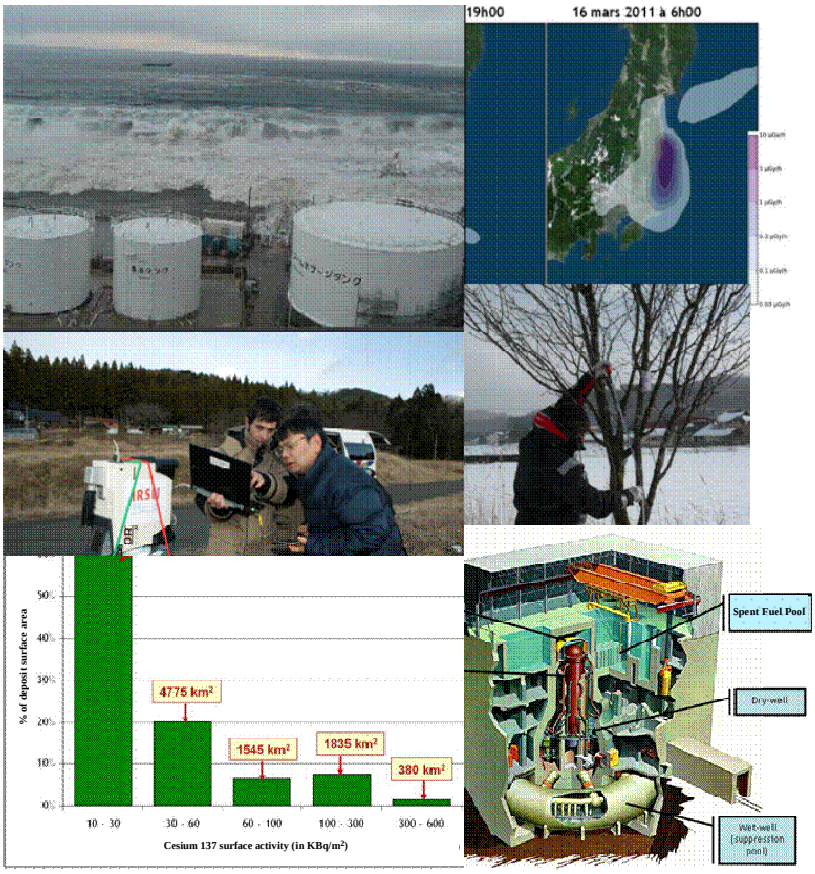
IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

Fukushima, one year later

Initial analyses of the accident and its consequences

Report IRSN/DG/2012-003 of March 12, 2012



Editorial

Starting on March 11, 2011, IRSN mobilized to assist in the analysis of developments and probable radiological consequences of the nuclear accident caused by the earthquake and tsunami at the Fukushima Dai-ichi site some 200 km northeast of Tokyo. IRSN's analyses, performed in real time using data provided by the facility operator and Japanese authorities, gave French authorities, including the French president and his administration, the French Nuclear Safety Authority (ASN), elected officials, and the French ambassador to Japan vital information during the critical phase of the accident to help protect the French expatriate community of several thousand people residing in Japan. IRSN provided perspective and forecasts with total transparency by systematically publishing the results of its analyses and facilitating media access to this information.

A year later, this mobilization continues on several fronts. First, by monitoring the situation in Japan, whether it concerns what will become of the damaged reactors, the radiological consequences of radioactive releases for workers, the environment and the population living in contaminated regions. This report covers what has been done in this area, often in close coordination with IRSN's scientific partners in Japan and other countries.

The conclusions to be drawn from this accident, which demonstrated for the first time that a cataclysmic natural event could cause a major nuclear accident, constitute another element of the IRSN's ongoing mobilization. With this in mind, IRSN in the framework of the European "stress test" approach has formulated ambitious proposals, which have now been adopted by the ASN, to increase the protection of nuclear installations from severe risks which until now had been considered too unlikely to be considered. These discussions on the need to improve risk prevention have also led to identifying the need for new research programs, which will be undertaken as part of an international framework, and seeking on European level to strengthen management in the event a major nuclear emergency, which would inevitably have major repercussions for most of the continent. The report submitted by IRSN to ASN on the results and proposals following the stress tests has been made public. With the same concern for transparency, IRSN will also publish the results of its research on additional means to prevent the risks of nuclear accidents.

Jacques Repussard

Abstract

The earthquake of magnitude 9 of March 11, 2011 with an epicenter 80 km east of the Japanese island of Honshu, and the subsequent tsunami, severely affected the region of Tohoku, with major consequences for its population and infrastructure.

Devastating the site of the Fukushima Dai-ichi nuclear power plant, these natural events were the cause of the core meltdowns of three nuclear reactors and the loss of cooling of several spent fuel pools. Explosions also occurred in reactor buildings 1 through 4 due to hydrogen produced during fuel degradation. Very significant radioactive releases into the environment took place. The accident was classified level 7 on the International Nuclear Event Scale (INES).

This report provides an assessment and perspective on the information gathered by IRSN during the first twelve months following the disaster in an effort to understand the condition of the installations, evaluate the releases and analyze and evaluate the consequences of the accident on workers and the impact on the population and the environment.

On the basis of available information, the report provides an initial analysis of the chain of events. It should be noted that a year after the accident, the full sequence of events is still not understood. Operating experience feedback from the 1979 Three Mile Island accident in the United States, in which reactor core damage was not confirmed until 1986, suggests that it may be several years before a detailed scenario can be constructed of the accident that led to radioactive releases. It will require access to the damaged installations.

The situation at the site remains dangerous (reactor pressure vessels and containments are not leaktight, diffuse releases, etc.). If it has significantly improved as a result of the significant resources deployed by the Tokyo Electro Power Company (TEPCO) to regain control of the installations, this effort must continue over the long term to begin evacuation of fuel from pools (in two years) and remove degraded fuel from reactors (in ten years), as has been announced.

An assessment of quantities of radioactive releases to the air and water as well as their dispersion is given here but must be considered provisional. It should be noted that a significant effort has been made in Japan to characterize environmental contamination, which has greatly diminished in the weeks and months following the accident due to the virtual disappearance of short-lived radionuclides. The highest risks for the population were concentrated in the initial months. Today and for years to come, the environment remains contaminated by radioactive cesium that will complicate the return of evacuated residents to the most contaminated regions. Removing residual deposits will be a difficult, long and waste-producing process. Another long-term impact may remain for the agricultural production in the most contaminated regions; it may be reduced using appropriate practices and close monitoring. Natural environments (forests) will remain the most vulnerable over time, also because of cleanup difficulties.

With regard to the health aspects of the disaster, IRSN's work concerned initial assessments of doses the Japanese population may have received during the release phase and external exposure to radioactive deposits during the first year after the accident. The various epidemiological monitoring studies on the Japanese population carried out locally are presented. According to Japanese authorities, received doses are less than 100 mSv. Although it is not certain that at this dose level an excess of the risk may be detected by epidemiological studies, these studies are nevertheless indispensable because they respond to a legitimate demand by the population. They also provide new information about exposure to low doses of ionizing radiation. There is however a lack of measurements for exposed persons, especially children exposed to radioactive iodine.
To date, the Japanese authorities have not provided any report on health consequences observed in workers. The only currently available information on doses received by workers is that provided by TEPCO for its employees and subcontractors involved in operations at the Fukushima Dai-ichi nuclear power plant. No precise information concerning the other categories of exposed workers (firemen, police officers, municipal employees, civilian security personnel) has been obtained, even though at least some of these workers have undergone dosimetric monitoring. To date no deterministic effect attributed to acute exposure to radioactivity has been observed, however it is very difficult at present to obtain precise information about worker exposure and its health effects.

The present report also describes work launched in 2011 by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) with a view to producing an initial report on assessing exposure levels in the environment and populations related to the accident at the Fukushima Dai-ichi nuclear power plant and the consequences for human health.

TABLE OF CONTENTS

FOREWORD

On the basis of information made public about the condition of the Fukushima Dai-ichi nuclear power plant, this report provides a summary, a year after the accident, of information gathered by IRSN on what is known about the accident and its health and environmental consequences.
Initially, during the weeks following the earthquake and tsunami that led to the accident, IRSN's emergency response center analyzed the situation to assist the French embassy in Japan and French public authorities in understanding the situation, its issues, scenarios and possible consequences, to inform the public at large and assist firms (French industrial firms in Japan, airlines, etc.) dealing with the consequences of the accident. In late April 2011, at the end of the emergency, a project structure was set up at IRSN to pursue the work of analyzing the accident and its consequences. The objective is to draw lessons from this disaster and advance scientific and technical knowledge, reconsider technical policies to help prevent the recurrence of such accidents, and better manage emergency and post-accident situations.
It should be noted that one year after the accident, the complete sequence of events is still not clear. Operating experience feedback from the Three Mile Island accident that took place the United States in 1979, in which reactor core damage was not confirmed until 1986, leads to the conclusion that it may take several years to reconstitute a detailed scenario of the accident that led to radioactive releases. This will require access to the damaged installations.

1. IRSN'S EMERGENCY RESPONSE CENTER

Operation of the emergency response center during the Fukushima accident

At 6:46 am Central European Time on Friday, March 11, 2011, a very high magnitude earthquake occurred east of the Japanese island of Honshu, resulting in emergency shutdown of some ten Japanese nuclear power plants. The earthquake was followed by a tsunami.
In response to the news from Japan, IRSN decided to activate its emergency response center at 11:00 am. At 11:52, the first conference call to assess the initial situation was organized by Météo France[1] (which had been alerted by the International Atomic Energy Agency, IAEA), Department of Civil Defense and Emergency Preparedness of the Interior Ministry and Nuclear Safety Authority (ASN). The emergency response center remained operational for six weeks, including four weeks with round-the-clock staff, until 11 am on April 29.
The emergency response centre initially included units for administration, installation assessment, assessment of radiological consequences, communication, and support and logistics. A general administrative unit was quickly added, as well as a health unit on Monday, March 14, responsible for handling outside requests concerning people that may have been exposed to releases from the accident or worried about their health, and an environment unit was set up on Saturday, March 19, to organize increased environmental monitoring of radioactivity in France and its overseas departments, regions and collectivities. On Tuesday, March 15, engineers from AREVA and EDF who could speak and read Japanese joined the emergency response center, where they served in shifts over the next four weeks. On Sunday, March 13, in coordination with the emergency response center, IRSN dispatched one of its experts to Tokyo as part of a civil protection mission assisting the French Ambassador. His mission lasted one month.

[1] French national meteorological service, French representative at the World Meteorological Organisation

During its four weeks of round-the-clock operation, the center numbered at least 30 experts during the day, including three spokespeople, and at least 20 at night. In total, 200 people were mobilized from IRSN's staff of 1,700.

IRSN's leaders participated in daily meetings organized by the secretary general of the presidency and the prime minister's cabinet director, as well as meetings with the Quai d'Orsay[2]'s emergency response team and the interministerial emergency response committee chaired by the secretary general of national defense and security.

IRSN's emergency response center was in permanent contact with the ASN's own emergency response center and participated in a daily conference call with the French embassy in Tokyo.

The need for information by the media and the public required adapting to communication resources and tools. Three representatives were quickly named for specific fields: facility safety, environment and health. IRSN's website was modified to handle the increased traffic, and the database of radioactivity measurements in France and its regions and collectivities abroad were made available to the public. Information bulletins for French nationals living in Japan were also issued regularly.

Lessons from operation of the emergency response center

The first operating experience feedback on the operation of the IRSN's emergency response center shows that the technical support center performed well (thanks to its tools and the training of the experts) and IRSN's work over the past several years in preparing post-accident situations (research on the Chernobyl accident) and its active involvement in the work of the steering committee for the management of the post-accidental phase of a nuclear accident (CODIRPA) have enabled it to anticipate health and environmental issues reasonably well.

Lessons, both technical and methodological, were however learned about atmospheric dispersion, the impact of radionuclides on the marine environment, deposits, radioactivity measurements, etc., as well as the need to internationalize IRSN's assessment tools to extend their use to the various types of nuclear facilities found abroad.

From an institutional perspective, IRSN fully performed its role as a public expert by supporting numerous public authorities that were involved in managing a major nuclear emergency, even if it took place abroad. This includes ASN, to which IRSN provides ongoing technical support, as well several ministries involved in various aspects of emergency management, including products imported from Japan, the embassy responsible for protecting and informing French nationals in Japan, and several large French firms working in Japan. In total, IRSN produced 58 information reports for French authorities and responded to more than 94 requests from various ministerial departments, including 36 from ASN.

[2] Minister of Foreign Affairs

2. INTRODUCTION TO BOILING WATER REACTORS

2.1. GENERAL DESCRIPTION

The boiling water reactor (BWR) is one of two types of light water reactors (LWRs); the other, used in France, is the pressurized water reactor (PWR).

BWRs (Figure 2-1) differ from PWRs in that water turns into steam when it passes through the reactor core and the steam goes directly to the turbine without use of an intermediate cooling system ("secondary system") in PWRs. In this sense BWRs closely resemble a traditional forced recirculation boiler.

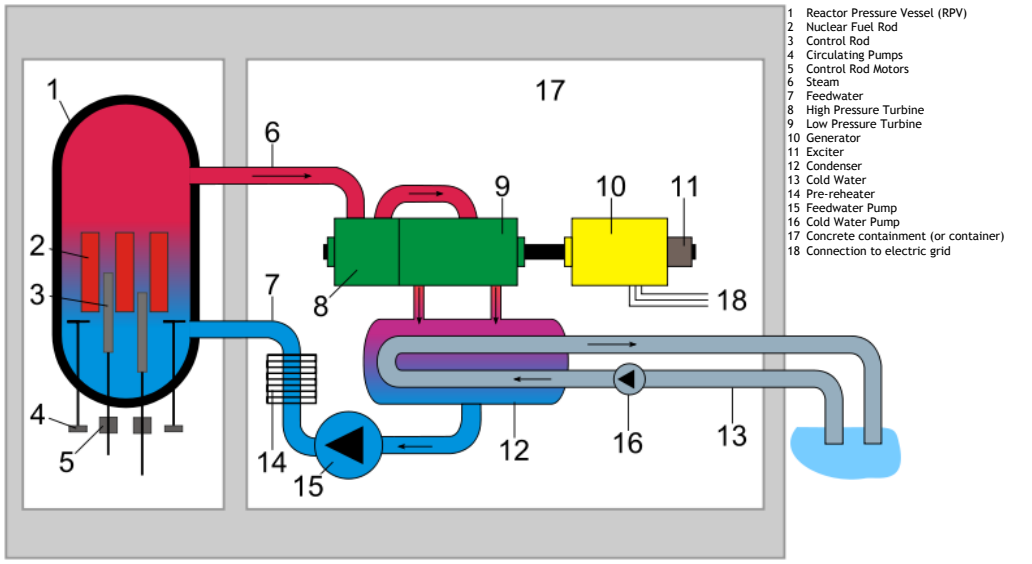


Figure 2-1 – Diagram of general operation of a BWR

2.2. CONTAINMENT BARRIERS

As with PWRs, there are three containment barriers between radioactive materials and the environment, with some differences:

a) Fuel element cladding. Fuel element cladding contains radioactive products. In BWRs, leaktightness is particularly important to avoid contaminating the turbine, as seen in the cladding being 50% thicker than that found in PWRs.

b) Main cooling system. In contrast with PWRs where water circulating in the system must remain liquid, water in BWRs boils and is not kept at the same high pressure (operating temperature for the two reactor types is similar). Consequently, parts making up the BWR reactor coolant system are not as thick.

c) Reactor containment. It has evolved over time. At Fukushima Dai-ichi, the containment for reactors 1 to 5 is the MarK I type (Figure 2-2) and MarK II for reactor 6 (Figure 2-3).

BWR reactor containments are very specific, but in general include:

- drywell, the upper part of the containment, the reactor pit; the drywell is made inert with nitrogen;
- wetwell, the lower part of the containment (which is toroidal in shape on the Mark I); the wetwell is half filled with water (suppression pool) and its free surface area is topped with nitrogen.

The drywell and wetwell are connected by several vents through the water contained in the wetwell.

The wetwell is mainly used in two situations:

- in the event of pipe rupture, the water/steam mix is directed to the suppression pool where it condenses through sparging in the water, which limits the pressure increase in the reactor containment, designed to resist a pressure of approximately 3.5 bars;
- if the containment pressure becomes too high, releases to the outside may occur. Lines with valves are connected to the wet- or drywell for this purpose;
- if necessary, water in the reactor pressure vessel (RPV) can be drained using pipes connecting the RPV and suppression pool.

In both cases, the suppression pool must be cooled using a dedicated system, which is one of the roles of the Residual Heat Removal System (RHRS).

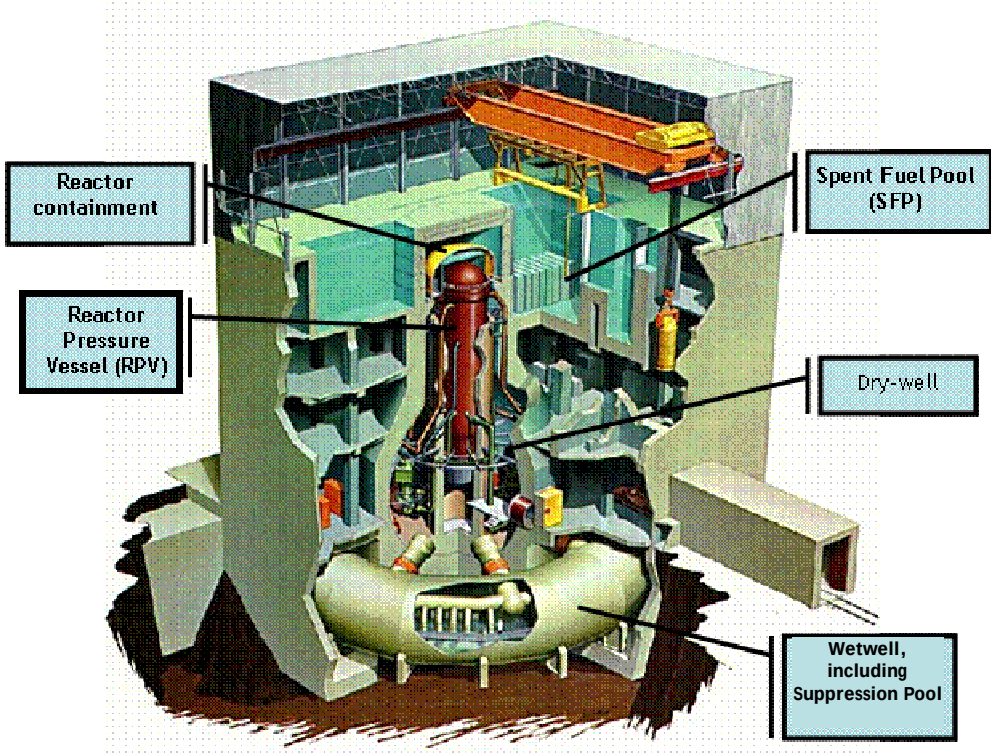


Figure 2-2 – Mark I reactor containment

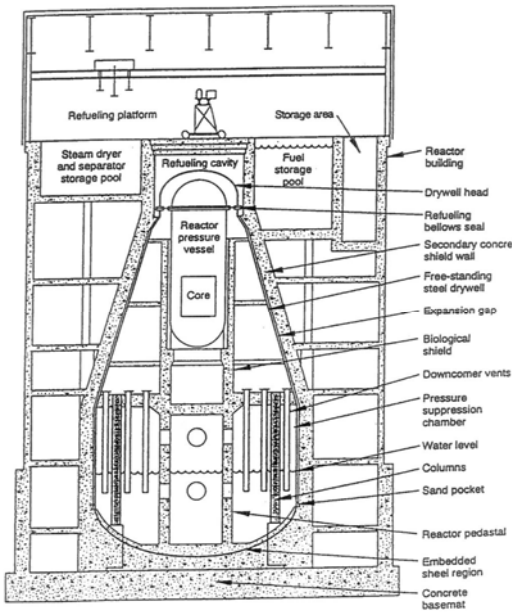


Figure 2-3 - Mark II Reactor Containment

The reactor building includes the reactor containment as well as the spent fuel pool (SFP) in which new and irradiated fuel assemblies are stored. The building is not considered leaktight.

2.3. SAFEGUARD SYSTEMS

Only a limited number of systems were challenged during the initial phase of the accident since the others were unavailable due to the lack of electrical power or cooling. These include:

1) Isolation Condenser (IC), which is only found on reactor 1, which is a BWR/3 model;
2) Reactor Core Isolation Cooling (RCIC), which is only found on reactors 2 and 3, which are BWR/4 model;
3) High Pressure Coolant Injection (HPCI), which is installed on the three reactors, but briefly functioned only on reactor 3;
4) Steam Relief Valves (SRV);
5) Hardened Venting System (HVS).

This chapter presents the operating principles of these systems using the acronyms given above.

2.3.1. ISOLATION CONDENSER - IC

This system (Figure 2-4) cools the core when the main condenser is not available to remove heat (12 in Figure 2-1). Steam flows through pipes located in the upper part of the RPV to a heat exchanger located in a water reserve. There, steam condenses and the heat exchanger/reserver serves as a condenser. Gravity forces condensed water to return to the RPV through pipes connecting the condenser and the lower part of the vessel. Natural forces provide for circulation without the need for pumping as long as valves are open. Nevertheless, the heat transmitted to the condensers is removed as water evaporates to the atmosphere, with the water reserve requiring makeup.

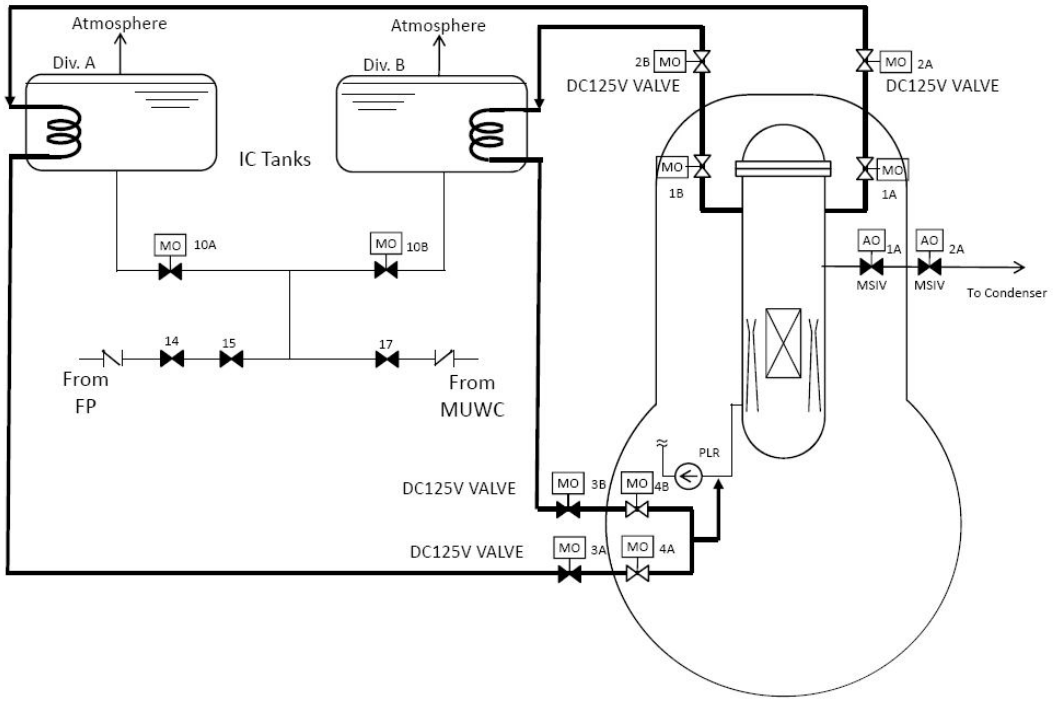


Figure 2-4 - Fukushima Dai-ichi – Schematic diagram of IC system (reactor 1)

2.3.2. REACTOR CORE ISOLATION COOLING SYSTEM – RCIC

This system (Figure 2-5) cools the core when the reactor is at shutdown or when normal feedwater systems are unavailable (steam isolation valves to the turbine are closed or the feedwater pump is unavailable). The steam produced in the RPV by residual heat runs a turbine that activates a pump which injects water from several possible sources (including the suppression pool and condensate storage tank) in the RPV. The steam in this turbine is then returned to the suppression pool where a dedicated system cools it (see section 2.2).

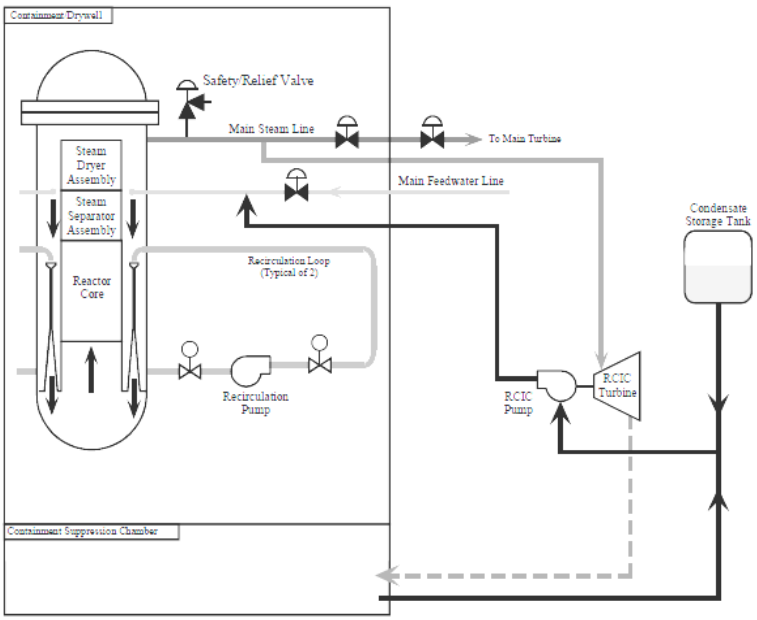


Figure 2-5 – Schematic diagram of RCIC system (reactors 2-5)

2.3.3. HIGH PRESSURE CORE INJECTION SYSTEM - HPCI

The system (Figure 2-6) injects water into the core using a spray ring located above the assemblies. The water comes from the condensate storage tank or suppression pool if no water is available from the condenser. The name of the system and the type of pump that ensure water circulation in the system vary by BWR type (for all reactors at Fukushima Dai-ichi, the system is HPCI and uses a pump supplied by a dedicated turbine).

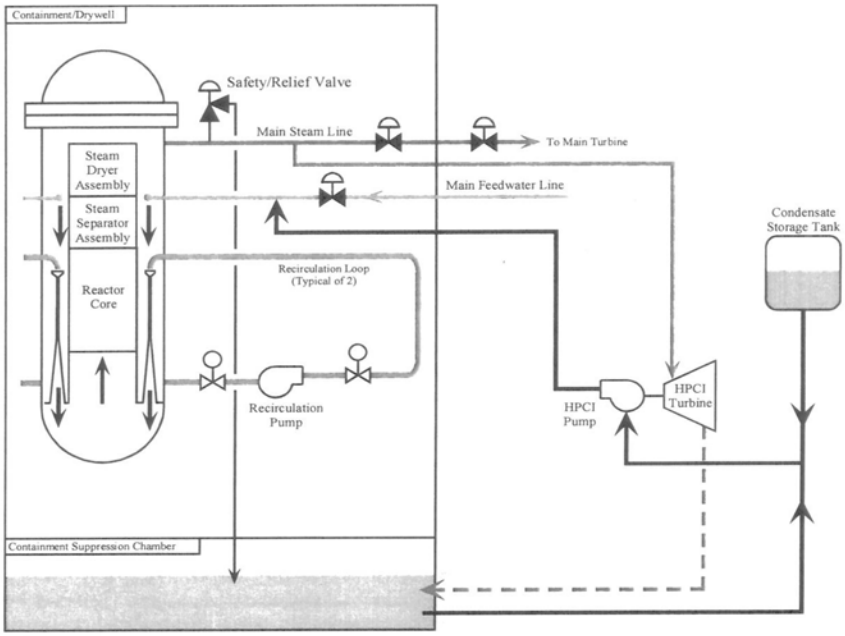


Figure 2-6 –Schematic diagram of HPCI system

2.3.4. SAFETY RELIEF VALVES – SRV

This system controls pressure in the RPV (Figure 2-7). There are two types of valves:

1) safety valves, three per reactor, open at relatively high pressure and release directly into the drywell,
2) main steam safety relief valves release water into the suppression pool. The valves are pneumatic, using compressed air. Air is provided to each valve through an air line using a solenoid valve (zig-zag). If electrical power is lost, the solenoid valves are unloaded and the safety relief valves are closed.

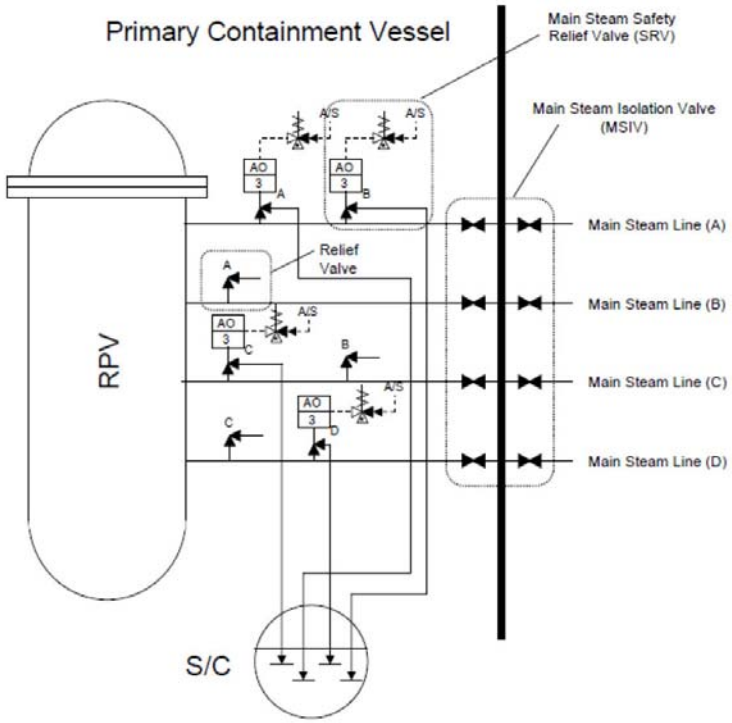


Figure 2-7 – Schematic diagram of safety release valve (SRV) on reactor 1

2.3.5. HARDENED VENTING SYSTEM - HVS

The pressure relief system for emergency situations is a recent modification. Before Chernobyl, these reactors had only a venting system for normal operation. The system was not designed to operate in severe accident conditions. Following the Chernobyl accident, the US Nuclear Regulatory Commission chose to modify General Electric's BWRs in the US by adding a Hardened Venting System for emergency situations. The HVS was installed on the Fukushima reactors between 1999 and 2001.

The pressure relief system for the MARK-I reactor containments in Fukushima 1, 2 and 3 is shown below.

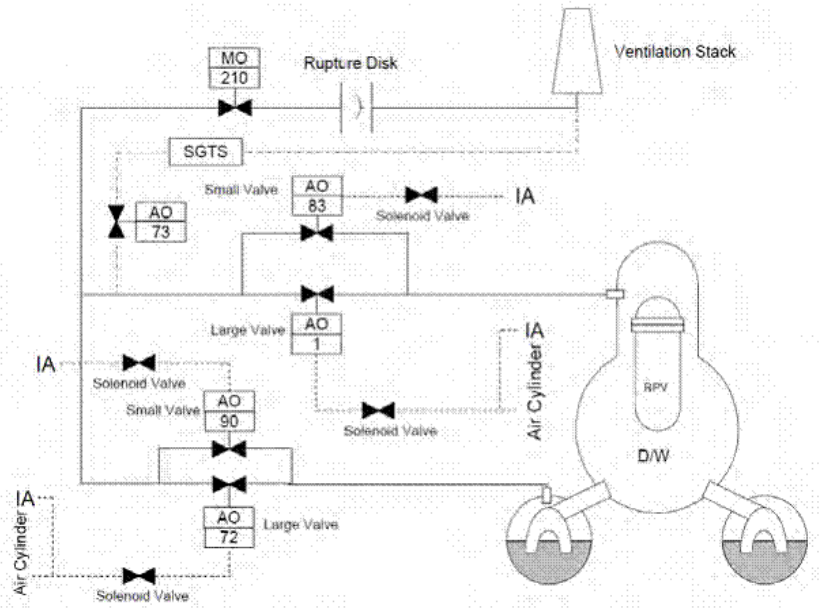


Figure 2-8 - Schematic diagram of containment pressure relief system – reactor 1

3. TOHOKU EARTHQUAKE OF MARCH 11, 2011

Throughout its history, Japan has known numerous deadly earthquakes. The most recent include Zenkoji (May 18, 1847, magnitude 7.4, 34,000 dead), Sanriku (June 15, 1896, magnitude 7.6, 22,000 dead), Tokyo (September 1, 1923, magnitude 8.3, more than 100,000 dead) and Kobé (January 16, 1995, magnitude 7.2, 5,502 dead).

At 2:46 pm local time on Friday, March 11, 2011, a powerful earthquake of magnitude 9.0 struck Japan. It was the strongest quake ever recorded in Japan and ranks as the fourth strongest quake recorded since the eighteenth century (Figure 3-1). The earthquake was centered 80 km off the coast east of Honshu and 370 km northeast of Tokyo. A very large tsunami (ranging in size from several meters to some ten meters) quickly ensued, striking the east coast of Honshu and producing a very large number of victims (some 20,000) and very significant material damage. Two days before, a strong temblor of magnitude 7.2 and three with magnitudes over 6.0 had already shaken the region without suggesting the subsequent catastrophe. In hindsight, the events are considered precursors to the March 11 earthquake.

Year	Location	Magnitude
1960	Chile	9.5
1964	Prince William Sound, Alaska	9.2
2004	Sumatra-Andaman Islands	9.1
2011	Near the East Coast of Honshu, Japan	9.0
1952	Kamchatka	9.0
1868	Arica, Peru (now Chile)	9.0
1700	Cascadia Subduction Zone	9.0
2010	Offshore Bio-Bio, Chile	8.8

Figure 3-1- Highest magnitude quakes recorded since 1700 (USGS/NEIC).

The Japanese archipelago is located in an area where three major tectonic plates converge and form a complex geodynamic structure (Figure 3-2). In the south, the Philippine plate slides under the Eurasian plate, while in the north (off the coast from Tokyo), the Pacific plate slides under the Philippine and Eurasian plates. The rapid convergence of these plates (~8-9 cm/year) makes the area highly seismic, primarily in areas where plates come into contact. The earthquake of March 11 took place at a depth of 32 km, where the Pacific and Eurasian tectonic plates are in contact.

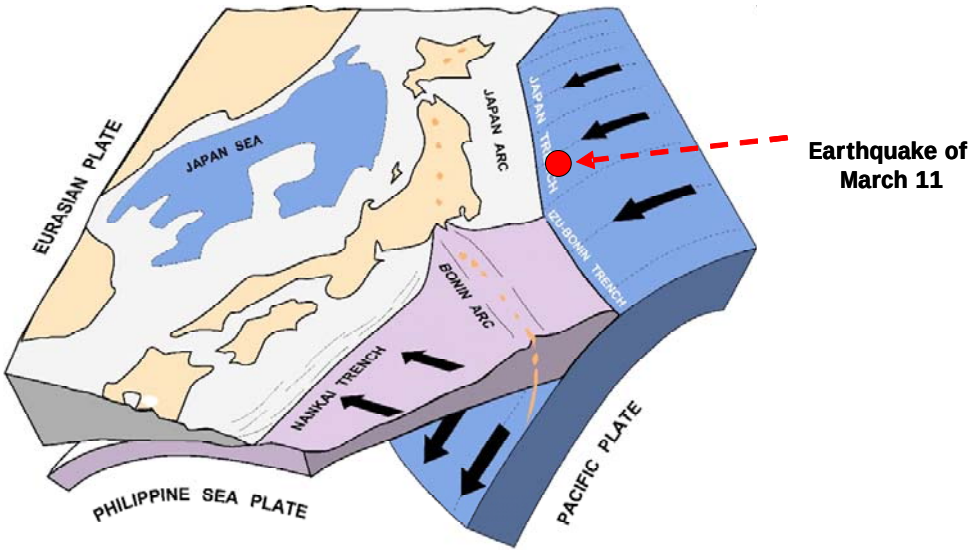


Figure 3-2 - seismotectonic situation of Japan (according to L. Jolivet).

The zone of the fault that ruptured during the earthquake of March 11, 2011 extends over more than 500 km, while slipping on the fault exceeded 25-30 meters in some points (Figure 3-4). Such exceptional dimensions explain

the long duration of the earthquake (more than two minutes in Tokyo). The colossal energy liberated during the rupture resulted in very significant movements of the ground over much of Japan. The Japanese earthquake recording network, the world's densest, maps the distribution of the maximum accelerations (Figure 3-3). In some locations, the accelerations exceeded that of gravity.

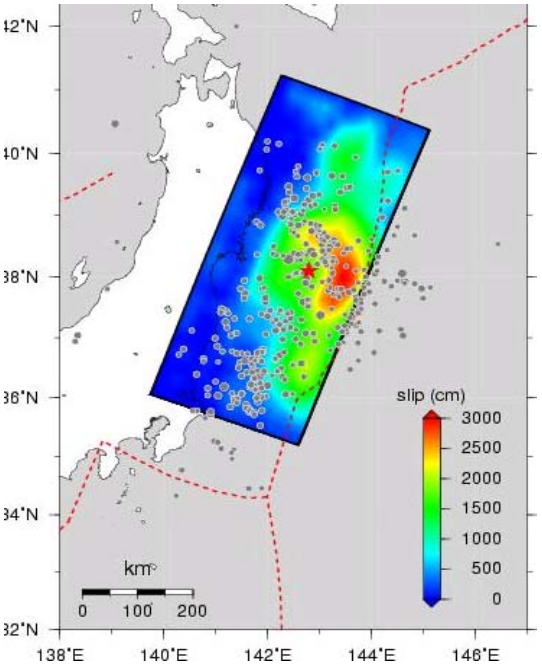


Figure 3-4 – Map of slip during the Tohoku earthquake (color scale, Wei et al., 2011) and aftershocks (gray dots). The surface projection of the fault zone active during the principal shock is represented by a black rectangle.

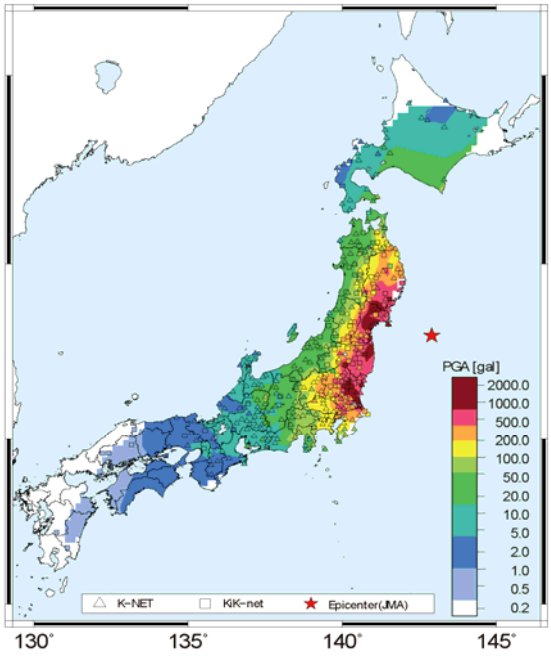


Figure 3-3 – Map of distribution of maximal accelerations recorded by the Kik-net and K-networks at ground level. For reference, an acceleration of 980 gal equals that of gravity (1g) (source: USGS/NEIC).

Analysis of data recorded by the many GPS stations of the Geospatial Information Authority of Japan (GSI) on the northern part of Honshu reveals that the north coast of the country shifted east by 2.4 meters on average, and by more than 4 meters in some places. Likewise, geodetic data indicates that the east coast subsided 50 cm on average, with the greatest subsidence occurring in East Miyagi prefecture, which reached 1.1 meters (USGS).

The relative displacement of the Pacific and Eurasian plates that took place in the Earth's crust during the Tohoku quake considerably modified the distribution of forces throughout the zone (change in state of stress). The readjustments required for a new equilibrium resulted in several thousand aftershocks (Figure 3-4), including several of high magnitude (four over 7.0 and more than 500 with a magnitude in excess of 5.0). Most of the aftershocks occurred along the subduction plane. It should nevertheless be noted that some aftershocks were observed in other geological structures activated over a great distance by the changes of the state of stress reacted over a greater distance. Major aftershocks occurred on land, resulting in significant damage and surface movements. The most important took place on April 11, 2011 (magnitude 7.1, see Figure 3-5). It will last several years before seismic activity related directly to the Tohoku earthquake subsides.

Figure 3-5 - Surface displacement following aftershock of 04/11/2011 (Hamadoori earthquake). Vertical scarp due to fault movement between 1-3 meters (Ishiyama et al., 2011)

An earthquake followed by a tsunami…

Less than an hour after the earthquake, beginning at 3:27 pm, a series of tsunamis affected the Fukushima Dai-ichi site, with some overtaking the seawalls protecting the site. The height of the first wave, which occurred at 3:27 pm, is estimated at four meters. At 3:35 pm, a second tsunami of unknown height rolled over the site.

In the end, the installations were submerged up to 14-15 meters above sea level, doubling the maximum forecast adopted by TEPCO over the past decade. Reassessment of the flooding risk led to a maximum level of 5.7 meters above sea level (1.3 meters for the tide and 4.4 meters for the tsunami). The Japanese tsunami warning system was activated, but the height of the wave predicted to hit Fukushima was only three meters. The platforms of reactors 1 through 4 are located at +10 meters from the reference level while the platforms for reactors 5 and 6 are located at +13 meters. Four meters of water thus submerged the platforms of reactors 1 through 4. Figures 3-6 and 3-7 illustrate the violence of the event and the extent of flooding.

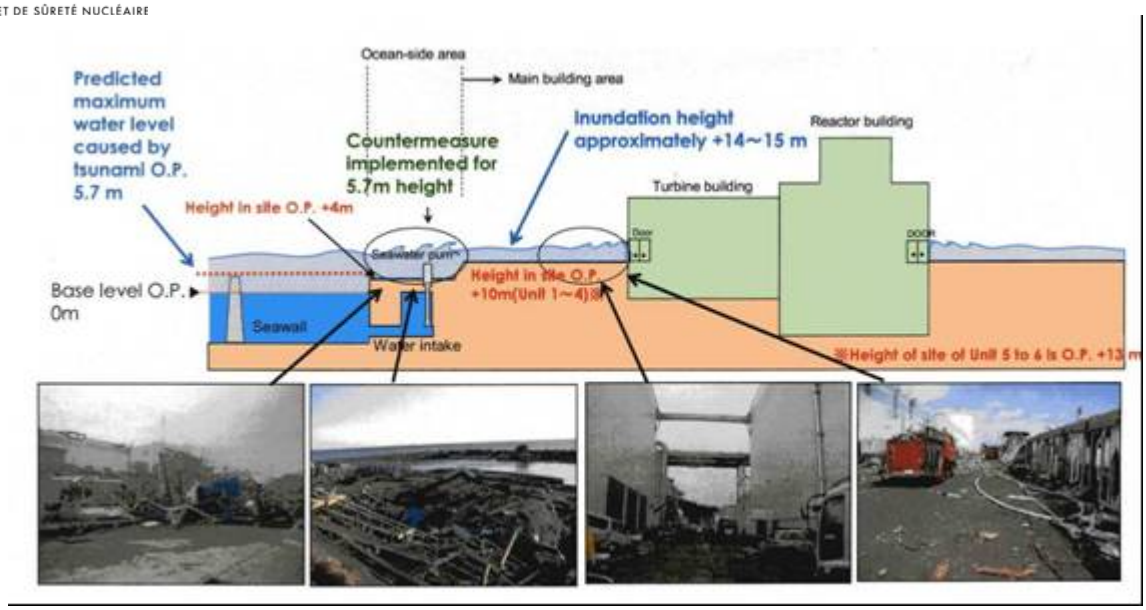


Figure 3-6 - Inundation of area of plant units 1 to 4 at Fukushima Dai-ichi site (source: TEPCO)

Figure 3-7 - Submersion of seawall at the Fukushima Dai-ichi site (source: TEPCO)

One year later…

Scientists worldwide have pored over the data recorded during the Tohoku earthquake and will continue to do so for years to come in an effort to understand its nature. The subduction megathrust earthquake or megaquake is the event that provides the greatest variety and quantity of high-quality observations. These data should improve the knowledge of physical mechanisms that govern the seismic behavior of rapid convergence zones and help to better assess associated earthquake hazards and related risks.

Another aspect deserves examination. It is clear that the Japanese scientific community was anticipating a major earthquake in the region over the medium term. Nevertheless, the knowledge acquired up until then had led a majority not to consider the possibility of a megaquake and an associated tsunami of such scale. The challenge today is to understand why the latter assumption was not given priority and to identify signals that could have obliged the scientific community to consider the possibility of such an event (Figure 3-8).

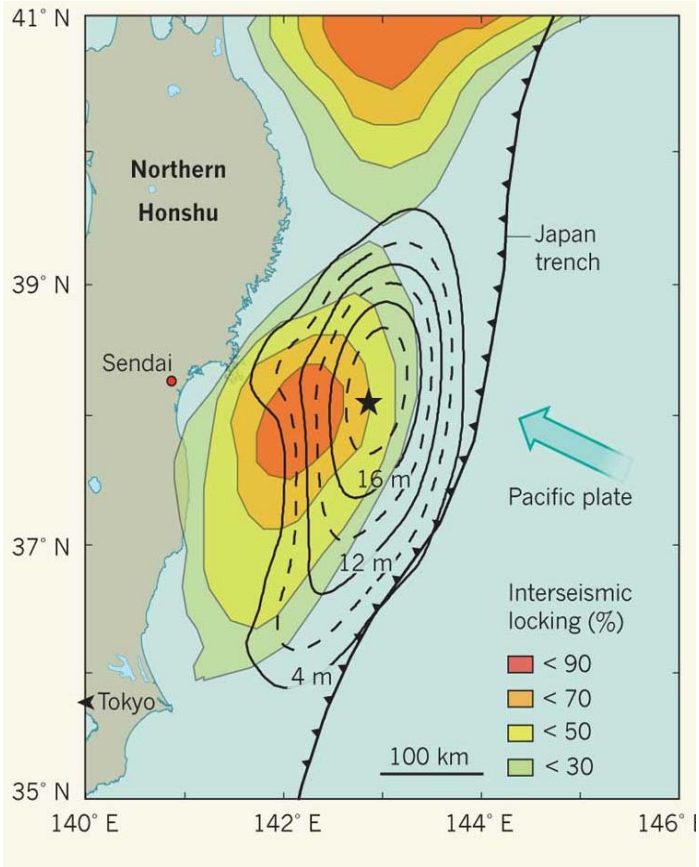


Figure 3-8 - Evaluation of coupling between Pacific and Eurasian plates. The results (obtained from data acquired over a period of 15 years) indicate that the contact zone that yielded during the Tohoku megaquake was significantly coupled. Elastic deformation (which is the motor of seismicity and the result of plate convergence) added to this, which a posteriori could have been the basis for anticipating a major event. Such results contradict hypotheses proposed until then to explain the deficit between the quantity of energy liberated by historically known quakes and that related to the convergence of tectonic plates. In effect, research considered that a significant part of the deformation brought on by convergence was dissipated aseismically (according to Avouac 2011).

4. CONSEQUENCES ON THE FUKUSHIMA DAI-INI, ONAGAWA, TOKAI, HIGASHIDORI AND HAMAOKA REACTORS

Eighteen BWR nuclear power plants were in operation at five sites along the east coast of Honshu (Figure 4-1). None of these reactors is currently operating (March 2012).

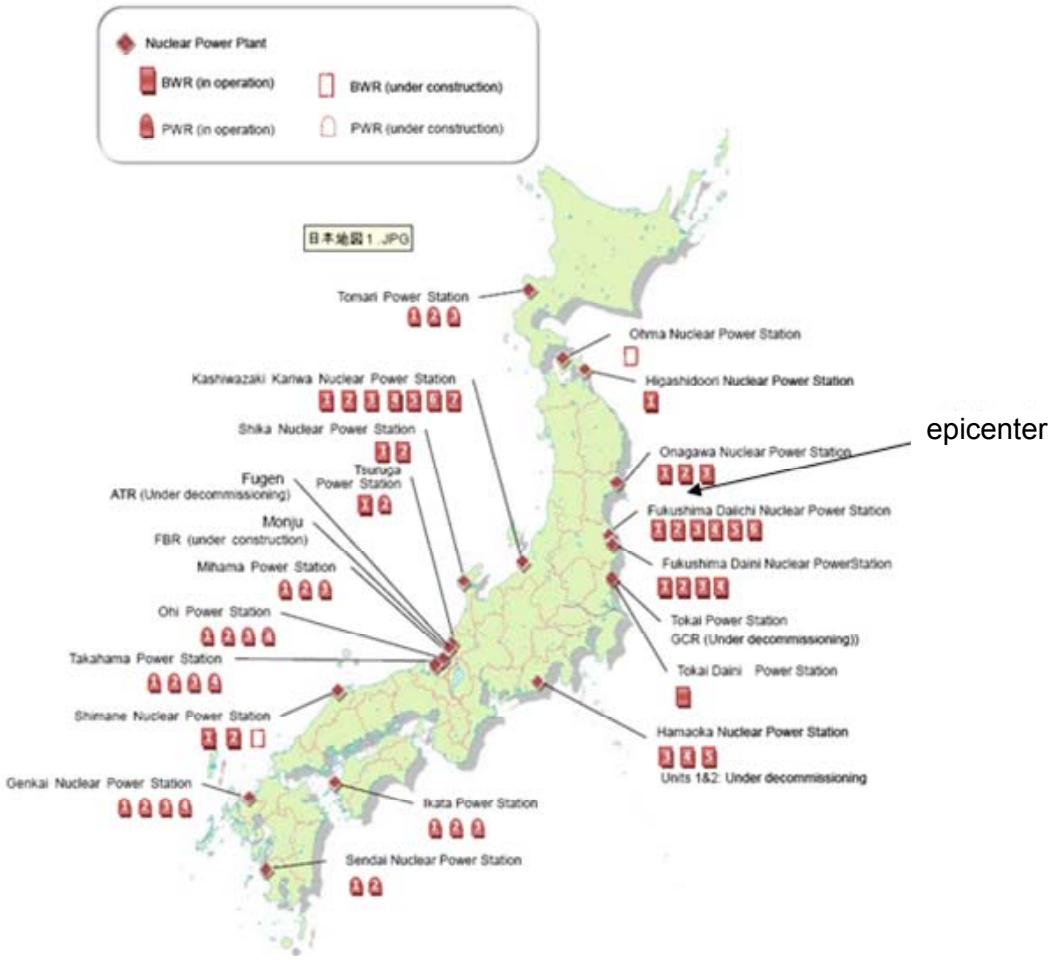


Figure 4-1- Location of Japanese nuclear power reactors

The four reactors at the Fukushima Dai-ini site (Fukushima prefecture) were at power at the time of the quake, which caused an emergency shutdown. At reactor 1, the tsunami led to the inundation and unavailability of electrical systems. In addition, cooling resources using seawater were considered unavailable following flooding. As a result, the equipment dependent on them, including emergency diesel generators (EDGs), were unavailable. Cooling to the spent fuel pool (SFP) was also unavailable. Removal of residual heat from the reactor core was ensured by water makeup in the reactor pressure vessel (RPV) by dedicated systems. Injected water, heated as it passed through the core, could not however be cooled. Nevertheless, gradual restoration of cooling and electrical supply—usually with temporary systems—avoided degradation of fuel assemblies. A similar scenario occurred in reactors 2 to 4, but the loss of electrical and cooling systems using seawater was only partial.

The three reactors at power or in restart mode at the Onagawa site (Myagi prefecture) shut down automatically as a result of the earthquake. They did not experience loss of off-site power (LOOP). However, failure of a transformer on reactor 1 led to switching to an EDG. On reactors 2 and 3, flooding of certain rooms housing cooling

resources using seawater had a limited impact since it was only partial. The situation was rapidly controlled at the three reactors and no core degradation was reported. The same was true for the SFPs for which cooling, lost following the earthquake, was restored the same day.

At the Tokai nuclear power plant (Ibaraki prefecture), the single reactor[3], which stopped automatically, experienced LOOP after the earthquake. Nevertheless, one of the EDGs whose cooling systems were not flooded remained operational. The EDG was used to supply electricity to the SFP the day after the earthquake.

In Aomori prefecture, the reactor at the Higashidori nuclear power plant, which was shut down for periodic inspection at the time of the quake, experienced LOOP. Power was restored during the night and an EDG supplied power in the interim.

Finally, some 500 km for the quake's epicenter, the three reactors[4] at the Hamaoka nuclear power plant (Shizuoka prefecture) encountered no special difficulty, with the two reactors in operation at the time of the quake remaining at power. Nevertheless, a decision by the government in May 2011 prolonged the outage of reactor 3 (which had been shut down for inspection at the time of the quake) and shut down reactors 4 and 5 to strengthen protection at the site.

5. FUKUSHIMA DAI-ICHI ACCIDENT

The Fukushima Dai-ichi (or Fukushima I) site includes six reactors. Figure 5-1 shows the site before the accident. Reactor buildings 1, 2, 3 and 4 can be seen at the center of the photo with reactors 5 and 6 off to the side on a higher platform. The site also includes a shared spent fuel pool that contained 6,400 fuel assemblies at the time of the accident.

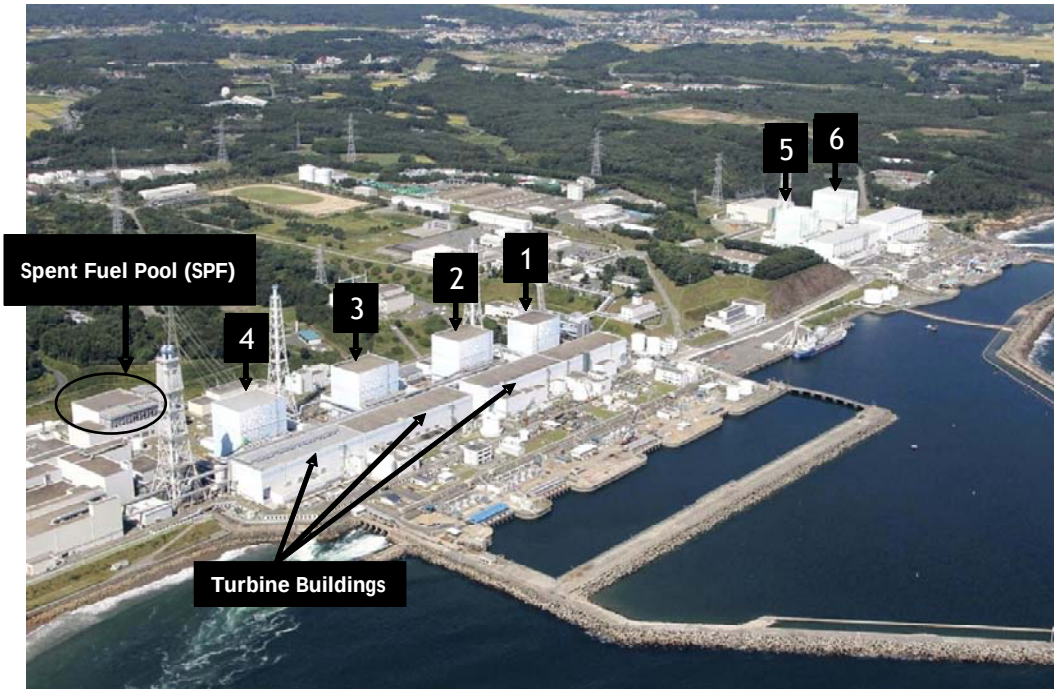


Figure 5-1 - Fukushima Dai-ichi site before the accident (photo: Google maps)

Located in the districts of Okuma and Futaba in Fukushima prefecture, the Fukushima Dai-ichi site is operated by the Tokyo Electric Power Company (TEPCO).

[3] Reactor 1, which is gas-cooled, was decommissioned in 1998.
[4] Two other reactors– 1 and 2 (BWR) – were shut down in the last decade and decommissioned in 2009.

It includes six BWRs with the following electrical output: 460 MWe (reactor 1), 784 MWe (reactors 2 to 5) and 1,100 MWe (reactor 6).
Reactors 1 to 5 are Mark 1 containment type. Reactor 6 is Mark II containment type. Table 5-I gives data about the reactors at the Fukushima I site, and their status and core inventories before the accident.

Table 5-I: Fukushima I facility data
reactor types and core inventories (PN nominal power)*

	Plant Unit 1	Plant Unit 2	Plant Unit 3	Plant Unit 4	Plant Unit 5	Plant Unit 6
Electrical Output (MWe)	460	784	784	784	784	1,100
Reactor Type	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Commissioning Date	March 1971	July 1974	March 1976	October 1978	April 1978	October 1979
Number of fuel assemblies in core	400	548	548	0	548	764
Reactor state before the accident	100% PN*	100% PN*	100% PN*	unloaded core	shutdown	shutdown
Fuel type	UO2	UO2	UO2 and 32 MOX	UO2	UO2	UO2

Reactors 1, 2 and 3 were operating at full power at the time of the earthquake. Reactor 4 had a scheduled outage that started on November 30, 2010. The core was completely unloaded and assemblies are stored in the SFP.
Reactors 5 and 6 also had scheduled refueling outages which began respectively on January 3, 2011 and August 14, 2010. Fuel assemblies were loaded in the cores.

5.1. ACCIDENT SEQUENCE, MARCH 11-25, 2011

Note: The following information was taken from reports published by the IAEA and Japanese organizations analyzing the accident. Uncertainties remain about the precise accident sequence. Damage to the installations and core states due to the earthquake is poorly known since the radioactive environment renders certain areas of the reactor buildings inaccessible. The following information may be revised and should be considered preliminary.

The earthquake that occurred at 2:46 pm JST[5] on March 11 caused a LOOP at the Fukushima Dai-ichi site. Following the earthquake, reactors 1, 2 and 3 were shut down automatically by inserting control rods in the core to stop the chain reaction. Residual heat removal systems started up (two per reactor). EDGs supplied electrical power. While the earthquake does not appear to have directly called into question the operational character of safety functions, damage to facilities and effects of any damage on the accident sequence are not accurately known at present.

[5] Japan Standard Time

Less than an hour after the quake, facilities at the site were flooded by a series of waves. The most devastating, with a height of 14-15 meters above sea level, was recorded at 3:42 pm JST.

The seawall at the site was submerged. The pumping stations for the six reactors were severely damaged and the cooling pumps, which were not protected from flooding, were under water, so that the reactors and the SFP no longer had a source for cooling. Water then penetrated the buildings of the nuclear islands, causing the loss of all or part of the EDGs and electrical switchboards that supply power to reactor safety systems and SFPs. With the exception of reactor 6, all of the reactors at the site experienced total loss of the emergency power supply system and loss of ultimate heat sink (LUHS).

The air-cooled EDG of reactor 6 alternately supplied power to reactors 5 and 6 to cool cores and SFPs.

Only the batteries of reactor 3 remained operational after the tsunami. The control rooms of reactor 1 and 2 thus had no lighting. Power supply to the control room of reactor 2 was not restored until March 22.

Battery loss also led to losing valuable data on the state of the facility, including the operation state of certain systems and parameters for monitoring facility state (RPV water level and reactor containment pressure). Data was obtained periodically using small generators.

Lastly, loss of electrical supply led to loss of communications resources included in the on-site emergency plan for updating emergency response teams. All of these aspects greatly disrupted accident management.

In reactor 3, the control room and part of instrumentation and control remained operational.

Figure 5-2 - Area inundated after the tsunami

5.1.1. REACTOR 1 ACCIDENT SEQUENCE

In the event of total loss of the emergency power supply system, reactor 1 has two cooling means to remove residual heat from the core after the nuclear reaction has stopped:

- a heat exchanger or isolation condenser (IC) that condenses steam that forms in the RPV from evaporation - removal of residual heat from the core - and using gravity to re-inject water in the RPV. It is an air-cooled heat exchanger. There are two redundant trains, i.e., two heat exchangers (cf. section 2.3). The pipes connected to the vessel are equipped with battery-operated isolation valves;
- a high pressure core-injection system (HPCI) injects water into the vessel from the condensate storage tank or the suppression pool using a turbine-operated pump run by steam produced in the vessel.

Following emergency shutdown of the reactor and closure of the isolation valves of the steam pipes, the IC system started up automatically shortly after the quake at 2:52 pm JST. In order to observe the cooldown gradient required by the operating procedures, i.e. 55°C/hour, the operators manually shut down the system at 3:03 pm on March 11. Then, from 3:10 to 3:30 pm, the operators operated the train 1 isolation valves on the IC system to control pressure and regulate water level in the RPV.

At the time of the tsunamis, valves on both IC trains were closed (trains A and B). Loss of electrical power prevented confirming operation state of the system.
The operators noticed the valves were in open position after 6 pm on March 11 after the power supply was restored. At 6:18 pm, the IC isolation valve reopened before closing again at 6:25. It opened again at 9:30 pm. The assessments show that at that time, the core was severely degraded; the system was not able to operate correctly, due either to the configuration of the isolation valve or the presence of hydrogen that blocked exchange. This issue remains to be confirmed.

At 5:12 pm on March 11, due to doubts surrounding IC operation and the lack of information about the water level in the RPV, TEPCO began to consider alternative sources of water supply. Use of a pump from the fire protection system connected to the spray nozzle assembly and taking water from an underground tank was considered. Assembling these resources on the site, given the damage caused by the earthquake and the tsunami, took time.

Without cooling, water in the RPV heated upon contact with the hot fuel assemblies and evaporated. Residual heat to be removed exceeded some ten MW when cooling was lost. Steam produced led to an increase in pressure in the RPV and the opening of relief valves of the main cooling system (RPV) in the wetwell.

Without any means to remove heat transferred to the suppression pool, the temperature of the water in the wetwell reached the boiling point. Pressure in the reactor containment then increased, causing it to exceed its design basis (4-5 bars), necessitating repeated implementation of a procedure of containment venting to avoid rupture. A pressure of 6 bars was measured in the containment of reactor 1 at 23:50 pm on March 11. Operations to prepare venting of the reactor containment were accelerated.

Confirmation of the evacuation of the village of Okuma was expected prior to venting. Evacuation was completed at 9:03 am on March 12. Operations to open the valves and relieve pressure in the reactor containment started at 9:15 am. The operators encountered a number of difficulties in opening the valves to align the venting system. The containment was not opened until 2:00 pm.
Considering the time required before venting could take place, it is possible that leaks formed in the reactor vessel head from the pressure, which may explain the presence of hydrogen in the superstructure of the reactor building.

After water in the RPV evaporated, the water level gradually diminished until the level no longer ensured removal of residual heat and cooling of fuel assemblies. This level was reached some two hours after the tsunami.

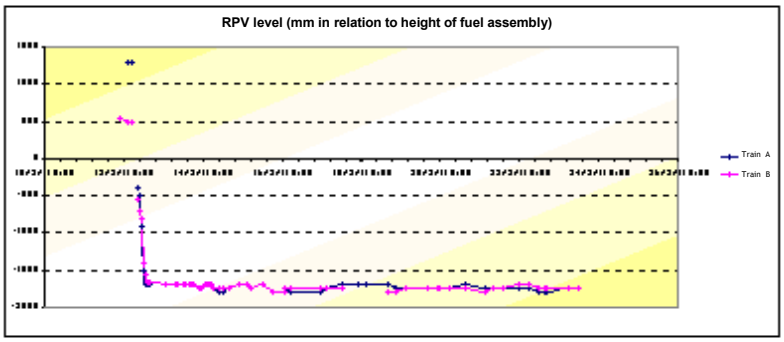


Figure 5-3- Change in water level in the pressure vessel of reactor 1 (from measurements available during the accident)

The melting point of fuel is approximately 2,800°C while zirconium cladding deteriorates around 800°C and ruptures around 1,200°C. The oxidation reaction between the zirconium cladding and water produces significant quantities of zirconium oxide and hydrogen, which mixes with steam and accumulates in the upper part of the main cooling system and the reactor containment. The higher the temperature, the faster the $Zr+H_2O$ reaction, which accelerates significantly above 1,200°C. It is an extremely exothermic reaction.

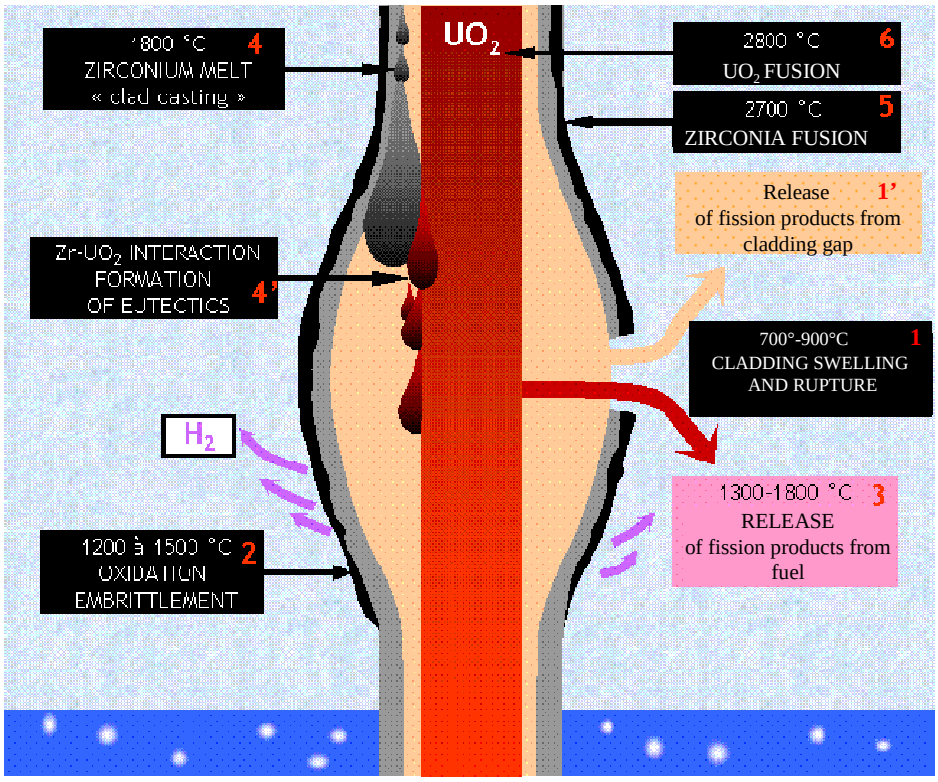


Figure 5-4 – fuel assembly behavior in severe accident conditions

Presumed leaks in the reactor vessel head and operations to release the pressure in the containment while core degradation had already begun caused very significant releases into the environment and the release of a significant quantity of hydrogen resulted in an extremely violent hydrogen explosion in the upper part of the reactor building over the SFP. The explosion destroyed the upper part of the building.

It should be stressed that the operations to relieve the pressure in the containment involved opening valves located in the wetwell, which significantly limited releases since radioactive aerosols remained in the water (radioactive aerosols were retained by a factor of approximately 1,000).

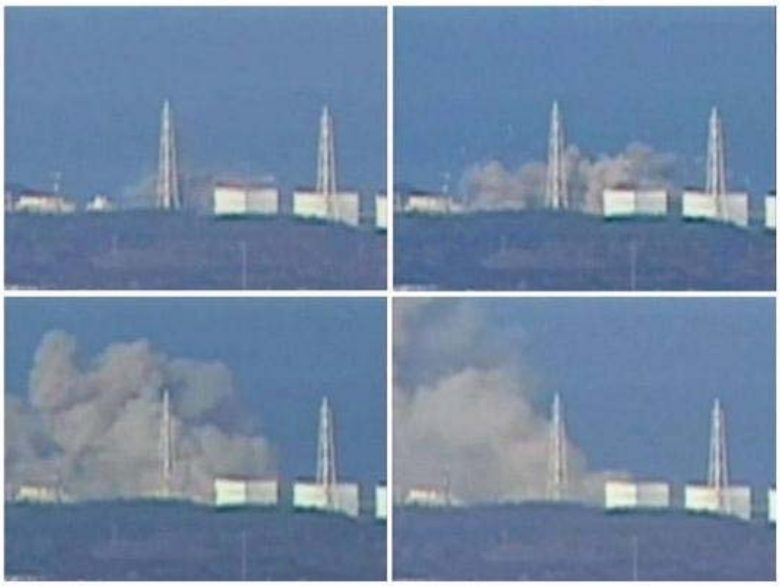


Figure 5-5 – 3:36 pm on March 12: Explosion in reactor building 1

Figure 5-6 – Schematic diagram of the explosion in reactor building 1

At 5:46 am on March 12, despite increasingly difficult radiological conditions, the operator was able to intermittently inject fresh water from available reserves and, beginning at 7:04 pm, borated sea water to cool the core using fire extinguishing pumps (pump discharge pressure on the order of 4-5 bars), which stabilized the situation.
Beginning on March 25, fresh water from naval barges was injected.
Overall, injection of water into the RPV was interrupted for approximately fourteen hours. Under these conditions, complete core meltdown, ex-vessel progression and the interaction between corium and the concrete of the reactor building are highly probable.

5.1.2. REACTOR 2 ACCIDENT SEQUENCE

In the event of total loss of the emergency power supply system, reactors 2 and 3 are also equipped with two cooling resources for injecting water in the RPV after shutdown of the nuclear reaction: Reactor Core Isolation Cooling (RCIC) system and the High Pressure Coolant Injection system (HPCI). The systems rely on turbine-driven pumps using steam from the RPV. They are equipped with isolation valves that run on emergency batteries.
After the earthquake, operators in plant unit 2 started the RCIC system manually at 2:50 pm on March 11. It stopped automatically several times due to the high level of water in the RPV and was restarted by the operators.

The injected water was initially taken from the condensate storage tank, and when it was empty, from the wetwell. The steam that is used to run the turbine pump then condensed in the wetwell. Since the cooling resources of the wetwell water were unavailable, the water heated and inevitably caused the system to shut down.
It should however be noted that the RCIC ensured heat removal from the core for approximately three days until 1:25 pm on March 14, a significant delay compared with the assumptions usually adopted for design studies, which are on the order of several hours.
Prepared for the loss of RCIC, TEPCO planned an alternative water supply. Firefighting equipment was readied to inject water if RCIC shut down. At 11:01 am on March 14, the explosion in reactor building 3 destroyed the firefighting pumps and pipes which had been prepared.

Following loss of RCIC and lacking a substitute resource (HPCI was unavailable and emergency firefighting equipment was destroyed in the explosion), the water level in the RPV decreased to the level where it was no longer possible to remove residual heat from the assemblies. Core meltdown of reactor 2 took place on March 14, generating, as for reactor 1, the release of a significant quantity of hydrogen fission products in the RPV and the reactor containment.

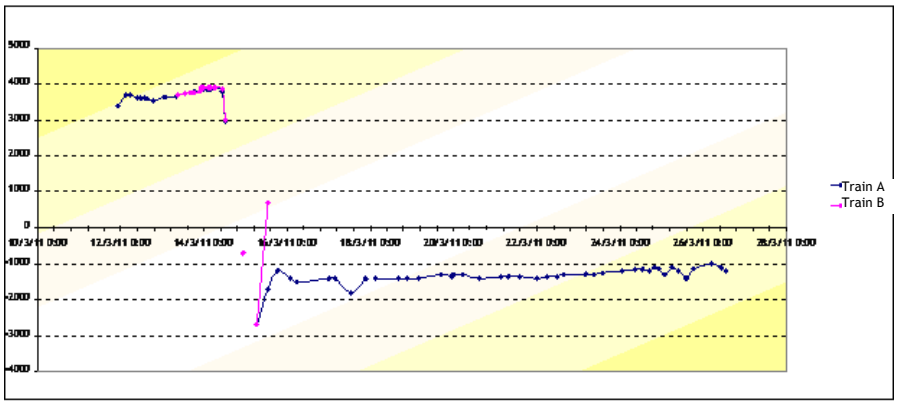


Figure 5-7 – Change in water level in RPV of reactor 2

TEPCO then began injecting seawater into the RPV. The injection requires that pressure be reduced in the reactor coolant system. The operation was made very difficult by the loss of the emergency power supply system, conditions at the site and aftershocks which interrupted work. Seven hours and twenty-four minutes passed without water being injected. At 7:54 pm on March 14, seawater was injected in the RPV using mobile emergency equipment. The injection stabilized the situation.

At the same time, as with the other reactors, the issue of venting the reactor containment arose. The operators prepared for venting operations by opening necessary valves. Nevertheless, containment pressure at this time was not sufficient for the rupture disk (see Figure 2-8) in the system to burst. As a result, the isolation valve in the venting system closed. After the explosion in reaction 3, the valve could not be reopened.
At 6:10 am on March 15, a significant increase in pressure occurred in the drywell. Efforts to vent the drywell were unsuccessful.

Since efforts to open discharge valves located in the drywell and wetwell failed, a rupture took place in the annular torus.
It is thought that a hydrogen explosion occurred following contact with air. As a result, highly contaminated water in the torus entered the reactor building.

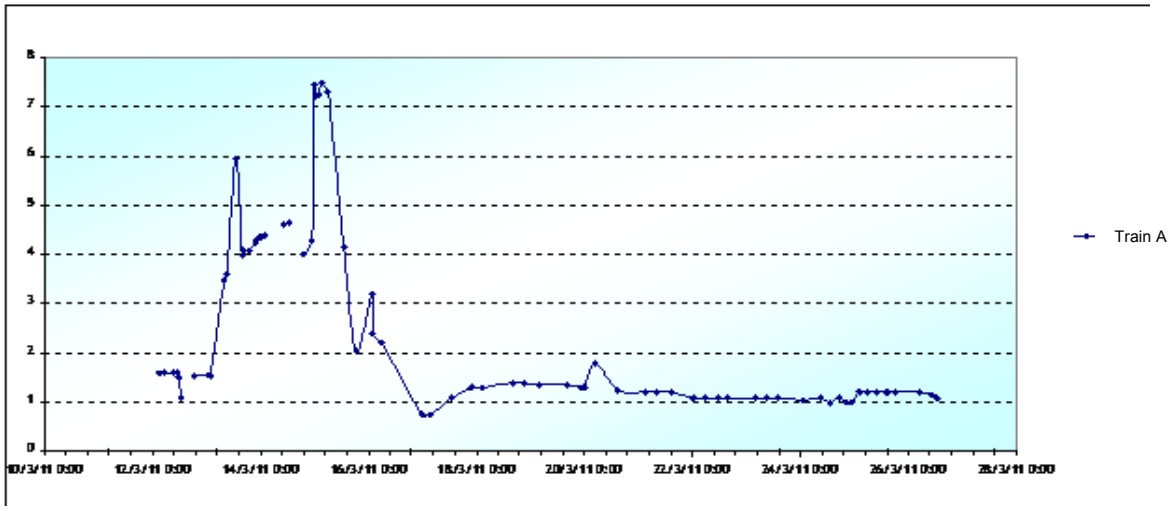


Figure 5-8 – Pressure change in the containment of reactor 2

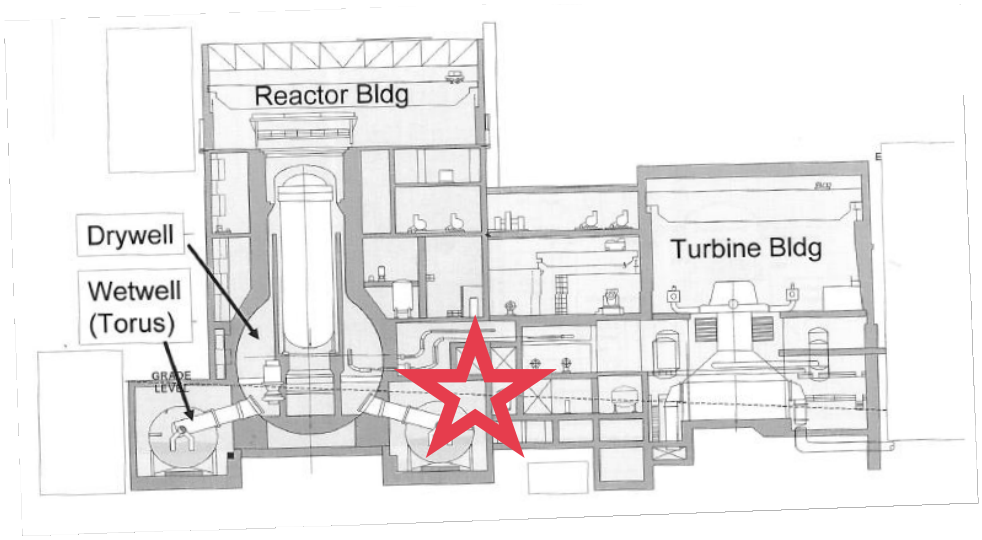


Figure 5-9 - Explosion in the lower part of reactor building 2 – 6:10 am, March 15

A connection to an outside source of electrical power was not re-established until March 22, 11 days after the start of the accident (restoring lighting to the control rooms). Previous efforts to establish an electrical supply, particularly for safeguard systems, had all failed due to the flooding of certain switchboards and short cuts on the switchboards.
Beginning March 25, clear water was injected into the RPV to replace the seawater.

5.1.3. REACTOR 3 ACCIDENT SEQUENCE

Reactor 3 is identical to reactor 2 (BWR/4 model). It is also equipped with RCIC and HPCI systems.
After the earthquake RCIC was started manually at 3:05 pm on March 11 as a preventive measure. At 3:25 pm, it was shut down since the water level in the RPV was too high.
At 3:38 pm, the two EDGs and the electrical switchboards became unavailable after the tsunami. In contrast, the batteries remained available, making it possible to regulate valves in these two systems from the control room and control RPV water pressure and level.
The RCIC started up again at 4:03 pm on March 11 and shut down at 11:36 am on March 12. At 12:35 pm, the high pressure core injection (HPCI) system started up automatically with a low level of water in the RPV. In preparation

for the batteries losing power, TEPCO planned alternative resources for injection. It required using emergency firefighting resources from reactors 5 and 6 as well as the Dai-ini nuclear power plant. Transport of this equipment to reactors 1-4 was difficult[6]. At 2:42 am on March 13, the HPCI system failed.
The water level in the RPV decreased, causing core meltdown.

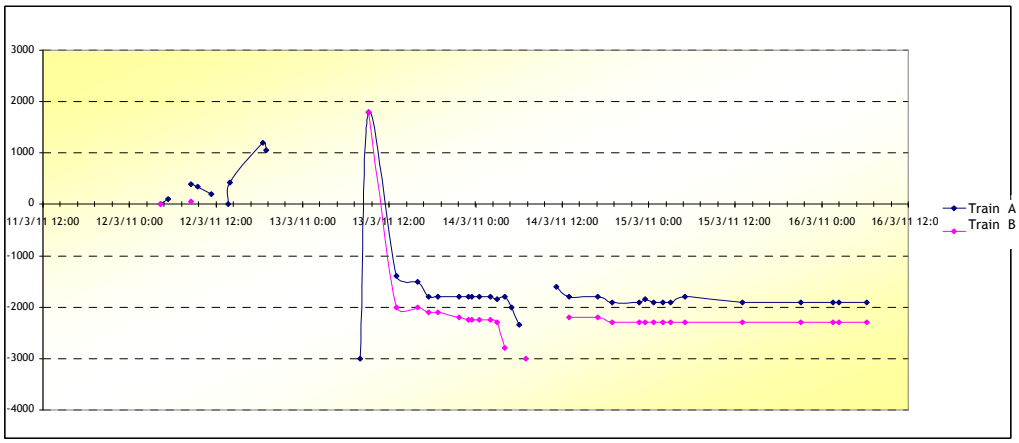


Figure 5-10 – Change in water level in RPV of reactor 2

Use of firefighting equipment required reducing the pressure in the RPV, which took time. The batteries lost power so that the RPV discharge valves could no longer be controlled. Batteries from the cars of TEPCO's employees were then collected and installed in the control room to supply the safety relief valves (SRVs).
The valves open at 9:08 am on March 13 so that pressure could be reduced in the RPV. Nearly seven hours after the loss of the HPCI, at 9:25 am on March 13, fresh water was injected. The water level in the RPV continued to decrease. At 12:20 pm, with the reserve of fresh water depleted, the decision was made to inject seawater. The task of switching the water intake was disrupted by aftershocks which forced workers to seek shelter in a protected area. At 1:12 pm on March 13, seawater was injected into the RPV and the situation stabilized.

The operations to reduce pressure in the reactor containment, necessary in the absence of a heat sink for the containment, started at 8:41 am on March 13. TEPCO made significant efforts to open the valves to implement the procedure. A new operation to vent the containment was needed at 5:20 am on March 14.
The explosion, which occurred in reactor building 3 at 11:01 am on March 14, had a consequential impact on the structure of the reactor building. Debris was scattered around the building, damaging water injection systems for reactors 2 and 3. At 4:30 pm on March 14, injections of seawater recommenced.

[6] For example, the road connecting reactors 1-4 and reactors 5-6 was no longer fit for use after the tsunami. Roadclearing and safety work was necessary before transporting the equipment.

Figure 5-11 – 11:01 am on March 14: explosion in reactor building 3

5.1.4. SPENT FUEL POOLS

The total loss of the emergency power supply system and heat sink that affected reactors 1-4 also affected the spent fuel pools (SFPs). Since cooling resources were not restored quickly, water temperature in the SFPs, on the order of 20-25°C before the accident, increased with a kinetics that depended on residual heat and thus on the number and age of the stored fuel assemblies.

Table 5-II gives an inventory of SFPs and an estimate of the residual power to be removed at the time of the accident.

	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5	Reactor 6
Number of fuel assemblies in SFPs	392 (including 100 new assemblies)	615 (including 28 new assemblies)	566 (including 52 new assemblies)	1,531 (including 783 spent, 548 recently unload and 20 new)	994 (including 48 new assemblies)	940 (including 64 new assemblies)
Residual heat in the SFPs[7]	0.18 Mw	0.58 Mw	0.51 Mw	2.39 Mw	1.07 Mw	0.86 Mw

Table 5-II – Inventory of SFPs at the time of the accident

The SFP with the largest inventory is that belonging to reactor 4, which had the equivalent of three cores, including one recently unloaded from the reactor (reactor 4 had a maintenance outage beginning on November 30, 2010). IRSN estimated the residual heat of the fuel stored in the pool to be 2.4 thermal MWs. TEPCO confirmed that the residual heat of the stored assemblies was 2.26 MW on March 11.

At the time of the accident, a gate separated the reactor cavity, which held a significant volume of water, and the SFP. It is quite possible that due to the gradual draining of the SFP, the water was transferred from the reactor cavity by partial elimination of the gate. TEPCO is now considering this hypothesis, which was put forward by IRSN's experts during the accident. This would explain the lack of dewatering of the assemblies stored in SFP 4.

There was thus a delay of several days before the start of dewatering of the assemblies in the storage racks (after March 18), as long as the pool and connected pipes remained intact. On March 15, several fires or hydrogen explosions took place in reactor building 4, causing extensive damage. Several hypotheses have been presented regarding the causes of these fires or explosions.

On November 8, TEPCO inspected reactor building 4 using remote-controlled robots (cf. Figure 5-12). This inspection confirmed the hypothesis that the explosion in the building was related to hydrogen that originated with a ventilation duct from reactor building 3.

[7] IRSN estimate of March 21 based on cooling time for various assemblies.

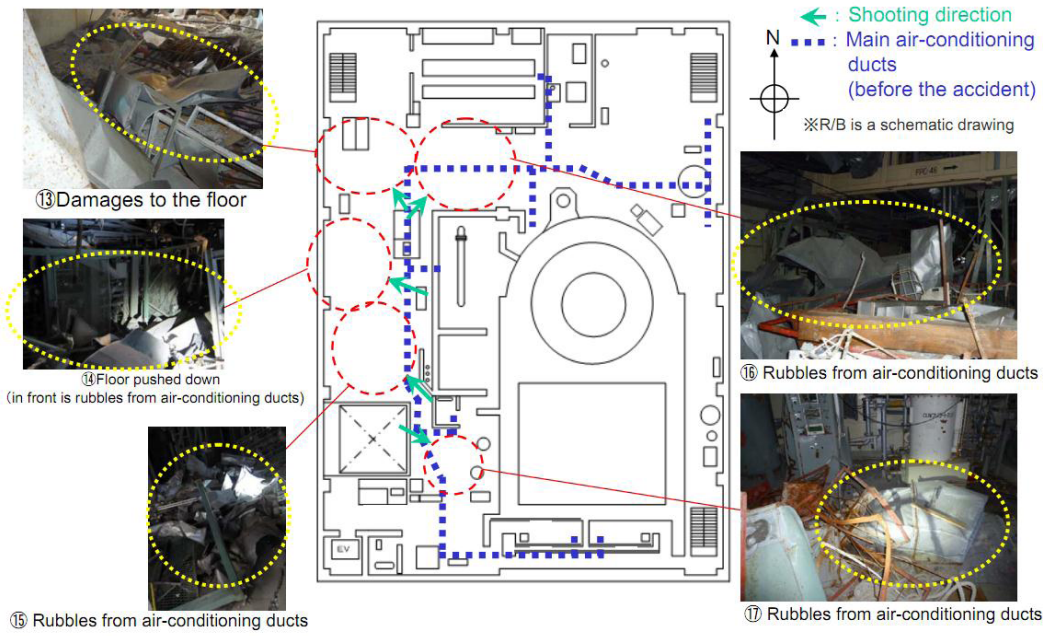


Figure 5-12 - Visual inspection using remote-controlled robots in reactor building 4 (2nd floor)

Gas treatment system pipes leading to the ventilation stack for reactors 3 and 4 have a common section through which part of the hydrogen produced during the degradation of core 3 passed on March 14. Released in significant quantities during operations to relieve the pressure in the reactor containment, it could have been transferred to reactor building 4 (cf. Figure 5-13).

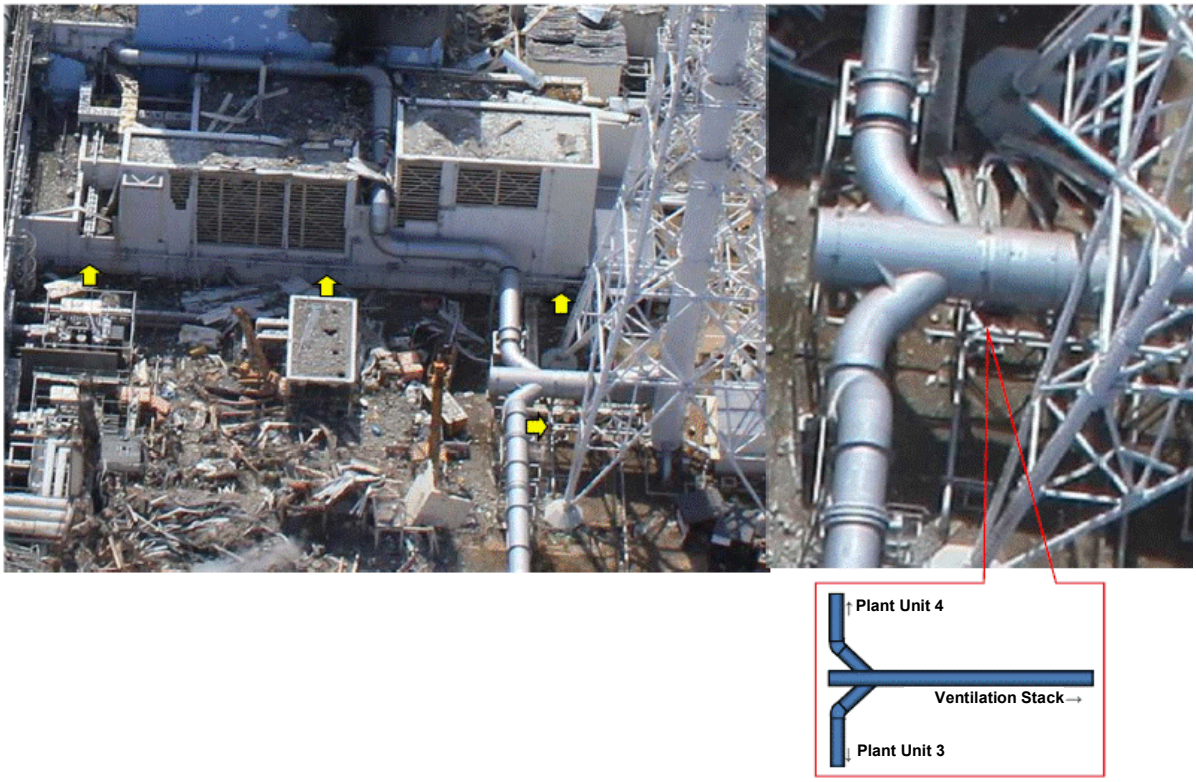


Figure 5-13 – Gas treatment system of reactors 3 and 4

It also appears that there was no significant degradation of fuel assemblies in this pool (films of the pool interior, measurement of water radioactivity).

Figure 5-14 - Spent fuel storage racks in pool 4 after the accident (source: TEPCO)

Water temperature in the other SFPs also increased, sometimes to the boiling point. In all cases, makeup to the pools was restored before stored assemblies were dewatered. Makeups to SFP 3 began on March 17 with drops from a helicopter, then with a fire truck (using a pump normally used to inject concrete). Makeups to SFP 2 began on March 20. Daily makeups were later necessary to compensate for the loss of water from vaporization (reactors 1-4).

The first significant makeups to SFP 4 were carried out using fire hose nozzles starting on March 20, then, on March 22, by a truck with a concrete pump for injecting water using an articulated arm.

The most notable point is without a doubt the impact of hydrogen explosion on the SFPs. Overall, it appears that the pools resisted the hydrogen explosions but a significant loss of leaktightness in the pools and dewatering of the fuel assemblies may have occurred, seriously aggravating the situation in terms of radiological conditions at the site and releases into the atmosphere. Figure 5-15 shows the extent of the destruction to reactor 4.

The water temperature of the shared pool also increased gradually following loss of cooling resources. It was however possible to inject water and to start up the cooling system before boiling occurred. Available time was quite significant.

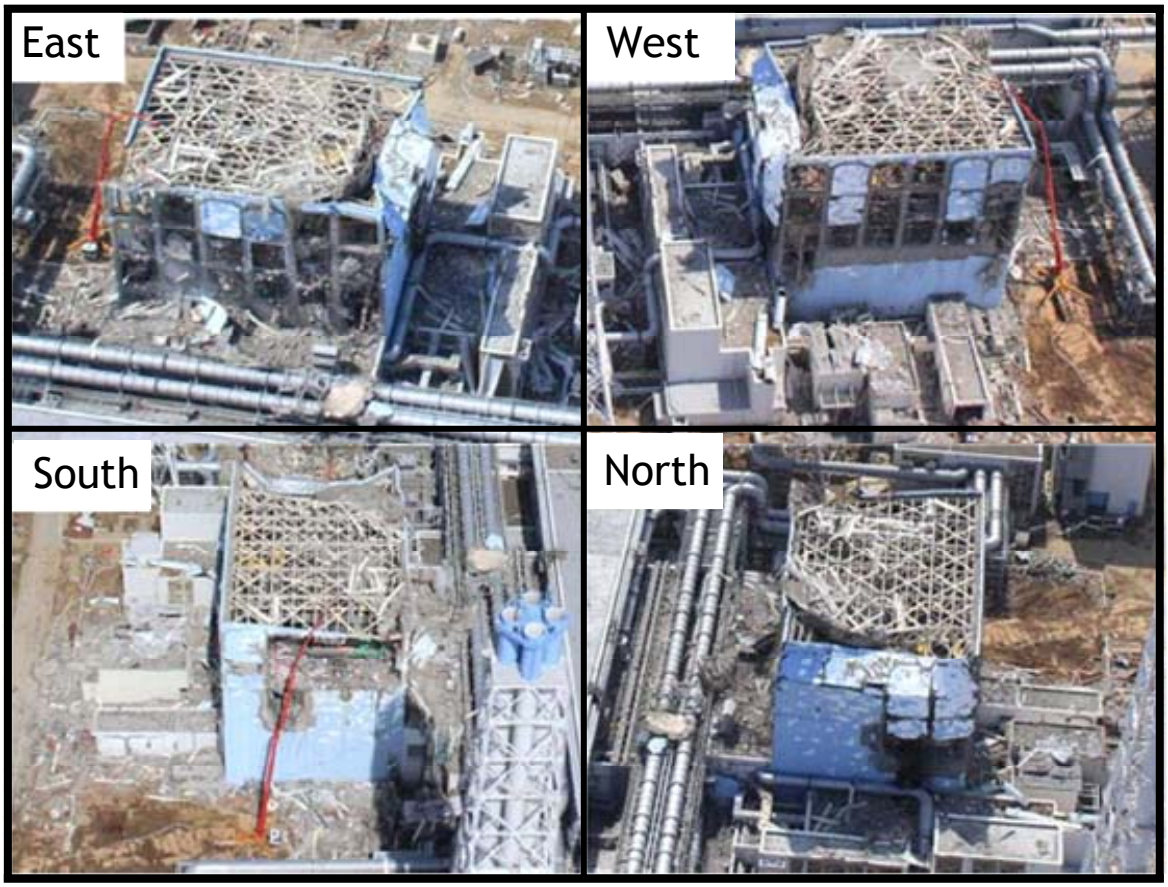


Figure 5-15 – Reactor building 4 after fires and explosion on March 15

5.1.5. ATMOSPHERIC RELEASES

During the fuel degradation process, hydrogen production from cladding oxidation is concomitant with the release of the most volatile core products. Operations to reduce pressure in the containments or supposed leaks in reactor vessel heads that took place after core degradation thus resulted in significant releases into the environment, not only of noble gases and gaseous iodine, but of radioactive products in the form of aerosols such as cesium 137. A significant share of the aerosols was however trapped in the water in the wetwells in reactors 1 and 3.

Atmospheric releases were produced initially in the form of puffs that could be identified by changes in dose measurements at site monitoring posts.

Figure 5-16 gives dose rate measurements at monitoring posts. Correspondence between dose rate peaks and operations to reduce pressure in containments was confirmed.

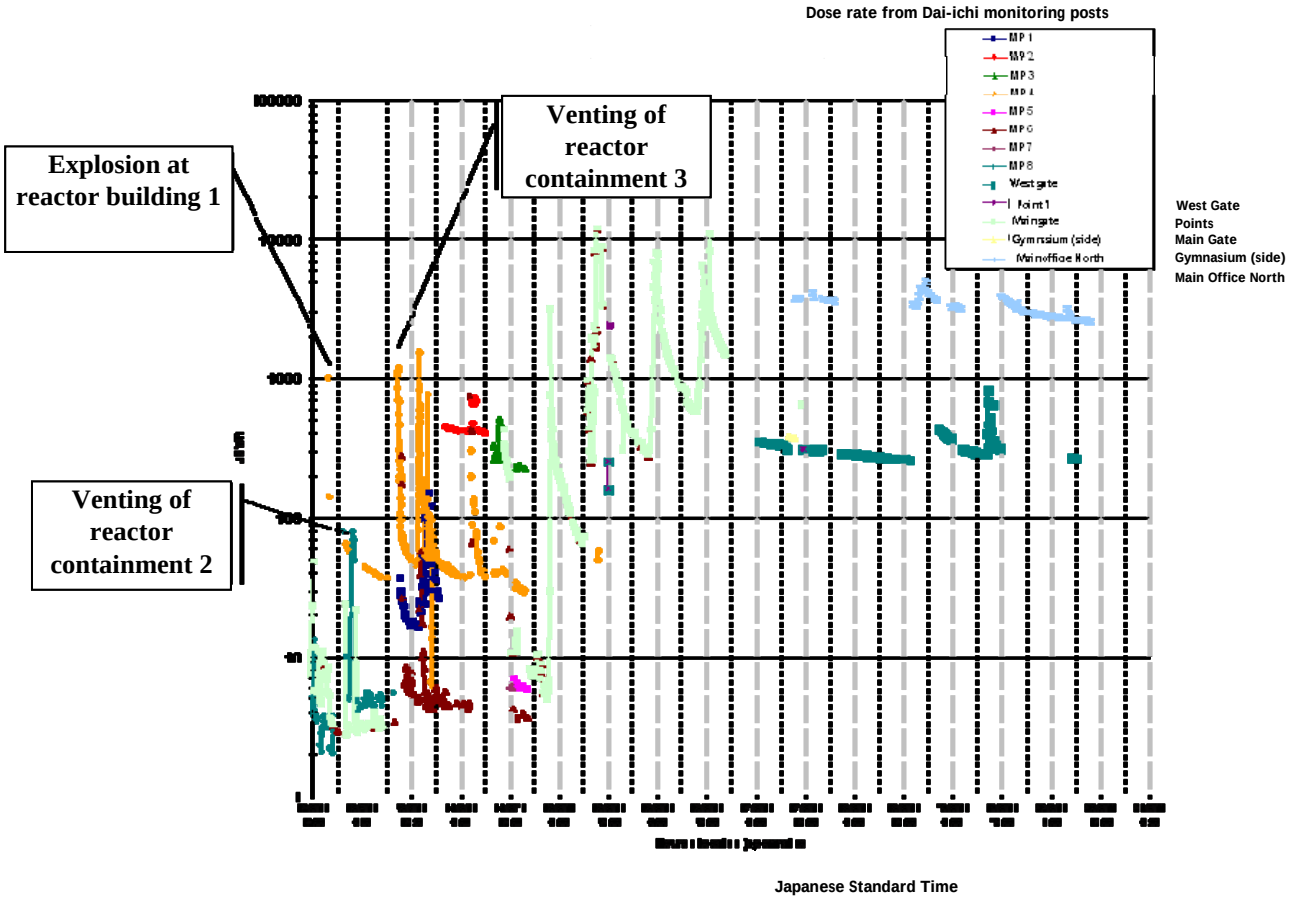


Figure 5-16 – Dose rate measurements in µSv/h at site monitoring posts

Monitoring post locations are given in the following figure.

Figure 5-17 Location of fixed and temporary monitoring posts at the Fukushima Dai-ichi site

IRSN's assessment of releases from the start of the accident were confirmed by estimates published in June by the Nuclear and Industrial Safety Agency (NISA). This point is described and discussed in section 6.1.

5.2. ACCIDENT SEQUENCE: MARCH 25-APRIL 17, 2011

On March 25, TEPCO announced that contaminated water had accumulated in the basements of the turbine buildings at depths varying from 40 cm to 1 meter. The water, which had most likely been in the basements since the tsunami, had been contaminated by water from the containment vessels when they lost their structural integrity during the accident. The highly contaminated water measured in the turbine building of reactor 2 most probably came from the wetwell that was damaged by the March 15 explosion. It is worth noting that this contamination demonstrates the effectiveness of the wetwells to retain air releases.
With the loss of the structural integrity of the containment vessels of reactors 1, 2 and 3, the contaminated water spread first to the reactor buildings, flooded the turbine buildings and ultimately flowed into the cabling trenches (see Figure 5-18).

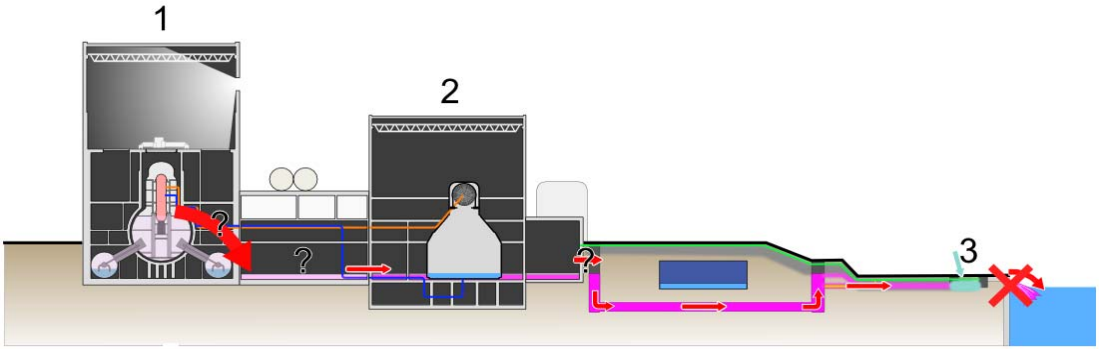


Figure 5-18 - Path of the water leaks

Managing effluent and the releases of radioactive water became a top priority in remediating the crippled site. TEPCO was forced to "intentionally" dump effluent (mildly contaminated water) in order to free up the storage tanks. Very highly contaminated water also leaked into the sea over a few days in late March. IRSN estimated that a total of 27 10^{15} Bq of cesium-137 was released into the sea up to mid-July (see section 6.4.3 of this report), with most being released before April 8 as planned. The releases estimated after this date make up only 18% of the total amount released.

5.3. FROM APRIL 17, 2011, ONWARD

5.3.1. GRADUAL REGAINING OF CONTROL OF THE FACILITIES

On April 17 TEPCO issued a two-phase, short-term plan to bring the Fukushima Dai-ichi plant back under control. The first phase had three goals: reduce the amount of radiation that was still being released (albeit at much lower levels than at the start of the accident); maintain and enhance cooling of the reactors and pools; and provide additional containers to store contaminated water. The first phase, which was estimated to last for 3 months, was completed by TEPCO on July 19.
A system to pump, decontaminate and desalinate the water in the turbine buildings was started up in June. Decontamination plants were built on site in record time with the assistance of foreign companies, including French firms Veolia and Areva. The decontaminated water was stored in tanks installed for such purpose and fed back into the vessels (see Figure 5-19).

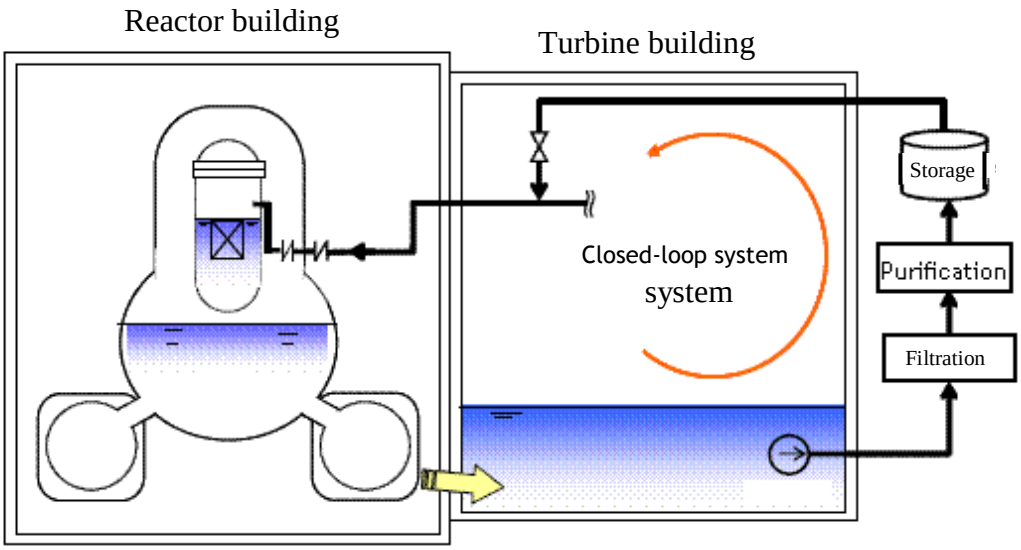


Figure 5-19 - Schematic diagram of treatment of the contaminated water

The second phase, scheduled to last for 3-6 months, had three goals: make the buildings secure in order to bring the radioactive releases under control; maintain stable cooling of the reactors (i.e. ensure that the water flowing in the core remains below 100°C so as to prevent the generation of steam); and reduce the amount of contaminated water on the site. Six months after the accident, the target of maintaining the vessels at below 100°C was met.

TEPCO's roadmap also called for covering reactor buildings 1, 3 and 4 in order to limit further radioactive releases into the atmosphere and raised the possibility of building an underground barrier to reduce the amount of contaminated water flowing into the ocean through the soil and groundwater.

Lastly, major efforts have been undertaken to improve work conditions on the site, which remain very difficult. Very high dose rates have been measured at various points on the site.

5.3.2. THE MID- AND LONG-TERM ROADMAP

A document titled *Mid- and Long-term Roadmap on Decommissioning of Fukushima Dai-ichi Nuclear Power Plant* was adopted on January 23, 2012. Divided into three phases, the roadmap for the decommissioning of reactors 1-4 will be implemented once the plant has been brought back under control:

- The main goal of Phase 1 is the removal of the fuel assemblies from the SFPs. TEPCO estimates that this phase will start within the next 2 years;
- The main goal of Phase 2 is the removal of the molten fuel from the cores of the reactors. The aim is to begin this phase within 10 years. The vessels will also be reinforced during this period;
- In Phase 3, the plant will be decommissioned over a period of 30-40 years.

5.4. REMEDIATION MEASURES

5.4.1. DAMAGE SUFFERED BY THE CORES OF REACTORS 1, 2 AND 3

TEPCO published the results of simulations of the accident performed using a thermal-hydraulic transient computer code that also made it possible to simulate the progression of the accident after the core meltdown. It confirmed that reactor 1 had suffered a complete meltdown and that its vessel has been breached. According to the analysis, the entire mass of corium dropped to the bottom of the reactor containment vessel and came into contact with the concrete of the foundation basemat, initiating a corium-concrete interaction. Although the corium ate away a 70 cm-deep hole into the basemat, TEPCO states that it would have had to melt through more than 1 m more of concrete before reaching the metal wall of the containment vessel. For TEPCO, the injection of water is enough to cool the corium.

IRSN considers that these results should be interpreted with precaution as a number of assumptions, including the mass of corium that dropped onto the basemat and how it ate through the basemat (radial or axial erosion), can have a very significant influence on them. In particular, the raft could be eroded more extensively than announced by TEPCO.

As for reactors 2 and 3, TEPCO considers that their cores also sustained heavy damage but that only a small amount of corium dropped onto the basemat, eating through a depth of just around 20 cm.

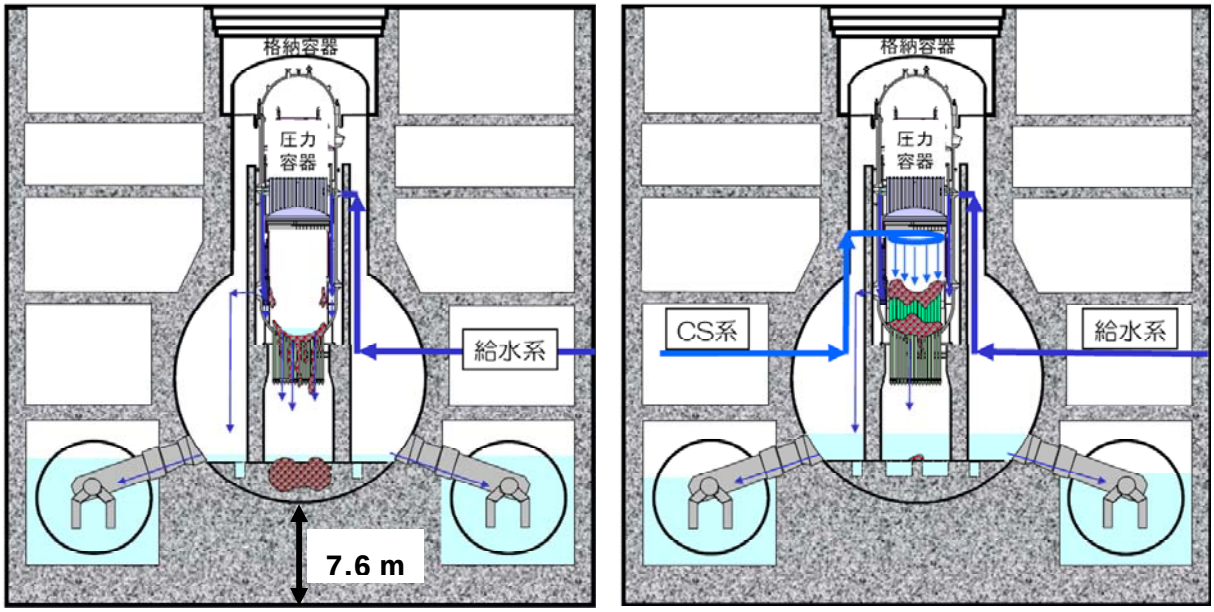


Figure 5-20 - Diagram illustrating the condition of the cores of reactors 1, 2 and 3 according to the analysis

Freshwater is continuing to be fed into the cores. As a result, the water temperature in the RPVs and PCVs of the three reactors remains below 100°C.

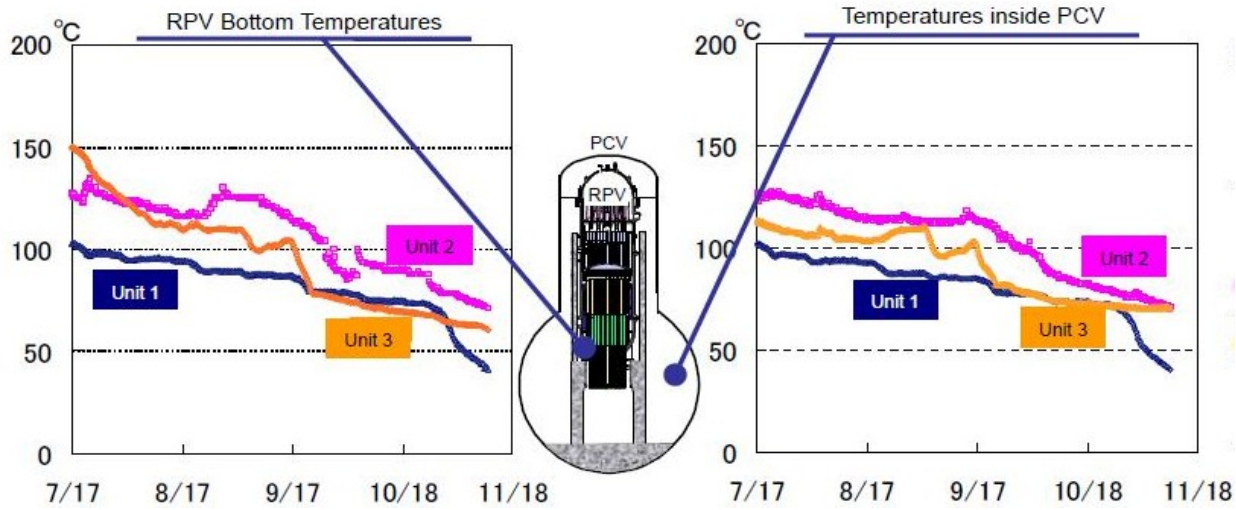


Figure 5-21 - Evolution of the temperatures in the RPVs and PCVs of reactors 1, 2 and 3 (measurements)

Nitrogen gas is continuing to be injected into the PCVs of all three reactors to prevent the risk of hydrogen combustion (hydrogen is produced in large quantities during a corium-concrete interaction and, in lower quantities, water radiolysis).

5.4.2. STATUS OF THE SFPS

Operations to desalinate the water in the SFP of reactor 4 in order to mitigate the risks of corrosion were started on August 20, 2011, and have proven their effectiveness. Operations to desalinate the water in the SFPs of reactors 2 and 3 are underway.
The water temperature in the pools is being maintained at between 20°C and 30°C.

5.4.3. CONTAINMENT OF THE FACILITIES

Work on covering the reactor 1 building ended on October 28, 2011 (see Figure 5-22). The buildings of reactors 3 and 4 are scheduled to also be covered. The purpose of these covers is to limit, filter and measure radioactive releases into the atmosphere and protect the buildings from the elements (flooding of the basements and trenches by heavy rain).

Figure 5-22 - Construction of the cover around the reactor 1 building

A system to control the pressure in the containment built to mitigate radioactive releases, as well as an air sampling system, have been or will be installed in reactors 1, 2 and 3.

5.4.4. PROTECTION OF THE FACILITIES FROM FUTURE EARTHQUAKES AND TSUNAMIS

Measures have been taken to reinforce the SFP of reactor 4. The earthquake resistance of the reactors' pools has been checked and the anti-tsunami seawall was raised first opposite reactors 1 to 4 and then reactors 5 and 6.

Figure 5-23 - Protection of the facilities from tsunami risks

5.4.5. CURRENT RADIOACTIVE RELEASES

Radioactive materials are still being released into the atmosphere, but at levels incommensurate with those from mid-March 2011.

Contaminated water is continuing to be treated in order to mitigate the risks of radiation being released into the ocean. The sludge storage tanks are filled to 75% capacity. TEPCO plans to concentrate the sludge more in order to reduce its volume. In other respects, seepage related to rain and the leaks from the containment vessels have made it impossible to dry out the site's buildings.

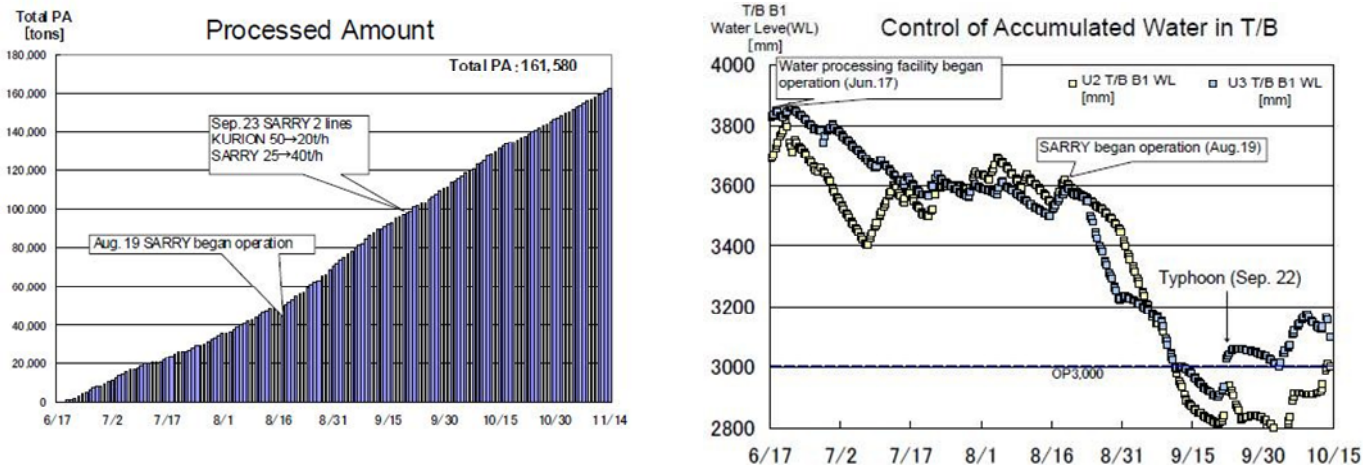


Figure 5-24 - Volumes of contaminated water treated since June 17, 2011

In addition to the measures taken to mitigate and control radioactive releases into the atmosphere and limit the amount of contaminated water on the site, on October 28, 2011, TEPCO began building a wall to limit the amount of radioactive water reaching the ocean through permeable layers of soil around the site (see Figure 5-25).

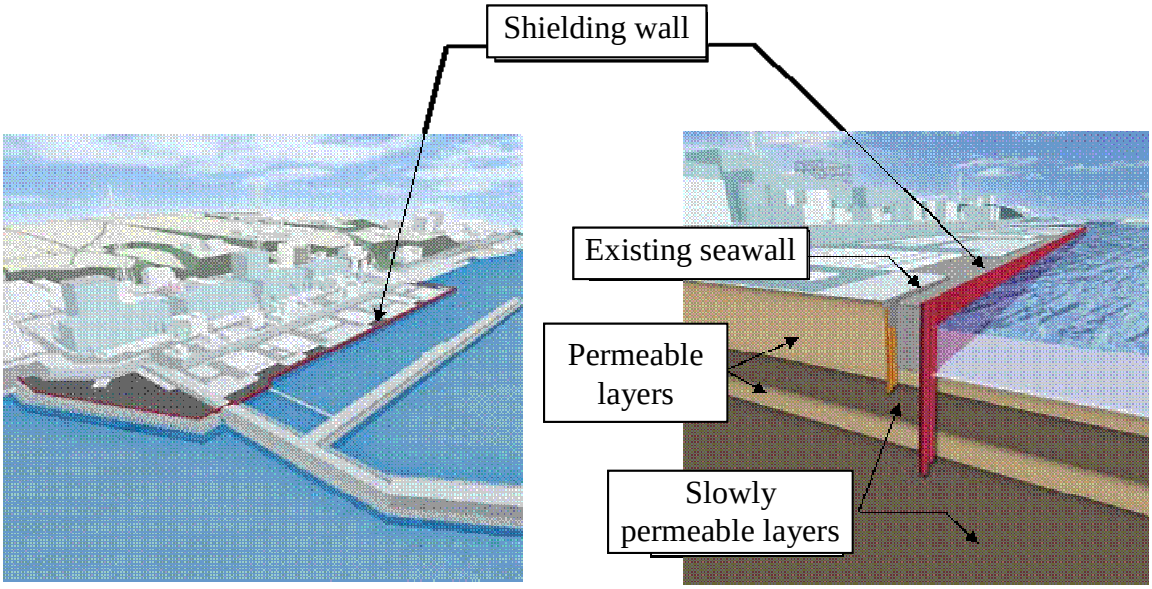


Figure 5-25 - Wall designed to limit releases of radioactive water

TEPCO has made very substantial efforts to regain control of the site, employing between 2,000 and 3,000 people since July 2011. Work to clear away debris, particularly with the use of remote-controlled heavy equipment, is continuing. The ambient dose rate outside the site's buildings remains low due to regular spraying of a polymer resin on the ground and structures. These agents also prevent the radioactive materials from being dispersed by the wind and rain.

6. ENVIRONMENTAL IMPACT IN JAPAN

The accident that occurred at the Fukushima Dai-ichi plant on March 11 and the following days resulted in the release of radioactive substances:

- into the atmosphere, in the form of radioactive gases or very fine radioactive particles dispersed into the air (aerosols), of which a portion settled on the surfaces of the soil in Japan, forming residual radioactive fallout;
- into the marine environment, directly in the form of water releases into the sea and indirectly due to fallout on the sea's surface from radioactive aerosols dispersed over the ocean.

Figure 6-1 shows maps of the northern portion of Honshu island and Fukushima prefecture to help you to locate the places mentioned in this section.

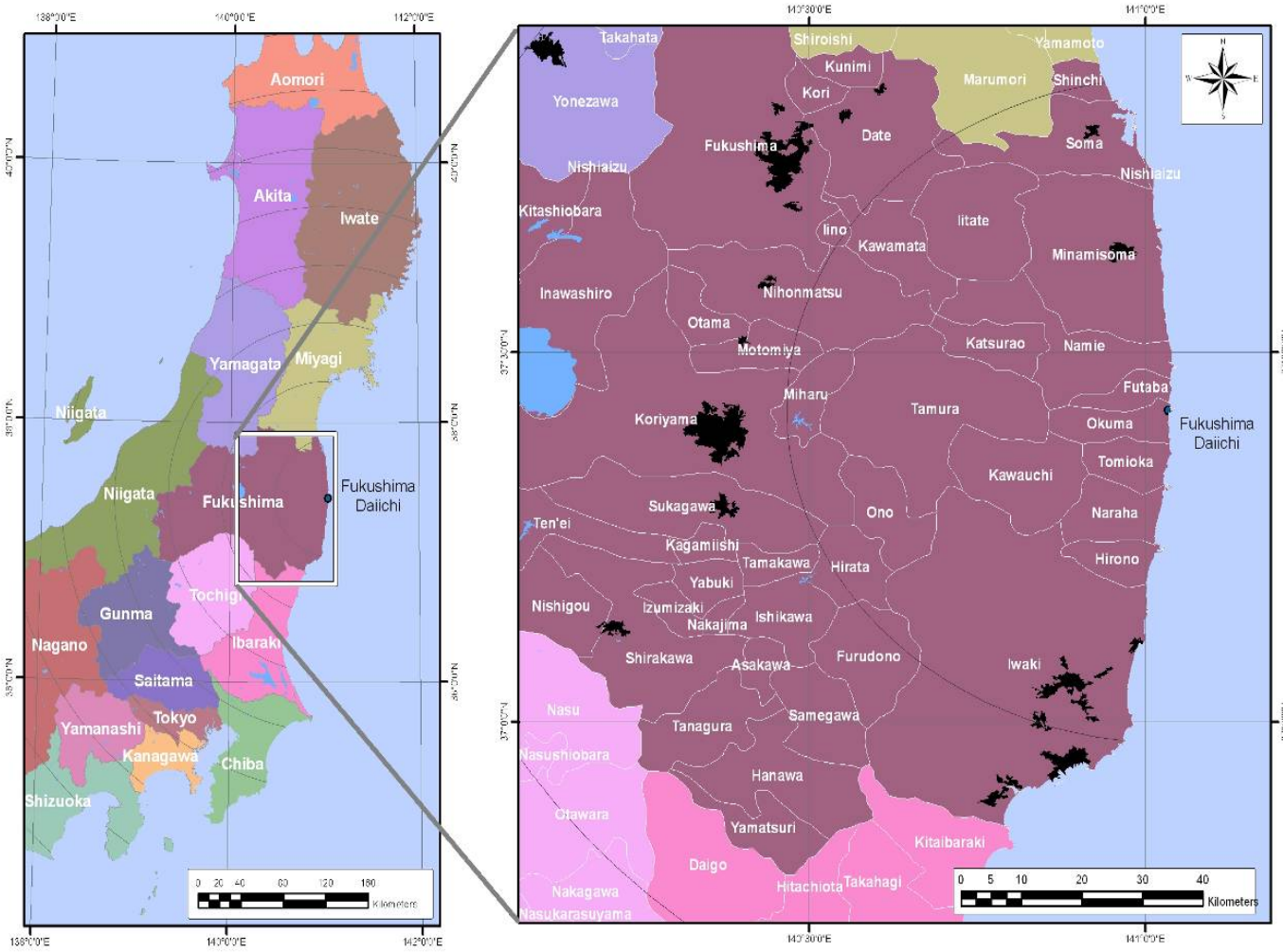


Figure 6-1 – Maps of the northern portion of Honshu island (left) and Fukushima prefecture (right).

6.1. ATMOSPHERIC DISPERSION OF RADIOACTIVE RELEASES

6.1.1. CHARACTERISTICS OF THE RADIOACTIVE MATERIALS RELEASED INTO THE AIR BY THE ACCIDENT

6.1.1.1 Work conducted by IRSN to estimate the radioactive releases into the atmosphere

Even one year after the accident, reconstructing the various sequences of releases of radioactive substances into the air and determining the characteristics of these releases remains a difficult task. The reason is that there are no direct measurements of these releases. Only indirect estimates have been able to be made by interpreting the data available during the emergency, namely: the chronology of the events at the facility (explosions, venting of the containments, smoke emissions, etc.), the parameters of the damaged reactors (pressure, water level in the vessels, etc.) and on-site dose-rate measurements taken by TEPCO (stationary and portable monitors) or taken by the automatic monitors in the SPEEDI network (System for Prediction of Environmental Emergency Dose Information).

• IRSN's initial estimates

As soon as it received news of the accident, IRSN began assessing the radioactive releases into the atmosphere and updating these assessments as new events occurred on the site and new data became available. IRSN's initial estimates on March 12 were very rough as they were based primarily on its knowledge of the inventory of radionuclides in the nuclear reactors and of how these radionuclides behave during a core meltdown. In particular, the lack of sufficient data on the state of the safety systems of the three damaged reactors at Fukushima Dai-ichi and on the measures taken by TEPCO made it difficult to predict the degradation kinetics of the cores and determine when future releases would occur. Despite these difficulties, with each day IRSN was able to construct a more and more accurate picture of the releases since the start of the accident and updated its findings as new events took place. **On March 22 IRSN published its initial estimate of the "source term"** (Table 6-I), or the atmospheric releases likely to have occurred since March 12, when the containment vessels were vented for the first time and the first hydrogen explosion occurred in reactor building 1. This estimate was based on:

- a diagnosis of the state of the three damaged reactors (understanding of the situation, state of the cooling systems, etc.);
- knowledge gained by IRSN through its research programs on the behavior of nuclear fuels during accident situations;
- information provided by the Japanese authorities concerning deliberate venting of the reactor containment vessels to protect the containments from the risk of degradation due to overpressure.

The assessment's conclusions were reinforced by comparing atmospheric contamination values calculated using a model with the results of field measurements taken in Japan.

The release kinetics as a function of time were reconstructed based on the interpretation of the dose-rate peaks observed along the site's boundary. Before March 17 the releases were related to ventings and explosions for which the timeframe is now well known. It is assumed that after March 17 the releases coincide with observations of smoke.

- **Update of the estimate of atmospheric releases**

After the events of March 2011 IRSN continued to estimate the releases from the Fukushima accident by analyzing a greater amount of available environmental data and by using its local- and regional-scale atmospheric dispersion models to interpret this data. The dose-rate measurements are the most abundant (Figure 6-2). The vast majority of the available readings was obtained by the automatic monitors in the SPEEDI network. However, because the earthquake and tsunami had rendered the SPEEDI monitors in Fukushima prefecture inoperative during the period of the releases, the data from the SPEEDI network was used only for comparison purposes with the results of the regional-scale model (several hundred kilometers). IRSN also used this data to estimate the source term using the tracer method, which involves modeling the dispersion of the individual "tracer" releases and correlating the passage of the resulting plume with the dose-rate peaks measured by the monitors at various locations throughout Japan. Furthermore, MEXT[8] published dose-rate readings taken in each prefecture, particularly Fukushima prefecture, and which were compared to the results of the local-scale model (under 100 km).

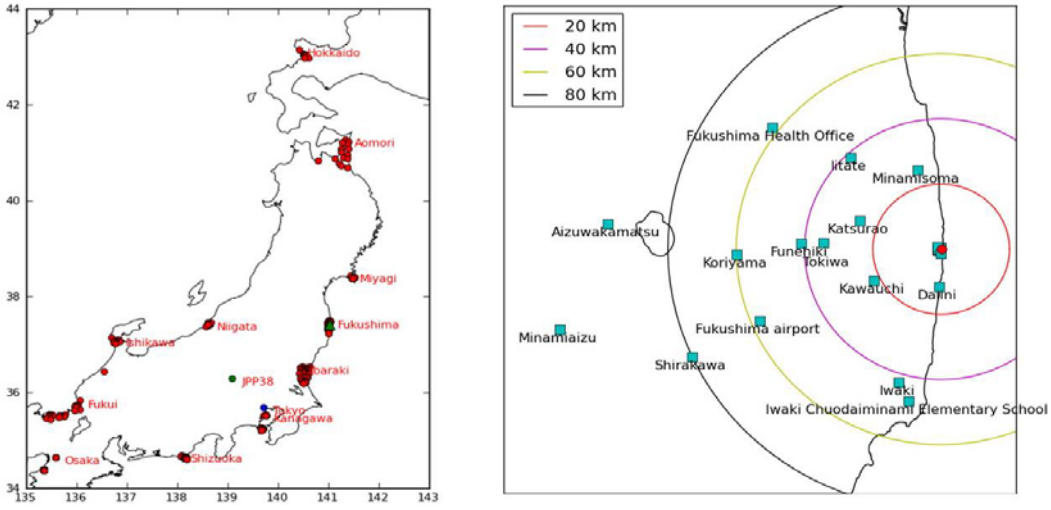


Figure 6-2 - Locations of the dose-rate monitoring stations: stations in the SPEEDI network (left) and monitors in Fukushima prefecture (right)

To date, very few atmospheric activity concentration measurements taken throughout Japan have been made public. The few results of genuine interest (because they span the entire period of the major releases) were obtained by the following monitoring stations:

- Tokyo-Shinjuku, located 250 km south-southwest of the plant;
- Tsukuba (Ibaraki Prefecture) located around 170 km from the plant in the direction of Tokyo,
- Takasaki (Gunma Prefecture) located 250 southwest of the plant.

However, because these monitoring stations are located in the same area, their readings are redundant. The only exception is that of the noble gas measurements taken by the Takasaki monitor.

IRSN's assessment after the accident made it possible to piece together a tentative overall picture of the substances released by each reactor into the atmosphere during the accident (Table 6-I and list in Appendix 6-1) and distributed across time (Figure 6-3). It is important to emphasize that, due to the lack of monitoring stations (particularly on March 13-14 and March 16-19), this reconstruction carries a high degree of uncertainty as to the releases that could have occurred as they spread across the Pacific Ocean. The releases from reactors 1 and 3 therefore remain highly uncertain. Another major source of uncertainty is the composition of the releases (isotopic composition and chemical forms, particularly for iodines). The main measurements available are dose-rate measurements, which give an overall picture of all the gamma-emitting radionuclides. However, this picture is not sufficient to deduce the composition of the releases. Furthermore, the activity concentration measurements

[8] Ministry of Education, Culture, Sports, Science & Technology, http://radioactivity.mext.go.jp/en/

of the airborne radionuclides are very few in number and generally cover the periods after March 17. For example, looking solely at the activity concentration measurements taken in Ibaraki Prefecture, it is assumed that the quantities of gaseous radioactive iodines were double those of iodine particles.

Other research agencies or teams published their own estimates of the atmospheric releases from the Fukushima accident based on different methods (Table 6-I). The source terms published in 2011 by NISA[9] and the NSC[10] in Japan were based essentially on an analysis of the events and phenomena in the damaged facilities; the source term estimated in the paper by *Stohl et al. (2011)* is based on measurements taken in Japan and at a very long distance and relate solely to xenon-133 and cesium-137.

Table 6-I – Estimates, made in 2011 by IRSN (during and after the accident) and various Japanese agencies and scientific teams, of the activities (× 10^{15} Bq) of the main categories of radionuclides released during the Fukushima accident. Releases from the Chernobyl accident are also provided for comparison.

		Noble gases (incl. Xe-133)	**Xe-133**	**Iodines** (incl. I-131)	**I-131**	**Cesiums** (incl. Cs-137)	**Cs-137**
IRSN ERS - March 22, 2011	**Total**	**2,080**	**2,000**	**182**	**90**	**26**	**10**
IRSN - 2011 research	Reactor 1	1,920	1,530	42	13	3	1
	Reactor 2	2,270	2,180	114	57	17	6
	Reactor 3	2,350	2,240	253	126	38	14
	Total	**6,550**	**5,950**	**408**	**197**	**58**	**21**
NISA (June 2011)	Reactor 1	-	3,400	-	12	-	0.6
	Reactor 2	-	3,500	-	140	-	14
	Reactor 3	-	4,400	-	7	-	0.7
	Total	-	**11,000**	-	**160**	-	**15**
NSC (April 2011)	**Total**	-	-	**630**	**150**	-	**12**
Chino et al. (2011), JAEA, NERH report	**Total**	-	-	-	**150**	-	**13**
Stohl (*Stohl et al. (2011)*)	**Total**	-	**16,700 (13,400-20,000)**	-	-	-	**35.8 (23.3-50.1)**
Morino et al. (2011)	**Total**	-	-	-	**142**	-	**9.94**
Chernobyl (*IAEA 2005)*	**Total**	**6,533**	**6,500**	**4,260**	**1760**	**168**	**85**

[9] Nuclear and Industrial Safety Authority - "Regarding the Evaluation of the Conditions on Reactor Cores of Unit 1, 2 and 3 related to the Accident at Fukushima Dai-ichi Nuclear Power Station, TEPCO"
[10] Nuclear Safety Commission – "Trial estimation of emission of radioactive materials (I-131, Cs-137) into the atmosphere from Fukushima Dai-ichi Nuclear Power Station"

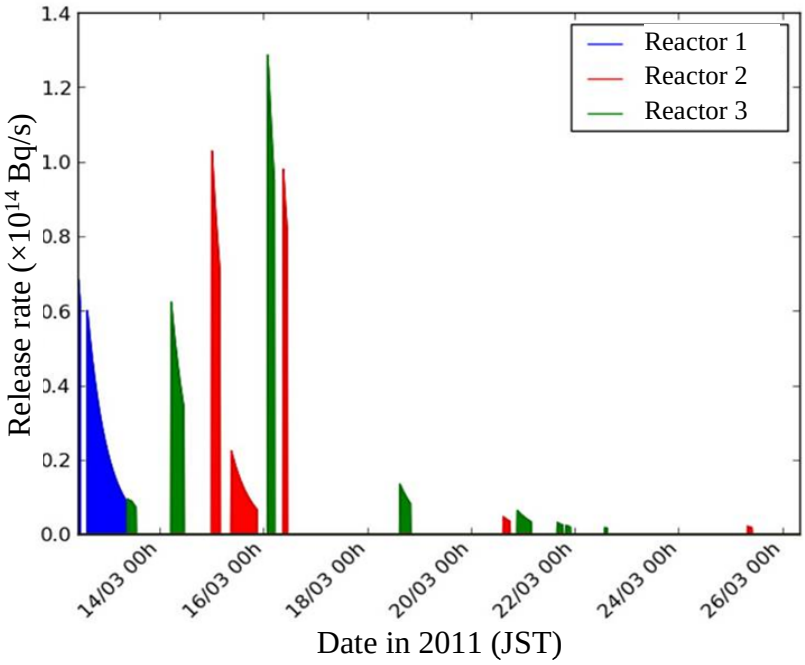


Figure 6-3 - Evolution in the per-reactor release rate for all the radionuclides released into the atmosphere during the Fukushima accident (blue: reactor 1; red: reactor 2; green: reactor 3).

6.1.1.2 Comment on the atmospheric releases

Altogether, IRSN estimates that nearly 15 release events occurred between March 12 and 25, with the largest releases probably occurring before March 17 (venting of the three damaged reactors' containment vessels). Given the extent of damage suffered by the facilities and the heavy contamination of the nuclear site, atmospheric releases must have continued over the course of the following months but at much lower levels not easily detectable in the environment.

IRSN's estimate of the distribution of the releases among the reactors is uncertain. For example, reactor 3 appears to be responsible for the largest releases (65% of cesiums and 62% of iodines). However, most assessments seem to agree that reactor 2 is responsible for most of the releases on account of the damage suffered by the containment during the hydrogen explosion. Moreover, there is no easy way to attribute releases to a specific reactor after the main release period ending on March 17.

Although the results of the various estimates of the atmospheric releases made by IRSN and other teams are inconsistent, they lie within the same ranges of value and reveal the following major trends:

- The releases of radioactive noble gases, the main one of which is xenon-133 (133Xe, half-life of 5.3 days), are estimated at between 6,500 and fewer than 20,000 PBq (petabecquerels, 10^{15} Bq). The latter value is probably overestimated since the activity concentration of 133Xe indicated in the paper by *Stohl et al. (2011)* is higher than the total activity concentration of 133Xe in the three reactors before the accident. Releases of radioactive noble gases from the Fukushima accident may be of the same order of magnitude, if not higher, as those from the Chernobyl accident. Of these gases, krypton-85 (85Kr) has the longest half-life (10.8 years). IRSN estimates that 33 PBq of 85Kr were released. As 85Kr is present only as a gas and is not very chemically reactive, it will remain in the atmosphere (no deposition) and be diluted in the air across the planet;
- The releases of radioactive iodines are estimated in the order of a few hundred PBq, which is around ten times lower than the Chernobyl accident. Of the radioactive iodines, iodine-131 is one of the most significant in terms of environmental and dosimetric impact. Current IRSN estimates place its release at 197 PBq, which is similar to the estimates published in other papers and nearly double the estimate made

by IRSN on March 22 during the emergency. Iodine-132, and to a lesser extent iodine-133, were also significant constituents of the radioactive iodines released (activity concentrations of 168 PBq and 42 PBq, respectively, according to IRSN estimates) but their impact on the environment was lower due to their short half-lives (2.3 hours and 20.8 hours, respectively);

- The releases of radioactive cesiums are estimated in the order of a few dozen PBq. They consist primarily of equal parts of cesium-137 and cesium-134 and, to a lesser extent, cesium-136 (estimated release of 9.8 PBq), which has a short half-life of 13.2 days. As regards cesium-137, which will persist the longest in the Japanese environment (half-life of 30.1 years), IRSN's current estimate of 21 PBq – twice as high as the March 22, 2011, estimate – accounts for around one-fourth of the cesium-137 released by the Chernobyl accident.

The study by *Stohl et al. (2011)* ascribes a portion of the releases to the pool of reactor 4 on account of the high water temperature (84°C) and the apparent correlation between the start of spraying of the pool and the lowering of the ambient dose rates on March 19. At present, IRSN considers that pool 4 was not a source of significant releases because the water level measured seems to indicate that the assemblies remained submerged and thus were not damaged. This analysis is confirmed by an American report published in November 2011 (*INPO (2011)*).

Altogether, IRSN estimated the radioactivity released for 73 radionuclides (135, counting their radioactive progeny)**, making this the most extensive source term ever published**. Besides the three aforementioned main categories of radionuclides, these include the **radioactive isotopes of tellurium**, also released in significant quantities (145 PBq, all its radioactive isotopes combined), particularly tellurium-132 (half-life of 3.2 days; estimated release of 108 PBq) and its decay product iodine-132, a radionuclide with a very short half-life (2.3 hours), and tellurium-129m (12 PBq) associated with its decay product tellurium-129 (8 PBq). According to IRSN estimates, the releases from the other radionuclides account for a total radioactivity of 28 PBq. Not all of these radionuclides have been detected in Japan's environment for one of two reasons: their overly short half-lives (a few minutes for some) or the excessively low amount of radioactivity released. Of those that have been measured in the environment (see section 6.2.3) barium-140 (estimated at 1.12 PBq) and strontium-89 (0.043 PBq) and strontium-90 (0.003 PBq) were released in lower quantities than the others because they are less volatile. That said, estimates of the radioactivity released for these radionuclides remain rough due to the lack of a sufficient body of measurements and information on the actual condition of the damaged reactors. The case is the same for plutonium and other transuranium elements. Their presence in the environment due to the accident has not been easy to detect on account of possible confusion with residual plutonium from atmospheric nuclear tests conducted in the 1960s. **However, the detection[11] of neptunium-239, which has a short half-life of 2.4 days, in soil and plant samples collected on April 10, 2011, along the boundary of the Fukushima Dai-ichi site and in the village of Iitate proves without doubt that transuranium radionuclides were released by the Fukushima accident.** This is also confirmed by the interpretation of certain results of plutonium measurements taken in the soils northwest of the Fukushima Dai-ichi site and published by MEXT (see section 6.2.3.3)**.** The decay product of neptunium-239, which has completely disappeared due to its short half-life and can no longer be measured, is plutonium-239 (half-life of 24,000 years). However, since its specific activity is much lower than that of neptunium-239, it is highly unlikely that it will be able to be detected and distinguished from the plutonium left from atmospheric nuclear tests.

[11] Article by Shozugawa et al, published in the January 2012 issue of Environmental Pollution (No. 163).

6.1.2. MODELING OF THE ATMOSPHERIC DISPERSION OF RELEASES IN JAPAN

As soon as the accident occurred, IRSN developed a model of the atmospheric dispersion of the releases that it had estimated, on a local and regional scale, using the codes from its *C³X* calculation platform installed at the Institute's emergency response center. These assessments were updated regularly as new data became available. However, the local-scale assessments (a few dozen kilometers around the site) were very rough on account of insufficient data on the release conditions and the local weather. On the other hand, the regional-scale (a few hundred to a few thousand kilometers) and global-scale results yielded by these assessments were satisfactory overall thanks to the better meteorological data.

Over the course of 2011, IRSN used environmental data available to continue modeling the atmospheric dispersion of the releases at local and regional scales. Its work allowed it to more realistically estimate the consequences of this dispersion, particularly in terms of doses potentially received by the population exposed to the radioactive plume (see Section 8).

6.1.2.1 Regional-scale modeling of the atmospheric dispersion (Japan)

IRSN used the three-dimensional *IdX* model of its *C³X* platform to model the atmospheric dispersion at the regional level (several hundred to several thousand kilometers). Developed over the past few years, ldX was validated by many comparisons with experiments (particularly ozone-pollution episodes) and the reconstruction of the contamination of the air in Europe after the Chernobyl accident. **The model's spatial resolution is that of the weather data used, i.e. around 12 km**. *IdX* is a Eulerian model, meaning that, at the scale of a unit cell (element volume of the atmosphere used in the modeling), the calculated activity concentration (as well as the deposition) is homogeneous. The results yielded by *IdX* are thus comparable with measurements only when the width of the plume was substantially larger than that of the cells. **In practice, the results yielded by *IdX* are usable at a distance of around 5-8 cells from the discharge point. In the case of Japan, this is around 50-80 km. Below this distance, the model does not make it possible to calculate the concentration gradients of airborne radionuclides**, which persist near the discharge point. A local-scale modeling tool should therefore be used (see Section 6.1.2.2).

The reliability of the results obtained with *IdX* depends largely on the quality of the data on the releases from the accident and the weather.

- **The initial estimates made by IRSN in March 2011**

On March 16, while the Fukushima accident was still taking place, IRSN began developing its first models with *IdX* using the release estimates it made between March 12-20 and regularly updating its models throughout the rest of the month. The calculation results obtained for cesium-137 and iodine-131 in Tokyo were compared with the results of air contamination measurements taken in the same city. Both showed good consistency (Figure 6-4).

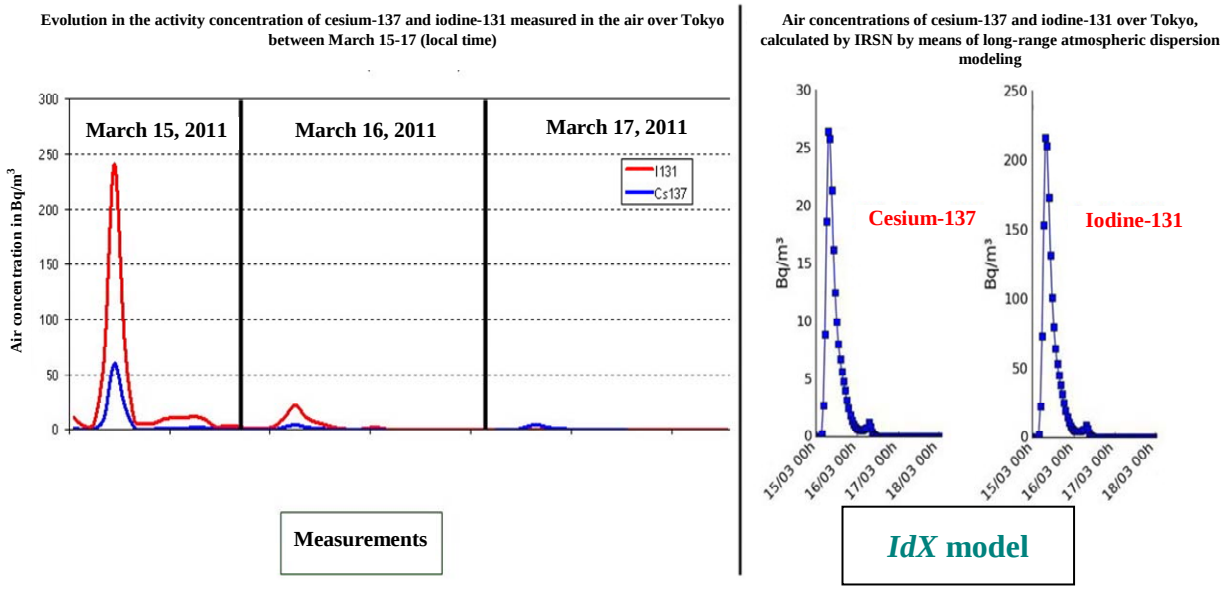


Figure 6-4 – Comparison of the results of the calculation of the air concentration of cesium-137 and iodine-131 over Tokyo, obtained by IRSN on March 19, 2011, using the IdX model (right) and results from measurements taken in Tokyo during the same period (left: SPEEDI monitoring station).

- **Update of the modeling of the dispersion of atmospheric releases**

Over the course of further work in 2011, IRSN reconstructed the history of radioactive contamination of the air in Japan during the Fukushima accident at the same time as it was estimating the source term described in Section 6.1.1.1. The results of the regional-scale model are generally consistent with the readings made by the ambient dose rate monitors in Japan and were used to identify the main air-contamination events in Japan:

- **The first releases, occurring between March 12-14, spread mainly northward** along the eastern coast of Honshu island, then toward the northeast and east, over the Pacific Ocean (Figure 6-5);
- **On March 15 and 16, the radioactive releases from reactor 2 spread over Japan**, but the weather conditions were changing rapidly (Figure 6-6);
- **On March 16 and the following days, the releases spread eastward, moving over the Pacific** and sparing most of Japan (Figure 6-7);
- **Between the afternoon of March 20 and March 23, the radioactive releases again spread over Japan** (Figure 6-8). After March 23, the contaminated air masses moved toward the Pacific. The subsequent releases have been too low to cause a significant increase in the radioactivity in Japan's terrestrial environment.

5:00 pm on March 12, 2011 *5:00 am on March 13, 2011* *12:00 pm on March 14, 2011*

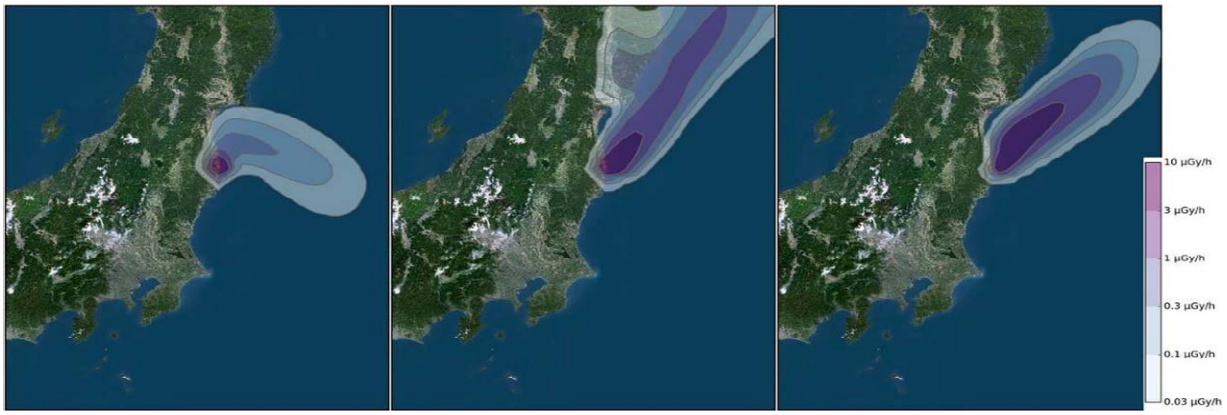


Figure 6-5 - Model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident between March 12-14 (excluding the contribution of radioactive fallout – IRSN's IdX model).

5:00 am on March 15, 2011 *7:00 pm on March 15, 2011* *6:00 am on March 16, 2011*

Figure 6-6 - Model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident on March 15 and the morning of March 16 (excluding the contribution of radioactive fallout - IRSN's IdX model), illustrating the first air contamination event on Honshu island.

11:00 a.m. on March 16, 2011 *2:00 p.m. on March 16, 2011* *3:00 a.m. on March 19, 2011*

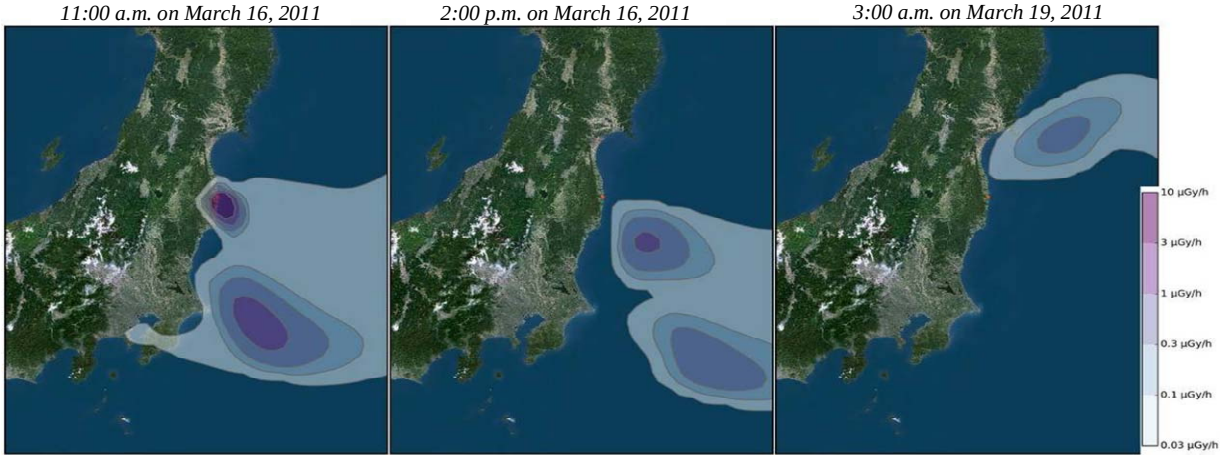


Figure 6-7 - Model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident between midday, March 16, and March 19 (excluding the contribution of radioactive fallout – IRSN's IdX model) illustrating the second dispersion event over the Pacific Ocean.

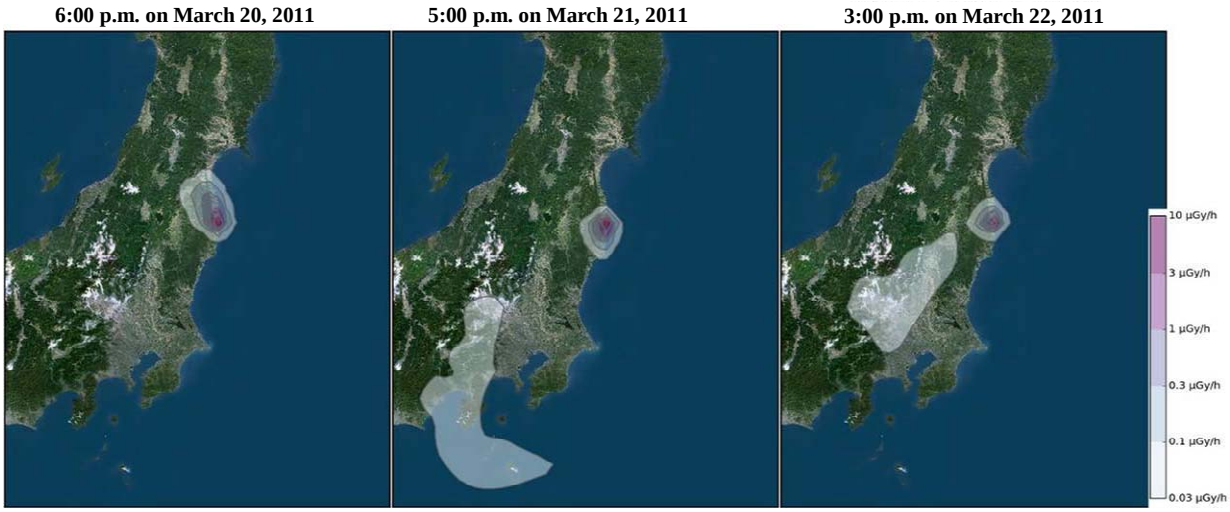


Figure 6-8 - Regional-scale model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident on March 20 and 22 (excluding the contribution of radioactive fallout - IRSN's IdX model), illustrating the second air contamination event on Honshu island.

6.1.2.2 Local-scale modeling of the atmospheric dispersion (Fukushima prefecture)

In order to model the atmospheric dispersion of the releases at the local scale (a few kilometers to a few dozen kilometers), IRSN used the *pX* model of its *C³X* calculation platform, which is suited to local-scale studies. Because *pX* is a Gaussian burst model, the choice of the law of standard deviation is crucial. IRSN's tests on the Fukushima accident led to the use of Pasquill standard deviations. The *pX* model takes into account the spatial heterogeneity of the wind across its range of calculation. In the case of Japan, it was applied to a circular area measuring 80 km in diameter around the Fukushima Dai-ichi plant.

During the Fukushima Dai-ichi emergency, IRSN had neither sufficient nor adequate data to allow it to construct a reliable local-scale model. In particular, it did not have the necessary meteorological data for the Fukushima region and had to rely on results from local observations. In France, this data is usually provided by Météo France using suitable meteorological models. Moreover, the layout of the environment near the Fukushima plant made it hard to model the wind. The coastal effects and the effects due to the complex orography (valleys, mountains) mean that the wind changes direction very often and is therefore hard to simulate. As a result, the work performed subsequently by IRSN in collaboration with Météo France showed that some meteorological events were very hard to model, even *a posteriori*. This was especially the case of the first release event in the direction of Japan on March 15-16: the meteorological models were unable to reproduce the wind directions observed. These difficulties also affected the regional-scale simulations, but less noticeably than at the local scale, where the plume was highly concentrated.

Various meteorological observations, made at the Fukushima Dai-ichi and Daini sites (TEPCO) or at various meteorological stations in Fukushima prefecture (available on the site of the JMA [Japan Meteorological Agency[12]]) were used by IRSN for analysis and comparison purposes with the meteorological models. However, the loss of power following the tsunami made them intermittently available or unavailable during the period of releases from the accident. Rainfall radar images available on the JMA's website were therefore used in order to best reproduce the wet deposition event of March 15-16 associated with the heavy localized rainfall.

The combination of the meteorological observations and the data from the CEP meteorological model yielded generally consistent simulations with the available environmental measurements (Figure 6-9 to Figure 6-12). The results of these simulations made it possible to obtain a more accurate picture of certain dispersion events described previously using the regional-scale model:

[12] http://www.jma.go.jp/jma/indexe.html

- **the initial releases that occurred on March 12, 2011, first passed over a small portion of Japan north of the Fukushima Dai-ichi plant** (particularly Minamisōma, the only place in Japan where this release event was detected by a monitor) then moved out to the Pacific Ocean over the course of the evening (Figure 6-9);

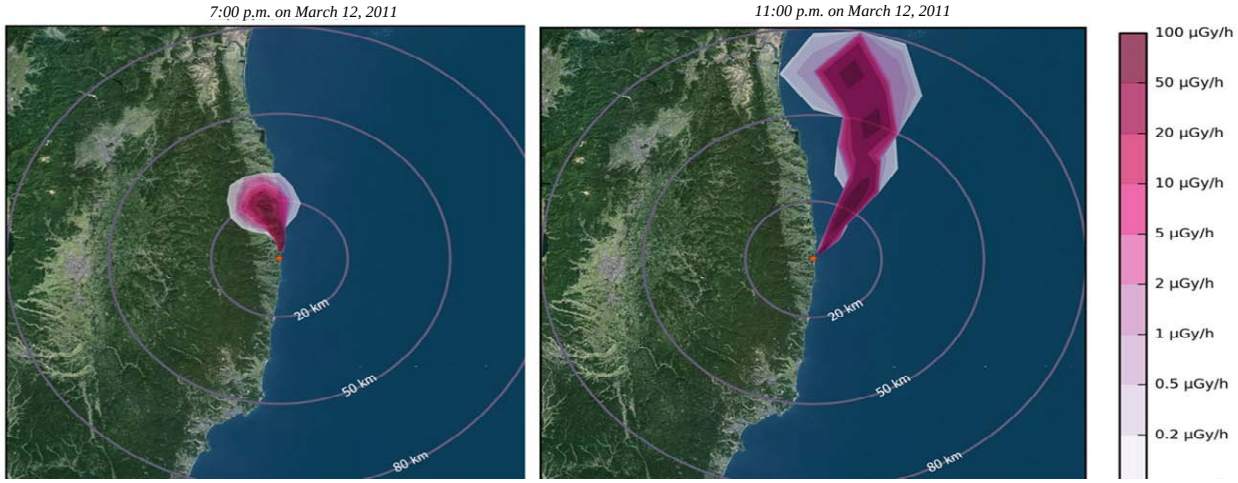


Figure 6-9 - Model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident over the course of March 12, 2011 (excluding the contribution of radioactive fallout – IRSN's pX model).

- **On the morning of March 15, the radioactive releases moved southward while those that had occurred the previous evening moved northwest of the plant (Figure 6-10);**

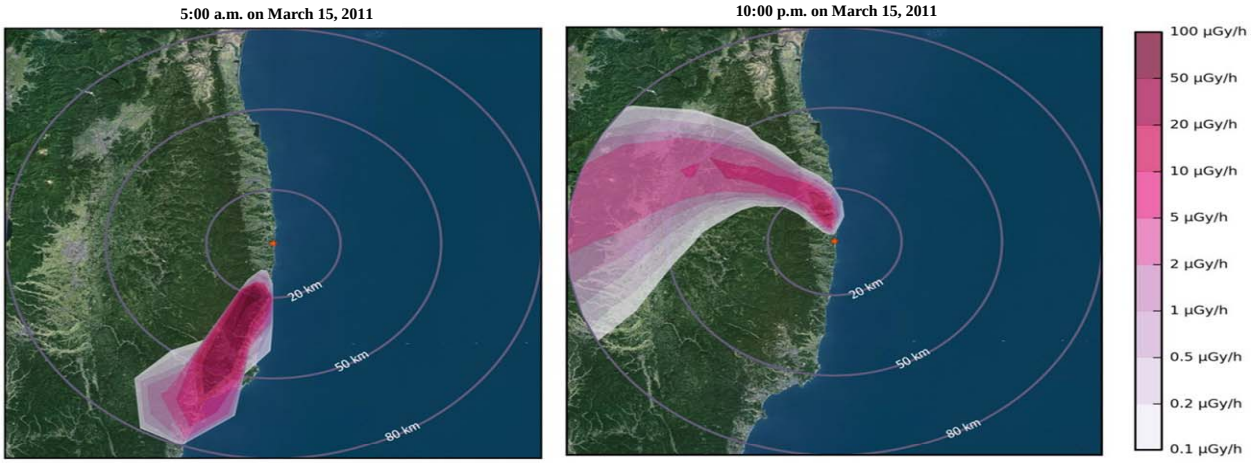


Figure 6-10 - Model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident over the course of March 15, 2011 (excluding the contribution of radioactive fallout – IRSN's pX model).

- **On the early morning of March 16, the plume released during the night of March 15-16 continued to move towards the northwest** then gradually turned southwest inland. The following releases moved due south then southeast as the day progressed (Figure 6-11);

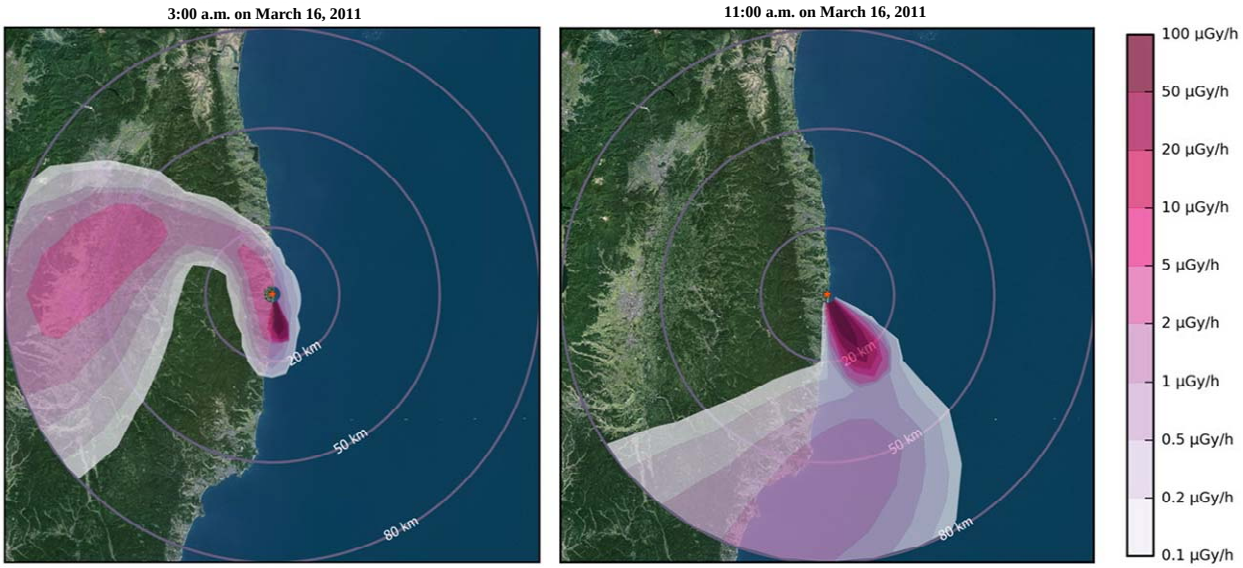


Figure 6-11 - Model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident over the course of March 16, 2011 (excluding the contribution of radioactive fallout – IRSN's pX model).

- **Finally, on March 21-22, several releases moved toward the south or southwest in the direction of Tokyo** (Figure 6-12)

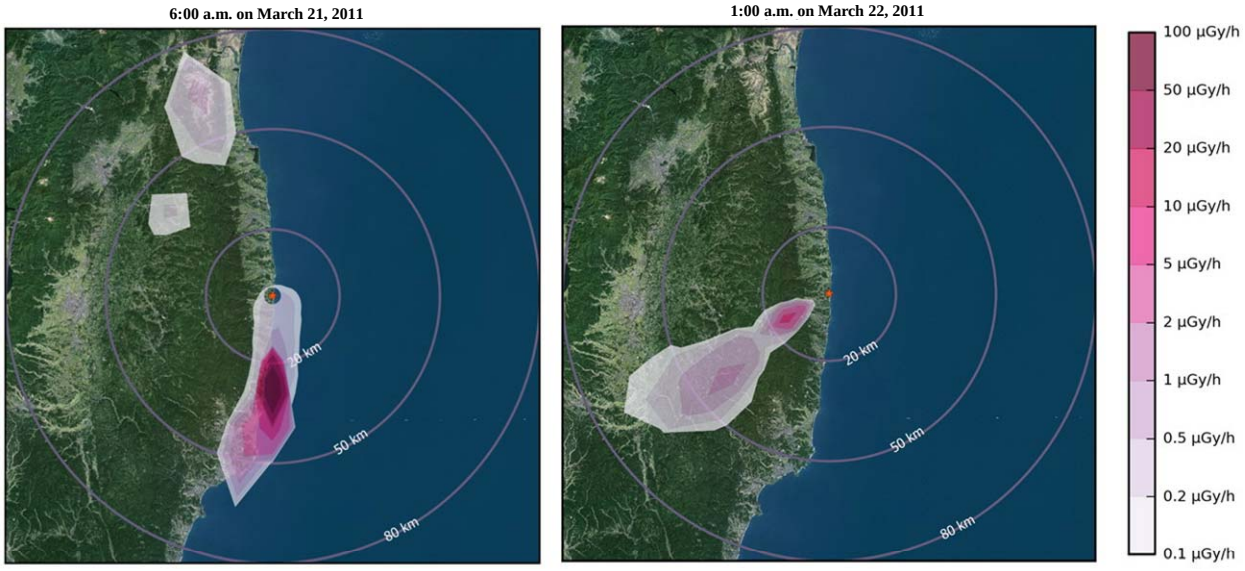


Figure 6-12 - Model of the ambient dose rate due to atmospheric dispersion of releases from the Fukushima accident on March 21 and 22 (excluding the contribution of radioactive fallout – IRSN's pX model).

6.2. CONTAMINATION OF JAPAN'S TERRESTRIAL ENVIRONMENT

6.2.1. GENERAL COMMENTS ON THE DEPOSITION OF RADIOACTIVE FALLOUT IN JAPAN

During the air-contamination events, a portion of the radionuclides released into the air in the form of very fine particles (aerosols) or soluble gases (a portion of the radioactive iodines) were deposited onto surfaces on the ground. This process is caused by two complementary subprocesses that are illustrated in Figure 6-13.

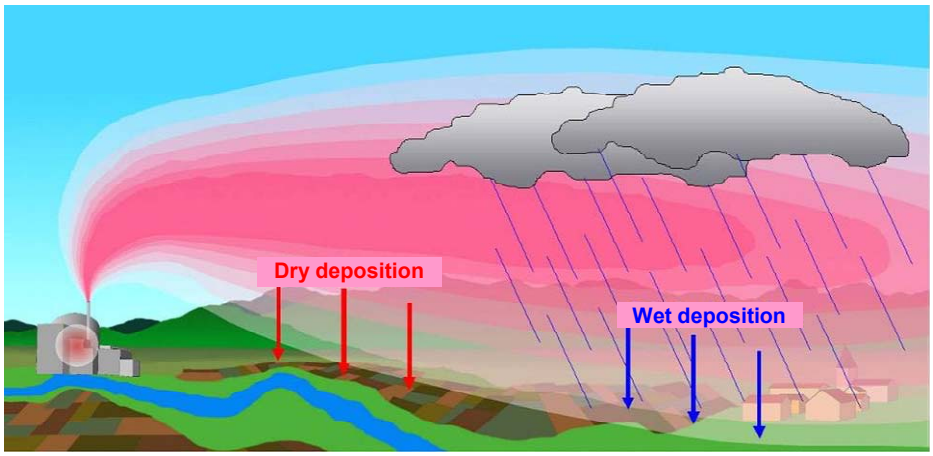


Figure 6-13 – Figure illustrating dry deposition and wet deposition of radioactive materials from a radioactive plume.

All surfaces of all types and directions (horizontal, vertical or reversed) were contaminated by **dry deposition**, i.e. the transport of airborne contaminants to surfaces by means of turbulence. The extent of this fallout depended especially on the concentration of airborne radionuclides at ground level and the duration of contamination of the air. Dry fallout was deposited inside buildings as the air inside them became contaminated.

Certain areas were contaminated by **wet deposition**, i.e. the removal of radioactive particle or soluble gases (case of iodine) from the radioactive plume by precipitation (rain or snow). This fallout did not affect building interiors. The distribution of the contamination of ground-level surfaces receiving these radioactive particles obviously varied across short distances based on whether the rain (or melting snow) flowed across the ground or infiltrated into the soil.

Both types of fallout led to contamination of Japan's terrestrial environment that persisted after the air contaminated by the accidental releases had been blown away. The geographical distribution and the magnitude of this contamination depend both on the subsequent trajectories of the radioactive plume created by the radioactive releases that lasted for several days and the location and extent of the rainfall at that time. This fallout had two main consequences:

- a permanent rise in the ambient dose rate due to gamma radiation emitted by the radionuclides contained in the fallout and which gradually lowered with time based on the radioactive decay of the radionuclides that were first deposited;
- contamination of agricultural products, more or less immediate and more or less long-lasting.

As will be later shown, the impact of radioactive fallout on the environment and health varies with time and is at its highest in the weeks following the deposition of this fallout. This is why it is important to gain a quick (and even rough) understanding of the geographical distribution and characteristics (radioactivity and isotopic composition) of this fallout in order to implement, as quickly as possible, early countermeasures to protect

populations from the two main routes of exposure: external exposure from fallout and the ingestion of contaminated foodstuffs.

Two additional methods are used to estimate the fallout from an accidental release of radioactive materials:

- atmospheric dispersion modeling of releases and ground-level radioactive fallout;
- measurement surveys involving the use of airborne measuring instruments or field teams collecting soil samples or taking *in situ* measurements.

The first method makes it possible to quickly obtain initial estimates. However, these estimates can be very rough in the case of insufficient understanding of the radioactive releases and weather conditions.

The second method gives a more representative and multiscale picture of reality. However, it has the major drawback of being long, especially in the case of vast distances, and can thus delay the implementation of the appropriate countermeasures.

The distinctive feature of the Fukushima accident is that it led to the overlap of a release phase – primarily over a dozen days (with the threat of new releases lasting for at least several weeks) and creating an immediate risk of exposure to radioactive plume (external exposure and inhalation) – with a fallout phase that became significant starting on March 16 while the radioactive releases were still occurring (Figure 6-14).

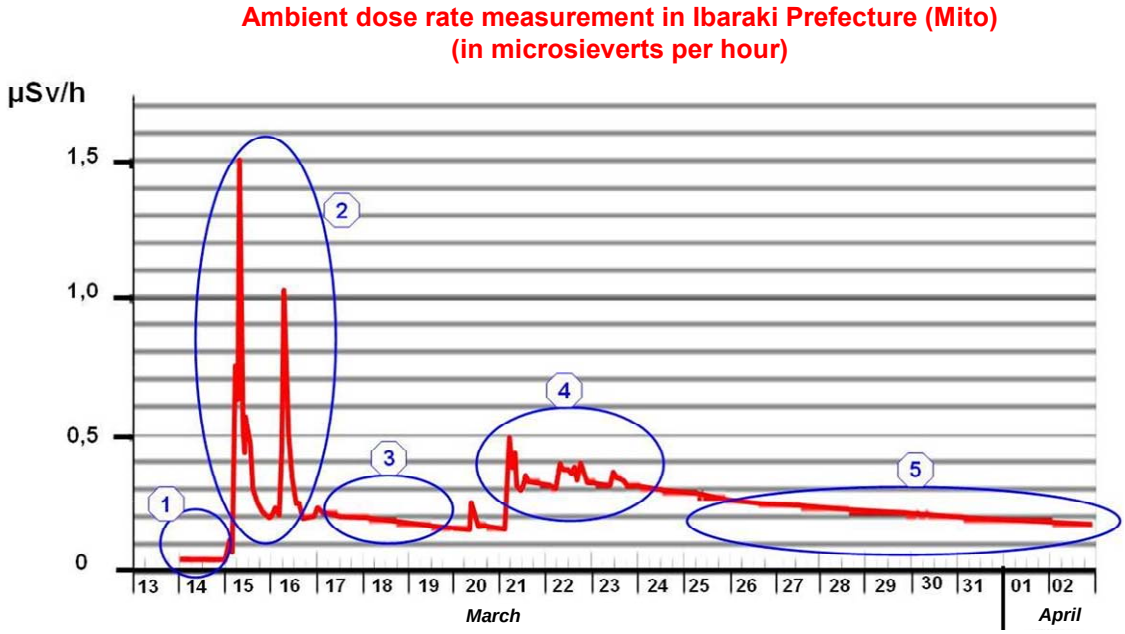


Figure 6-14 – Timeline of the measurement of the ambient gamma dose rate in Ibaraki showing the overlap of the release phase and the fallout phase from the Fukushima accident. ①: ambient dose rate before the accident; ②: first event of atmospheric contamination; ③: dose rate from residual radioactive fallout deposited during the first event of atmospheric contamination; ④: second event of atmospheric contamination; ⑤: dose rate from the residual radioactive fallout deposited during the subsequent events of atmospheric contamination.

Series of ambient dose rate measurements comparable to those illustrated by Figure 6-14 and taken at various points throughout Japan show similar events but at times and with intensities that occasionally differ (Figure 6-15). Readings by most of the monitors that were still operational after the accident show that the ambient dose rate began rising on March 15 or 16, except in Minamisōma, located some 20 kilometers north of the damaged nuclear power plant, where the measurements taken by the monitor show that the first events of atmospheric contamination started on March 12.

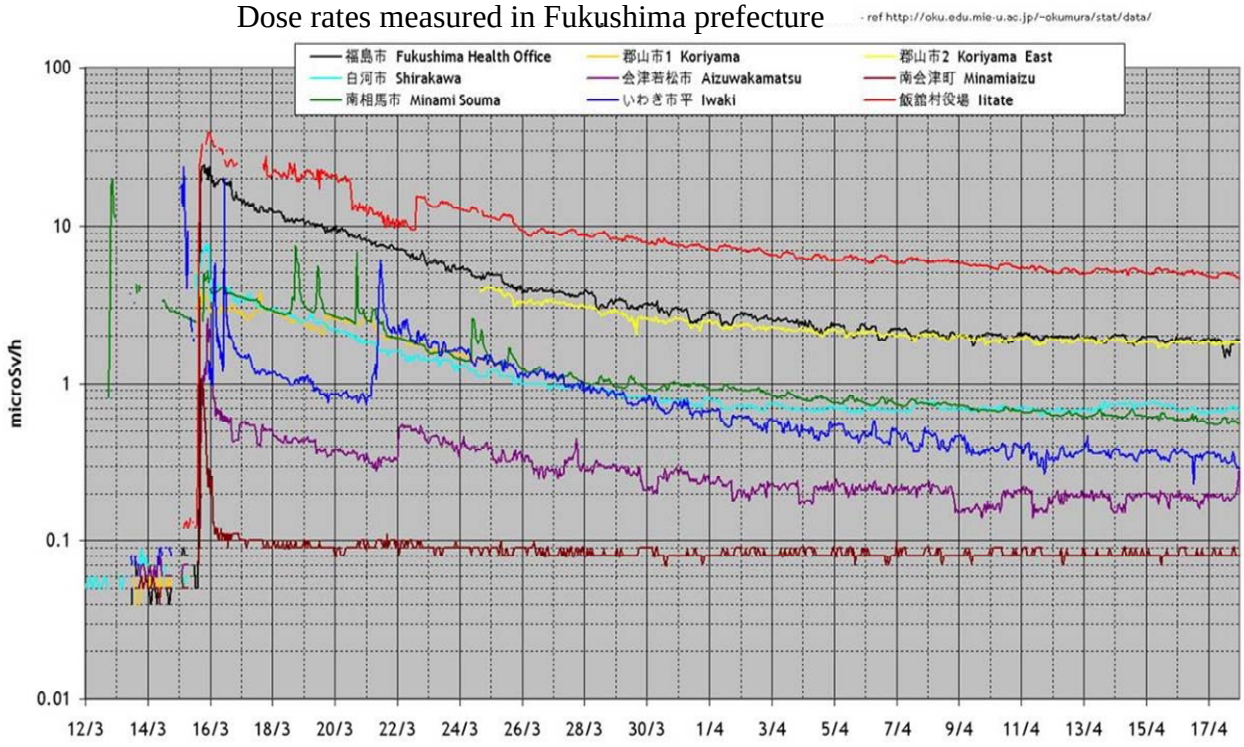


Figure 6-15 - Evolution in the ambient dose rate measured at several municipalities in Fukushima prefecture. The difference in the level of background radiation (nearly a factor of 100 between Iitate and Minamiaizu) is due to the variable magnitude of the radioactive fallout. The general downward trend during this observation period is caused by the gradual disappearance of the short-lived radionuclides.

The complexity of the Fukushima accident, with multiple release events and changing weather conditions, and the lack of sufficient data in IRSN's possession at the time of the accident made it very difficult to estimate the extent and geographical distribution of the fallout with the help of modeling tools. The measurement surveys conducted in Japan are therefore what made it possible to gradually gain a clearer understanding of the radioactive fallout.

6.2.2. MAP OF THE RADIOACTIVE FALLOUT IN JAPAN

Many measurement surveys have been conducted in Japan since late March 2011 to map the radioactive fallout from the Fukushima Dai-ichi accident, primarily by means of airborne techniques. These maps are of the ambient dose rate caused by the fallout as well as the surface activities of cesium-134 and cesium-137. Coordinated and organized by the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT), these airborne measurement surveys have been conducted with the JAEA[13] and NUSTEC[14] with the technical support of the U.S. DOE/NNSA[15]).

In addition, soil samples (first 5 cm) were collected for laboratory analysis by a consortium of Japanese universities under the auspices of MEXT in order to better understand the fallout and check the consistency of the

[13] Japan Atomic Energy Agency
[14] Nuclear Safety Technology Center
[15] U.S. Department of Energy, National Nuclear Security Administration

results obtained with the results of the airborne surveys. The first collection surveys took place between June 6 and July 8, 2011, at 2,200 points throughout Fukushima prefecture. Similar surveys, including one in December 2011 involving the participation of an IRSN team, were subsequently conducted in order to monitor changes in the contamination. These surveys also provided the opportunity to compare the results obtained with various measurement techniques, such as *in situ* gamma spectrometry or radiation meters onboard vehicles circulating within the contaminated areas.

The data from these surveys is presented in a general map of radioactive fallout in the northern portion of Honshu island.

Due to the conditions under which the airborne measurements were taken (see Appendix 6-2), the resulting maps of the northern portion of Honshu island only provide an indication of the average level of ground fallout at the scale of 1 kilometer. They do not make it possible to better characterize local variations in the fallout from sources such as the runoff or accumulation of fallout-laden rain or the melting of fallout-laden snow. This characterization was made possible only by measurement surveys conducted in the field with radiation meters, particularly in urban areas.

6.2.2.1 Map of the ambient dose rate from the radioactive fallout

Following a number of initial reconnaissance surveys in March, in particular during a mission carried out with the support of the U.S. DOE from March 30 to April 3, 2011, the first three airborne measurement surveys were limited to an 80-km radius around the Fukushima Dai-ichi plant. They took place from April 6 to April 29, from May 18 to May 26, and from May 30 to July 2.

By way of illustration, Figure 6-16 shows the map of the ambient dose rate measured at 1 m above ground published by MEXT after the first survey in April.

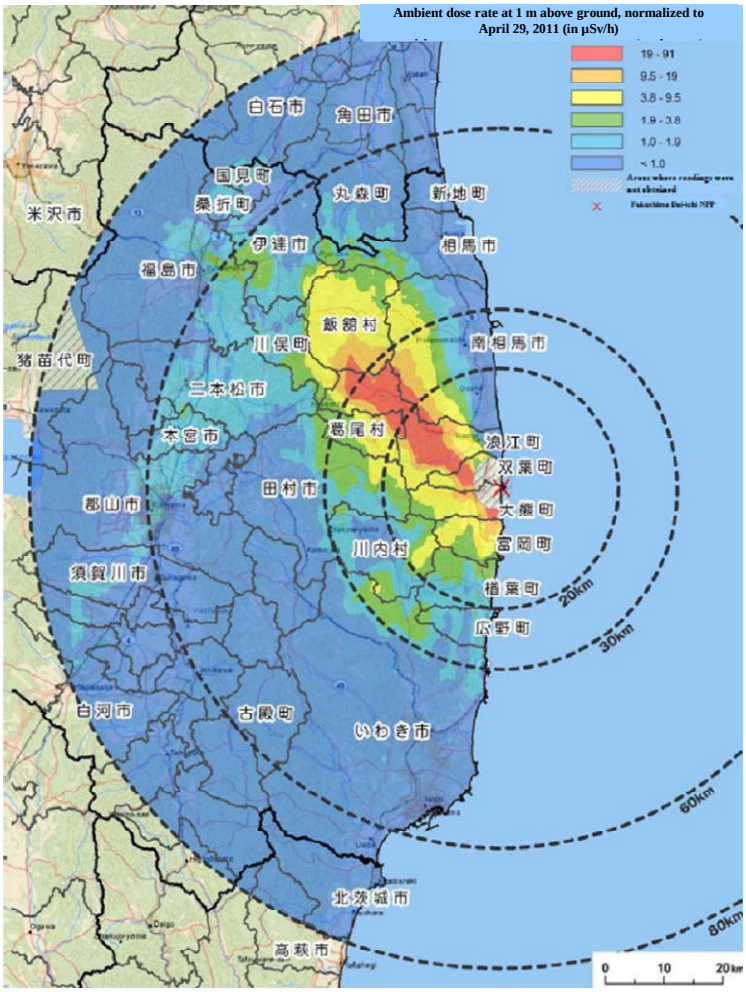


Figure 6-16 - Map of the ambient dose rate at 1 m above ground (in µSv/h, normalized to April 29, 2011) published by MEXT after the first airborne measurement survey conducted from April 6 to April 29 within an 80-km radius around the Fukushima Dai-ichi nuclear power plant.

This map shows a main zone of radioactive fallout extending more than 50 kilometers northwest of the Fukushima Dai-ichi plant. The ambient dose rates measured in this area ranged from greater than 2 µSv/h (i.e. 20 to 40 times higher than the level due to naturally occurring radiation) to more than 20 µSv/h in its worst-affected portion. Southwest of the plant is an area of less fallout where the dose rate was greater than 1 µSv/h. At the time of this first survey, the deposition must have been made up of nearly 75% cesium-134 and cesium-137, in more or less equal amounts, and the rest consisting essentially of iodine-131 (half-life of 8 days) and tellurium-129m (half-life of 33.6 days). After the third survey (July 2), the Japanese authorities indicated that the ambient dose rate within the same area of the map had decreased by around 20%. This decrease is consistent with the continued radioactive decay of iodine-131 and tellurium-129m, and to a lesser extent, cesium-134 (the activity ratio of $^{134}Cs/^{137}Cs$ must have been near 0.85 at this date, versus 0.9 to 1 on March 15, the date on which the bulk of the fallout was deposited in Japan).

Starting in late June, MEXT began implementing airborne measurement surveys across a much wider area in order to verify the absence of extensive fallout beyond the main fallout zone already identified. As of December 1, 22 prefectures in the northern half of Honshu island had been mapped. MEXT has published an overview of this map (see Figure 6-17).

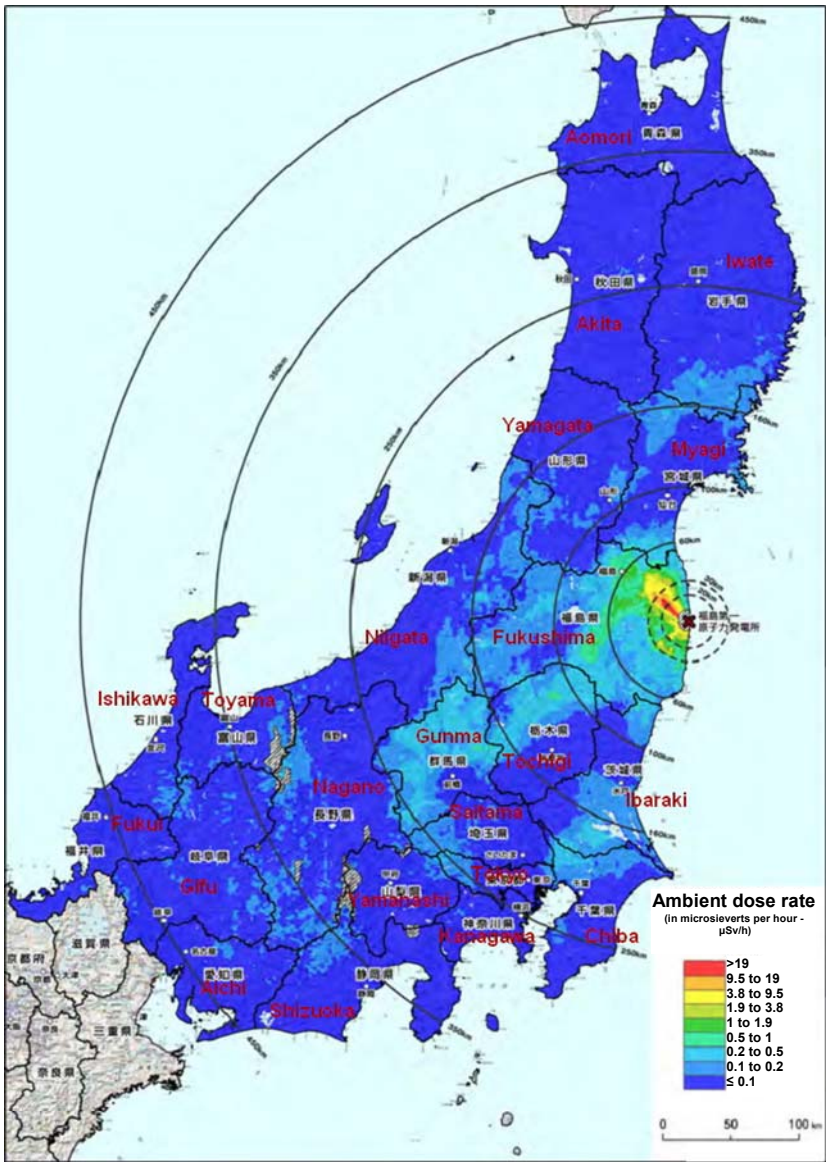


Figure 6-17 - Map of the ambient dose rate at 1 m above ground (in μSv/h, normalized to November 1, 2011) published by MEXT after the various airborne measurement surveys conducted since late June 2011 for 22 prefectures within the northern end of Honshu island.

Apart from Fukushima prefecture, the location of the aforementioned main fallout zone, this expanded map raises the following comments:

- the areas where the ambient dose rates are less than 0.1 μSv/h (in dark blue on the map) can be considered to be free of significant fallout from the Fukushima accident. This level is comparable to the ambient dose rate due to the radiation of cosmic or terrestrial origin – between 0.05 and 0.2 μSv/h depending on the altitude or the geological nature of the ground – that makes up natural "background noise";
- a number of prefectures located far from Fukushima contain more or less extensive zones with dose rates of between 0.1 and 0.5 μSv/h, and between 0.5 and 1 μSv/h locally (Gunma, Tochigi). As these levels are significantly higher than the natural background noise from gamma radiation, they attest to residual fallout from the Fukushima accident deposited over long distances from the damaged plant after materials released by the accident were dispersed into the atmosphere. The prefectures where these levels were recorded over at least a significant portion of their areas are Tochigi, Gunma, Ibaraki, northern Chiba, western and northeastern Tokyo, western Saitama, eastern and northeastern Niigata, as

well as other, less affected prefectures (southern and northern Miyagi et southern Iwate, Yamagata, Nagano, northern Shizuoka, eastern Toyama).

MEXT also published prefecture-specific maps. Figure 6-18 shows the maps of the ambient dose rates at 1 m above ground for the Gunma and Tokyo Metropolis Prefectures.

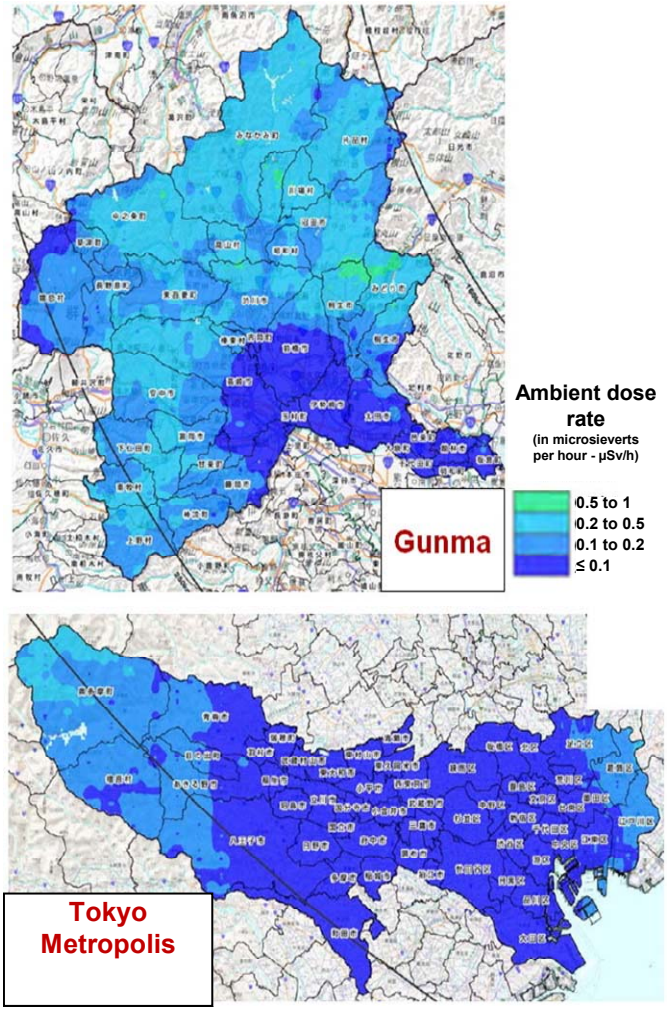


Figure 6-18 – Examples of the maps of the ambient dose rates at 1 m above ground (in µSv/h) published by MEXT for the Gunma and Tokyo Metropolis Prefectures (the list of surveys and their start and end dates is provided in Appendix 6.2).

The map of the ambient dose rates in the eastern portion of Fukushima prefecture was published in late April; the map of its western portion has since been made available (Figure 6-19). Apart from a drop in the dose rate due to the disappearance of short-lived radionuclides, this new map does not significantly differ from the map published at the end of the April survey (Figure 6-16). However, its scale of values has a higher level of detail.

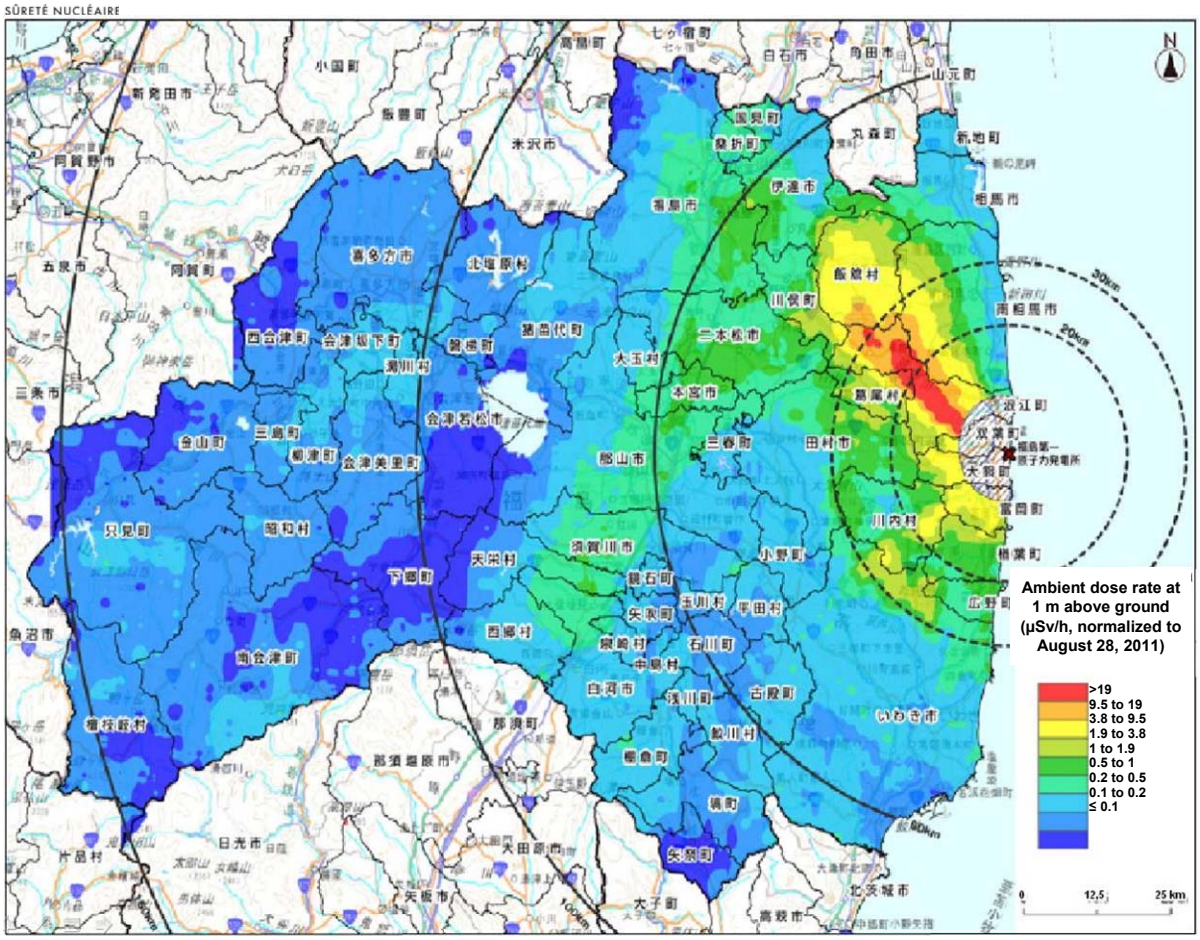


Figure 6-19 – Updated map of the ambient dose rate at 1 m above ground (in μSv/h, normalized to August 28, 2011) published by MEXT for Fukushima prefecture.

Many detailed maps showing the results of dose rate measurements taken during field surveys have been published in Japan. Conducted under the auspices of various ministries or at the initiative of prefectures or local associations, they show variations – at times significant – in radioactive fallout at the local scale. The detailed dose rate maps published on February 24, 2012, by the Japanese Ministry of the Environment merit pointing out. These maps were created using measurements taken between November 2011 and January 2012 by instruments installed on vehicles circulating in the most heavily contaminated areas, including in the vicinity of the crippled site (see Figure 6-20. This map shows measurement points located close together in areas accessible by vehicle; there are no readings for the mountainous areas. At this level of detail, a lobe of fallout extending in a north by northeast direction can be distinguished from the main lobe heading towards the northwest. This lobe was probably formed during a different release event.

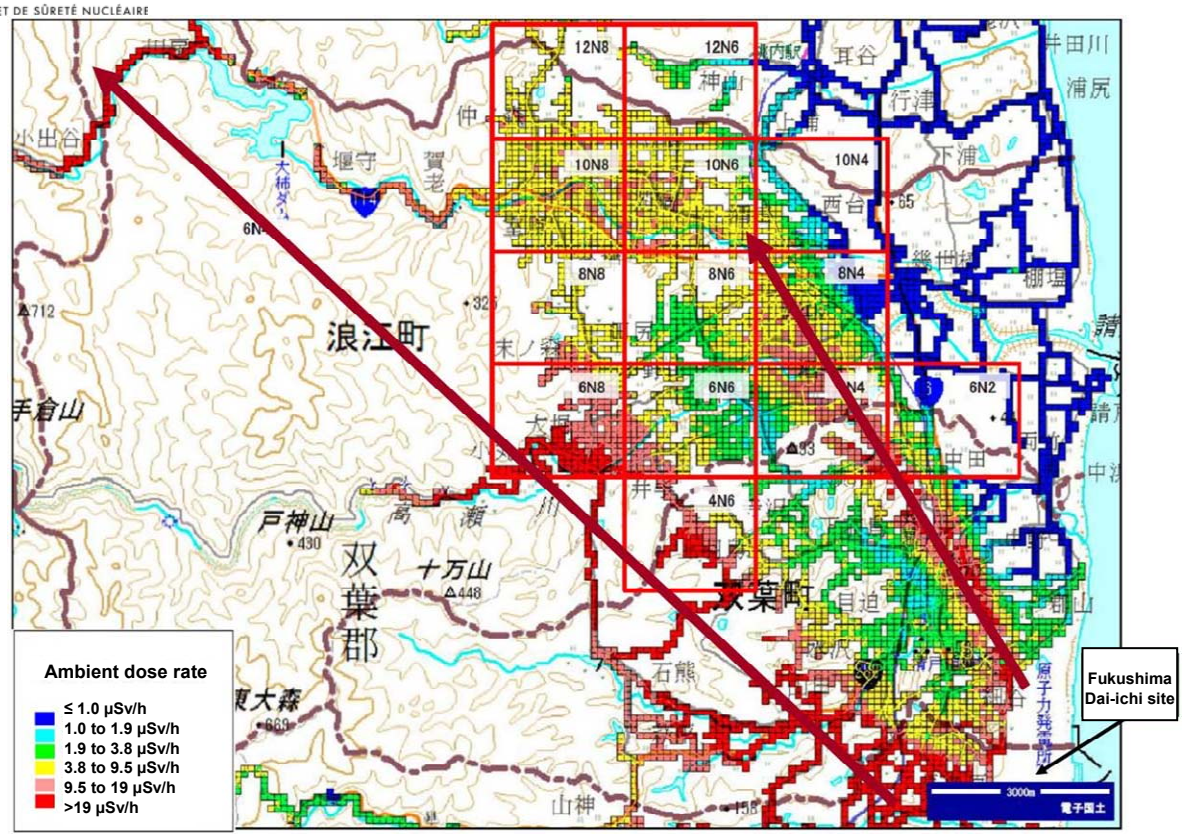


Figure 6-20 - Detailed map of the ambient dose rate northwest of the Fukushima Dai-ichi plant, produced using the results of measurement taken by instruments installed on cars between November 2011 and January 2012 (source Japanese Ministry of the Environment). The arrows show the directions of the main cloud of radioactive fallout (headed northwest) and a secondary cloud headed in a north by northwest direction.

6.2.2.2 Map of the surface depositions of radioactive cesium

As of late April 2011 cesium-134 and cesium-137 became the two prevailing radionuclides in the radioactive fallout from the Fukushima accident. As indicated in Section 6.2.3.4, their proportion in the total fallout increased as the short-lived radionuclides gradually disappeared. After December 1, the activity of these two radionuclides accounted for nearly 99% of the total activity of the residual fallout.

After continuing the airborne measurement surveys mentioned previously, MEXT published an updated version of the map of the cumulative surface activities of cesium-134 and cesium-137 in the northern portion of Honshu island (Figure 6 21-a). Similar maps have been produced for just cesium-134 and cesium-137 (Figure 6 21-b) since, within a few years, cesium-137 will make up the vast bulk of the residual fallout in Japan (94% of the activity of the residual fallout in 2020)

Because radioactive cesium emits gamma radiation and is predominant in the fallout, it is the main cause of the rise in the ambient dose rate mapped in Japan (see Figure 6-17). The results of in-field measurements conducted in June and July in order to check the representativeness of the fallout maps produced using airborne measurements enabled MEXT to draw a relatively satisfactory correlation between the ambient dose rate and the total surface activity of cesium-134 and cesium-137. Fallout of 276,000 Bq/m^2 would therefore correspond to an increase in the ambient dose rate of 1 µSv/h (July 2011). Due to the 20% decrease in the ambient dose rate between April and July, caused by the gradual disappearance of the short-lived radionuclides (see Section

6.2.2.1), this correlation value published by MEXT is consistent with what IRSN had estimated in its report[16] published on May 23, 2011, i.e. 300,000 Bq/m^2 for 1 µSv/h in late April.

These maps also confirm that, outside the main fallout zone (located less than 80 km from the Fukushima Dai-ichi plant), significant amounts of lower-level fallout also formed along the direction of the main fallout zone and even beyond, in the form of isolated spots (leopard-spot distribution). Outside Fukushima prefecture, the surface activity of cesium-134 and cesium-137 is generally below 100,000 Bq/m^2, except in a few areas where it can be as much as 300,000 Bq/m^2. These levels are comparable with those observed in Sweden, Austria and other countries in Europe after the Chernobyl accident. These secondary fallout zones are located primarily in Tochigi, Gunma and Ibaraki prefectures, northern Chiba, and the borders Miyagi prefecture shares with Fukushima and Iwate prefectures.

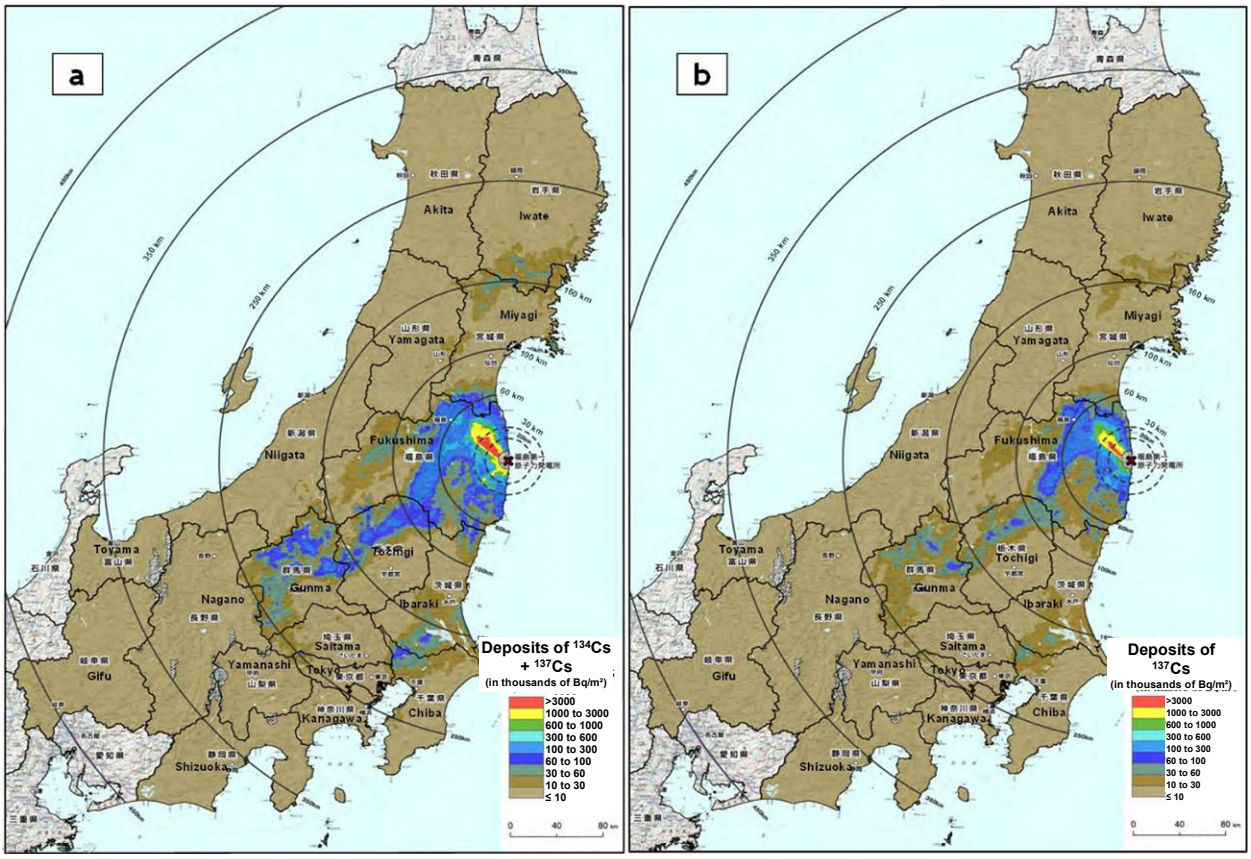


Figure 6-21 – Map of the cumulative deposition of cesium-134 and cesium-137 (a) and cesium-137 (b) published by MEXT following airborne measurement surveys conducted since late June 2011.

At the scale of the available maps, it appears that the other mapped prefectures either were spared from any fallout or received low amounts of fallout containing radioactive cesium with a surface activity of no more than 10,000 Bq/m^2 (as was the case in most of France, except for its eastern part, after the Chernobyl accident).

The airborne surveys conducted over the summer also made it possible to refine the map of cesium deposition in Fukushima prefecture (Figure 6-22). As for the neighboring prefectures, this map shows secondary fallout zones in the west, also in the form of leopard spots, with surface activities of several dozen becquerels per square meter.

[16] Rapport IRSN DRPH n°2011-10 « Évaluation au 66ème jour des doses externes projetées pour les populations vivant dans la zone de retombée nord-ouest de l'accident nucléaire de Fukushima »

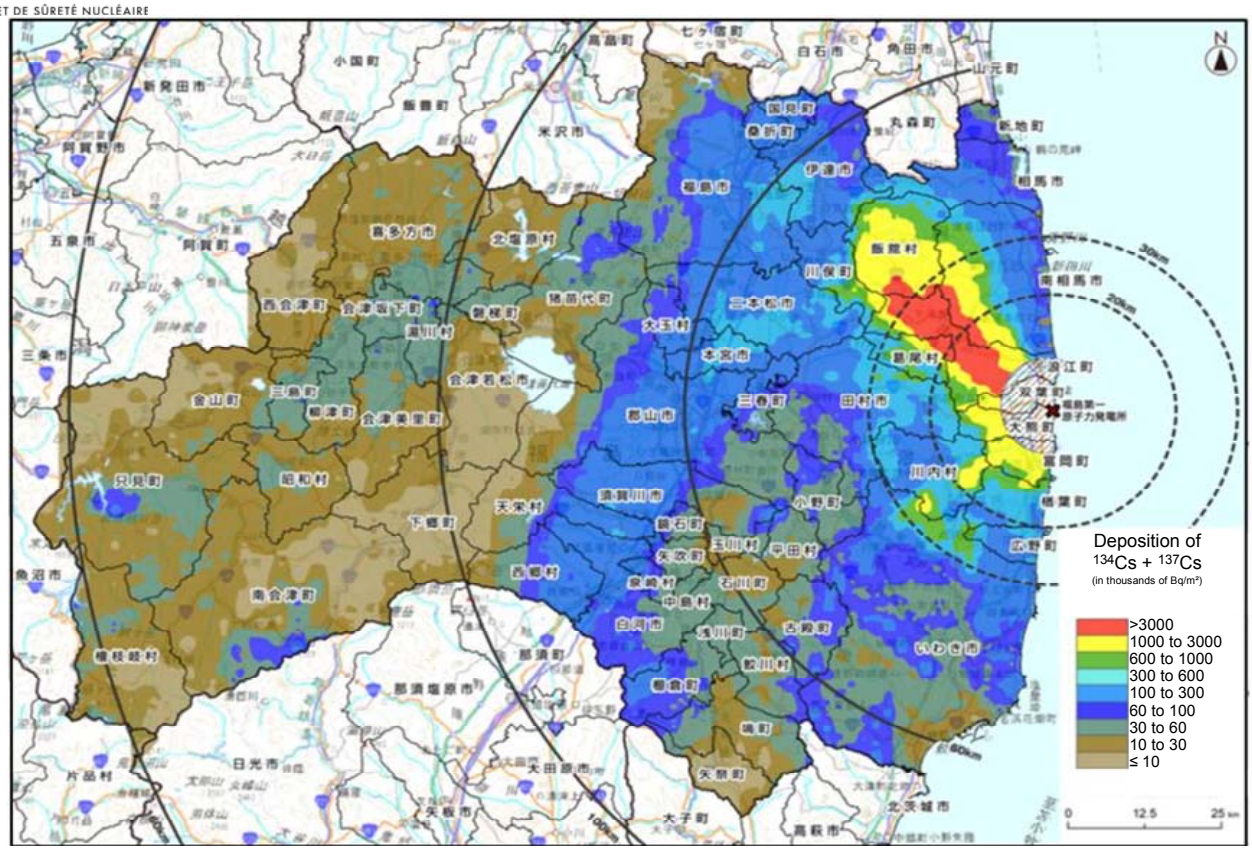


Figure 6-22 - Updated version of the map of the cumulative deposition of cesium-134 and cesium-137 in Fukushima prefecture published by MEXT.

In late August 2011 MEXT also published maps of radioactive cesium-137 fallout (Figure 6-23) which superimpose the map of the surface activities of cesium-137 determined from airborne measurements of the gamma radiation emitted by the fallout (colored zones in the background) and the results of the measurements of the activity in soil (first 5 cm) obtained during sampling surveys conducted at 2,200 points by a consortium of Japanese universities between June 6 and July 8 (colored dots). The results of these measurements have been normalized to June 14, taking into account the radioactive decay of the radionuclides.

Superimposing these two sources of results shows a good overall consistency of the mapping of fallout at this scale.

These maps also raise the following comments:

Inside the 20-km zone that was evacuated immediately after the accident occurred, the surface activities of cesium-137 measured on the soil samples vary between less than 30 kBq/m^2 and 15,000 kBq/m^2, or a difference of a factor of 500 between the extreme values. Of the more than 100 sampling points in this zone, 11 measured a surface activity of cesium-137 of more than 3,000 kBq/m^2. The highest activities were observed immediately west of the plant (dot inside of a black circle on the map in Figure 6-23): 14,000 kBq/m^2 of cesium-134 and 15,000 kBq/m^2 of cesium-137.

In the planned evacuation zone set up on April 22 (pink area on Figure 6-23, and spanning the municipalities of Iitate, Katsurao and portions of Namie, Kawamata and Minamisōma), the surface activities of cesium-134 and cesium-137 range between less than 60 kBq/m^2 and 8,000 kBq/m^2. Of the more than 100 sampling points in this zone, three measured a surface activity of cesium-137 of more than 3,000 kBq/m^2.

Apart from these two zones, the cumulative surface activities of cesium-134 and cesium-137 do not exceed 600 kBq/m^2, except 20-30 km to the southwest (Figure 6-22).

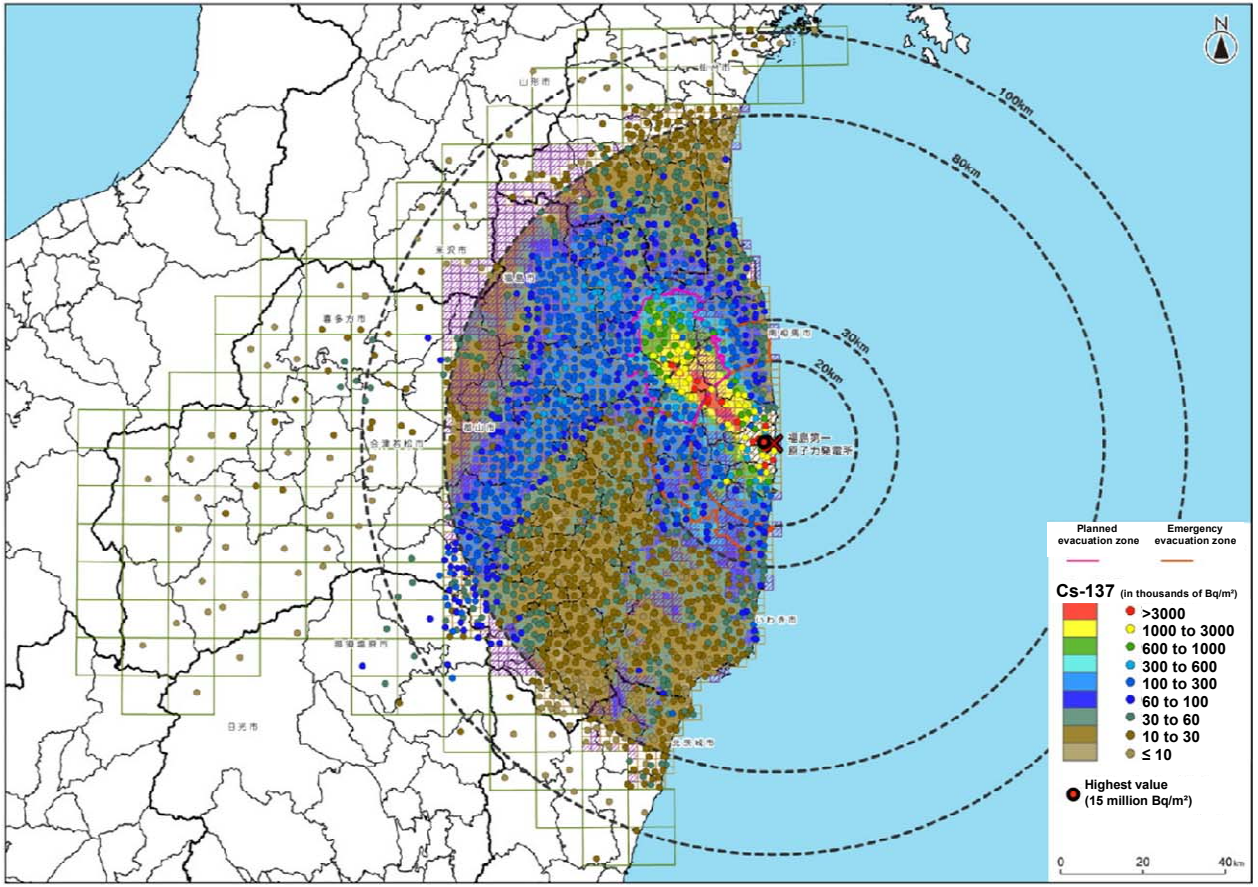


Figure 6-23 - Map of the surface activities of cesium-137 published by MEXT (normalized to June 14, 2011). Colored zones: based on airborne measurements of ambient gamma radiation (MEXT). Colored dots: based on measurements of samples (first 5 cm of soil). Black circle: highest cesium-137 reading.

Using the cesium-137 fallout maps published in the fall of 2011 by MEXT, IRSN estimated the surface areas of the affected areas based on the extent of the fallout. It excluded the area nearest to the Fukushima Dai-ichi plant (within a 9-km radius and with an area of 133 km^2), which was not mapped at this scale. Under to its estimates :

- altogether, the surface area of the areas where cesium-137 fallout from the Fukushima accident has been identified (surface activity exceeding 10,000 Bq/m^2) is estimated to be in the region of 24,000 km^2. 420 km^2 of this zone is located 250-300 km away from the crippled plant, corresponding to the maximum spread of the radioactive fallout;
- the surface area of the zones with the highest amount of fallout (surface activity of cesium-137 exceeding 1 million Bq/m^2) is estimated to be 262 km^2 (and nearly 400 km^2 if the 9-km zone is assimilated with a high-deposition zone) northwest of the crippled plant. The fallout in at least 60 km^2 of this zone is estimated to exceed 3 million Bq/m^2;
- all the zones where the cesium-137 fallout exceeds 300,000 Bq/m^2 are less than 50 km from the plant. As a result, the cesium-137 fallout is between 600,000 and 1 million Bq/m^2 across a 225 km^2 area and between 300,000 and 600,000 Bq/m^2 across a 379 km^2 area;
- the chart in Figure 6-24 shows, by amount of surface activity, the surface area proportions that were affected by the fallout. As expected due to the atmospheric dispersion of the releases that deposited this fallout, the larger the surface area, the less the amount of fallout.

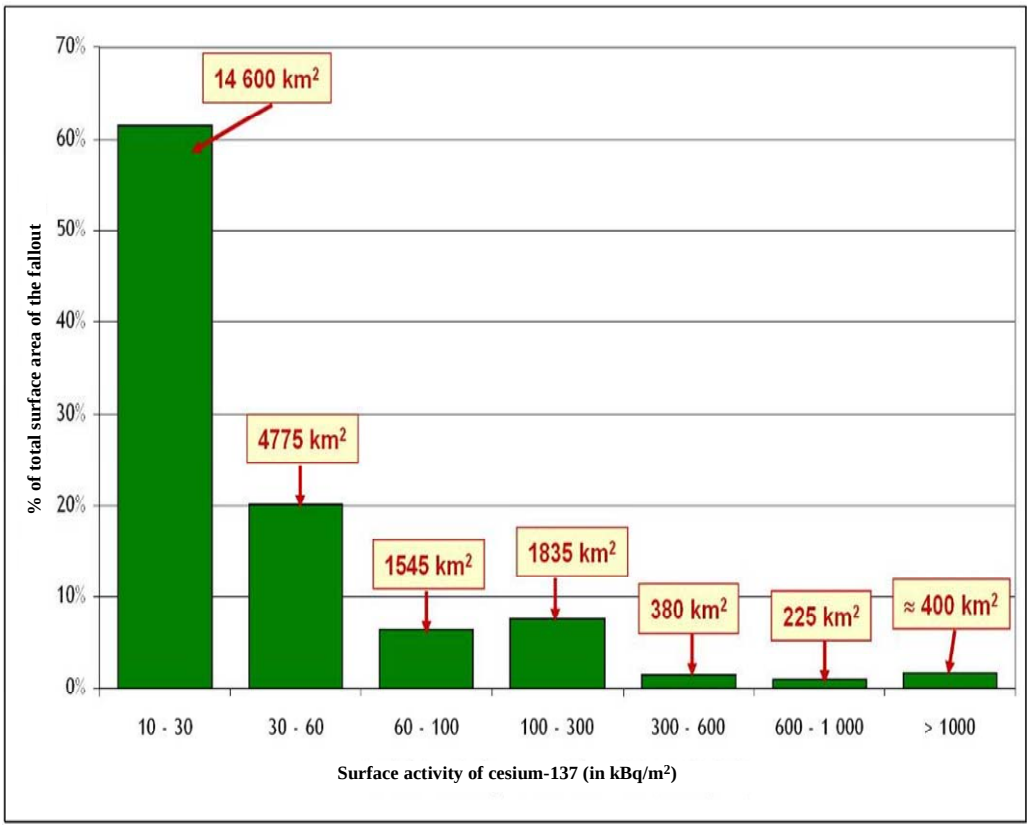


Figure 6-24 – Proportion of surface area affected by the cesium-137 deposits as a function of the amount of this fallout (assuming that the fallout in the 9-km area is highest overall)

Table 6-II below compares the surface areas contaminated after the Fukushima and Chernobyl accidents. For the same level of contamination, clearly smaller surface areas were affected in Japan than in Ukraine. This is explained in particular by the fact that a major portion of the releases from the Fukushima accident drifted over the Pacific Ocean, leaving no residual fallout. Compared to the 13,000 km^2 of land around Chernobyl, only around 600 km^2 of land in Japan – or 20 times less than in Ukraine – is contaminated by more than 600,000 Bq/m^2 of cesium-137 (including the land located within the 20-km zone). However, as IRSN indicated in May 2011, in addition to the 80,000 residents evacuated as an emergency measure in the 20-km zone, a population of 70,000 lives in these areas. In all, this amounts to more than half the number of people who were living in the most heavily contaminated areas around Chernobyl (270,000 people for cesium-137 fallout measurements greater than 555,000 Bq/m^2).

Table 6-II – Comparison of surface areas contaminated in Japan (IRSN assessments, based on MEXT maps) and in Ukraine after the Chernobyl accident.

Chernobyl accident		**Fukushima accident**	
^{137}Cs fallout measured in 1986-87	**Surface area by country**	**^{137}Cs fallout measured in summer 2011**	**Surface areas**
Exclusion zone		*Exclusion zone (20 km)*	
Circle with a 30 km radius	around 2,800 km^2	Semi-circle with a 20 km radius	around 600 km^2
outside exclusion zone		*Outside exclusion zone (20 km)*	
More than 1,480 kBq/m^2	Russia: 300 km^2 Belarus: 2,200 km^2 Ukraine: 600 km^2 Other countries: /	More than 1,000 kBq/m^2	Japan: 170 km^2
555 to 1,480 kBq/m^2	Russia: 2,000 km^2 Belarus: 4,000 km^2 Ukraine: 1,000 km^2 Other countries: /	600 to 1,000 kBq/m^2	Japan: 150 km^2
37 to 555 kBq/m^2	Russia: 56,000 km^2 Belarus: 40,000 km^2 Ukraine: 40,000 km^2 Other countries: 45,000 km^2	30 to 600 kBq/m^2	Japan: 8,200 km^2

6.2.3. ISOTOPIC COMPOSITION OF THE FALLOUT, CHANGES OVER TIME AND SPATIAL VARIATIONS

The isotopic composition of the radioactive fallout from the Fukushima accident kept changing on account of the fast radioactive decay of the short-lived radionuclides (from a few hours to a few days). As illustrated by the series of measurements taken 30 km northwest of the Fukushima Dai-ichi plant (along the limits of Namie and Iitate) from March 18 to April 5 (Figure 6-25), this fast decay had a direct effect on the trend toward a decrease in the ambient dose rate from radioactive fallout. The decay began to slow down in mid-April when the radionuclides with very short half-lives, initially abundant in number, had virtually disappeared.

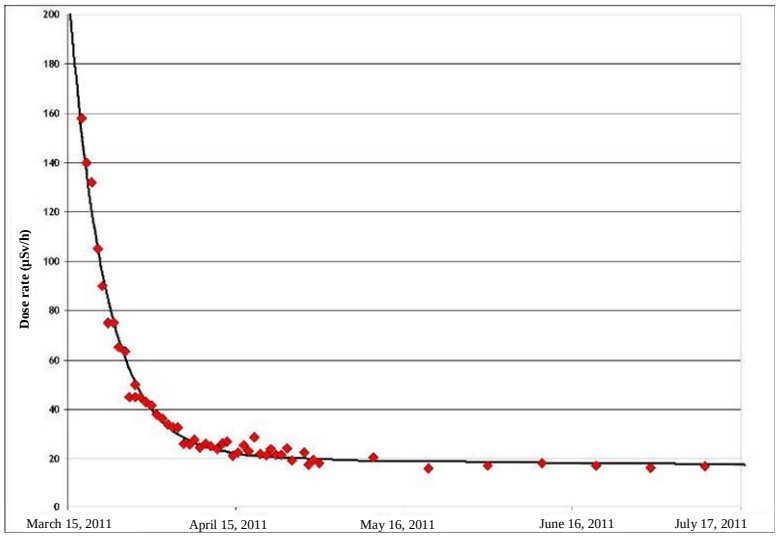


Figure 6-25 – Evolution in the ambient dose rate due to radioactive fallout, measured in Namie (Akougi Teshichiro), 31 km northwest of the plant (MEXT measurement point #32).

For this reason, measurements taken on soil samples (or samples of plants that had received fallout) during the second half of March or throughout April are what provided the most complete information on the initial isotopic composition of the radioactive fallout. In order to compare the measurement results obtained on samples collected at different dates, the values should be corrected by the radioactive decay of each identified radionuclide by normalizing them to the same date. Given that the main fallout formed during the night of March 15-16, 2011 (see Section 6.2.4), the convention adopted for the purposes of comparing the results was to normalize all values to March 15.

The results obtained from soil samples collected in Japan were regularly published by MEXT in 2011. IRSN also analyzed samples sent to it. In France, ACRO[17]also performed many measurements on samples from Japan.

6.2.3.1 Measurements taken by IRSN on a soil sample from Iitate Maeta

IRSN analyzed a topsoil sample (first 2 cm) collected on March 31 in Iitate Maeta, located some 40 km northwest of the Fukushima Dai-ichi plant (50 g sample provided by ACRO; see map in Figure 6-26 for the location). Gamma-emitting radionuclides as well as strontium-90 (a pure beta source) were quantified in these samples. The results are given in Table 6-III below. Iodine-131 is the most abundant radionuclide, followed by cesium-137 and cesium-134, which have similar activities. Generally speaking, volatile radionuclides (iodines, cesiums and telluriums) predominate. Semi-volatile elements (barium, lanthanum, silver, strontium) account for less than 1% of the total activity of the sample. The reason for this is that the conditions of the releases during the accident (depressurization of the containments of the three damaged reactors) were very different from those during the Chernobyl accident (the explosion of the reactor released significant quantities of semi-volatile or non-volatile elements).

By adjusting the isotopic composition of the analyzed sample in order to normalize it to the date of the formation of the radioactive fallout, which was estimated at March 15, it became clear that iodine-131 and the[18] tellurium-132/iodine-132 pair were largely prevalent. At that time, their activity accounted for more than 80% of the total activity of the initial fallout at this point (also see Figure 6-29), with around eight times more iodine-131 and six times more tellurium-132/iodine-132 than cesium-137. These values are consistent with the isotope ratios deduced from the source term estimated by IRSN for reactor 2 (responsible for the bulk of the contamination in this area) and which are 9 for iodine-131, 8 for iodine-132 and 5 for tellurium-132.

[17] Association pour le Contrôle de la Radioactivité dans l'Ouest (Association for Radioactivity Monitoring in Western France).
[18] Because iodine-132 is produced by the radioactive decay of tellurium-132 and has a half-life that is much shorter than that of its parent, both radionuclides are always found together in the environment at relatively similar levels on account of the quasi-equilibrium between their activities. The same is true of the barium-140/lanthanum-140 pair and the tellurium-129m/tellurium-129 pair, although, in the case of the latter, the equilibrium activity of tellurium-129 accounts for only 63% of the activity of its parent element (tellurium-129m), which has two modes of radioactive decay.

Table 6- III - Results of measurements of the specific activity of radionuclides found in a topsoil sample collected on March 31 in Iitate Maeta (at point [Acro] on the map in Figure 6-26) and estimation of the corresponding activities on the assumed date of formation of the radioactive fallout.

Radionuclide (half-life)	Specific activity on the sampling date (March 31, 2011) (Bq/kg)	Specific activity normalized to the assumed date of formation of the fallout (March 15, 2011) (Bq/kg)
Iodine-131 (8 days)	86,680	345,345
Iodine-132 (2.3 hours)	7,084	≈'250,000
Cesium-137 (30.1 years)	44,362	44,407
Cesium-134 (2.1 years)	45,343	46,003
Cesium-136 (13.2 days)	4,442	10,317
Tellurium-129m (33.6 days)	34,472	47,953
Tellurium-129 (1.2 hours)	21,692	≈'30,000
Tellurium 132 (3.2 days)	7,961	253,652
Barium-140 (12.7 days)	859	2,057
Lanthanum-140 (40.2 hours)	1,128	≈'2,000
Silver-110 m (249 days)	309	323
Strontium-90 (29.1 years)	33	33

6.2.3.2 Measurements regularly taken at various locations around the Fukushima power plant

In early June 2011 MEXT published the results of measurements of radioactivity in soil samples collected at more than 100 points located within 20-62 km of the Fukushima Dai-ichi plant (a few are depicted on the map in Figure 6-26).

The point where the highest specific activities were measured was in Namie (place name: Akougi Kunugidaira; see point on map [83]), around 24 km from the power plant. The chart in Figure 6-27 shows the evolution in the specific activities measured in soil collected in Namie (approx. first 5 cm). The activity of cesium-134 and cesium-137 is very high (several hundred thousands of Bq/kg). The activity of iodine-131 was at the same level in early April, but steadily decreased to reach, as expected, a 100 times lower value in late May. At this measurement point, there may have been around seven times more iodine-131 than cesium-137 in the initial fallout (March 15 estimate). The results published by MEXT for samples collected in May also provide indications for tellurium-129m (activity slightly lower than 100,000 Bq/kg) and cesium-136 (activity around 1,000 Bq/kg), and reveal the presence of semi-volatile radionuclides (strontium-89 and strontium-90, silver-110m, lanthanum-140, niobium-95) with activities ranging from a few hundred to nearly 1,000 Bq/kg.

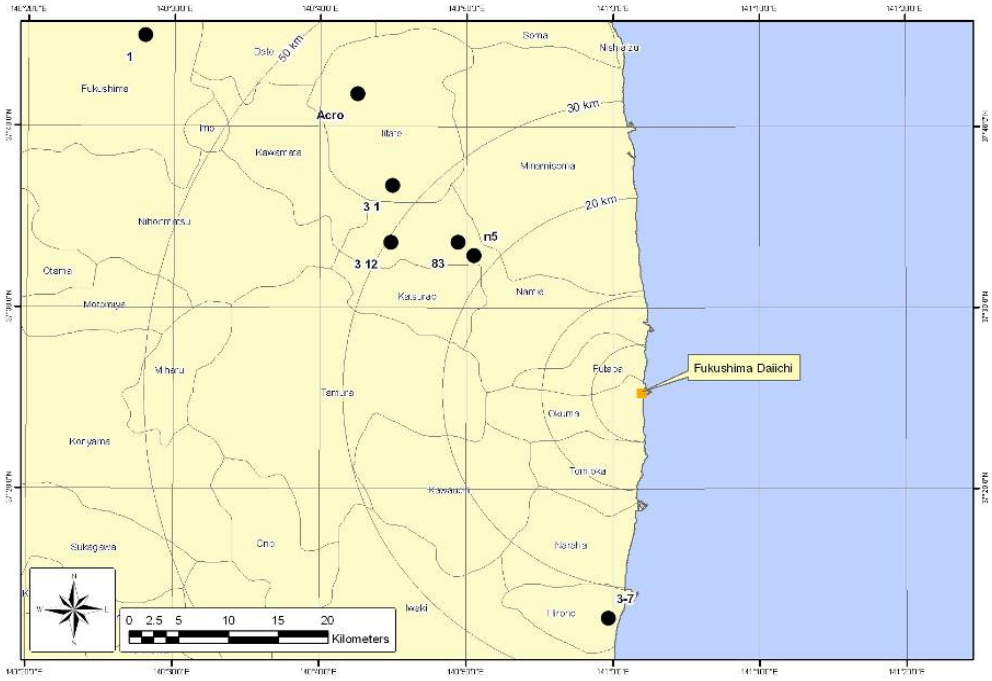


Figure 6-26 - Locations of a few of the points where soil samples were regularly collected and sampled by Japanese laboratories ([1], [3-1], [3- 12], [83], [n5] and [3-7]) and of the soil sample analyzed first by ACRO then by IRSN.

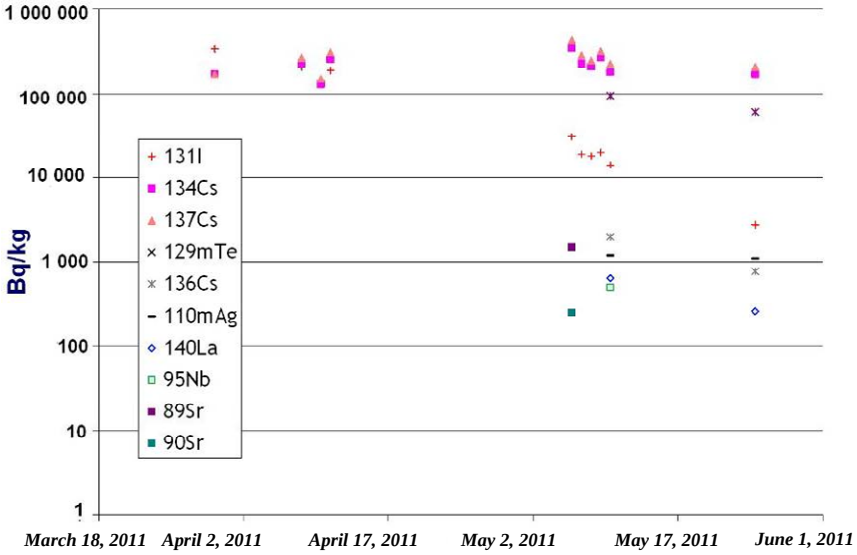


Figure 6-27 – Evolution in the specific activity in topsoil samples collected in Namie (point 83).

A soil sample collected on June 13 in Namie at location [n5] and measured on June 14 by the JAERI[19] yielded the specific activities indicated in Table 6-IV. At this date, the radionuclides with very short half-lives (tellurium-132, iodine-132) were no longer detectable and the ambient dose rate due to the gamma radiation emitted by the residual radioactive fallout was 34 µSv/h (i.e. more than 500 times the normally measured value). The specific activities estimated for the assumed fallout formation date (March 15) are virtually 10 times higher than those of the sample collected in Iitate Maeta (identified as [Acro]) and analyzed by IRSN. The isotope ratios normalized to cesium-137 are similar for these two sites: 8 for iodine-131 and 0.87 for cesium-134.

[19] Japan Atomic Energy Research Institute

Table 6-IV - Results of measurements of the specific activity of radionuclides found in a topsoil sample collected on June 13 in Namie at point [n-5] and estimation of the corresponding activities on the assumed date of formation of the radioactive fallout.

Radionuclide (half-life)	Specific activity on the sampling date (June 13, 2011) (Bq/kg)	Specific activity normalized to the assumed date of formation of the fallout (March 15, 2011) (Bq/kg)
Iodine-131 (8 days)	1,300	3.096 152
Iodine-132 (2.3 hours)	< detection limit	Inestimable
Cesium-137 (30.1 years)	420,000	422,397
Cesium-134 (2.1 years)	340,000	368,808
Cesium-136 (13.2 days)	510	58,383
Tellurium-129m (33.6 days)	78,000	499,373
Tellurium-129 (1.2 hours)	50,000	≈'315,000
Tellurium 132 (3.2 days)	< detection limit	Inestimable
Barium-140 (12.7 days)	Undetermined	Inestimable
Lanthanum-140 (40.2 hours)	220	≈'30,000
Silver-110 m (249 days)	1,600	2,056
Niobium-95 (35 days)	430	2,556

The other sampling points northwest of the plant show evolutions comparable to those observed at the Namie station, but with different specific activities (in reference to cesium-137): several tens of thousands of Bq/kg at points [3 1] in Iitate (place name: Nagadoro) and [3 12] in Namie (place name: Tsushima), and around 10,000 Bq/kg in Fukushima City (place name: Sugitsuma, point [1]). In this last place, strontium-90 was measured at a concentration of about 10 Bq/kg; in early June, the iodine-131 concentration in the same place was around 100 Bq/kg.

6.2.3.3 Case of plutonium

In late September 2011, MEXT published a memo reporting the results of plutonium (and strontium) measurements in soil samples collected between June 6 and July 8 within an 80-km radius around the Fukushima Dai-ichi plant. The results (expressed in surface activity in the soils, in Bq/m^2) were plotted on a map (an excerpt is provided in Figure 6-28). These results relate to plutonium-238 (^{238}Pu; half-life of 87.7 years) and plutonium-239 and plutonium-240 combined[20] ($^{239+240}$Pu; half-lives of 24,100 years and 6,564 years, respectively).

Interpreting the results obtained is not task, for these plutonium isotopes were already present in Japan's soil before the Fukushima accident. According to MEXT, the mean surface activities throughout Japan, estimated using measurement results obtained between 1999 and 2008, were 0.498 Bq/m^2 and 17.8 Bq/m^2 for ^{238}Pu and $^{239+240}$Pu, respectively, with peak values of 8 Bq/m^2 and 220 Bq/m^2, respectively. Despite a certain degree of dispersion of these values, the activity ratio of ^{238}Pu/$^{239+240}$Pu, which is 0.0261 in Japan, can be considered as characteristic of the persistence of fallout from atmospheric nuclear weapons tests (however, the Japanese data shows that, before the Fukushima accident, this ratio could be up to 10 times higher for some results).

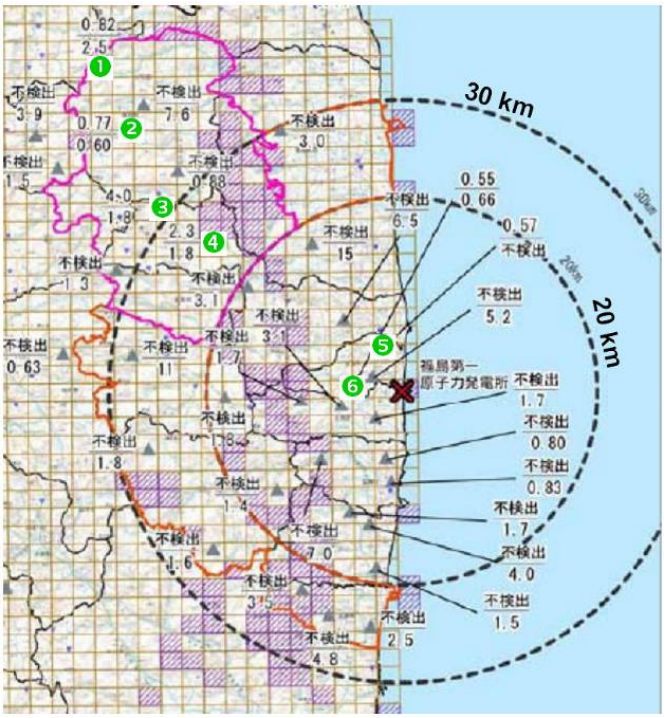


Figure 6-28 – Locations of the plutonium measurement points around Fukushima Dai-ichi (adapted map taken from the map published by MEXT on September 30, 2011). For each point, the top result refers to ^{238}Pu and the bottom result to $^{239+240}$Pu. The surface activity values in Bq/m^2 are normalized to June 14, 2011.

The numbers in the green circles indicate points where the measured surface activity of ^{238}Pu exceeded the detection limit; the results are given in Table 6-IV.

The map published by MEXT shows 64 measurement points within an 80-km radius. Six of these points show a surface activity of ^{238}Pu above the detection limit of the measurement technique used, which, according to MEXT, is 0.5 Bq/m^2. These six points are shown on the map in Figure 6-28 and the results are given in Table 6-V.

[20] As ^{239}Pu and ^{240}Pu emit similar levels of alpha radiation, the alpha spectrometry measurements do not make it possible to quantify the activity of these radionuclides separately. This is why the results are provided for both radionuclides combined.

Table 6-V – Results of the surface activity measurements of ^{238}Pu and $^{239+240}$Pu for the six points shown on the map in Figure 6-28. The result at point 5 for $^{239+240}$Pu is below the detection limit (< DL) of around 0.5 Bq/m^2. Under these conditions, the ^{238}Pu/$^{239+240}$Pu ratio for this point is necessarily above 1.

Point No.	^{238}Pu in Bq/m²	$^{239+240}$Pu in Bq/m²	^{238}Pu/$^{239+240}$ratio
1	0.82	2.5	0.328
2	0.77	0.6	1.283
3	4	1.8	2.222
4	2.3	1.8	1.278
5	0.57	< DL	> 1
6	0.55	0.66	0.833

For all 64 measurement points, the results for $^{239+240}$Pu range between 0.44 (or the detection limit) and 7 Bq/m^2, corresponding to the residual background noise from fallout from nuclear testing. For the six points where ^{238}Pu was detected, the surface activities range from 0.55 to 4 Bq/m^2 and the ^{238}Pu/$^{239+240}$Pu ratio is between 0.33 and 2.2, far higher than the characteristic ratio for fallout from atmospheric nuclear weapons tests. To confirm this observation, IRSN measured the plutonium in the soil sample from Iitate Maeta provided by ACRO (see above). The specific concentrations of ^{238}Pu and $^{239+240}$Pu are 0.33 and 0.41 Bq/kg fresh weight, respectively, yielding a ^{238}Pu/$^{239+240}$Pu ratio of 0.8 that is fully comparable to those determined using the results published by MEXT. **These results therefore show that plutonium was released during the Fukushima accident**. More specifically, the fact that all these values were obtained at points located within the main fallout zone extending to the northwest makes it possible to attribute this plutonium to releases from reactor 2 after its containment was damaged by the hydrogen explosion on March 15. **It should be noted that the environmental impact of this release of plutonium is low, as no more than a few Bq/m^2 of fallout have been measured in Japan. This is much lower than the fallout measured around Chernobyl, where the surface activity of $^{239+240}$Pu exceeds 3,700 Bq/m^2 over a distance of more than 30 km and is even as high as several hundred thousand Bq/m^2 within a few kilometers of the plant.**

The highest values for ^{238}Pu were measured more than 20 km from the Fukushima Dai-ichi plant, at points 3 and 4 northwest of Namie and south of Iitate. They are most likely due to the wet deposition that must have been heavy in this area, as shown on the fallout map in Figure 6-23.

6.2.3.4 Change over time in the activity and isotopic composition of radioactive fallout in Japan

The activity and isotopic composition of the fallout are influenced by two main phenomena:

- radioactive decay of the radionuclides;
- deposition of fresh atmospheric fallout of radionuclides due to continuing small releases from the Fukushima Dai-ichi plant.

Other phenomena, such as migration into deep soil layers and surface erosion caused by wind or runoff, may have also come into play. However, their influence on the temporal evolution of the fallout must have been generally low during the first year. As a result, it is difficult to quantify.

- **Effect of radioactive decay**

As shown by the results in Tables 6-III and 6-IV as well as the chart in Figure 6-25, the radionuclides making up the fallout decayed at a particularly fast rate in the first few weeks after their formation. To illustrate, the chart in Figure 6-29 shows the decrease in activity of a contaminated soil having the same isotopic composition as the Iitate Maeta sample analyzed by IRSN (Table 6-VI).

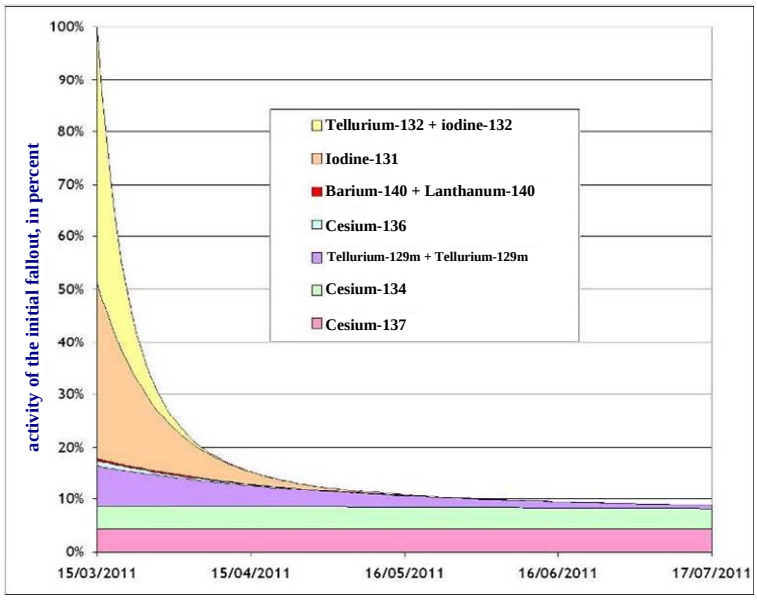


Figure 6-29 – Evolution in the activity of the main radionuclides in the fallout, deduced from the analysis performed by IRSN on a topsoil sample collected on March 31, 2011, in Iitate Maeta (Table 6-III).

This chart shows the same kinetics of radioactive decay for the fallout as that for the ambient dose rate measured in the same sector (Figure 6-25). As of April 5, the total radioactivity of the residual fallout amounted to less than 20% of the initial activity on March 15. This rapid decrease is a clear illustration of the fact that the bulk of radioprotection measures in Japan were carried out in the first month after the accident in order to protect the public as much as from doses potentially received through external exposure to the fallout as from the risk of contamination of plant-based (leafy vegetables) and animal-based (milk) foodstuffs produced in the areas that received the radioactive fallout (see Sections 6.3 and 7).

This chart also shows the respective contributions of the various radionuclides in the fallout. The tellurium-132/iodine-132 pair initially accounted for nearly 49% of the activity of the fallout, but disappeared from the environment very quickly (less than 5% of the total activity of the residual fallout as of early April). Iodine-131 was the second main contributor to the activity of the fallout, accounting for as much as 40% of the activity at this location on March 23 (it will be seen later that the proportion of iodine-131 in the fallout varied by location), while the tellurium-132/iodine-132 pair accounted for just 21%. As of May 1, iodine-131 accounted for less than 5% of the activity of the fallout. In the following weeks, it virtually disappeared from Japan's environment except in areas with the highest fallout, where it remained measurable until summer 2011 (in late June, the residual activity of iodine-131 was 10,000 times lower than its initial activity)

The contribution of the tellurium-129m/tellurium-129 pair to the fallout increased with time, from 8% on March 15 to 26% on April 15, before itself dropping to less than 5% of the residual activity of the fallout August 1, 2011.

Although cesium-136 and the barium-140/lanthanum-140 pair were detected in the environment in the weeks following the accident, their contribution to the total activity of the fallout never rose above 1.7% and 0.7%, respectively, in early April. More generally, all the radionuclides detected in small amounts, regardless of their radioactive half-life, contributed – and will contribute – only marginally (less than 1%) to the activity of the fallout and thus the exposure of the population.

Although they accounted for just 9% of the initial activity combined, cesium-134 and cesium-137 make up most of the residual fallout in terms of time. As of May 20, they accounted for 80% of the activity of the fallout in Japan, which explains why they were the only radionuclides that appeared on fallout maps published in Japan. Due to its shorter half-life, cesium-134 decays at a noticeable rate. Its contribution to the fallout was at its maximum around mid-September 2011 (46%). Since then, it has continued to slowly decrease (43% one year after the accident) and will drop below 5% in March 2020, or nine years after the accident.

- **Deposition of fresh radioactive fallout**

Monitoring of the deposition rate continued in each prefecture in the months following the March phase of significant atmospheric releases responsible for the bulk of radioactive fallout found in Japan. MEXT published the results of this monitoring for three radionuclides (iodine-131, cesium-137, and cesium-134). These results show the persistence of low atmospheric deposition probably due to continued low-level releases from the Fukushima Dai-ichi plant and possibly resuspension in the air of previously deposited surface contamination. As a result, the deposition rate recorded on April 18-19 in two prefectures south of Fukushima prefecture rose to:

- 290 Bq/m^2 of ^{131}I and 160 Bq/m^2 of ^{137}Cs in the town of Hitachinaka (Ibaraki prefecture);
- 368 Bq/m^2 of ^{131}I and 137 Bq/m^2 of ^{137}Cs in the town of Saitama (Saitama prefecture).

At its highest, the daily deposition rate of iodine-131 was around a dozen Bq/m^2 in early May in the various towns where this radionuclide was being monitored. No traces of iodine-131 have been detected in any prefecture since late May (even with a detection limit lowered to 7 Bq/m^2/month, or 0.02 Bq/m^2/day).

The total daily deposition rate of cesium-134 and cesium-137 in Fukushima (Fukushima prefecture) varied greatly from day to day between May 2011 and February 2012, regularly reaching a few Bq/m^2/day and occasionally exceeding 100 Bq/m^2/day. IRSN considers that these values and their variations may be due to resuspension of previously deposited cesium, which can lead to air concentrations of a few mBq/m^3, followed by fresh surface deposition of variable amounts depending on the weather conditions of the day (higher fallout levels with rainfall). These variations in resuspension are too low to be observed by ambient dose rate measurement monitors.

The monthly deposition rates of cesium-134 and cesium-137 during fall 2011 were:

- around 4,000 Bq/m^2/month in Futaba (Fukushima prefecture) in the immediate vicinity of the plant;
- a few dozen Bq/m^2/month in Hitachinaka (Ibaraki prefecture) and Saitama (Saitama prefecture);
- a few Bq/m^2/month in seven other prefectures (Iwate, Yamagata, Tochigi, Gunma, Chiba, Tokyo, Kanagawa).

These deposition rates are low compared to the rates recorded in March. Due to the decay of the short-lived radionuclides described above, they do not compensate for the general decrease in the total surface activity initially deposited in March 2011.

6.2.3.5 Spatial variations in the isotopic composition of the fallout

Outside the main fallout zone located northwest of the plant, the fallout is lower and its isotopic composition is different. The activities measured on a soil sample collected on May 3 in the town of Hirono, 23 km south of the plant, are as follows:

- ^{131}I: 2,600 (Bq)/kg
- ^{134}Cs: 3,900 Bq/kg
- ^{137}Cs: 4,700 Bq/kg
- ^{89}Sr: 30 Bq/kg
- ^{90}Sr: 1.9 Bq/kg

The ambient dose rate measured at this point was 0.2 µSv/h. The fallout (in reference to cesium-137) is nearly 100 times lower than at station 83 in Namie, which is located at a comparable distance from the plant. On the other hand, projecting these results at the date of March 15 yields an iodine-131/cesium-137 ratio of 38, well above that observed at the high-fallout spot located northwest of the nuclear site (near 8). Further away, some 30 km south of the plant, the iodine-131/cesium-137 ratio on March 15 is estimated to be around 50.

IRSN collected and interpreted the results of specific activity measurements of iodine-131, cesium-134, cesium-136, cesium-137, tellurium-129m and silver-110m performed on soil samples collected starting in mid-March 2011. Published by MEXT, these results came from nearly 160 sampling points unevenly distributed within a semi-circle having a radius of 20-80 km around the crippled plant. Starting in mid-March 2011, one or more samples consisting of the first 5 cm of soil were taken at more or less frequent intervals at each point, yielding several hundred – if not several thousand – values for each of the six radionuclides. By adjusting the measured activities in order to normalize them to March 15 (date of formation of the main fallout), in view of the radioactive decay of the radionuclides, IRSN was able to estimate the initial specific activities for each radionuclide with a specific degree of uncertainty at each sampling point. These specific activities (Bq/kg fresh soil) were converted into surface activities (Bq/m^2).

IRSN used geostatistical analysis to estimate the spatial distribution of these specific activities within a spatial domain containing all the sampling stations and was able to deduce their activity ratios (in relation to cesium-137, the reference radionuclide) on March 15. The activity ratio values for each radionuclide were presented in the form of a statistical distribution in order to determine their mode or modes (i.e. the value or values most frequently found in the area being studied) and the standard deviations (Table 6-VI).

Table 6-VII - Law of distribution (mode±standard deviation) of the activity ratios (in reference to cesium-137) on March 15, 2011, within the 20-100 km radius around the Fukushima Dai-ichi site. The distributions of the isotope ratios for iodine-131 and tellurium-129m present two modes corresponding to two different geographic sectors.

^{134}Cs/^{137}Cs	^{136}Cs/^{137}Cs	^{131}I/^{137}Cs	^{129m}Te/^{137}Cs	^{110m}Ag/^{137}Cs
0.89±0.05	0.39±0.2	11.7±4.6 (northwest) 48.2±7 (south)	1.56±0.62 (northwest) 6.1±1.4 (south)	0.05±0.06

The most frequent values of the ^{131}I/^{137}Cs ratio range between 10 and 15 (11.7 mode) and relate to the heaviest fallout that formed on March 15 northwest of the crippled site. This means that the initial surface activities of iodine-131 within this zone were able to rise past 30,000 kBq/m² on March 15 (red area in Figure 6-23).

The map in Figure 6-30 shows significant variations in the ^{131}I/^{137}Cs activity ratio (on 15 March 15) based on the location. The ratio rose to its highest level south of the Fukushima Dai-ichi plant, ranging between 30 and 80 (corresponding to the second mode shown in Table 6-VII for iodine-131). In this sector, where the radioactive fallout was lower than in the northwest, the higher proportion of radioactive iodine could be explained by:

- different fallout formation conditions (predominance of dry deposition)
- differences in the physicochemical forms of iodine (gas or aerosol) in the air at the time of deposition;
- or differences in the isotopic composition of the subsequent releases emitted by the stricken reactors (the accident caused several puff releases from three different reactors; see Section 6.1.1).

This also means that if the residual fallout south of the Fukushima Dai-ichi plant is relatively lower, it is possible that the concentrations of radioactive iodine in the air may have been as high as in the northwestern sector in the hours following the radioactive releases, as IRSN's 2001 model of the atmospheric dispersion of releases also seems to show (see Section 6.1.2).

In late September 2011, MEXT published a map of the surface activity ratios of $^{131}I/^{137}Cs$ normalized to June 14 (Figure 6-31) based on the new soil surface activity measurement results (first 5 cm) obtained from samples collected at 2,200 points by a consortium of Japanese universities between June 6 and July 8, 2011. The colored dots on the map show the sampling points where iodine-131 was detectable on the analysis date. As expected, due to the radioactive decay of iodine-131, the values of the $^{131}I/^{137}Cs$ ratio are much lower than those estimated by IRSN for March 15, 2011. However, the geographic variability of these ratio values is consistent between both data sources.

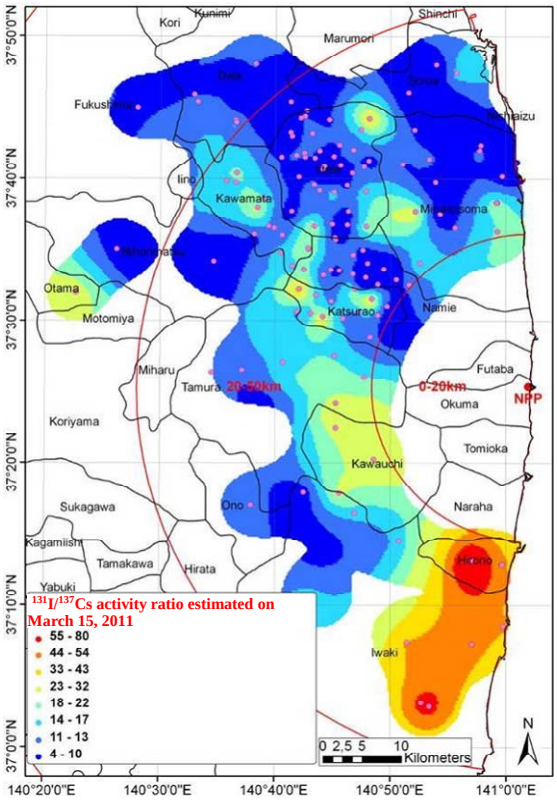


Figure 6-30 – Map showing the distribution of the ratio of the specific activities of $^{131}I/^{137}Cs$ in the soils around the Fukushima Dai-ichi plant on March 15, 2011 (date of formation of the main fallout) obtained by IRSN through geostatistical analysis of the measurement results published by MEXT. The pink dots show the soil sampling stations.

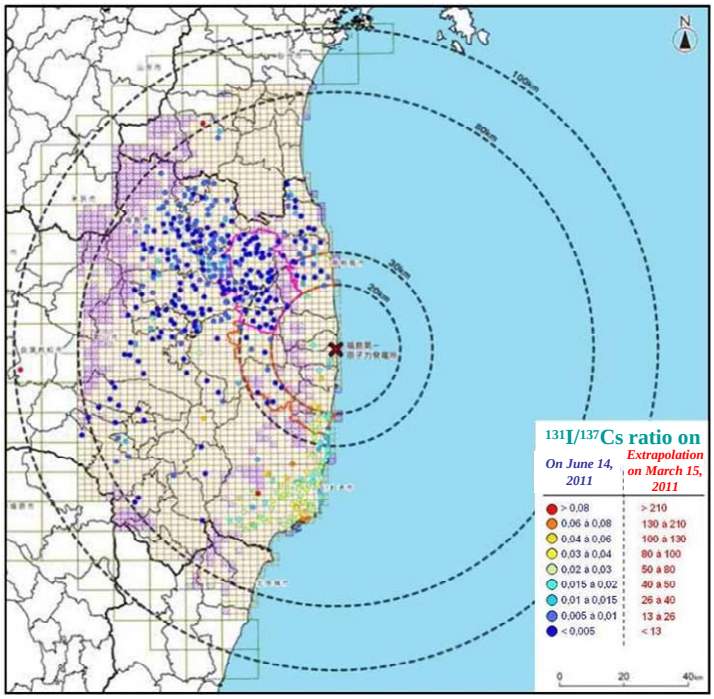


Figure 6-31 – Ratios of the surface activities of $^{131}I/^{137}Cs$ in the soils around the Fukushima Dai-ichi plant on 14 June 2011 (MEXT, from a survey conducted in June-July) and extrapolation on March 15, 2011.

In late October 2011, MEXT published two similar maps (Figure 6-32 and Figure 6-33), one for tellurium-129m and another for silver-110m, based on the same samples collected by the Japanese universities in June and July. Both maps also use cesium-137 as the reference and were normalized to June 14. As for iodine-131, the $^{129m}Te/^{137}Cs$ ratio is higher on along the coast south of the plant. In the case of silver-110, the ratio is higher along the entire coast both north and south of the plant.

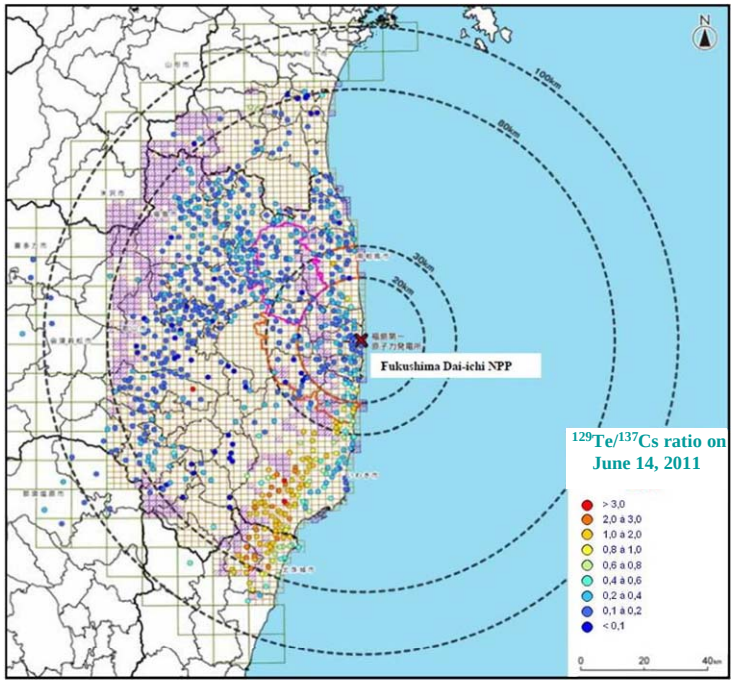


Figure 6-32 – Ratios of the surface activities of $^{129m}Te/^{137}Cs$ in the soils around the Fukushima Dai-ichi plant on 14 June 2011 (MEXT, from a survey conducted in June-July).

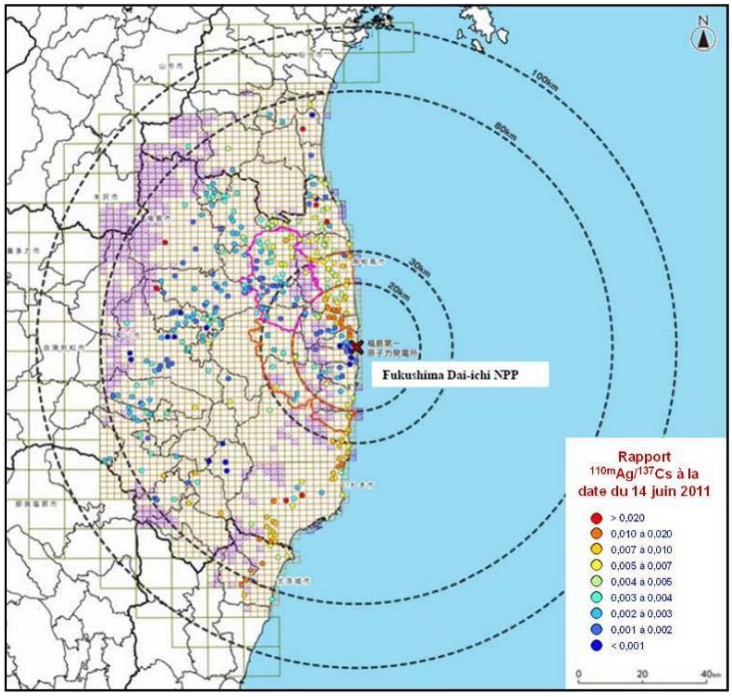
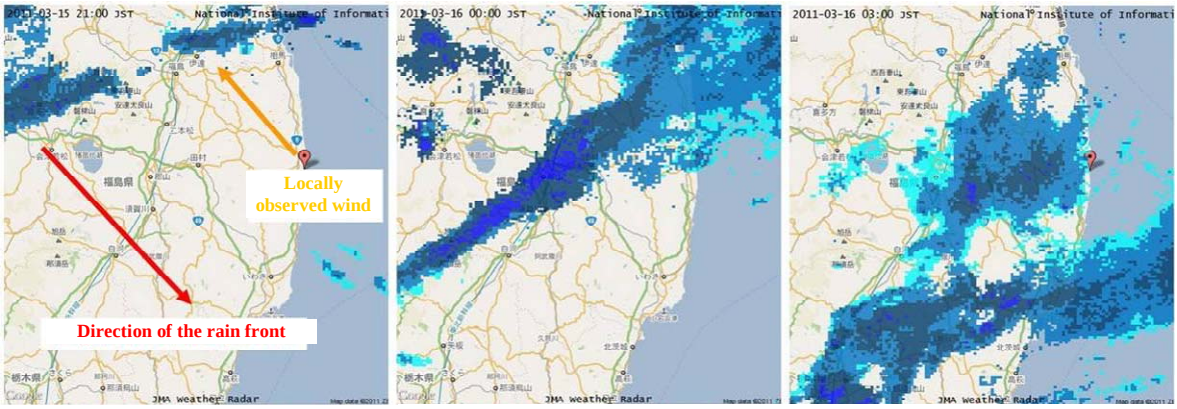


Figure 6-33 – Ratios of the surface activities of $^{110m}Ag/^{137}Cs$ in the soils around the Fukushima Dai-ichi plant on 14 June 2011 (MEXT, from a survey conducted in June-July).

6.2.4. INTERPRETATION OF THE SOURCE AND DISTRIBUTION OF RADIOACTIVE FALLOUT IN JAPAN

The two main events of dispersion of releases from the Fukushima Dai-ichi plant, on March 15-16 and March 21-23, coincided with more or less heavy rainfall (or snowfall in high-altitude areas). Thus, after interpreting the evolution over time of the ambient dose rate measured by the various monitors installed in Fukushima prefecture, IRSN considers that the main fallout zone northwest of the Fukushima Dai-ichi plant may have been created by the release of radioactive materials somewhere between 1:00 p.m. and 11:00 p.m. on March 15, 2011. These materials may have been carried towards the northwest during the period of heavy rainfall or snowfall, particularly over the village of Iitate (Figure 6-34 and Figure 6-35).



March 15 at 9:00 p.m. (local time) **March 16 at 12:00 a.m. (local time)** **March 16 at 3:00 a.m. (local time)**

Figure 6-34 - Movement of the rain/snow front during the night of March 15-16, 2011, in the Fukushima area (radar images).

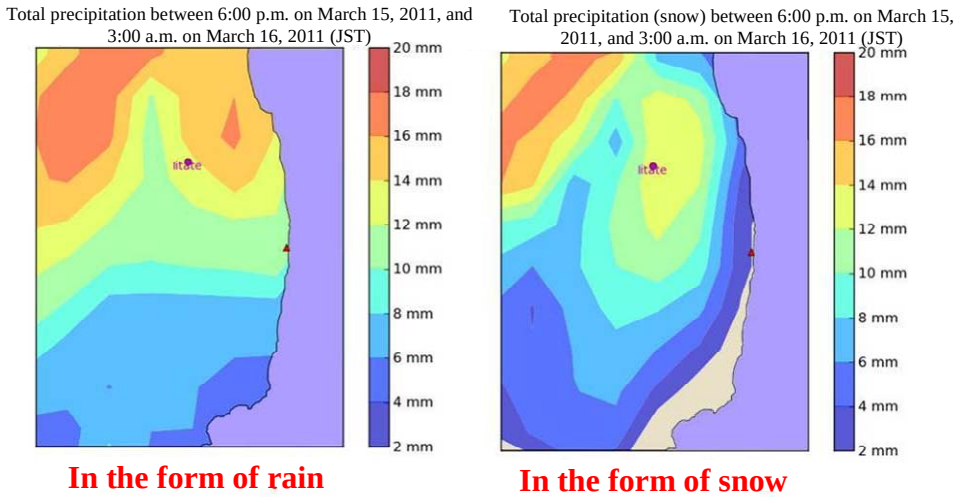


Figure 6-35 - Estimation of the total rainfall (map on left) and snowfall (map on right) during the night of March 15-16, 2011 (data from the European Center for Medium-Range Weather Forecasts [ECMWF] provided by Météo France).

Moreover, the scattered spots of fallout observed at a distance from the Fukushima Dai-ichi plant, in Fukushima prefecture and the other prefectures listed in section 6.2.2, corresponding to areas where the precipitation must have been heavier than elsewhere, with the total rainfall exceeding 100 mm locally when the releases were dispersed across Japan. The distribution of the fallout is also influenced by the conditions under which the radionuclides were dispersed in the air, particularly in the sector closest to the crippled plant, where the deposition, both dry and wet, reflects the footprint of the radioactive plume with a high concentration gradient.

In addition to these regional variations in the fallout, clearly illustrated by the maps obtained after the airborne measurement surveys, the local distribution of fallout can also be highly variable between the plant cover and the soil, as illustrated by Figure 6-36.

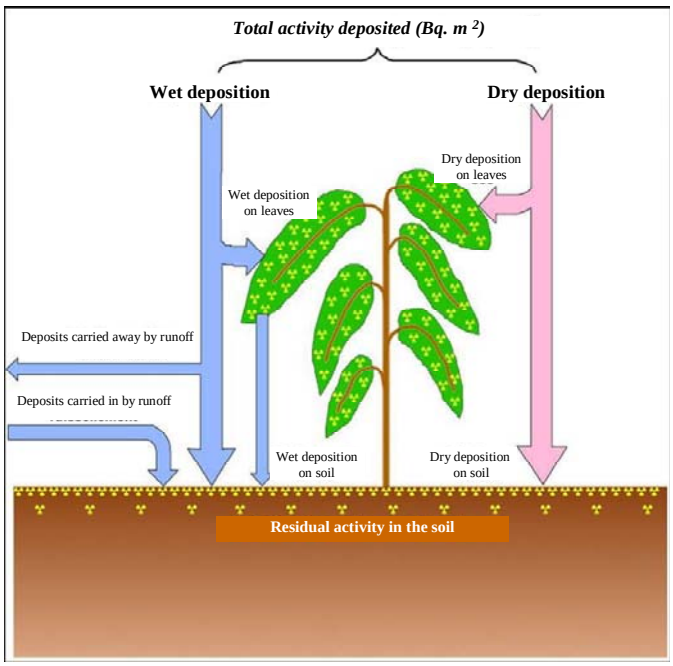


Figure 6-36 - Diagram illustrating the distribution of wet and dry deposition between the plant cover and soil, as well as the redistribution of wet deposition under the influence of surface runoff of rainwater.

Thus, when the plant cover is dense and very leafy (such as with a forest), dry deposition tends to be higher and accumulate primarily on plants. Conversely, wet deposition (contaminated rain) tends to drip from the plant cover and either seeps into the soil (thus contributing to continual soil contamination, known as "residual fallout") or runs along its surface depending on its impermeability and slope (particularly if the runoff is heavy). This results in a local redistribution of wet radioactive fallout, resulting in higher amounts of residual fallout forming, for example, around trees (from the dripping of contaminated rain from leaves), under rain gutters, in storm sewers, and in natural accumulation zones (impluvium) at the foot of more or less extensive catchment basins. Inversely, it can lead to the formation of lower amounts of residual fallout on impermeable or sloped surfaces. Some of this wet deposition may also be carried away by the river system.

In the case of wet deposition by snowfall, the contamination temporarily stored in the snow cover may be moved by the wind (snowdrifts) and then drip into the soil during the thawing season, creating small yet heavily contaminated "spots" (Figure 6-37).

Figure 6-37 - A thawing firn dripping water. The radioactive materials contained in the firn converge at the point where the drops fall, forming a spot of contamination in the soil just below.

All these phenomena can therefore lead to high local differences in residual fallout that can vary by a factor of 10 or more. Points where rainwater accumulates or infiltrates the soil can thus become "hot spots", with local surface activities that are much higher than in the rest of the area.

These local differences in radioactive fallout do not appear on the maps obtained from the airborne measurement surveys, which are not precise enough. Only field surveys with radiation meters or portable spectrometers, or soil samples analyzed in the laboratory, make it possible to identify hot spots. The various measurements published by the Japanese authorities thus revealed these differences, particularly in urban areas.

There are always differences in fallout levels in urban areas because air turbulence from buildings creates accumulation points in areas where the air is recirculated. Moreover, the adherence of fallout depends on the type of surface (horizontal, slanted, etc.) and its material (hard or soft, smooth or rough, impermeable or porous, etc.). The rougher the surface, the better dry fallout will adhere; the smoother and more impermeable the surface, the easier wet fallout will flow. In addition, the ground directly under downspouts is particularly conducive to the accumulation of radioactivity and thus the creation of hot spots.

6.3. IMPACT OF RADIOACTIVE FALLOUT ON AGRICULTURE IN JAPAN

In order to monitor variations in the contamination of plant- and animal-based foodstuffs in Japan, IRSN collected the results of measurements performed on these foodstuffs and published on the website of the Japanese Ministry of Health, Labor and Welfare (MHLW).

6.3.1. HOW DID CROPS AND ANIMAL-SOURCE FOODS BECOME CONTAMINATED?

Generally speaking, radioactive fallout resulting from the dispersion of the radioactive plume contaminated the parts of plants exposed to the air and, consequently, crops for human and animal consumption.

Leafy vegetables (salads, spinach, leeks, etc.) were most directly affected by this contamination. The level of contamination depended not only on the intensity of the fallout, but also on its wet or dry deposition. As Figure 6-36 above shows, only a portion of wet deposition (rain) is retained by leaves; the rest flows down the leaves and infiltrates the soil or runs along its surface. The wet deposition capture efficiency of the leaves of a given type of plant depended on the depth of the rainfall that deposited this fallout: the heavier the precipitation (high rainfall depth), the lower the capture efficiency of the leaves. Thus, although the wet deposition may have been much higher than the dry deposition at the same location, the contamination of the leaves did not increase proportionally to this deposition and reached a saturation level during heavy rains.

Leaf contamination was highest immediately after the deposition of the fallout but decreased rapidly as new leaves produced by the plants did not receive any radioactive fallout (typically, salads harvested 50 days after an accident are 100 times less contaminated than salads that reach maturity immediately afterward). Furthermore, as shown previously (Figure 6-29 in Section 6.2.3.4), the short-lived radionuclides, which predominated immediately after the deposition of the fallout, decreased at a fast rate in the following days. This was observed in Japan after the Fukushima accident, including more than 100 km away from the stricken plant, as is illustrated by the case of spinach harvested in Ibaraki prefecture between mid-March and late April (Figure 6-38). The models of radionuclide transfer in land environments (plants and animals), such as those used by IRSN (ASTRAL or SYMBIOSE), accurately simulate this effect of radioactive decay and biological dilution through plant growth, as illustrated in Figure 6-38.

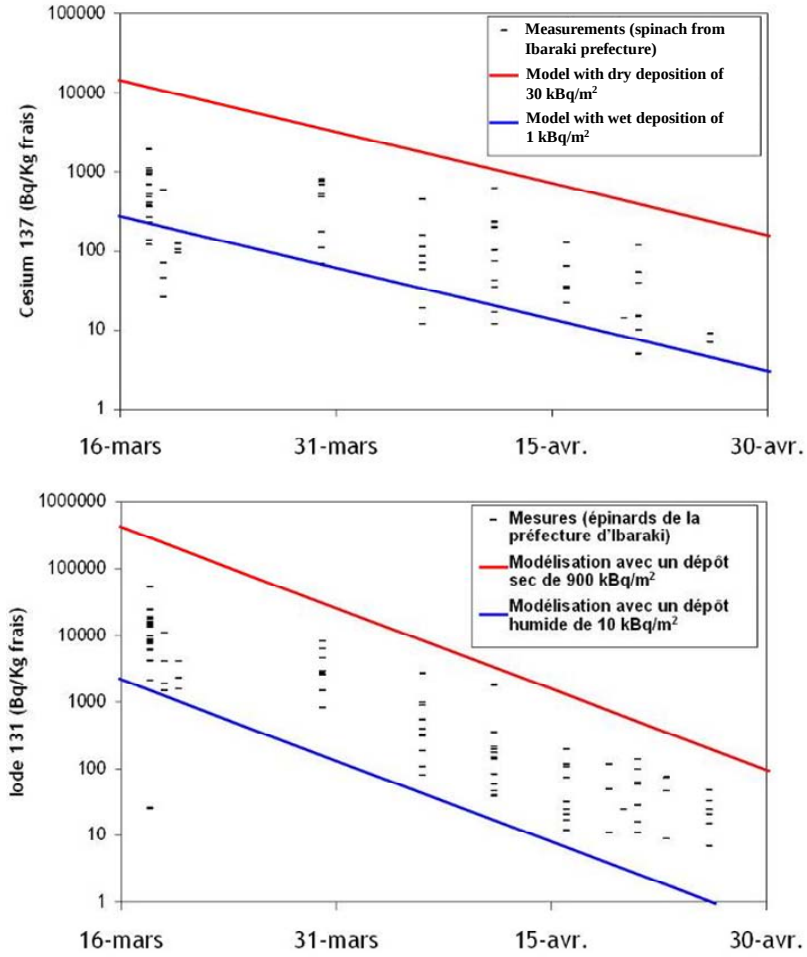


Figure 6-38 - Evolution of cesium-137 (top) and iodine-131 contamination (bottom) measured in spinach[21] grown in Ibaraki prefecture (MHLW data). Comparison with the model results obtained by the SYMBIOSE software (for leafy vegetables) with various scenarios of radioactive fallout deposition on March 15, 2011.

The evolution in the contamination of leafy vegetables was calculated with SYMBIOSE using extreme, yet realistic for Ibaraki prefecture, assumptions on the surface activity deposited on March 15, 2011. The red lines in the chart in Figure 6-38 correspond to a maximum dry deposition (30 kBq/m² of cesium-137 and 30 times more iodine-131). The blue lines correspond to a minimum wet deposition (1 kBq/m² of cesium-137 and 10 times more iodine-131).

The contamination deposited on the leaves of plants was rapidly absorbed and carried by their sap to their other parts, particularly the storage tissue that they formed in the weeks following the accident (fruits and fruit-type vegetables, cereal grains, tubers, wood, etc.). Called "translocation", this type of contamination through uptake and storage in plants leads to persistent contamination, even of new shoots, primarily during the first year and, to a lesser extent, the following years (variable depending on the type of plant). As a result, the contamination levels of some crops harvested in Japan several weeks and even several months after the Fukushima accident were high, although not as much as immediately after the accident. This was particularly the case of Japanese apricots, bamboo shoots and tea leaves (see Section 6.3.2).

[21] In light of the absence of precision, some of this data may relate to greenhouse spinach (nonetheless, most of this data relates to field-grown spinach). On the other hand, the protective effect of greenhouses is not included in the SYMBIOSE calculations.

If surface-deposited radionuclides penetrate into soil, they can be partially absorbed by plant roots. This is known as root uptake. For the same amount of fallout, plant contamination by root uptake is always much lower (around 100 times lower) than initial contamination from fallout on foliage. Moreover, given the soil migration time of radionuclides, root uptake is significant only for radionuclides with sufficiently long half-lives, such as cesium-134 and cesium-137. Rice crops in Japan's contaminated areas are what risk being most susceptible to contamination by root uptake. Moreover, given that rice is grown in paddies, uptake can occur directly through contact with contaminated water. It is probably this mode of uptake that explains why significant yet low levels of cesium contamination have been observed in some rice harvests in Fukushima prefecture since 2011 (see Section 6.3.2). Unlike contamination via foliage, which is transient and especially high in the weeks following an accident, contamination by root uptake will last for years, albeit at lower levels, if no human intervention is taken to mitigate it. This can create a risk of chronic contamination of some crops and is the reason why, in 2011, the Japanese authorities prohibited the cultivation of land where the soil contamination exceeded 5,000 Bq/kg of radioactive cesium per kilogram of earth[22]. When a root uptake factor (plant/soil concentration ratio) of 0.1 (a conservative value) is considered, the cesium contamination of crops growing in soil with 5,000 Bq/kg might reach 500 Bq per kg of fresh produce. This corresponds to the marketing or consumption standard laid down in 2011 by Japan for foodstuffs.

The contamination of animals or animal-source foods (meat, milk, eggs, etc.) was caused primarily by the ingestion of contaminated fodder and, to a lesser extent, drinking water. Animals fed with foodstuffs not directly exposed to the radioactive fallout, imported (a frequent case in Japan), or harvested prior to the accident and sufficiently protected from its fallout, therefore could not have high levels of contamination. Conversely, herds that were given grass in their feed might have become rapidly contaminated. Like all other foliage plants, grass is immediately affected by radioactive fallout and is the most susceptible type of fodder.

A portion of radionuclides contained in ingested foods remains in the blood after digestion. There, they spread throughout the body and contaminate animal products before being eliminated. The intensity and persistence of this uptake depends on the biokinetics (metabolization) of the radioactive element absorbed into the body. For example, iodine is absorbed by the mammary glands, where it contaminates milk. Cesium spreads throughout the body, particularly muscles (meat), and can contaminate milk. The iodine content of milk is highest three days after contaminated fodder is first ingested. If the quantity and quality of subsequent fodder remain the same, the iodine activity in milk drops quickly over a period of around 4-5 days under the combined effect of radioactive decay and the metabolic elimination of iodine-131 from the animal's body. Under the same conditions, the cesium content in meat is highest only after a few weeks of gradual accumulation. If cesium continues to be absorbed, the contamination of meat stabilizes at a balance point between ingestion and elimination. If cesium ingestion is stopped, the contamination of meat decreases slowly and is completely eliminated in around 3 months (decrease in the contamination of meat by half in 3 months).

6.3.2. OVERALL ASSESSMENT OF CONTAMINATION OF FOODSTUFFS IN JAPAN

Between mid-March 2011 and 8th February 2012 (the date of writing of the present report), the Japanese Ministry of Health (MHLW) published test results on its website (specific activity in iodine 131, cesium 134, and cesium 137) from 104,318 food samples (whatever their origin). Of those 104,318 samples, 1111 showed signs of contamination exceeding the standard limits for sale or consumption in Japan[23]. For the Fukushima district alone, 18,350 products were tested, of which 642 exceeded the limits.

These products found to be outside the limits belonged to the following categories:

[22] Guideline. Assuming that the cesium is evenly distributed in the first 10 cm of soil, which has a density of around 1,500 kg/m^3, soil contamination of 5,000 Bq/kg corresponds approximately to a surface deposition of cesium of 750,000 Bq/m^2, a level that is virtually unseen in Japan except in the main contamination zone northwest of the Fukushima Dai-ichi plant and within less than 30 km southwest of it (see Figure 6-23).

[23] The standards for sale or consumption of foodstuffs were adopted in Japan in the days following the accident. For iodine 131, the limits were 300 Bq/liter for milk and other liquids for human consumption, and 2 000 Bq/kg for other foods. For the cesiums (^{134}Cs+^{137}Cs), they were 200 Bq/liter for milk and other liquids for human consumption, and 500 Bq/kg for other foods.

- Leafy vegetables (e.g., spinach), flower vegetables (e.g., broccoli), and root vegetables (e.g., turnips),
- Fruit from fruit trees (Japanese apricot, fig, pomegranate, persimmon, yuzu, loquat, kiwi) and chestnuts,
- Tea leaves and the leaves of medicinal plants,
- Bamboo shoots,
- Cereals (wheat, rape, rice),
- Mushrooms,
- Farmed meat (beef) and game (boar, pheasant, etc.),
- Cow's milk,
- Sea and river fish,
- Shellfish and crustaceans,
- Marine algae.

The specific activities attained and how they change over time vary greatly from one category to another. They are listed below.

IRSN has no information concerning the details of the sampling protocols used to obtain the measurements published in Japan. These data were probably not obtained with a view to conducting a scientific study of the environmental contamination caused by the accident, but rather for the operational purpose of monitoring, to manage the boundaries within which the sale of foodstuffs produced in the contaminated territories should be banned, or to guarantee quality for certain sectors deemed to be sensitive by the producers or consumers (such as rice and beef).

It is important to note that, as is customary, the measurements were all expressed in becquerels per kilogram of 'raw' product as sold, which is not necessarily the same as the contamination of products as consumed. Tea, for example, is normally consumed as an infusion, after processing (refer to the inset below concerning the measurements performed by IRSN). In the list above, products may be consumed raw or following some type of processing. There is no way to predict whether such processing would be likely to concentrate or to dilute the radionuclides present in the raw products.

Radioactivity measurements performed by IRSN on tea imported from Japan and on the infusion made with this tea

The IRSN performed measurements on tea from the municipality of Omaezaki (Shizuoka district), taken from a batch imported into France and intercepted by the French customs authorities at Charles de Gaulle Airport (Paris) in June. This tea, which contained significant cesium 134 and 137 contamination, was prepared by infusion, using 50 grams of tea leaves per liter of water (the dosage recommendations range from 10 to 40 g/L according to the type of tea). The results of the measurements (on 21st June 2011) are given in the table below.

Results of the measurement of specific activity of the radionuclides present in the tea sample from Omaezaki (Shizuoka district)

	Tea leaves (Bq/kg)	**Infusion (Bq/L)**	**Rate of transfer into the infusion**
Cesium 137	480	22	92%
Cesium 134	450	18	80%
Cesium 136	1.2	< 0.248	-
Potassium 40	560	23	82%

The sum of the specific activities of the cesiums (931 Bq/kg) in the tea leaves exceeds the maximum allowable level stipulated in European regulation No. 297/2011 dated 25 March 2011, modified on 11 April 2011, which is 500 Bq/kg for foodstuffs other than liquid foods and dairy products. Note that potassium 40, a naturally-occurring radionuclide always present in food, has 560 Bq/kg of specific activity, which is not taken into account under the regulations. This high value is due to the fact that the tea leaves are dehydrated, which tends to concentrate the radionuclides in the dry mass.

More than 80% of the cesium contained in the tea leaves is transferred to the infusion. The same applies to potassium 40, which is an alkaline element like cesium, and has the same chemical properties. The radioactive cesium concentration in the infusion is 40 Bq/L, which is below the upper limit specified by the modified European regulation dated March 25th (200 Bq/L).

Assuming that this tea infusion is consumed at the rate of 1 liter per day, the effective dose taken would be 0.6 microsievert (µSv) per day, and 220 µSv/year (i.e., approximately 0.2 mSv per year). Considering a less concentrated infusion prepared using 6 g of tea in 30 cL of water (the dose usually recommended for this type of tea), and applying the same rate of transfer of the cesium into the infusion, the effective dose taken in for daily consumption of one liter would be 0.24 microsievert (µSv) per day, and **90 µSv (or approximately 0.1 mSv per year).**

6.3.2.1 Report on plant-based foods

- **Vegetables**

Of all data transmitted by the MLHW on edible goods, with all categories mixed together, leafy vegetables demonstrated the earliest and highest-level contamination:

- 54,100 Bq/kg wet of iodine-131 in a sample of spinach taken on 18 March in Hitashi (Ibaraki district), approximately 120 kilometers south of the plant;
- 41,000 Bq/kg wet of cesium-134 and 41,000 Bq/kg of cesium-134 in a kukitachina sample (a local leafy vegetable) taken on 21 March in Motomiya (Fukushima district), approximately 60 kilometers west of the plant.

During the month of March, many vegetable samples from the Fukushima, Ibaraki, Chiba, and Tochigi districts contained cesium and/or iodine 131 contamination exceeding the standards for sale or consumption; most of these samples were spinach, but there were also other local leafy vegetables (komatsuna, kukitachina, shinobuhuyuna, Japanese parsley, etc.) and broccoli (flower vegetables). In April and May, occasional overshoots of these standards were still being observed (for the cesiums only). Until the end of June, cesium activities that were detectable but below sales and consumption standard limits were still found. This fast transition is illustrated by the example of spinach from the Ibaraki district, as already seen (Figure 6-38), and spinach from the Fukushima district (Figure 6-39).

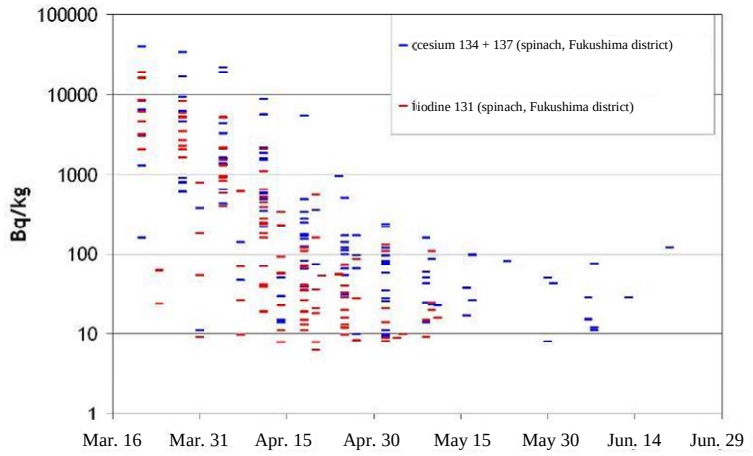


Figure 6-39- Change in iodine-131 and cesium-134 and -137 contamination in spinach from the Fukushima district (MHLW data, Bq/kg wet)

For root vegetables such as turnips and wasabi, the edible part was not directly contaminated by the radioactive fallout. As already indicated (Para. 6.3.1), they were contaminated via translocation of the foliar deposit. The specific activity measurements are much lower than those for leafy vegetables, with the maximum values concerning a sample of turnips from April 3rd 2011 (Fukushima district), at 1000 Bq/kg wet iodine 131, and 4100 Bq/kg wet cesiums 134+137. In mid-November, samples of wasabi (the root part) taken from the Fukushima district still contained cesium in excess of the standards for sale or consumption.

Fruit vegetables (such as tomatoes and melons) suffered very little contamination, with no cases of overshooting the standards. For tomatoes, the maximum activity levels reached were in March 2011, with about twenty Bq/kg wet iodine, and about a hundred Bq/kg wet cesium.

- **Tree fruits**

From May 2011 until the fall, detectable contamination, sometimes exceeding the standards for sale or consumption, were detected in tree fruits.

The first fruits in which significant activity was observed, from late May onwards, were Japanese apricots. **Japanese apricots (umé)** are the fruit of a very early-flowering tree, which had probably already blossomed by mid-March. This fruit tree is comparable to something between a plum tree and an apricot tree. It seems to flower like French apricot trees: the blossoms bloom early in the spring (March or April), and sometimes even in January or February, according to the climate. The leaves appear much later, and the fruit reaches maturity around the end of May. The most recent measurements obtained from Japanese apricots picked in the Fukushima district vary from 137 to 700 Bq/kg wet of cesiums 134+137. The highest levels of contamination observed in the spring of 2011 were the result of very large deposits.

The maximum specific activities on fruits were observed on yuzu fruits: up to 2400 Bq/kg wet on August 26th in Minamisoma and, later, 860 Bq/kg wet on October 11th in Date (Fukushima district). **Yuzu fruit** grows on a medium-sized prickly tree. The yuzu looks like a small grapefruit, and its color ranges from green to yellow according to its degree of ripeness. The fruit has little flesh and many large seeds. It has an acidic taste. The yuzu originated in China, but nowadays it is most commonly grown in Japan. In Japan, an ornamental version of the yuzu tree is grown for its flowers (flower water) rather than its fruit. Yuzu is also used, for its zest, in Japanese cooking. Since the yuzu tree is related to the lemon tree, it probably produces flowers and fruit throughout the year, as many citrus trees do (a lemon tree yields 200 to 600 fruits per year).

High values were also reached in **kiwis** picked in the fall, with specific cesium activity of up to 1100 Bq/kg wet on November 14 in Minamisoma.

Figs also turned out to have relatively high cesium contamination, up to 520 Bq/kg wet on July 19th in Minamisoma. In September 2011, specific activity of a few tens to a hundred Bq/kg wet of cesium was still being recorded in figs. In October 2011, the values were less than 10 Bq/kg wet. Specific activity in cesiums of 560 Bq/kg wet was also measured on **pomegranates** sampled in Date (Fukushima district) on October 13th.

With regard to **nuts**, high specific activity in cesiums was also observed in chestnuts, with one sample in Minamisoma on September 6th (2000 Bq/kg wet) and another in Kashiwa (Chiba district) on October 11th (200 Bq/kg wet).

Most other fruits from fruit trees (apples, pears, peaches, plums, etc.) might have reached specific cesium activity of a few tens of Bq/kg, without exceeding the standard limits for sale or consumption.

- **Bamboo shoots and tea leaves**

In May and June 2011, raw or refined bamboo shoots and tea leaves had significant cesium 134 and 137 contamination, with the sum of the activities of those two radionuclides occasionally exceeding the limits for sale or consumption in Japan (Figure 6-40).

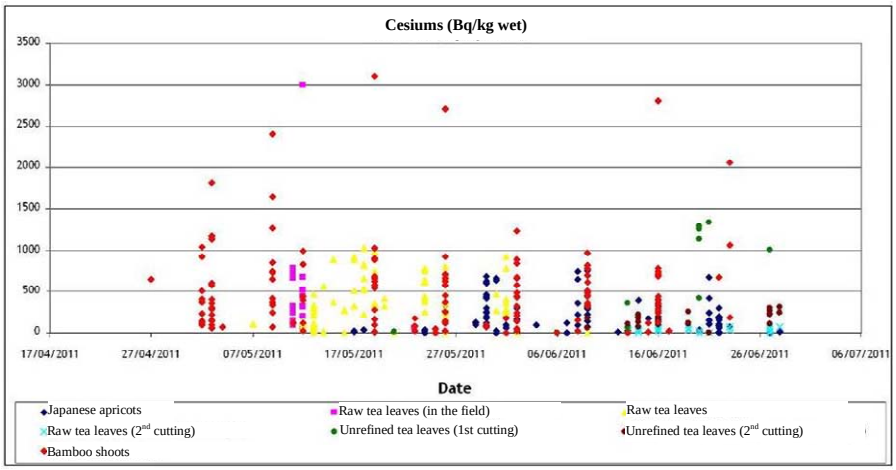


Figure 6-40- Changes in caesium-134 and -137 contamination in Japanese apricots, tea leaves and bamboo shoots harvested in different Japanese districts.

At the time of the deposit, the bamboo and tea plants had evergreen leaves, which intercepted the radioactive deposits. The radionuclides intercepted by the leaves, particularly cesium, were assimilated by the plant, and the sap transported them throughout the tissues and organs, leading to the overall contamination of the plants (translocation effect). Because tea plants and bamboo have significant biomass (e.g. 7 to 14 kg dry matter per square meter for tea), the interception of radioactive deposits was especially effective in March, even for slight deposits far from the damaged power plant. Some of the foliar deposit was assimilated by the plants and transferred to the new shoots harvested from the end of April onwards, which explains the significant cesium contamination observed in new tea leaves and bamboo shoots, even if they grew several weeks after the deposits were formed.

The specific activities measured (cesiums 134+137) managed to exceed 1000 Bq/kg wet for tea from the first harvest (1330 Bq/kg wet in Kanagawa and 981 Bq/kg wet in Shizuoka on June 21st) **and 2000 Bq/kg wet for bamboo shoots** (2060 Bq/kg in Minamisoma and 1 070 Bq/kg in Souma on June 23rd). These contamination levels could correspond to relatively moderate cesium deposits, estimated at a few tens of thousands of Bq/m^2, which could have formed up to a few hundred kilometers from the Fukushima Dai-ichi power plant (see the map in Figure 6-21). The measurements performed on tea leaves and bamboo shoots concerned the first harvest after the deposits.

Note that unrefined leaves from the Saitama district (harvest number not specified) still had 1300 Bq/kg wet of cesium specific activity in November.

Rice and other cereals

In view of how it is grown, rice could have been contaminated by interception of radioactive deposits if the plant was on the ground at the time of the radioactive fallout, via water contamination, or via soil contamination alone (root transfer). At the time of the accident in March, rice had probably not yet been planted, and therefore it did not receive any direct radioactive fallout. To prevent excessive contamination by root absorption of the cesiums present in soil, the Japanese government authorized rice-growing only in soils whose maximum cesium content was less than 5000 Bq/kg, leading to the assumption that the maximum cesium concentrations in raw grains of rice harvested would not exceed the standard limits for sale or consumption in Japan (500 Bq/kg; see Para. 6.3.1).

In agricultural areas (mainly in the Tohoku and Kanto regions), where the specific concentration of cesiums in the soil exceeded 1000 Bq/kg (whilst remaining below 5000 Bq/kg), the Japanese government instituted a two-stage monitoring process:

- Preliminary inspection of the rice one week before harvest,
- Main inspection after harvest.

If the result of the preliminary pre-harvest inspection revealed cesium concentrations above 200 Bq/kg, the area of origin of the samples tested was considered a priority area, and post-harvest rice tests were performed at a large number of farms in that area. If not, there were fewer post-harvest tests. Nonetheless, whilst the preliminary pre-harvest tests in the Fukushima district had indicated cesium concentrations of only 136 Bq/kg, the tests carried out after the harvest revealed a contamination of 630 Bq/kg in rice from one of the two farms tested. This was the highest results. The insufficient reliability of the initial tests raised concerns about the monitoring protocol. Certain municipalities therefore demanded that the central government should set up a system of screening all batches of rice.

Several factors can affect the contamination of a grain of rice before and after it has been picked:

- Between the preliminary test carried out before the harvest and the test performed after the harvest, the maturing of the rice naturally leads to some drying of the grain. The cesium concentrations therefore naturally increase between the tests.
- Most of the contamination in the rice is stored in the husk that surrounds the grain. This means that the processing by which it is transformed into white rice (removal of the husk, bran, and germ, and polishing of the grain) lowers the contamination levels. The rice bran, on the other hand, which can be used for human or animal consumption, contains the largest proportion of the cesium in the rice.

Moreover, before going on sale, rice crops are usually mixed at the time of processing. It is therefore possible that the white rice analyzed in Japan could in fact have been a mixture of rice from several different paddy fields, which could have resulted in a reduced level of contamination in the product placed on sale, due to dilution.

In view of the monitoring procedures implemented, rice underwent a large number of tests (approximately 3900 tests of raw or refined rice between August and January). The cesium 137 and 134 contents measured were usually below the detection limits of the measuring instruments. Fewer than 10% of tests revealed detectable cesium contamination (mainly samples from the Fukushima district). Three tests revealed content exceeding the authorized limits (rice samples from the Fukushima district and rice bran from the Miyagi district).

With regard to **cereals**, occasional overshoots of the limits for sale or consumption were observed in **wheat** and **rape**.

6.3.2.2 Overall assessment of contamination of animal-based foods

- **Cow's milk**

In general, based on the results published in Japan, the activities measured in milk seem to have been relatively moderate in comparison to the very high levels of deposits and the contamination of grass to the northwest of the damaged power plant. Thus, the higher activities measured in milk were 10 to 100 Bq/L, with a maximum measurement of 210 Bq/L for each of the cesiums (in Iitate, March 19th, 2011) and 100 to 1,000 Bq/L, with a maximum measured value of 5,300 Bq/L for iodine-131 (in Kawamata, March 20th). Between March 2011 and the beginning of February 2012, out of approximately 2000 analyses of milk and milk product samples, only 23 exhibited iodine or cesium activities that exceeded permitted sales standards.

It is likely that the date of the accident, occurring at the end of winter, limited animal contamination (and thus milk contamination), as animals must be fed with either local fodder harvested during the previous season or imported fodder (the importing of animal feed seems common in Japan). Figure 6-41 presents the results of measurements taken on weeks from the Iitate area (blue diamonds). The iodine 131 activities measured reached 2.5 MBq/kg wet immediately after the deposits.

The simulation carried out using IRSN's ASTRAL software (blue line) shows that these activities in weeds could correspond to iodine 131 deposits of the order of ' MBq/m^2 (estimated initial surface activity at the date of formation as at March 15th 2011) that could have formed, mainly in wet form (contaminated rain). The change in activity observed in these plants matches the predictions of the simulation. The same assumptions concerning the probable conditions of contamination of weeds in Iitate were applied in order to estimate the possible theoretical contamination of milk if the livestock had eaten these weeds: The red curve in Figure 6-41 shows that this

contamination could have reached 100,000 Bq/L in the first few days, during the week following the formation of radioactive deposits, and then dropped by a factor of 100 after one month.

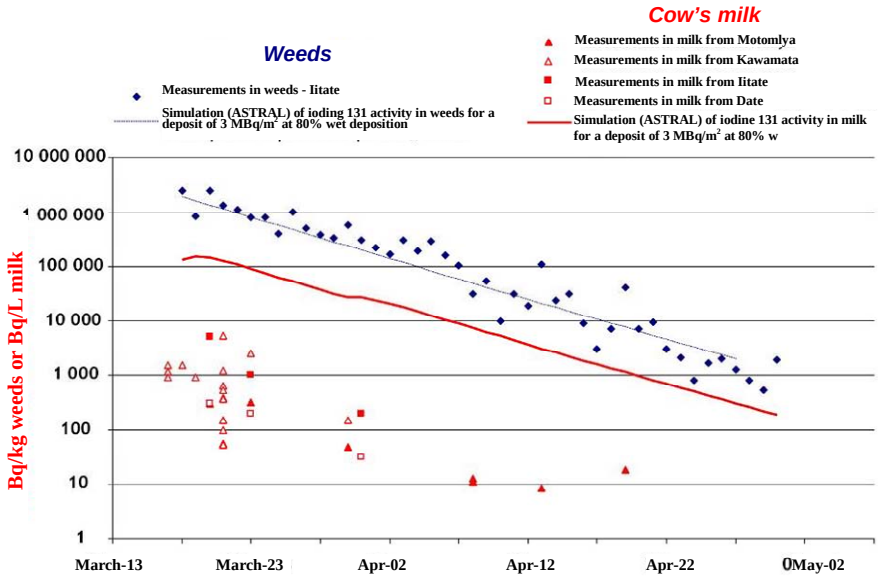


Figure 6-41- Specific (volume) activity of iodine 131 in milk samples with the highest contamination levels, from the Iitate-Kawamata-Date region, as well as Mitomiya (red symbols). Specific (mass) activity of iodine 131 measured in weeds sampled in Iitate (blue diamonds) and simulation using ASTRAL software of iodine 131 activities in these plants (blue line) and milk (red line) produced by cows assumed to have eaten these plants. The model was created assuming an initial iodine-131 deposit of 3 MBq/m2 at 80% in the form of a wet deposit.

The Iitate, Kawamata, and Date areas, from which the most highly contaminated samples came, are located in the zone that received the most deposition, to the north-west of the damaged power plant. The iodine 131 activity in milk in those areas was a maximum of a few thousand Bq/L. This figure also shows that milk from Motomiya, which is about forty kilometers south-west of Kawamata, outside this area of heavy deposition, was contaminated to a comparable level. This appears to confirm that the contamination of milk is not caused primarily by the regular consumption of local grass, but rather is related to the ambient contamination in these areas (accidental ingestion of surface contamination, or contamination in fodder or drinking water exposed to a contaminated environment).

Figure 6-41 also shows a fast decline in iodine 131 content in both weeds and milk, and great variability in the activities observed in a single area, as shown by the significant batch of samples taken in Kawamata on March 20th. This variability is related to the variable nature of fodder contamination, which in turn is probably more related to the nature and origin of the fodder that the variability of the radioactive deposits in this area. The reduction observed, corresponding to an effective decay period of the order of 4.5 to 5 days, matches that seen in French milk in 1986 after the Chernobyl accident, and is in good agreement with radioecological models. It is caused by the radioactive decay of iodine 131 in fodder and its elimination by the animal, particularly through the milk itself. After mid-April, the iodine 131 activity levels in the milk samples fell below the detection limits, which were often of the order of 10 to 50 Bq/L. The iodine 131 activity in milk nevertheless inevitably fell to less than 1 Bq/L before the end of May 2011 because of the radioactive decay of this radionuclide.

Figure 6-42 presents the cesium 137 contents of these samples.

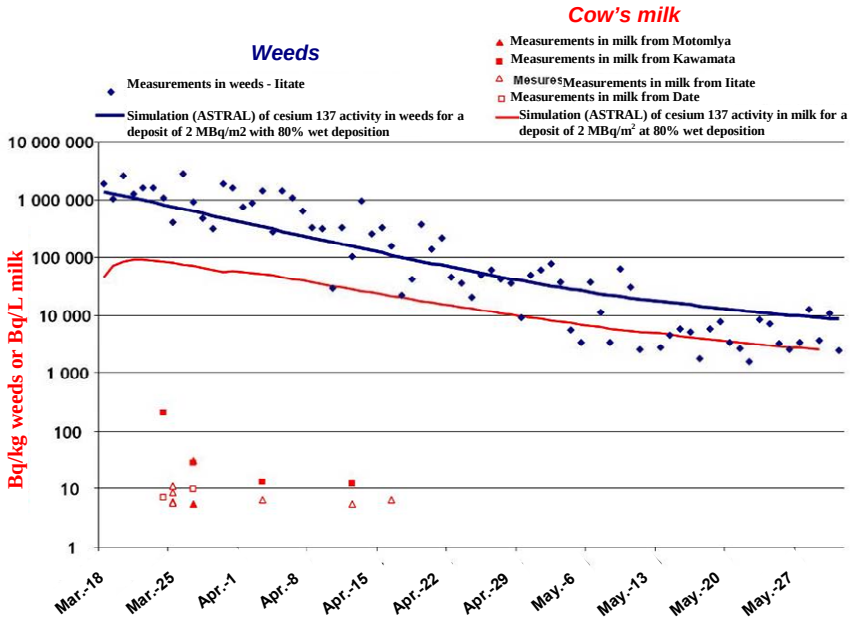


Figure 6-42: Specific (volume) activity of cesium 137 measured in milk samples with the highest contamination levels from the Iitate-Kawamata-Date region, as well as Mitomiya (red symbols). Specific (mass) activity of cesium 137 measured in weeds sampled in Iitate (blue diamonds) and simulation using ASTRAL software of cesium 137 activities in these plants (blue line) and milk (red line) produced by cows assumed to have eaten these plants. The model was created assuming an initial cesium-137 deposit of 2 MBq/m2 at 80% in the form of a wet deposit.

These results were interpreted in a similar way to those for iodine 131 above. Once again, the levels of cesium 137 contamination in the weeds can be explained by significant deposits of a few MBq/m^2, corresponding to the cesium 137 surface activity mapped in the municipality of Iitate (see Figure 6 23 page 66). Moreover, as for iodine 131, the cesium 137 concentrations measured in milk are much lower than those that could have been reached if livestock had been fed nothing but locally-grown contaminated plants. There is no way of knowing how the contamination of milk changed after mid-April 2011, because the cesium 137 concentrations in the milk probably remained below the detection limits of the measurement methods used.

Iodine 131 and cesium 134 and 137 activities in milk samples from Ibaraki, south of the damaged power plant, were also measured at similar levels to those mentioned above. That area also received significant radioactive deposits, with a higher proportion in dry form than the area to the north-west of the power plant, which could have contaminated plants more efficiently.

- **Meat**

Like the activity detected in milk (and probably for the same reasons), the iodine and cesium activity in meat remained moderate, considering the radioactive deposits in the worst-affected areas. Iodine-131 was almost never found in the meat: the activities remained below detection limits, which admittedly are rather high (usually 20 to 50 Bq/kg). Of some 65,000 meat sample analysis results (between March 2011 and February 2012), about 200 had cesium activities exceeding sales limits, including 67 game samples (mainly wild boar meat) and 141 samples of beef. Game meats are discussed in greater detail below (Para. 6.3.2.3.1).

For the sake of comparison, if the animals had consumed grass having the same activity level as the weeds measured in Iitate, the cesium-137 contamination in the meat could have reached 200,000 Bq/kg wet in mid-April 2011.

The cesium contamination of meat followed a very different curve from that of milk because of the far longer persistence of cesium in muscle tissue, and possibly because feeding practices differ for different types of livestock farming. Figure 6-43 presents the activities of cesium 134+137 measured in samples of beef between March and November 2011 in areas where the most testing of beef was performed because some of the highest activity levels were found. With very few exceptions, the cesium activity in beef did not start to regularly exceed 20 Bq/kg until late April because of the gradual accumulation of cesium. The highest activity levels (cesium 137+134), between 1000 and 4350 Bq/kg wet (Kawamata-Machi), were reached in early July.

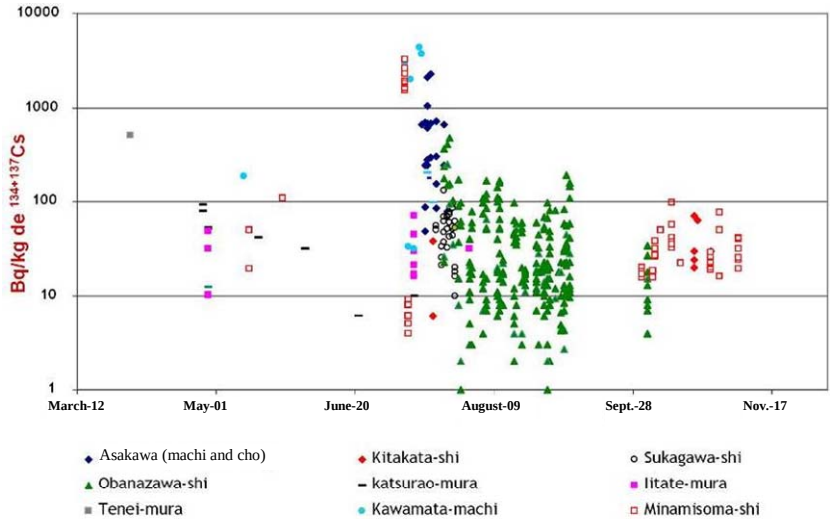


Figure 6-43 presents the activities of cesium 134+137 measured in samples of beef between March and November 2011 in areas where the most testing of beef was performed because some of the highest activity levels were found.

More than the location and size of these deposits, it is food production practices that are the determining factors. Thus, two batches of meat samples were analyzed on 8 and 9 July in Minamisoma-shi, north of the Fukushima Dai-ichi plant, on a farm located just outside the 20-km exclusion zone. The results of the two batches are drastically different: 1500 to 4200 Bq/kg for the first batch and 4 to 10 Bq/kg for the second. As pertains to the 11 bovines involved in the first batch with the highest activities, and based on information published on July 12th in the Mainichi Daily News, since the beginning of April, the livestock farmer had been feeding his livestock rice straw harvested the previous autumn that had been stored outside and was consequently contaminated by atmospheric radioactive fallout in March. A similar deviation appears in Kawamata-machi.

The fact that the contamination of beef from an area such as Obanasawa, located in Yamagata district more than 150 km north-west of the Fukushima power plant, on surfaces where the deposits should not have exceeded 30 kBq/m^2, is as high as, or higher than, that of meat from municipalities such as Minamisoma, Katsuroa, Iitate and Kawamata, which are located in, or on the edge of, the area worst affected by radioactive fallout, confirms the importance of animal feeding practices.

Likewise, in the period from September to November 2011, the highest cesium activities measured in beef, which regularly reached a few hundred Bq/kg, or occasionally 1000 Bq/kg, came from places in the Miyagi district (particularly Kurihara), nearly 150 km north of the damaged power plant, where the deposits did not exceed 60 kBq/m^2.

For all meats whose activities exceeded 500 Bq/kg, the decision by the Japanese Ministry of Agriculture, Forestry and Fisheries, dated April 14th, to limit fodder for bovine animals to 300 Bq/kg (cesium 134+137), was not complied with. Certain sets of measurements seem to indicate that, following the discovery of these cases, which concern only a very small number of farms, decisions were taken concerning the corresponding farming practices, leading to a fall in the levels of contamination of meat, although this was slow because of the biological elimination period of cesium (around three months).

It can then happen that new farms, which are often more distant but had not made any special arrangements because of their remoteness and moderate levels of contamination, are stigmatized precisely because of the relative stability of the activity levels observed. That is what happened to one farm in Fujinomya (Shizuoka district, more than 100 km south-west of Tokyo), where activity of a few tens of Bq/kg was observed on a regular basis from July until quite recently. At such a distance from the damaged facility and in an area where the deposits were probably very slight, the source of this activity and the reason for its persistent nature needs to be investigated.

With regard to other meats and foods of animal origin, tests performed on chicken meat and eggs remained negative (below the detection limits, except sporadically a few very low iodine 131 readings), which is to be expected in view of the foods they eat: often products made with cereals harvested the previous summer, and therefore prior to the accident. The same applies to pork meat and offal, although activity levels of 100, or even up to 200 Bq/kg have been observed very occasionally. Unlike the tests carried out on beef, a great majority of tests on game (wild boar, Asian black bear, deer, Japanese pheasant) produced results above the detection limits, but the cesium activities measured remained close to those of farmed cattle: from a few tens to a few hundred Bq/kg, very occasionally reaching 1000 Bq/kg.

In the coming years, activities in caesium-134 and caesium-137 in animal products, milk and beef in particular, will continue to depend mainly on the practices used to feed animals. So, even though the activity levels in fodder potentially produced in the worst-affected areas may have fallen by a factor of nearly 1000 from the maximum values in mid-March and the observations in September, like the case of the weeds tested in Iitate, any increase in the proportion of those local products in the animal feed could lead to an increase in the activity in milk and meat. Therefore, a livestock practice that strictly respects the fodder contamination limit of 300 Bq/kg for the production of beef and milk (MAFF decisions, April 14th, 2011), could lead to activities in milk that would be near the sales standard for milk (500 Bq/L) and above-limit activities for meat.

6.3.2.3 Contamination of foodstuffs from natural and semi-natural environments

Natural or semi-natural foodstuffs such as mushrooms, berries, game, and products from rivers and lakes, such as fish and crawfish, have special characteristics that make them more sensitive, and for a longer time, to atmospheric radioactive fallout. These characteristics are related to the environments in which these organisms live, as well as their physiology and their way of life (nutrition in particular).

6.3.2.3.1 Forest products

There are often more significant dry deposits in wooded areas than on grassland or cultivated areas, because the leaves of trees are efficient at trapping the radionuclides present in the air. Moreover, the wet deposits (formed by rain) can vary widely on a local scale because of a specific topography or the redistribution of rain deposits by dripping (most notably along trunks or on leaves).

Since then, the cycle of organic matter in forests has maintained high availability of cesium (the only radioactive element that has persisted in the environment after the Fukushima accident) for plants and animals. From the first year, the falling of leaves that intercepted the radioactive deposits will create a bed where cesium is concentrated, and which will continue to be fed regularly by a cycle that includes the transfer of the cesium from this bed to the soil, its absorption by tree roots, and its transfer to the new leaves, etc.

These effects will maintain the contamination of forest products at levels that will fall only very slowing, and certainly much more slowly than farm products. 25 years after the Chernobyl accident, forest products may have

levels of cesium 137 up to 10,000 times higher than agricultural foods subjected to an equivalent initial radioactive deposit, and mushrooms may still exceed the limits for sale or consumption.

- **Mushrooms**

The item commonly known as a 'mushroom', which we eat, is in fact a reproductive organ called the 'carpophore'—generally an above-ground and ephemeral part of the plant. The permanent part of the mushroom consists of a network of filaments called 'mycelium'. The mycelium usually grows underground, generally at a fairly shallow depth although this depends on the type, or on dead wood, tree trunks, or stumps. In the event of atmospheric fallout in the form of rain, any mycelium near the surface (at a depth of a few centimeters) can be reached quickly by the contaminated water that penetrates the soil. Radionuclides are then transferred to the carpophore very quickly. That is why activities in iodine-131 and cesium-134 and -137 ranging from a few dozen to thousands of Bq/kg were measured starting in the month of April in mushrooms from the Fukushima district, demonstrating this rapid transfer.

According to the results published in Japan, more than 120 mushroom samples taken between April 2011 and January 2012 had cesium activity ($^{134}Cs+^{137}Cs$) in excess of the limits for sale or consumption (500 Bq/kg), and of those, about 15 exceeded 2000 Bq/kg. The majority of mushrooms with high contamination were dried shiitake mushrooms (it should be noted that drying can concentrate the cesium up to tenfold), but level activity levels were also measured in fresh mushrooms. The highest cesium (134Cs+137Cs) activity identified among the published results was 28,000 Bq/kg; it was measured in a "weeping milk cap" (Lactarius volemus) mushroom, picked on September 1st 2011 in Tanagura-machi (Fukushima district). The highest iodine 131 activity, 12,000 Bq/kg, was measured in a (shiitake) mushroom picked on April 8th in Iidate-mura. The cesium 134+137 activity in that sample was 13,000 Bq/kg. These highest activity levels correspond to moderate deposit areas, and it is likely that much higher cesium contamination levels will be found in the future in the worst-affected areas.

The contamination of a mushroom depends directly on the environment in which it grows, on a very local scale. This leads to very wide variations in cesium content. This variability is further reinforced by the differences between species, modes of nutrition (saprophyte, parasite, or symbiont), and depth of mycelium. Thus, during the first years, species whose mycelium is nearest the surface of the ground will be the most sensitive. As the years go by, those with a deeper mycelium will become more contaminated with the downward migration of cesium, slow though this might be.

It is important to note that, as seen in the aftermath of the Chernobyl accident, mushroom contamination will no doubt continue for a long time—years or even decades—with cesium activity levels similar to, or even higher than, those measured in Japan in 2011, in the areas worst affects by the radioactive fallout from the Fukushima accident.

- **Wild berries**

No measurement result on wild berries (wild strawberries, raspberries, blueberries, etc.) seems to have been published to date. Although in general, in an equally contaminated environment, berries have cesium content similar to the least sensitive species of mushroom, their activities in the years to come should also become more and more different from those of agricultural products.

- **Game**

Almost 350 tests were performed on game in Japan between April 2011 and January 2012, mostly since fall 2011. They concern boar meat (155 tests), Asian black bear (85 tests), pheasant (42 tests), and deer (65 tests). Unlike in livestock products (beef), the cesium activities (134Cs+137Cs) were most often above detection limits. The highest levels were observed in wild boar and bear meat. Figure 6-44 presents the specific activities measured in wild boar meat. They are extremely variable: from a few Bq/kg wet to a few thousand Bq/kg wet (maximum recorded value of 14,600 Bq/kg wet), the highest being those from the Fukushima district.

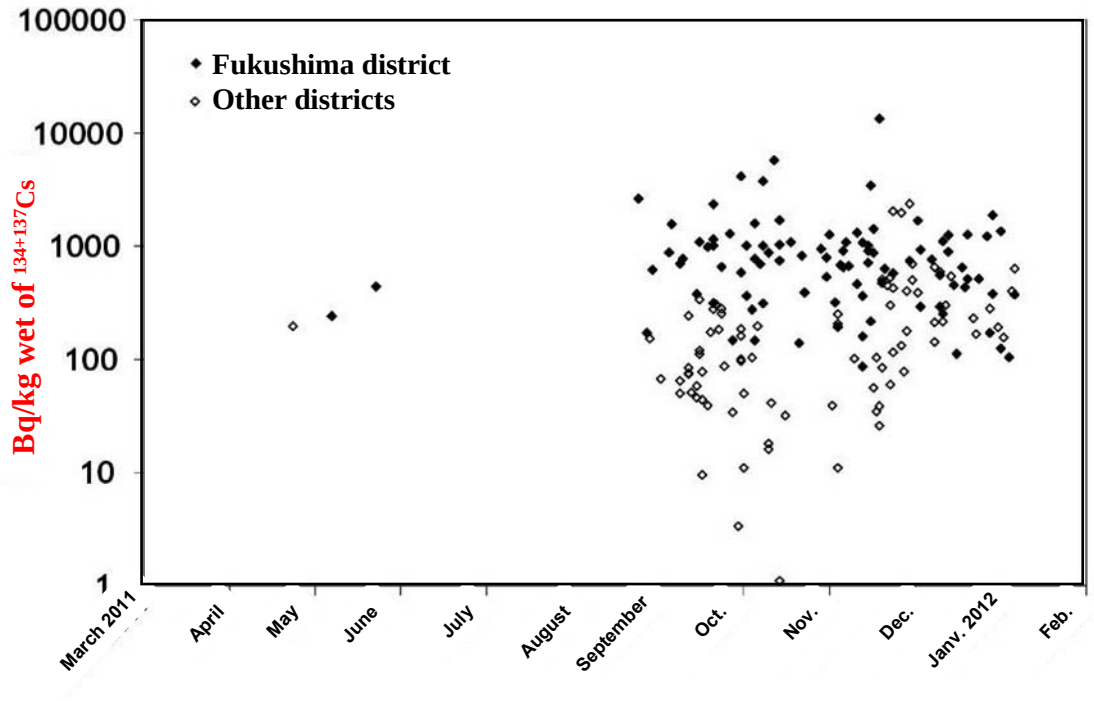


Figure 6-44 - Cesium ($^{134}Cs+^{137}Cs$) concentrations measured in boars taken from different districts (solid symbols: Fukushima; hollow symbols: Chiba, Gifu, Gunma, Ibaraki, Kanagawa, Miyagi, Saitama,Tochigi, Yamagata).

The activity levels in bear meat had similar levels and variability, with a maximum value of 1850 Bq/kg.

The cesium contents of pheasant and deer meat were lower: no more than a few hundred Bq/kg.

The unfavorable context of forest environments and the way of life of wild animals explain the variable, and generally higher, contamination than in beef. Thus, in the case of boars, the spatially heterogeneous nature of the contamination of the environment is combined with a large seasonal fluctuation, related to herbivorous/fructivorous eating in the spring and summer (although the boar is a highly opportunistic omnivore), and burrowing in the autumn and winter (acorns, roots, tubers, worms, larvae). Note that, after the Chernobyl, accident, similar seasonal variability was observed for roe deer in relation to mushroom consumption; the meat of an animal slaughtered in the fall can be ten times more contaminated than that of an animal slaughtered in the spring.

6.3.2.3.2 Aquatic species

- **Summary of measurement results in Japan**

From the end of March, various freshwater and marine organisms were analyzed in Japan. More than 3000 samples were taken between March and November. The case of marine species is presented in Section 6.4.7.

Of the various species taken from fresh water, five frequently had higher contamination levels in the Fukushima district, regularly exceeding the limits for sale or consumption, and were subject to regular monitoring (Figure 6-45). These species were: dace (tribolodon hakonensis), white spotted char (salvelinus leucomaenis), ayu sweetfish (plecoglossus altivelis), cherry salmon (oncorhychus masou), and wakasagi smelt (hypomesus nipponensis). All of these fishes, except dace, are able to migrate between fresh water and salt water (amphihaline species), but certain populations seem to be confined to fresh water only. The results are very variable, however what clearly stands out is the fact that the most affected samples were all collected from rivers or lakes in the Fukushima district (shown in red) except for a few specimens fished from lakes in the Gunma district (shown in blue). The highest levels were found in fish caught near the town of Minamisoma in the Fukushima district.

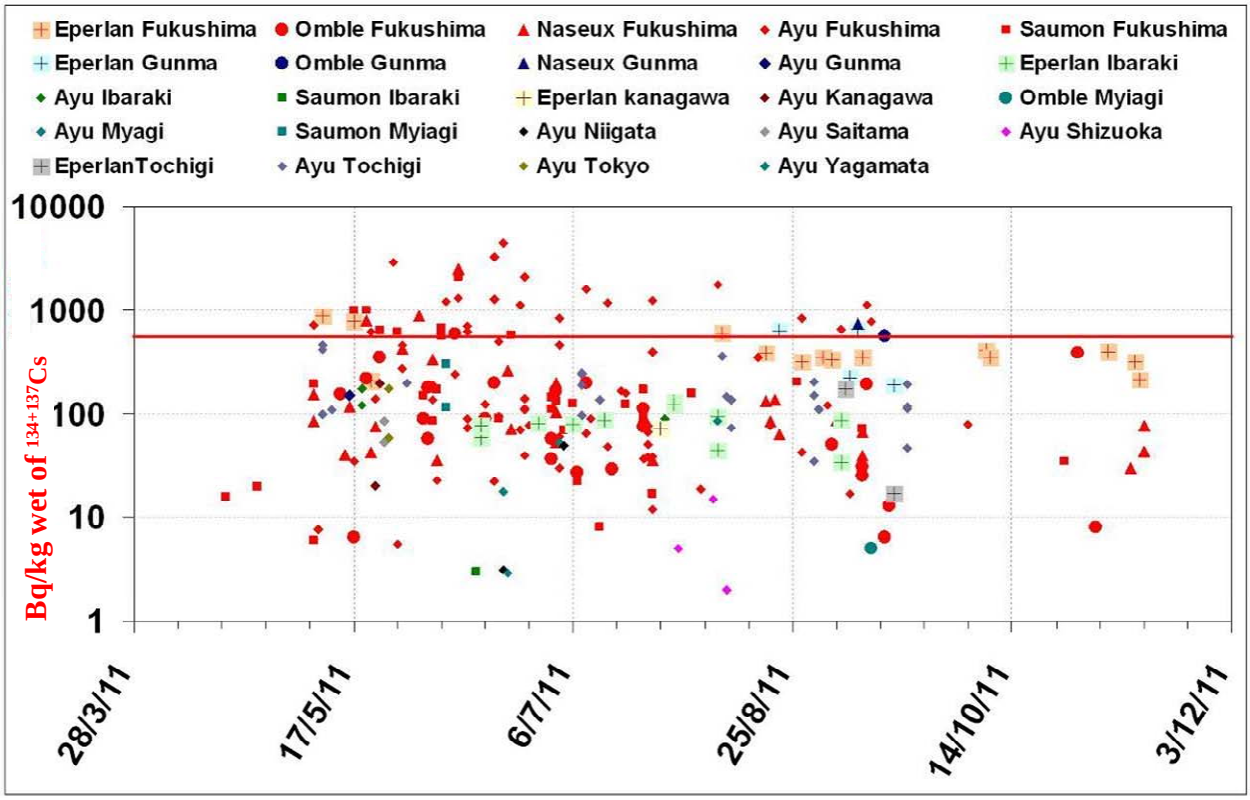


Figure 6-45 - Concentrations of radioactive cesium (^{134}Cs+^{137}Cs, in Bq/kg wet) measured in five species of fish caught in rivers or lakes in various Japanese districts.

Other aquatic species have been subjected to more or less regular monitoring, such as various types of freshwater clam, crabs, crawfish, shrimps, carp, and salmon. In most cases, the cesiums (^{137}Cs+^{134}Cs) were detected in those species at levels below 200 Bq/kg wet.

Note that one species of salmon, the chum salmon (*Oncorhyncus keta*), was also monitored regularly in the districts of Hokkaido and Fukushima. The results published are all below the detection limits (except for one sample taken on November 11th in the Fukushima district, measured at 41 Bq/kg wet). This can be related directly to how this species lives; only adult specimens are found in rivers, and they do not eat during that phase of their lives, which tends to highlight the importance of food as the main source of contamination in fish.

The contamination in fish will diminish all the more slowly as water and sediment are renewed slowly, particularly in lakes and ponds. In those environments, after the Chernobyl accident, effective half-lives (the time required for cesium contamination to be halved) of 100 to 200 days, and sometimes longer for carnivorous species, were observed.

- **The progress of contamination in the aquatic environment**

Although surface aquatic media received atmospheric fallout directly, that contribution was often small compared to the contributions related to trickling from neighboring surfaces when the radioactive deposits are mainly from rain, as in the most contaminated are to the north-west of the Fukushima Dai-ichi power plant. The contamination of bodies of water resulting from these effects must have been intermittent and almost simultaneous with the deposition. The IRSN is not aware of any measurement results with which this initial episode of contamination of the aquatic environment may be characterized.

The levels of contamination of surface water reached during this initial contamination episode could have been extremely variable according to the characteristics of the catchment basin, particularly the surface area, topology, morphology, pedology, vegetation cover, and the duration of deposit formation. Smaller bodies of water located upstream from the river network may be more sensitive than rivers in the downstream part of the hydrographic network because of dilution, in particular by the accompanying water table. It is important to remember that whatever its magnitude, this initial contamination episode only slightly affects aquatic organisms because of its transient nature.

After this early contamination episode, continental aquatic environments are then subjected to a supply of radionuclides, mainly cesium, related to soil drainage (supply of particles from contaminated soil and water). The renewal of river waters causes a significant proportion of this contamination to be exported quite quickly towards the rivers and the sea. Nevertheless, a fraction becomes fixed more or less permanently in the sediment, which then becomes a source of delayed contamination for water and aquatic life. **The resulting activities in water in the months following the deposits are generally 10 to 100 times weaker than those observed during the initial episode, but will contribute to the long-term contamination of aquatic organisms**. Little information is available concerning current activities in bodies of water in Japan, except for a series of measurements taken by the Japanese Ministry of the Environment in bodies of water in the Fukushima region in September 2011.

6.4. CONTAMINATION IN THE MARINE ENVIRONMENT

The marine environment was affected at the time of the accident and the following days by fallout of aerosols emitted into the atmosphere at the time of their dispersion above the ocean (§ 6.1.2) as well as by the release of liquids directly into the sea. In future, the leaching of contaminated soils will be the main source of long-term contamination of the marine environment.

6.4.1. DESCRIPTION OF THE MARINE AREA EXPOSED TO DISCHARGES

The Fukushima power plant is located on the coast of the island of Honshu, 200 km north-east of Tokyo. The coast runs north-south, facing the Pacific Ocean. The seabed shelves off gently to a depth of 200 m, 50 km from the coast and then drops suddenly to more than 5,000 m, about a hundred kilometers offshore (Figure 6-46).

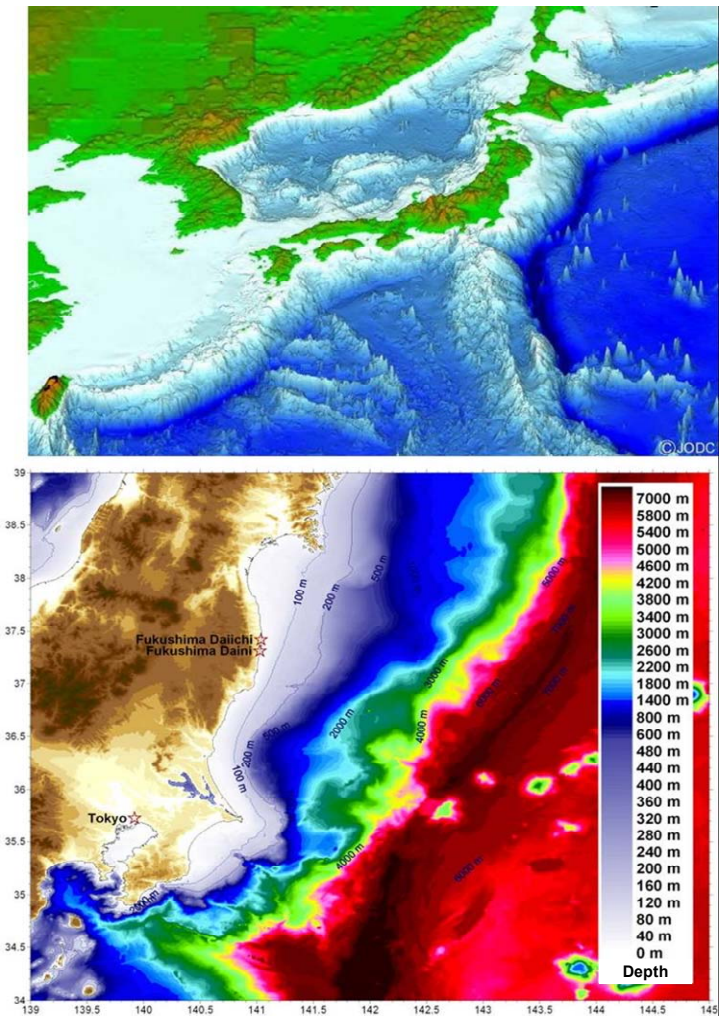


Figure 6-46 - Topography of the sea bed in Japan and bathymetry off the east coast.

In the zone affected by radioactive pollution, the currents are generated by the tide, wind and the general Pacific circulation. In the short term, the tidal effect predominates. The tide moves the masses of water according to an alternating movement along the coast towards the north and the south, with speeds in the region of one meter per second and a periodicity of 12 hours. The wind influences the circulation of surface waters.

The general larger-scale circulation is the result of the interaction between the Kuroshio oceanic current, which comes from the south and runs along the coasts of Japan, and the less powerful Oyashio current, which comes from the north (Figure 6-47 and Figure 6-48). The intensity and scale of the Kuroshio are comparable to those of the Gulf Stream. The coastal waters in the vicinity of the Fukushima Dai-ichi plant are situated in the zone where these two currents interact, creating weak and variable gyratory currents. It is these currents which were determining factors in the medium-term dispersion of the radioactive pollution.

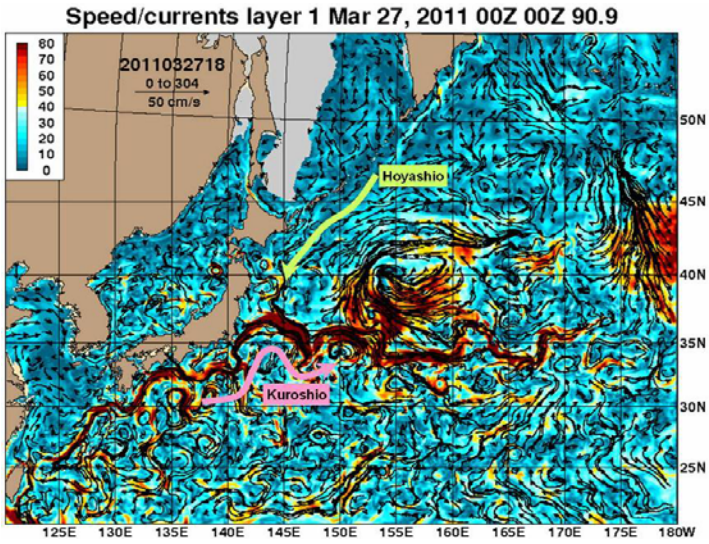


Figure 6-47 - Surface currents in the north-west Pacific (http://www.hycom.org/)

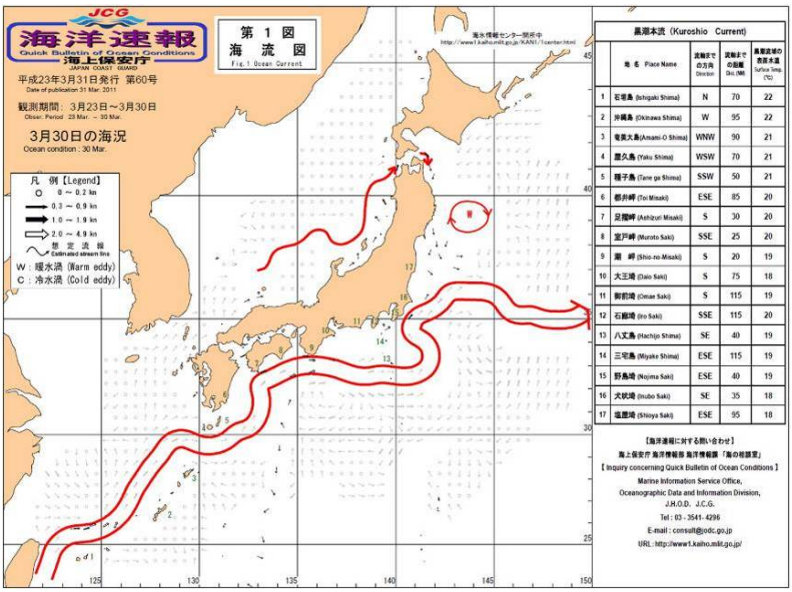


Figure 6-48 - Observations of surface currents in the north-west Pacific. The Kuroshio (red) runs from the south-west to the east (http://www1.kaiho.mlit.go.jp/KANKYO/KAIYO/qboc/2011cal/cu0/qboc2011060cu0.html).

6.4.2. CHARACTERISTICS OF MARINE RADIOACTIVE POLLUTION AROUND THE FUKUSHIMA DAI-ICHI POWER PLANT

From 21st March and in the days that followed, strong radioactive pollution was observed in the marine environment near the Fukushima Dai-ichi nuclear power plant. This pollution was characterized mainly via measurements performed on samples of seawater, sediments, and species living in the marine environment. The results have been published by MEXT and TEPCO. The IRSN is not in a position to perform measurements in Japan, but has regularly collected and analyzed these results in order to monitor the progress of the radioactive pollution in the marine environment.

The measurement results published in Japan mainly concern gamma-emitter radionuclides, listed in Table 6-VII. The impact of these liquid releases started to be observed on March 21st near the power plant (1484 Bq/L in ^{137}Cs, 5066 Bq/L in ^{131}I) (Figure 6-49). The concentrations in seawater then increased from March 25th to 28th (up to 12,000 Bq/L in ^{137}Cs, 74,000 Bq/L in ^{131}I). Another increase was measured on March 29th and 30th (up to 47,000 Bq/L in ^{137}Cs,

180,000 Bq/L in ^{131}I). For the sake of comparison: before the Fukushima accident, the cesium 137 concentration levels in seawater off the Japanese coast were just a few mBq/L (1 to 3 mBq/L) and no iodine 131 was detected.

Table 6-VIII – Main radionuclides measured in seawater

Main radionuclides detected	
Radionuclide	*Half-life*
Iodine 131 (^{131}I)	8 days
Cesium 137 (^{137}Cs)	30.1 years
Cesium 134 (^{134}Cs)	2.1 years
Cesium 136 (^{136}Cs)	13.1 days
Tellurium 132/Iodine 132 (^{132}Te-^{132}I)	78 hours

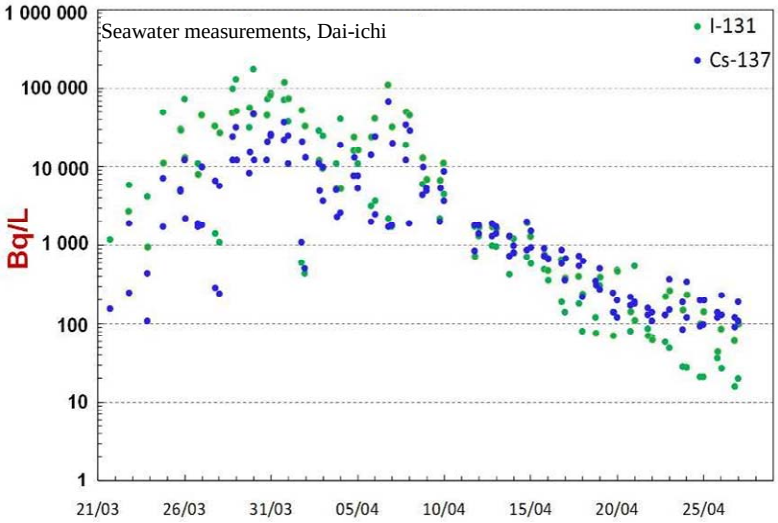


Figure 6-49- Evolution of concentrations of iodine 131 (131I) and cesium 137 (137Cs) in the seawater less than 500 m from the Fukushima Dai-ichi power plant.

Iodine 131 (131I) and cesium 137 (137Cs) are the main radionuclides that were monitored in 2011 in the marine environment. Although it was predominant at the time of the accident, the amount of iodine-131 fell sharply in the weeks following the accident, due to its rapid radioactive decay. After the end of May, it was no longer detectable.

Other artificial radionuclides, most with a short half-life, have also been detected occasionally, at lower concentrations. Tellurium 129m/tellurium129 (T = 33.6 days), barium 140/lanthanum 140 (T = 12.7 days), ruthenium 105 (T = 4.4 hours), ruthenium 106 (T = 368 days), molybdenum 99/technetium 99m (T = 65.9 hours), cobalt 58 (T = 70.9 days). There are fewer measurements concerning pure beta-emitter radionuclides: Nine results for strontium 90 in seawater, at concentrations between 1 and 10 Bq/L, representing from 1 to 20% of the radioactivity of cesium 137 measured in the same samples, i.e. a higher proportion than that observed in the atmospheric fallout from the accident onto land areas of Japan, which was in the region of 0.1%.

The high concentrations measured in the seawater in the immediate vicinity of the Fukushima Dai-ichi plant were the result of liquid radioactive releases which no doubt had several origins. This would include the water used to cool the damaged reactors, which was in contact with materials heavily contaminated by the atmospheric releases, and some of which trickled out to sea. Another part came from the water which escaped from the containments of reactors 2 and 3. In particular, a crack in the pit adjacent to the reactor 2 turbine hall led to the release of heavily contaminated water directly into the sea. On April 6, at approximately 6 am local time, TEPCO successfully stopped this release by plugging the leak with an injection of sodium silicate. The estimate of the release directly into the sea made by the Japanese authorities is based on the quantification of this leak.

This coastal radioactive pollution made its way southwards between the 25th and 28th of March, with an increase in the iodine 131 and cesium 137 concentrations of the order of a factor of 10 in Iwasawa (approximately 20 kilometers south of the damaged power plant starting on March 28th and especially on March 29th.

The radioactive pollution in the sea was also caused by the fallout on the marine surface of some of the radionuclides contained in the radioactive plume during the atmospheric dispersion of the releases occurring mainly from March 12th to 23rd 2011. This diffuse pollution of the surface waters occurred dozens of kilometers from the nuclear power plant. Thus, the concentrations measured 30 km offshore from the damaged power plant before March 30th were probably mainly caused by atmospheric deposits. They varied from 2 to 27 Bq/L for cesium 137 and 3 to 57 Bq/L for iodine 131. After falling to a minimum on 30th March, the concentrations in the seawater rose during the first half of April because of the offshore dispersion of liquid radioactive releases from the power plant.

The changes in time and space of the concentrations of ^{131}I and ^{137}Cs are representative of those of all the radionuclides released into the sea. The results are summarized by the two figures below:

- The concentrations measured near the outfall pipe, which are representative of the flow of radionuclides released in that location (Figure 6-50),

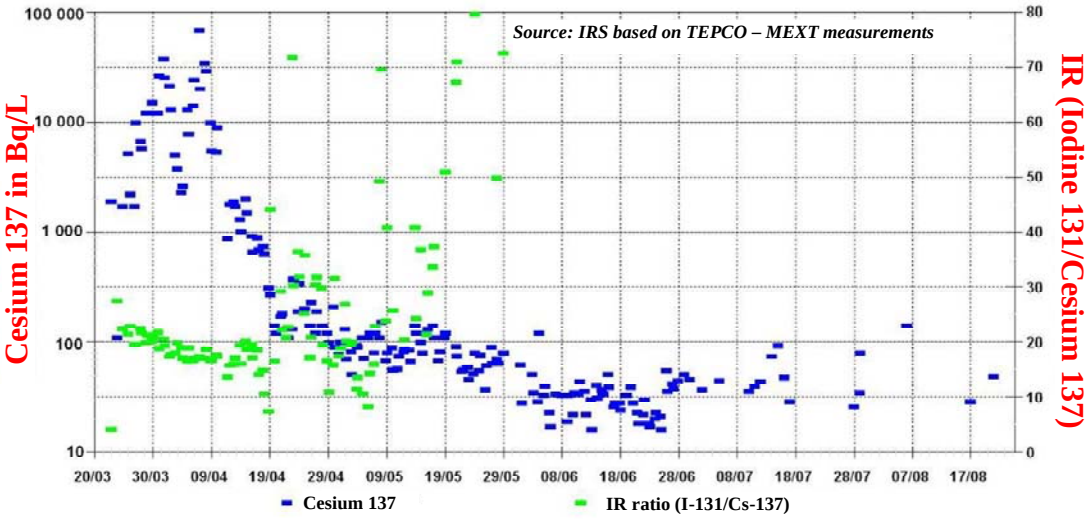
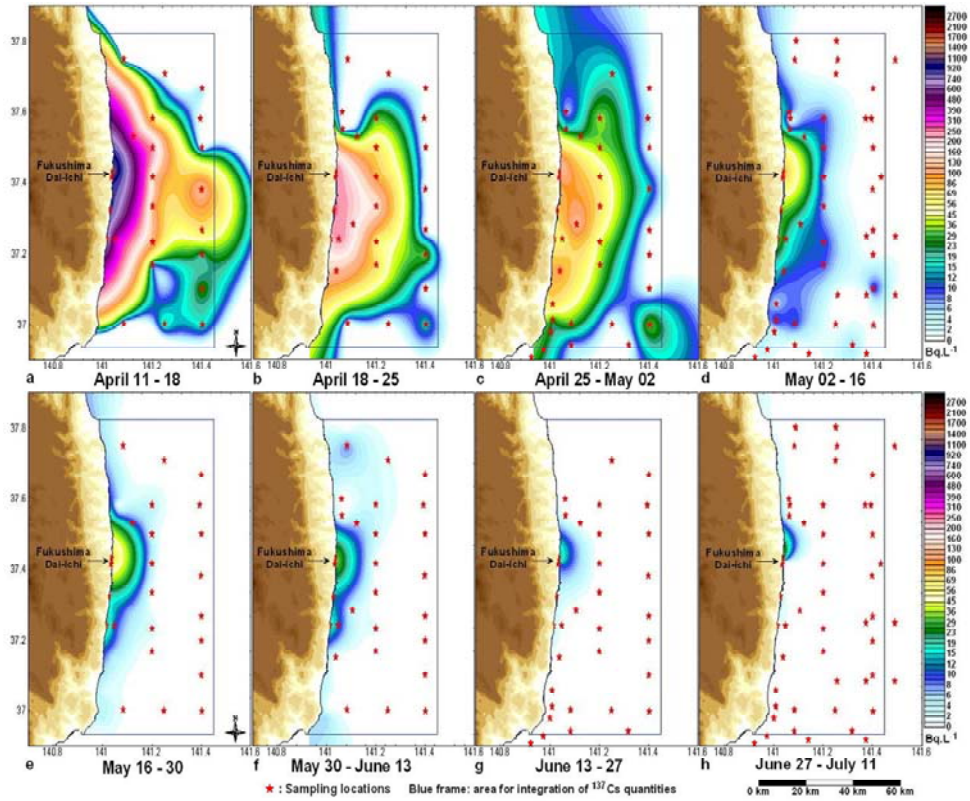


Figure 6-50– Change in ^{137}Cs concentrations in seawater and IR ratio ($^{131}I/^{137}Cs$), within 500 m of the Fukushima Dai-ichi power plant. The value of the IR ratio was corrected for radioactive decay and normalized to 11th March for the purpose of making the results comparable to each other.

- Cesium 137 concentration isovalue maps, showing the distribution of radioactive pollution in seawater at different periods (Figure 6-51).



Source: IRSN based on TEPCO-MEXT measurements

Figure 6-51 – Changes in the spatial distribution of 137Cs concentrations in seawater between April 11th and July 11th 2011.

The measurements performed near the installation give a relatively uniform IR ratio ($^{131}I/^{137}Cs$) in the region of 20, with a gently falling trend over time until April 19th. This reduction, which is not due to the radioactive decay of iodine, and already taken into account in the calculation of the ratio, suggests a process of regular elimination of the iodine 131 measured in the seawater, with an apparent decay period (half-life) of 35 days. A similar trend was observed at 10 and 20 km to the south between March 27th and April 16th, but it is not detectable far from the coast. The causes of this gradual elimination of iodine in the seawater have not yet been identified. This effect could be a sign of a behavior specific to iodine, either in the damaged installations before discharge, or in the marine environment. It could also result from a gradual mixing with another source that has a lower isotopic ratio.

After April 19th, the IR ratio ($^{131}I/^{137}Cs$) became highly variable, no doubt because of the increasing inaccuracy of the results of measuring iodine 131 in seawater as its radioactivity decreases due to decay. These variations could also be the result of fluctuations in the composition of residual discharge from the damaged site, even though this must have been greatly reduced from April 11th onwards, at which time a significant decrease in radioactivity in the seawater near the power plant began.

The maps in Figure 6-51 represent the spatial distribution of the mean cesium 137 concentrations for successive periods between 11th April and 11th July, whose duration (7 days from 11th April to 2nd May, and then 14 days for the following periods) was chosen by the IRSN to provide a sufficient number of measurements spread over the scope of the study to perform a representative interpolation. These maps show a similar distribution of the pollution from the vicinity of the nuclear power plant towards the open sea. The concentrations fell sharply over time, and the area of the colored zones, corresponding to measurements above the detection limit (around 5 Bq/L), decreased accordingly.

After July 11th, the concentrations measured at sea were mostly below the detection limits of the measurement methods used for monitoring. From that time onwards, it was no longer possible to perform a representative inventory of the residual pollution at sea.

6.4.3. ESTIMATE BY IRSN OF THE QUANTITIES OF CESIUM 137 RELEASED INTO THE SEA

6.4.3.1 Direct liquid releases

The precise quantities and the duration of the liquid releases into the sea are difficult to estimate directly. The first IRSN estimate, using the concentrations measured in the water of the n°2 reactor turbine hall, $2.3x10^{+15}$ Bq (2.3 million billion becquerels) of cesium 137 could have been released into the sea. In addition, from April 4th to 10th, TEPCO discharged "slightly contaminated"' water into the sea. This was 10,000 tons of liquid effluent stored in tanks. These discharges, estimated by TEPCO at $1.5x10^{+11}$ Bq, did not significantly increase the concentrations resulting from the previous releases.

Based on the maps in Figure 6-51, the IRSN updated its estimate of the quantities of ^{137}Cs present at sea, in the zone located in the blue frame shown on these maps. This estimate took the bathymetry into account, as well as the mixing depth deduced from the salinity-temperature profiles drawn up by MEXT, when this depth is less than the depth of seawater. The results are presented in Tableau 6-VIII and the change over time of these estimated quantities is represented in Figure 6-52.

Table 6-IX – Quantities of ^{137}Cs in the coastal sea zone near the Fukushima Dai-ichi power plant, estimated from the interpolation of individual measurements in seawater over different periods from April 11th.

Inventory period			Number of measurements	Quantity of ^{137}Cs (Terabecquerels)
Start	End	Middle		
11/04/11	18/04/11	14/04/11	92	11,600
18/04/11	25/04/11	21/04/11	77	4,750
25/04/11	02/05/11	28/04/11	118	3,380
02/05/11	16/05/11	09/05/11	293	667
16/05/11	30/05/11	23/05/11	233	261
30/05/11	13/06/11	06/06/11	227	163
13/06/11	27/06/11	20/06/11	250	42
27/06/11	12/07/11	04/07/11	202	2.4

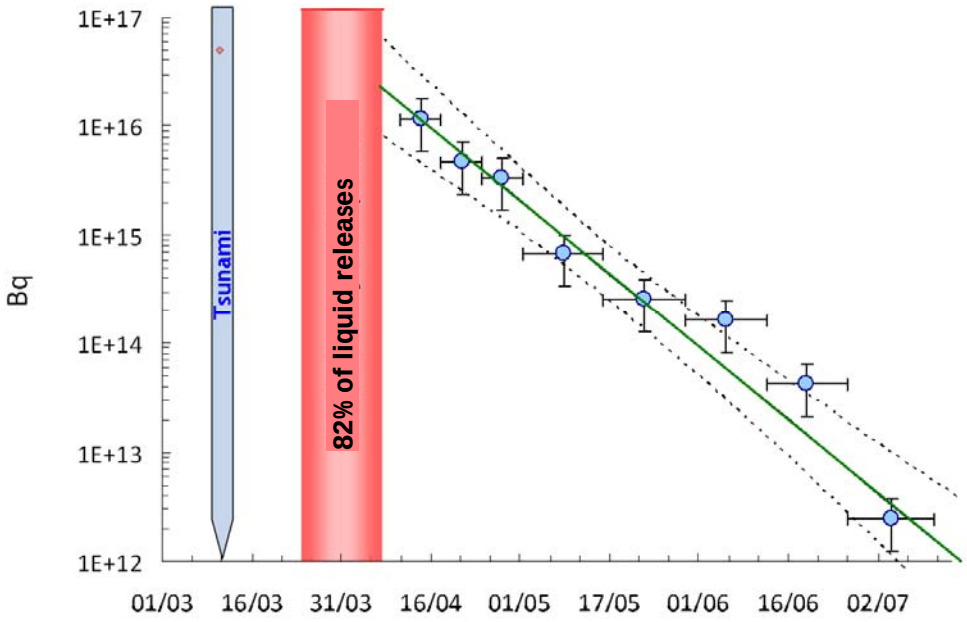


Figure 6-52 - Changes in the ^{137}Cs quantities in seawater in the coastal area near the Fukushima Dai-ichi power plant from April 11th to July 11th 2011. The horizontal error bars represent the periods during which the measurements were taken into account. The vertical error bars represent the error in the estimated quantities of ^{137}Cs. It is related to the estimate of the thickness of the mixture layer (+-50% for all values).

This quantity follows an exponential curve, decaying with a half-life $T_{1/2}$ of 6.9 days (95% confidence interval: 5.7 - 8.6 days). **This means that the quantity of cesium 137 present in seawater inside the calculation zone was halved every 6.9 days. This decrease was due to the dilution of the polluted seawater by sea currents that brought a regular supply of uncontaminated water into the zone concerned.** This is an especially fast renewal rate. It is due to the strength of the Kuroshio and Oyashio currents, which meet in this area, and their general orientation towards the open sea. The regularity of the dilution is also remarkable, taking into account the variability of the turbulent flow observed in this mixing zone.

This active dilution effect tended to reduce the impact of the accident on coastal waters. Contaminated waters were carried swiftly eastward, toward the center of the Pacific, where they continued to be diluted due to the dispersion of ocean waters.

Over the longer term, the rate of this dilution could have been modified by two effects:

- Seasonal variations in the ocean currents (Kuroshio and Oyashio),
- The return into the zone of ocean waters previously polluted by discharge from the Fukushima Dai-ichi accident due to the recirculation of water masses in the northwestern Pacific. This phenomenon could prevent or delay the return to cesium 137 concentrations comparable to the pre-accident levels (between 0.001 and 0.004 Bq/L)[24].

[24] Nakanishi, T., Zheng, J., Aono, T., Yamada, M., Kusakabe, M., 2011. Vertical distributions of 99Tc and the 99Tc/137Cs activity ratio in the coastal water off Aomori, Japan. J. Env. Radioactivity V.102, 8, 774-779.
Povinec, P.P., Hirose, K., Honda, T., Ito, T., Scott, E.M., Togawa, O., 2004. Spatial distribution of 3H, 90Sr, 137Cs and 239,240Pu in surface waters of the Pacific and Indian Oceans--GLOMARD database. J. Env. Radioactivity V.76, Issues 1-2, 113-137

Thus, unlike in the terrestrial environment, where a residual deposit will persist for several years, the acute contamination period of the marine environment was contained within a period of about six months. This duration is not a general characteristic of accidental pollution in a marine environment. It is the result of especially favorable hydrodynamic conditions related to the dynamics of the currents, the fact that they are directed towards the open sea, and the size of the receiving medium (the Pacific Ocean). If this event had taken place in an enclosed sea (e.g., to the west of Japan), or in a bay, the short- and long-term consequences could have been ten times worse. By way of comparison, the half-life of the waters in the Normandy-Brittany Gulf, where the Flamanville power plant is located, is approximately three months (twelve times the half-life observed in the Fukushima region), even though the tidal currents in that area are very strong.

The extrapolation of the regression curve to April 8th provides an estimate of the total quantity of ^{137}Cs discharged at the end of the main discharge period (March 26th – April 8th). The quantity estimated by extrapolation is 22.10^{15} Bq (22 million billion becquerels), with a 95% confidence interval from 20.8 to 23.1 10^{15} Bq. The main error associated with this calculation is related to the estimate of the mixing depth. This uncertainty is evaluated at around 50%. This evaluation of the cesium 137 releases at sea produces a higher result than the first estimate mentioned above, which was obtained using a different method, but in view of the major uncertainties in these estimates, the orders of magnitude can be considered to be close.

IRSN has also been able to establish an empirical correlation between the total quantity of cesium 137 estimated for this period from March 26th to April 8th and the mean cesium 137 concentrations measured in seawater in the immediate vicinity of the damaged power plant during the same period: for each Bq/L measured near the facility, there are 1.06.10^{11} Bq released per day (Figure 6-53). By applying this correlation to the measurements taken up to July 18th, after which the number of significant measurements became too small to perform an adequate measurement of the released flux, **IRSN was able to determine the overall quantity of cesium 137 released into the seawater until mid-July. The value thus obtained is 27.1015 x 10^{15} Bq. As expected, most of the release took place before April 8th, and the estimated release after that date accounted for only 18% of the total release. This is the largest one-off injection of artificial radionuclides into the marine environment ever observed.** After July 18th, the number of significant measurements is too low for any reasonable estimate of the released flow to be made.

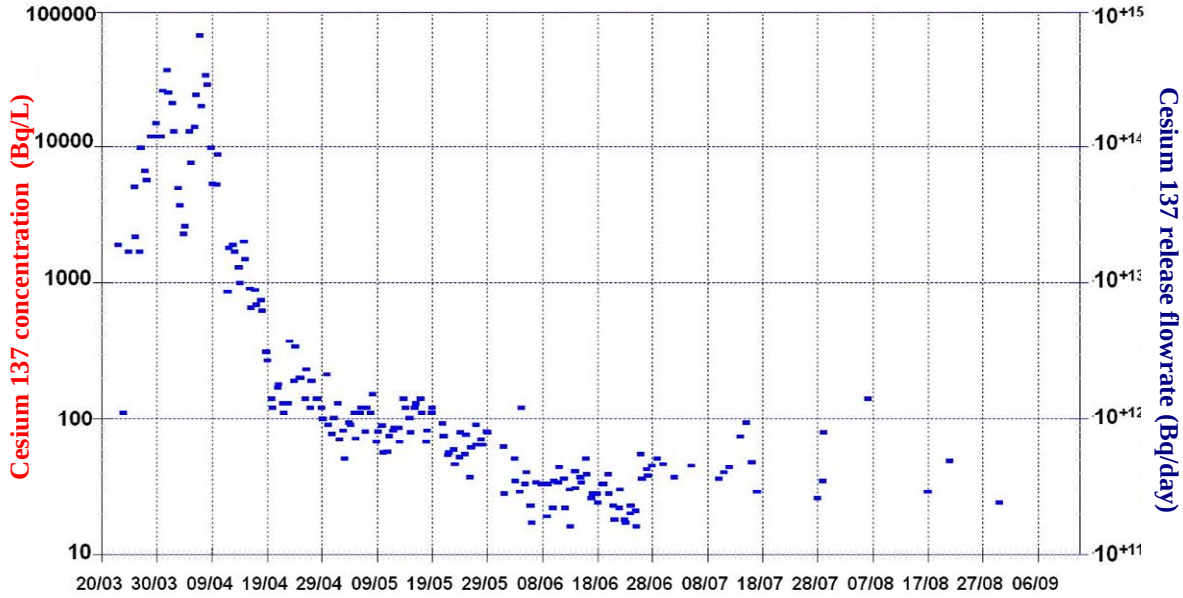


Figure 6-53 - Concentrations of ^{137}Cs within 500 m of the Dai-ichi power plant (Bq/L) and the corresponding flux in seawater (Bq/jour).

By comparison with other major sources of artificial radionuclides in the marine environment, the direct releases from Fukushima Dai-ichi represent the largest emission recorded in such a short time in a limited area. Table 6-X summarizes the main sources and the conditions of their release for ^{137}Cs.

Table 6-X - Inventory of the main sources of ^{137}Cs in the oceans, in PBq (10^{15}Bq).

Atmospheric fallout from nuclear tests	Spent fuel reprocessing 1951 -> 2010		Chernobyl accident	Immersion of solid waste in the sea (beta + gamma emitters)	Fukushima Dai-ichi	
	BNFL Sellafield	Areva-NC The Hague			Direct release	Atmospheric deposition
948 [a]	41.21	1.04	15-20 [a]	78 - 82 [a, b]	27 [c] (12 - 41)	0.076 [c] (80 km radius)

a: Aarkrog (2003); b: Linsley *et al.* (2005); c: IRSN (Bailly du Bois *et al.* (2011))

The highest concentrations measured in the open sea that could be compared to the concentrations measured near Fukushima Dai-ichi are those measured in the Irish Sea in 1974 - 1976 with ^{137}Cs levels above 10 Bq/L (Figure 6-54). Those values were a factor of a thousand less than the maximum values observed near the Fukushima Dai-ichi power plant, but they concerned the entire Irish Sea, and persisted for several years in accordance with the controlled releases from the Sellafield plant. Since July 2011, concentrations above 10 Bq/L have not been measured outside the immediate vicinity of the Fukushima Dai-ichi power plant.

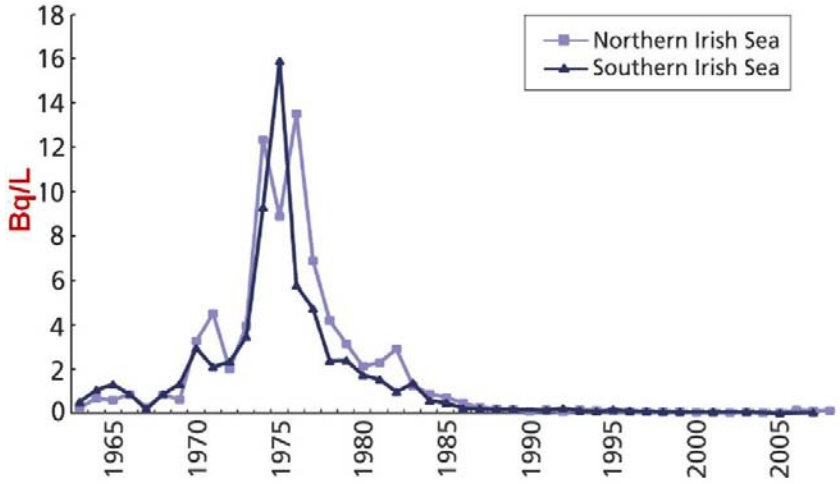


Figure 6-54 - ^{137}Cs concentrations in the Irish Sea (RIFE, 2009).

For reference, this total contribution of 27 x 10^{15} Bq of cesium-137, diluted at a depth of 0 to 100 meters throughout Pacific Ocean, would lead to an added concentration of 0.002 Bq/L, which would be double the residual background in the seawater due to the fallout from atmospheric nuclear tests (0.002 Bq/L). Although measurable with current techniques, these concentrations would represent only one 3000th of the natural potassium 40 concentrations in seawater (12 Bq/L). The cesium is essentially dissolved in the seawater and will remain measurable for decades. Thus, the cesium 137 resulting from the atmospheric nuclear tests of the 1960s remains clearly identifiable on a worldwide scale. At the time of the Fukushima accident, the radioactivity of the cesium 134 released into the sea was at the same level as that of the cesium 137, but because these two radionuclides have different half-lives, 2 and 30 years respectively, the radioactive ratio $^{134}Cs/^{137}Cs$ will fall over time, and can be used for many years to identify and date bodies of water contaminated by discharge from Fukushima on the scale of the surface waters of the North Pacific.

6.4.3.2 Atmospheric fallout onto the surface of the sea

There are few measurement results that can reveal the scale and extent of the atmospheric radioactive fallout on the surface of the ocean, because the surface water that receives the atmospheric fallout is quickly mixed in with the rest of the seawater via advection and dispersion. Only seawater measurements taken a small number of days after the deposit can provide information about the impact of this radioactive fallout. Before March 24th, when there was still relatively little direct liquid release, the concentrations measured in seawater more than 10 km from the installation could be attributed to atmospheric fallout (cf. § 6.4.2). The IR ratio ($^{131}I/^{137}Cs$) determined at that

distance, before March 30th, is from 5 to 12, which is comparable to that observed in the terrestrial environment in Japan (see § 6.2.3).

During the same period, the measurements published in Japan revealed the presence of another polluted zone along the coastline, more than 10 km to the south of the facility, with values from 20 to 100 Bq/L of ^{137}Cs, and an IR ratio (^{131}I/^{137}Cs) from 35 to 110. This pollution can be attributed to other atmospheric fallout or to direct liquid release prior to that identified from March 21st onwards.

The atmospheric fallout onto the ocean surfaces was evaluated by IRSN using the updated model for atmospheric dispersion of release from the Fukushima Dai-ichi power plant (§ 6.1.2.1). **According to this estimate, the cumulative deposit of cesium 137 onto the sea in an 80 km radius was 76.10^{12} Bq (76,000 billion Becquerels)**, a value approximately 10 times lower than the value estimated in July. This supply of contamination into the sea represents only 0.3% of the overall radioactivity from cesium 137 released directly into the sea by the Fukushima Dai-ichi power plant, estimated by IRSN in Section 6.4.3.1. The map in Figure 6-55 represents the spatial distribution of this fallout onto the Japanese marine environment. **Apart from the deposit that formed in this coastal domain and the one that formed on Japanese land, most of the atmospheric releases of cesium must have been deposited in a scattered manner on the oceans and continents of the northern hemisphere, across great distances.**

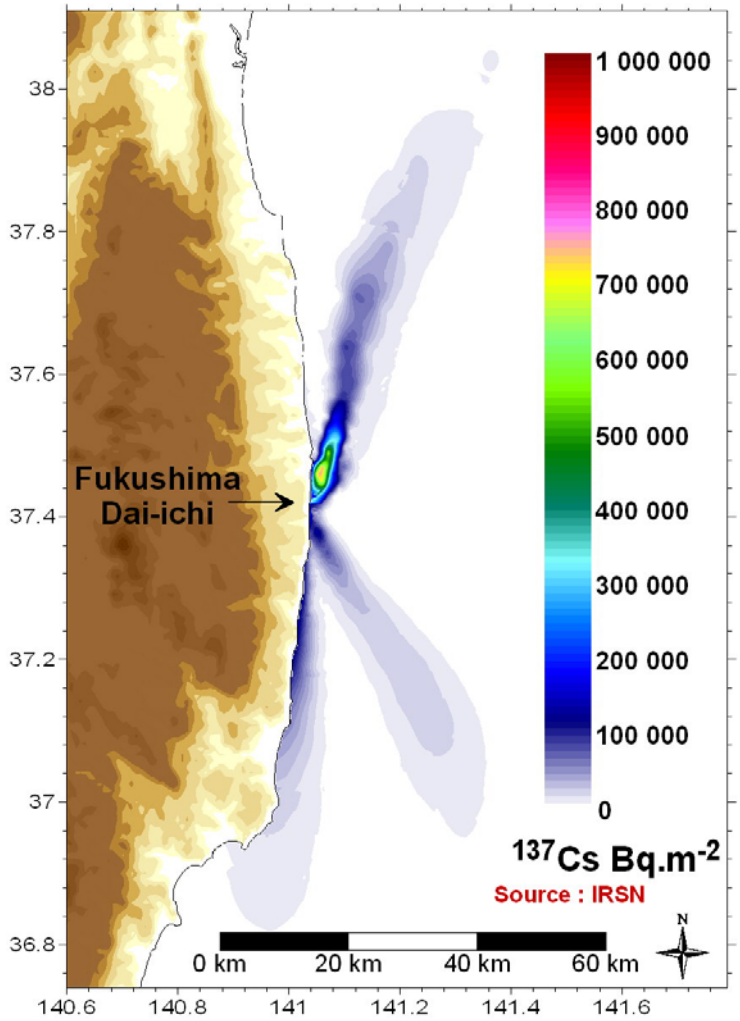


Figure 6-55 - Distribution of the total atmospheric deposit of ^{137}Cs on the sea as at March 23rd, estimated by IRSN by simulating the atmospheric scattering of releases from the Fukushima Dai-ichi accident.

6.4.3.3 Transport of radioactive pollution by leaching of contaminated soil

The radioactive deposits that formed in the terrestrial environment during the dispersion of the atmospheric releases from the Fukushima Dai-ichi plant were able to be partially leached by rainwater and then transported to the sea by run-off. The contaminated land areas thus drained can represent several thousand km^2 (cf. § 6.2.2.2).

There is currently no predictive model for these exports to the sea and how they evolve that is sufficiently robust and operational to provide reliable forecasts over a period of several years. Since the Chernobyl accident, empirical models have generally been the most widely used and completed. In this context, IRSN has developed the HAMSTER database, which collects all transfer function parameters available in the literature. The results presented in Figure 6-56 come from a first use of this database to predict the flux over ten years of cesium 137 activity at the outlet of the Ukedo river (river from the catchment basin most contaminated by the Fukushima accident). Initially, the cartography of the surface deposits and the variability of the parameters deduced from this database allow a (wide) range of possible values for the flow at the outlet to be calculated. Based on the first radioactivity measurements performed at that outlet by the Japanese Ministry of the Environment in September 2011, the second stage is to reduce this range according to the local variability of the hydro-sedimentary parameters such as flow rate, size of particles in suspension, the partitioning coefficient, etc.

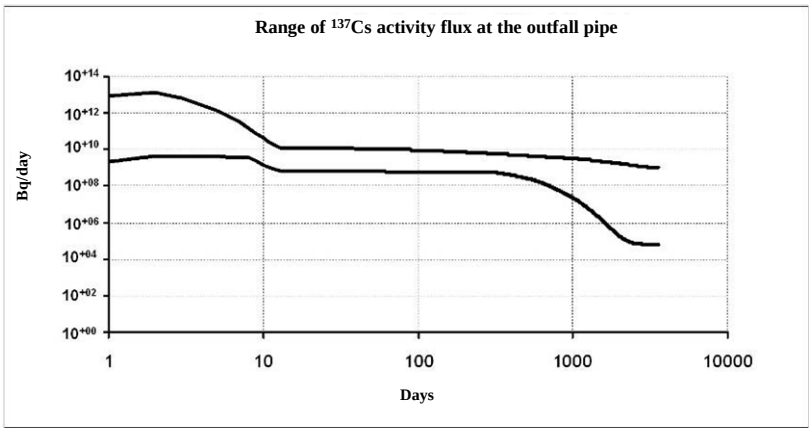


Figure 6-56 – High and low prediction of the change during the 10 years following the accident of the flux (Bq/day) in ^{137}Cs at the outlet of the Ukedo basin.

Although much smaller than the uncertainties of the 1st stage, the uncertainties of the 2nd stage are still high, because the shortage of local hydro-sedimentary data makes it necessary, for the time being, to associate them with a wide variability range. If flow rates were known, these uncertainties could be very significantly reduced. These initial calculations are currently extended to all contaminated Japanese catchment basins, and they will be continually refined as new data are obtained.

6.4.4. SIMULATION OF THE DISPERSION OF CESIUM 137 IN SEAWATER OFF THE COAST OF JAPAN

IFREMER was approached by IRSN to run simulations of the dispersion of the discharge from Fukushima Dai-ichi. The Mars 3D model is used, the hydrodynamic limit conditions come from Mercator-Ocean, and the meteorological forcing is given by the European ECMWF model.

The cesium 137 discharge used in this simulation comes from the calculations presented in Section 6.4.3.1. The assumption that cesium 137 was dispersed in soluble form was applied.

The concentrations measured and simulated less than a kilometer from the installation give results in agreement; the source term taken into account reproduces the small-scale dispersion well (Figure 6-57-a). With regard to the full set of ^{137}Cs measurements available in July (Figure 6-57-b), although there are significant deviations, the model does not significantly under- or overestimate the concentrations.

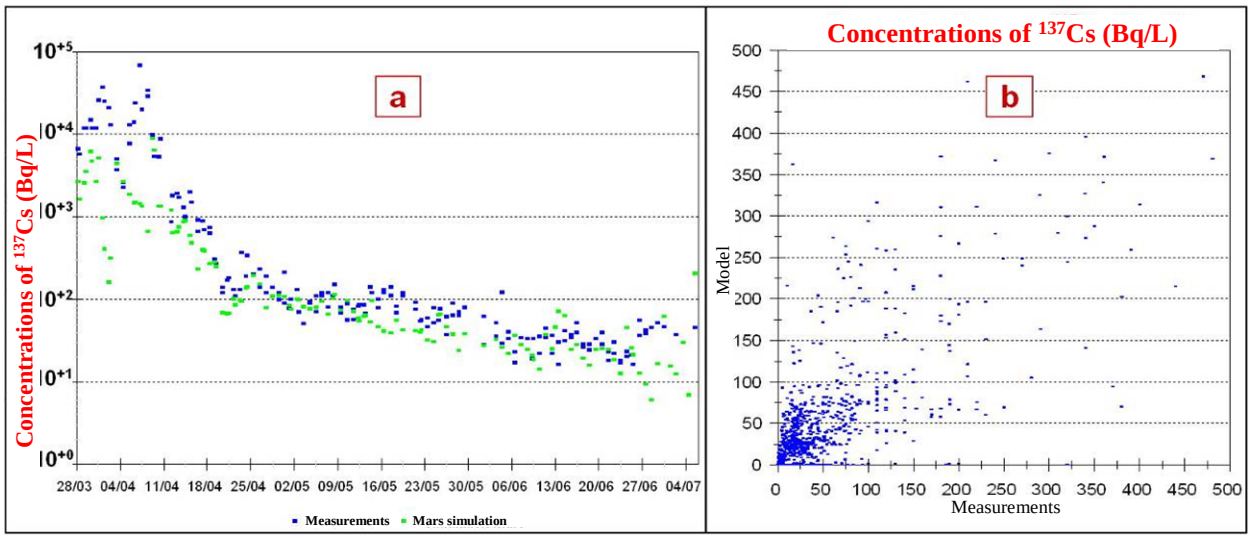


Figure 6-57 - Comparison of the concentrations measured and simulated by the Mars model. (a): Within one kilometer of the facility; (b): For all 137Cs measurements at sea.

Figure 6-58 reproduces the results of the simulation of the dispersion of discharge from Fukushima on the scale of the north-west Pacific. It illustrates the complexity and variability of the currents resulting from a comparison of Kuroshio, arriving from the south, and Oyashio, arriving from the north. The dispersion structures are comparable to those simulated by the Sirocco model in Toulouse.

After July 1st, the simulated concentrations were generally below the detection limits applied to the monitoring measurements. They could have been identifiable with the classic methods used in oceanography (LD < 0.001 $Bq.L^{-1}$).

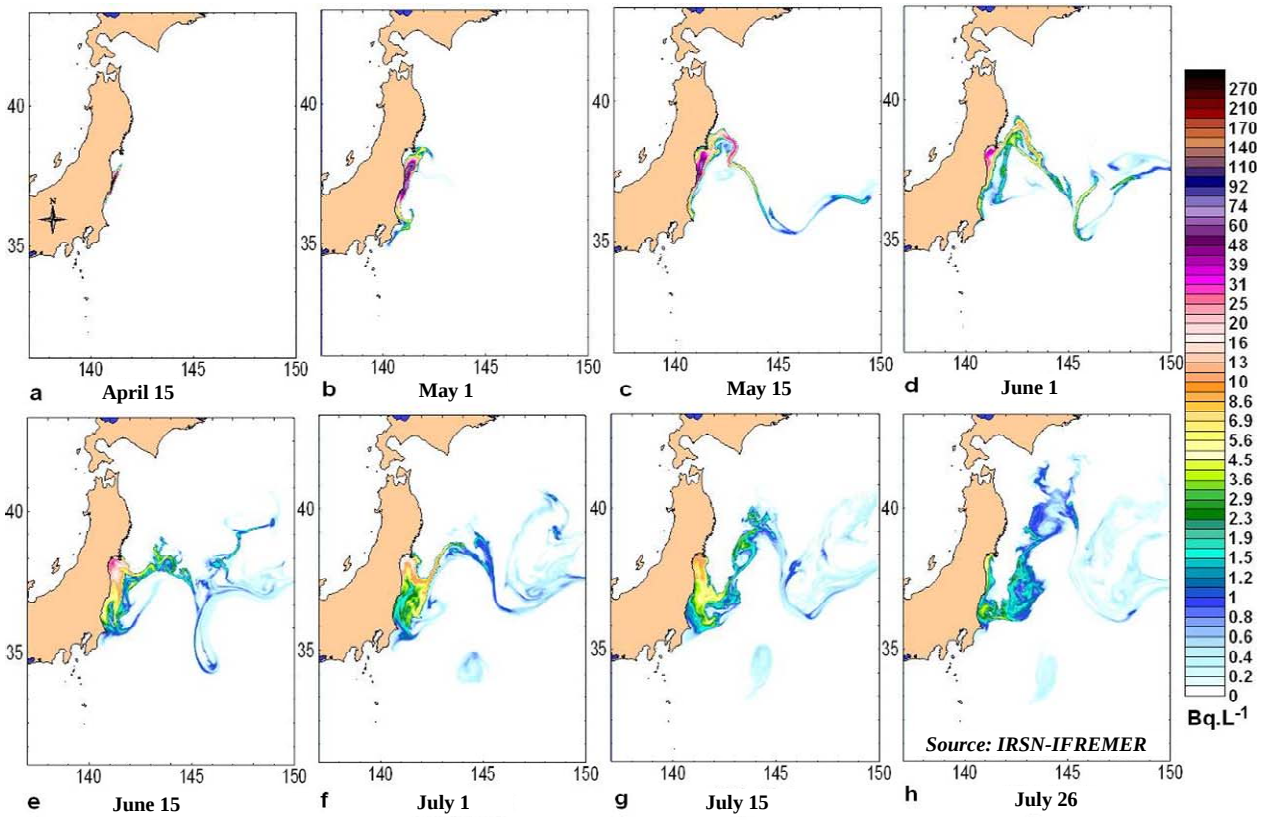


Figure 6-58 - 137Cs concentrations in seawater simulated by Mars 3D between April 15th and July 26th 2011 in the north-west Pacific.

6.4.5. COMPARISON OF THE EVALUATIONS OF RADIOACTIVE RELEASES AT SEA

Since the Fukushima accident, four scientific publications have presented estimates of the direct liquid releases into the sea caused by the accident: the Japanese government (NERH), which draws on the TEPCO calculations; Kawamura et al., (2011) and Tsunume *et al.* (2011) who performed comparisons of dispersion models to measurements at sea; and IRSN (Bailly du Bois *et al.* 2011), based on the interpretation of measurements at sea. The estimates given in these publications are shown in Table 6-XI; this table also mentions the publications that specifically concern radioactive deposits on the sea.

With regard to ^{137}Cs, the estimates vary in a ratio of 1 to 27.

Table 6-XI – Estimates of the releases at sea caused by the Fukushima accident according to the various scientific publications.

		Direct release at sea		*Deposit*	
Source	**Method**	**^{137}Cs (PBq)**	**^{131}I (PBq) (^{131}I/^{137}Cs)***	**^{137}Cs in PBq (surface in km²)**	**^{131}I in PBq (^{131}I/^{137}Cs)***
NERH 2011 (TEPCO)	Calculation of leak rate	**0.94**	**18.7*** (19.9)		
Kawamura *et al.* (2011)	Comparison of model (SEA-GEARN) /measurements at sea	**4**	**11** (2.8)	**5** (1,700 x 1,700)	**57** (11.4)
Tsunume *et al.* (2011)	Comparison of model (ROMS) /measurements at sea	**3.5** (± 0,7)		Less than direct release	
IRSN (Bailly du Bois *et al.* (2011)	**Quantities deduced from sea measurements and dilution + *pX* simulation**	**27** (12 - 41)	**540*** (20)	**0.0076** (50 x 100)	**0.1*** (14)
Honda *et al.* (2011)	Comparison of model (JCOPE2) / measurements in Japan			**0.18** (1,500 x 1,500)	
Morino *et al.* (2011)	Comparison of **CMAQ model /measurements in Japan**			**1** (600 x 600)	
Yasunari *et al.* (2011)	Comparison of **FLEXPART model /measurements in Japan**			**1** (1,700 x 1,700)	

* When data are available, the values are corrected for decay to March 11th 2011.

The uncertainties associated with each type of evaluation are significant. They are discussed in the sections that follow.

6.4.5.1 Release Calculated by TEPCO (NERH Report)

The calculation of the release at sea is based on an estimate of the flow rate through a hole in the containment of Unit 2, which was discovered on April 2nd. The calculation uses the diameter of the hole (approximately 3 cm), height, drop distance, and initial concentration to evaluate the radionuclide flux. This is considered constant at 4.3 m^3/h for 120 hours. With 1.8x 106 Bq/cm^3 of ^{137}Cs, TEPCO estimates a release of 0.94 PBq in 120 hours. TEPCO's overall estimate is 4.7x10^{15} Bq released, taking all radionuclides together.

Comments

Tsunume *et al.* (2011) IRSN (Bailly du Bois *et al.* (2011) indicate a period of release from March 26th to April 6th or 8th 2011 respectively (264 h – 312 h, Figure 6-59), based on measurements in seawater which show a sharp net rise in the concentrations starting on March 26th. It therefore seems that the release duration indicated in the NERH report (120 hours) is an underestimate by at least a factor of 2.

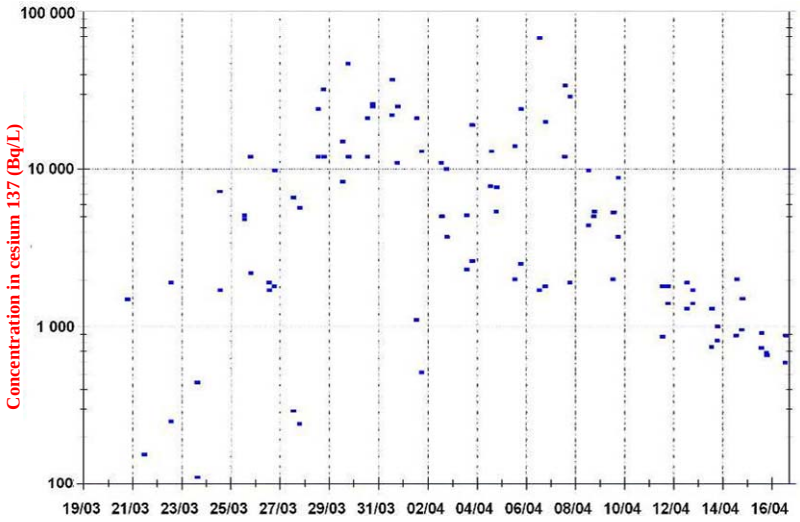


Figure 6-59 - Concentrations measured in seawater within 500 m of the Fukushima Dai-ichi power station, detail from March 10th to April 17th 2011.

In addition, TEPCO's estimate of the flows released was performed on the basis of a concentration measurement taken on April 2nd downstream from the leak. However, the period from April 2nd to 4th corresponds to a minimum concentration in the measurements in seawater in the vicinity of the facility (Figure 6-59), since the concentrations are considerably higher before and after that period. It is possible that this mean concentration applied to the entire duration of the release is in fact an underestimate of the mean release.

Tsunume et al. (2011) also suggest the hypothesis that the releases prior to April 1st could be explained by direct releases with a different origin.

6.4.5.2 Release Calculated by Tsunume *et al.* (2011)

The marine release is evaluated by comparing simulations using a marine dispersion model (ROMS model with a 1 km mesh), with the *in situ* measurements. According to Tsunume, direct release is the main source of radionuclides at sea.

The direct release taken into account lasts 11 days, from March 26th to April 6th 2011, with a constant flux of $2.2.10^{14}$ Bq/j during this period, followed by exponential decay until April 24th.

There is good agreement between the concentrations simulated and measured near the outfall pipe and along the south coast, until April 2nd. After that date and far from the outfall pipe, the divergences become greater and greater, and the measurements can be up to a factor of 10 higher. 30 km offshore, the divergence between model and measurements is even more pronounced (Tsunume et al.) (2011), Figure 6-60).

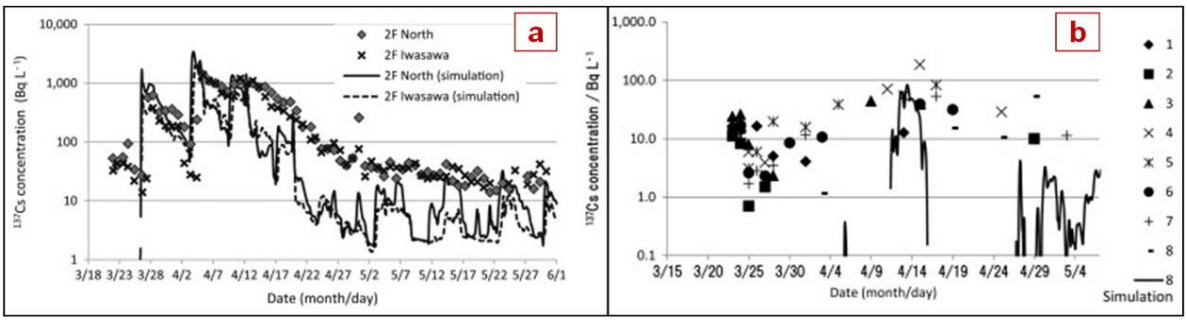


Figure 6-60 - Concentrations measured and simulated on the coast (a) and offshore (b), according to Tsunume et al. (2011).

The total direct release is estimated at 3.5 ± 0.7 PBq in ^{137}Cs. Of the 15 PBq released into the atmosphere (NERH), the deposition in the calculation zone is apparently weaker than the direct releases.

The main source of error associated with this calculation concerns the representativeness of the hydrodynamic model used.

6.4.5.3 Release Calculated by Kawamura *et al.* (2011)

The marine release is evaluated by comparing simulations using a marine dispersion model (SEA-GEARN model with a 2 km mesh), with the *in situ* measurements. The model/measurements comparison is performed at two points, on the coast and 15 km offshore.

The direct release is evaluated on the basis of daily concentrations measured near the outfall pipe from March 21st to April 30th 2011. An adjustment coefficient is used to match a radionuclide flux to the concentrations measured, by making the measured values and those simulated by the model coincide. This calculation method is very sensitive to the size of the computational unit mesh and the dilution conditions in the vicinity of the outfall pipe.

The deposition on the ocean is calculated using the WSPEEDI-II model, based on the release figures published by Chino et al. (2011).

The concentrations simulated and measured at 15 km are of the same order of magnitude (Kawamura et al. (2011), Figure 6-61). There are no results at the other measurement points.

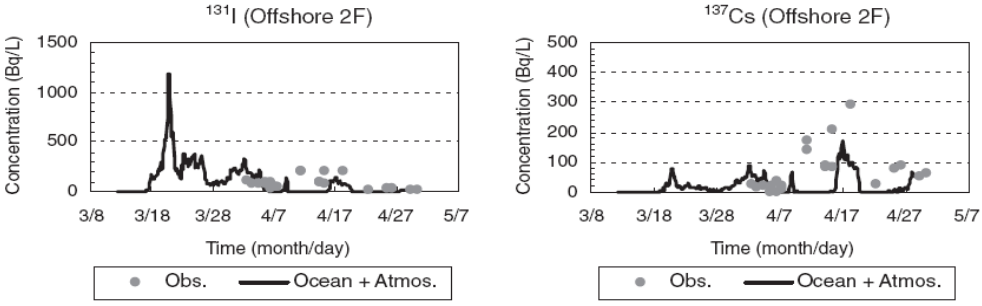


Fig. 3 Same as Fig. 2 except that black lines denote the results of the numerical experiments with the direct release into the ocean and deposition from the atmosphere

Figure 6-61 - Measured and simulated concentrations (solid line) 15 km from the coast according to Kawamura et al. (2011).

According to Kawamura et al., atmospheric deposition represents 5 PBq deposited on the sea in the zone covered by the model (1700 x 1700 km). Direct releases account for 4 PBq in ^{137}Cs.

The main source of error associated with this calculation concerns the representative nature of the hydrodynamic model used and the dilution of the release near the power plant.

6.4.5.4 Release calculated by the IRSN (Bailly du Bois *et al.* (2011))

The calculation method is described in Section 6.4.3.1. The main uncertainty concerns the thickness of the mixing layer applied to extrapolate the measurements obtained on the surface to the bottom. The robustness of this calculation is based on: simple integration that does not require the prior validation of models, large number of measurements available for the reports (from 77 to 293 for each inventory period, Table 6-IX); the regularity of the renewal of waters in the area (Figure 6-52).

The results obtained with the Ifremer model in Section 6.4.4 (Figure 6-57) are comparable to those obtained by the models of Tsunume *et al.* and Kawamura *et al.,* but with a release more than six times higher. It is currently not possible to determine which of these three models is the most realistic. The area where the release was introduced is the seat of a variable turbulent flow that is difficult to reproduce deterministically. The representativeness of the

various models used could be tested by performing quantitative inventories of the ^{137}Cs present over time, to check whether they reproduce the fast renewal of the masses of water observed from the measurements.

6.4.6. RADIONUCLIDES IN SEDIMENTS

The materials in suspension in the seawater tend to fix some of the radionuclides dissolved in the water column according to the levels of radioactivity in the surrounding water. These materials end up as sediment on the sea floor, creating a contaminated superficial deposit. In a coastal environment, the contributions via leaching by contaminated catchment basins will ultimately constitute a delayed but long-lasting source of contamination of this compartment.

Sediment samples were collected as far as 186 km from Fukushima Dai-ichi and 70 km offshore, at a depth from 20 to 200 m. The sampling depth and conditions, and the nature and granulometry of the samples had not been reported at the time of publication of the km offshore, at a depth from 20 to 200 m. The sampling depth and conditions and the nature and granulometry of the samples had not been reported at the time of publication of the results. Because these parameters can have a major effect on the mass concentrations of the measured sediments, the measurement results published in Japan should be interpreted with caution. The results are given in kg of dry mass whenever this is specified (one in ten times).

Of the 184 samples measured since April 29th, the main radionuclides measured in the sediments are:

- Cesium 137 (183 significant results):
- Cesium 134 (178 significant results), with a $^{134}Cs/^{137}Cs$ ratio normalized to March 11th at 0.95,
- Cesium 136 (6 significant results):
- Iodine 131 (17 significant results from the end of April; no detection after June 9th), with an $^{131}I/^{137}Cs$ ratio normalized to March 11th at 23,
- Tellurium 129 and 129m (28 and 36 significant results, from 10 to 16,000 $Bq.kg^{-1}$),
- Strontium 89 and 90 (two significant results, from 10 to 140 $Bq.kg^{-1}$),
- Plutonium 239 and 240 (six significant results, from 0.09 to 0.49 $Bq.kg^{-1}$),
- Barium 140 (one significant result of 2,900 $Bq.kg^{-1}$).

Figure 6-62 shows the development of ^{137}Cs concentrations in all of the samples inventoried, as well as the respective distance to the outfall pipe. Except in the vicinity of the Fukushima Dai-ichi power plant, the concentrations usually vary from 1 to 10,000 $Bq.kg^{-1}$, with on average an increasing trend over time This trend may be the result of the kinetics of the transfer of the cesium towards the sedimentary particles and the processes by which the finer particles are deposited. In view of the reduction of concentrations in seawater, this curve should stabilize over the coming months. The highest concentrations are recorded near the outfall pipe (100,000 and 150,000 $Bq.kg^{-1}$). Four values greater than 10,000 $Bq.kg^{-1}$ had been recorded at a distance greater than 38 km before April 7th, but these have not been confirmed by subsequent measurements.

Figure 6-63 shows a map of the distribution of ^{137}Cs concentrations in the sediments. It was drawn up by IRSN, excluding the six measurements near the site, which gave concentrations in excess of 10,000 $Bq.kg^{-1}$. The concentrations reached are generally less than 1,000 $Bq.kg^{-1}$; they are relatively low in view of the equilibrium distribution coefficient of cesium between the seawater and the sediments, which is usually greater than 1000. Thus, with concentrations greater than 100 Bq/L measured in the coastal seawater, we might have expected to find concentrations of 100,000 $Bq.kg^{-1}$ in the sediments. The transient pollution of the seawater by cesium 137 probably did not allow equilibrium to be reached with the sedimentary stock sampled. Only recently-deposited particles contributed to the marking of the superficial sediments, and these represent only a fraction of the volume sampled.

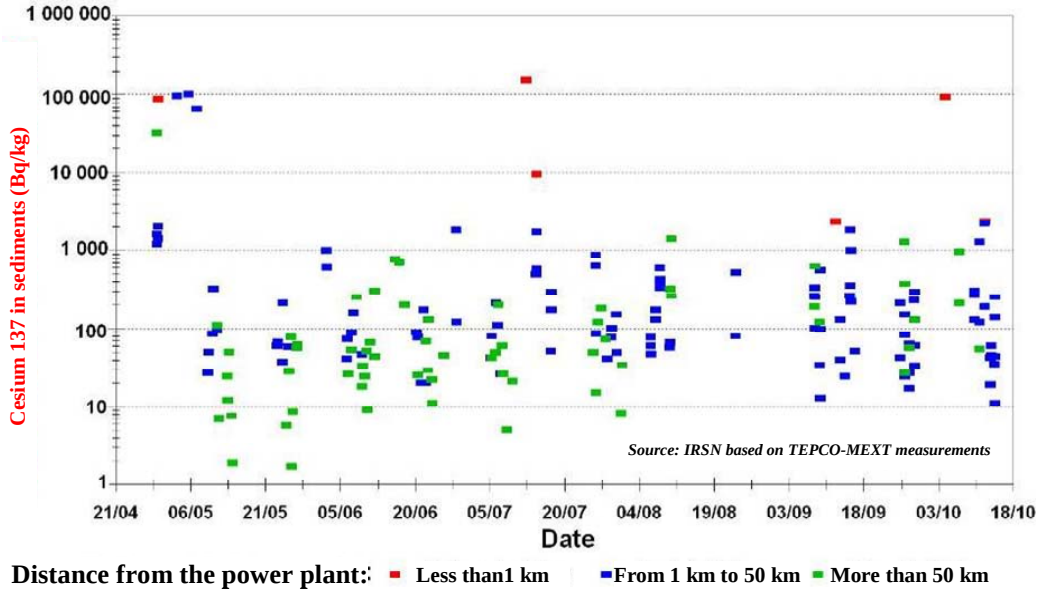


Figure 6-62– Graphical representation of ^{137}Cs concentrations measured in sediments as a function of time, with indication of the distance between the sampling point and the Fukushima Dai-ichi power plant (Bq/kg sec)

Ultimately, some of the radionuclides fixed on the sedimentary particles are likely to be remobilized in the seawater column. The sediments will then behave as secondary sources of contamination, which are delayed, distant, and diffuse. In coastal regions, the contamination of sediments was mainly the result of direct contact between polluted seawater and the surface sediments, and could propagate by transport and mixing with deeper sediments. In the pelagic domain, one would expect to find traces of radionuclides at the water-sediment interface following their transport toward the bottom via processes related to biological activity in the open sea (primary production of solid matter by phytoplankton, grazing by zooplankton, production of feces, and direct transport toward the bottom).

According to the map in Figure 6-63, the stock of cesium 137 fixed on the sediments appears to be relatively low. It should not lead to very high marking of the seawater by unloading in the future. The cesium unloading half-life observed in the sediments of the Irish Sea is two years[25]. Under these conditions, the first ten centimeters of sediment contaminated to 1,000 $Bq.kg^{-1}$ would contribute 500 $Bq.dm^{-2}$ in two years to the 20 to 200 m of water above it. In view of the renewal kinetics of the water observed (50% renewal every 6.9 days), the resulting concentrations would be approximately 5 to 50 Bq/L in seawater, on average. These concentrations should not have an impact on pelagic organisms in terms of radiation protection.

These concentrations could be higher in less deep zones, or zones with a lower renewal rate. Benthic organisms living in direct contact with the sea bed, or filtering organisms, could then be directly concerned by the residual pollution in the sediments.

[25] Finegan, P., Vintró, L.L., Mitchell, P.I., Boust, D., Gouzy, A., Kershaw, P.J., Lucey, J.A., 2009. Accumulation, solid partitioning and remobilisation of 99Tc in subtidal and intertidal sediments in the Irish Sea. Continental Shelf Research Volume 29, Issues 16, Pages 1995-2010.
Jones, D.G., Kershaw, P.J., McMahon, C.A., Milodowski, A.E., Murray, M., Hunt, G.J., 2007. Changing patterns of radionuclide distribution in Irish Sea subtidal sediments. Journal of Environmental Radioactivity Volume 96, Issues 1-3, Pages 63-74.

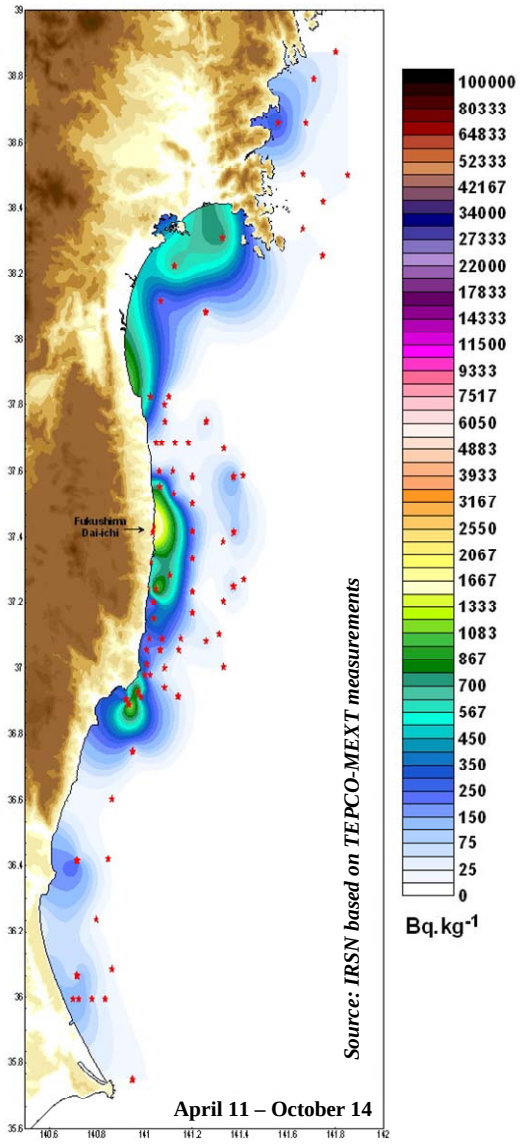


Figure 6-63– Mapping of 137Cs concentrations in sediments (mean of values measured up to October 14th).

6.4.7. RADIONUCLIDES IN MARINE AND RIVER–MARINE SPECIES

6.4.7.1 Aquatic species that have exceeded the cesium limits for sale or consumption

The list of species for which the cesium content exceeds the limits for sale or consumption (500 Bq/kg for the sum of cesiums 134 and 137), drawn up by the Japanese authorities, has changed over time according to the products caught (Table 6-XII). In general, the species included in this list during the summer of 2011 were:

- Either species that were very infrequently sampled before the month of June and the monitoring of which intensified during the summer,
- Or species that were not sampled until the summer of 2011.

It is therefore not possible, with this information alone, to attribute the increase in the number of species with a high level of contamination to a change in the contamination of the marine environment. It is important to emphasize the fact that all of these organisms come from the Fukushima district, and that no organism fished **from the sea** outside the area near the power plant or in the open sea exceeds the standard limits for sale or consumption.

Table 6-XII – Lists of aquatic organisms (animals or plants) with cesium 134+137 concentrations greater than the maximum allowable levels for consumption since monitoring began

List as at June 7th 2011	List as at August 21st 2011	List as at January 12th 2011
Arame (algae) Hijiki (algae) Wakame (algae)	Arame (algae) Hijiki (algae) Wakame (algae)	Arame (algae) Hijiki (algae) Wakame (algae)
Sea urchins Clams Sandeels (Japanese sand lances) Boe drums Mediterranean mussels	Sea urchins Clams Sandeels (Japanese sand lances) Boe drums Mediterranean mussels	Sea urchins Clams Sandeels (Japanese sand lances) Boe drums Mediterranean mussels
Japanese smelts (caught in fresh water) Ayu (caught in fresh water) Masu salmon (caught in fresh water) Tribolodons (freshwater)	Japanese smelts (caught in fresh water) Ayu (caught in fresh water) Masu salmon (caught in fresh water) Tribolodons (freshwater) Char (freshwater) Cyprinide fish (bred in fresh water)	Japanese smelts (caught in fresh water) Ayu (caught in fresh water) Masu salmon (caught in fresh water) Tribolodons (freshwater) Char (freshwater) Cyprinide fish (bred in fresh water)
	Ainame Flounder (flatfish) Halibut (flatfish) Hakeling Redfish Rays Crabs	Ainame Flounder (flatfish) Halibut (flatfish) Hakeling Redfish Rays Crabs Bass

6.4.7.2 Concentrations observed in marine animals

Figure 6-64 shows the measurement results concerning the marine species for which data are obtained on a fairly regular basis.

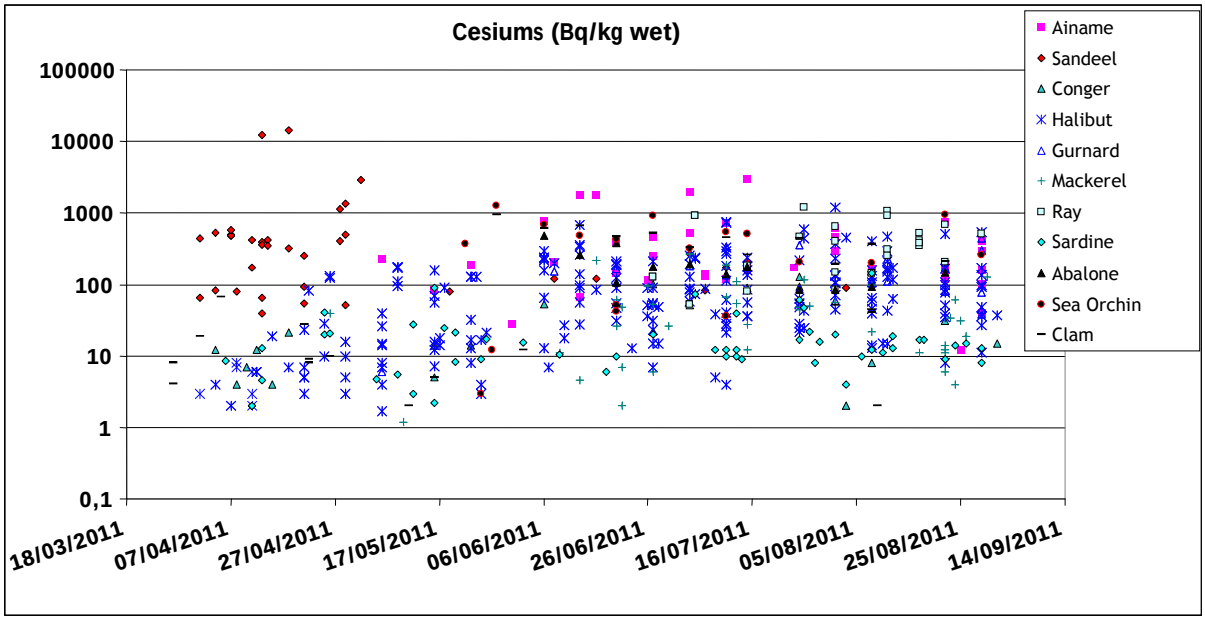


Figure 6-64 – Change over time of 137Cs+134Cs (Bq/kg) concentrations in some sea products.

Of the marine products sampled, those with the highest contamination levels, detected early in the fishing products monitoring program, were the Japanese sand lances (sandeels) (Figure 6-65). Caesium-137 and -134 have been detected in all samples of this species taken from the Fukushima and Ibaraki districts; the maximum concentrations reached 12,500 Bq/kg wet (134Cs+137Cs) off the shore of Iwaki on 13 April. The Japanese fish and eat the sandeel, or Japanese sand lance (*Ammodytes personatus*) in the larval and juvenile stages, which are pelagic stages (living in the water column) in the period from January to April. The adults, however, live buried in the sediment from May to December, and are no longer fished, which explains why the data for this species practically vanishes from late April onwards.

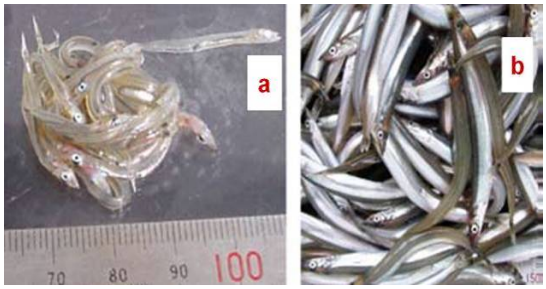


Figure 6-65 – Japanese sandeels (Ammodytes personatus (Girard)). (a) larvae, (b) juveniles.

In addition to the concentrations in sandeels, Figure 6-64 shows the concentration curves for both cesium isotopes in other species that are regularly sampled. It is difficult to identify a change in the contamination of fish over time, given the wide spread in the results obtained. However, halibut, rays, and to a lesser extent, gurnards, all of which have a characteristic way of life in close contact with sediment, tend to be amongst the higher values in the cesium concentration range observed in Japan.

Note that the measurement results obtained on samples of sea urchin, abalone and clam taken from the Fukushima district also managed to reach some high levels.

With regard to iodine 131: this has not been detected in the organisms since mid-June, in accordance with the trend in its levels in the surrounding environment (Figure 6-66).

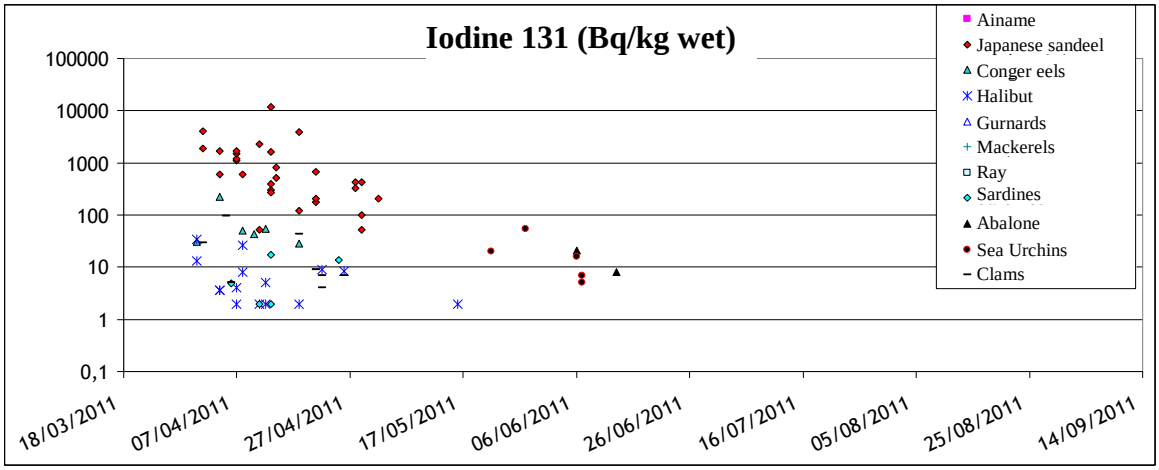


Figure 6-66 – Change over time of iodine 131 concentrations (Bq/kg) in some sea products.

6.4.7.3 Expected curve for marine species

With regard to filtering species such as mussels, oysters, and clams, the trend in the absence of new releases should be a downward one. And, in fact, the changing levels over time in these organisms reflect the changes in the surrounding environment quite well, and the trends clearly show a reduction in the concentrations over time (Figure 6-67).

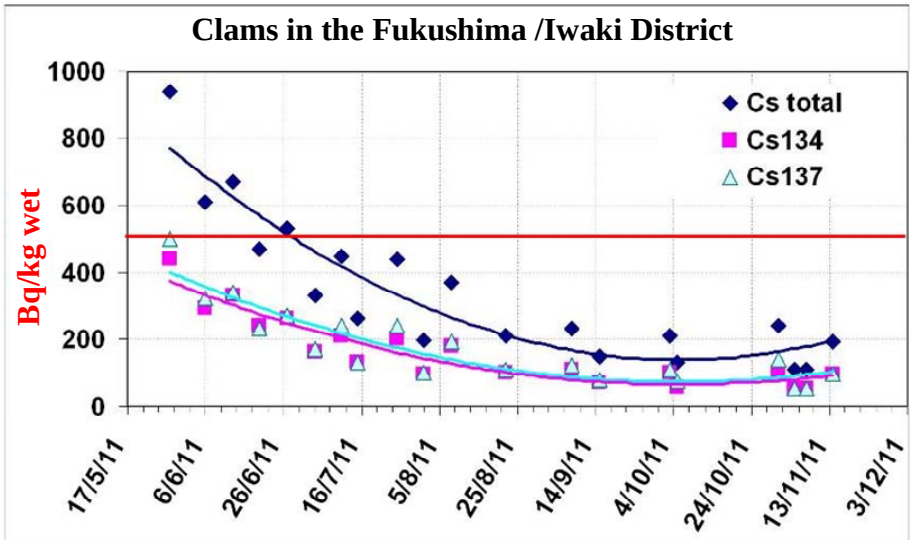


Figure 6-67 Change of cesium concentrations over time in clams (Pseudocardium sachalinense) taken off the coast of Iwaki in the Fukushima district. In red, the limit for sale or consumption (500 Bq/kg for the sum of cesiums 134 and 137).

With regard to fishes, their contamination curve does not follow the decay observed in the waters. Figure 6-68 gives the example of the change in concentration in a species of ray (Okamejei kenojei) caught in the waters near Iwaki like the clams (Figure 6-67).

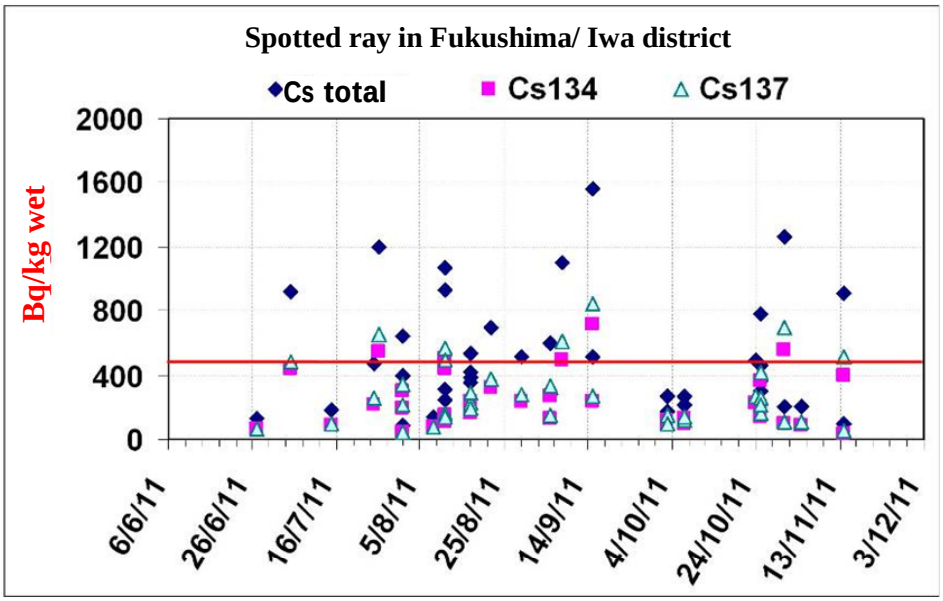


Figure 6-68 - Change of cesium concentrations over time in a species of spotted ray (Okamejei kenojei) caught off the coast of Iwaki in the Fukushima district. In red, the limits for sale or human consumption (500 Bq/kg for the sum of cesiums 134 and 137).

In fish, variations in concentration could very well be due to their movement, for species that are not strictly confined to the area where they were fished, but they also reflect the complex trophic regimes of these organisms, which differ from one species to the next.

Generally speaking, fish will be the best medium- and long-term indicators of cesium contamination in the marine domain. Cesium presents higher concentration factors in fish, and tends to increase in species that are higher up in the trophic chain. Consequently, although in the short term the highest concentrations tend to be found in species positioned at the beginning of the food chain, in the longer term, once the transfer to the different links of the trophic networks has taken effect, the predators at the top of the food chain should present higher levels. These levels should be even higher for species whose way of life involves close contact with sediments and whose habitat is close to the contaminated zone.

Thus, even if the cesium contamination in the sea water has fallen sharply in the vicinity of the Fukushima Dai-ichi power plant, there is justification for continuing to monitor the marine species fished from the coastal waters of north-east Japan.

6.5. FORESEEABLE IMPACT ON THE TERRESTRIAL AND MARINE ECOSYSTEMS

The analysis of the ecological consequences of the Fukushima accident is very complex because these consequences are combined with those of two other major natural events: earthquake and tsunami. To this, we must add the impact of uncontrolled release of toxic chemical substances including metals or persistent organic pollutants (HAP, PCB, pesticides, etc.) from a variety of industrial facilities that were damaged by the natural catastrophe. A review article in the American journal 'Environmental Health Perspectives' raised awareness of this exceptional case of multiple pollution[26]. This special context heightens the uncertainties concerning the forecasting of the radiological impact on ecosystems of the nuclear accident. Guidelines for evaluating the ecological impact of a nuclear accident

[26] Anonymous (2011). "Chemical aftermath: contamination and cleanup following the Tohoku Earthquake and Tsunami". Environmental Health Perspectives 119(7): A290-A301.

6.5.1. BASIC PRINCIPLES FOR ASSESSING THE ECOLOGICAL IMPACT OF A NUCLEAR ACCIDENT

Following a major nuclear accident such as Chernobyl or Fukushima Dai-ichi, ecosystems exposed to ionizing radiation because of radioactive substances released into the receiving environments (air, river, sea, etc.) react according to a complex dynamic. So-called ecotoxic responses, observed at different levels of biological and ecological organization, are extremely varied (Figure 6-69), particularly because of the heterogeneous exposure of the various species that provide biodiversity.

In a given place and at a given time, the radiological dose administered can vary in quality (i.e. exposure pathway via external or internal irradiation; alpha, beta, or gamma radiation) and quantity. This variation can cover several orders of magnitude between species (Figure 6-70a) and between individuals of one species, for example at different stages in its life. All of this is combined with a variability range covering six orders of magnitude to express the sensitivity to ionizing radiation of the biodiversity of fauna and flora (Figure 6-70b).

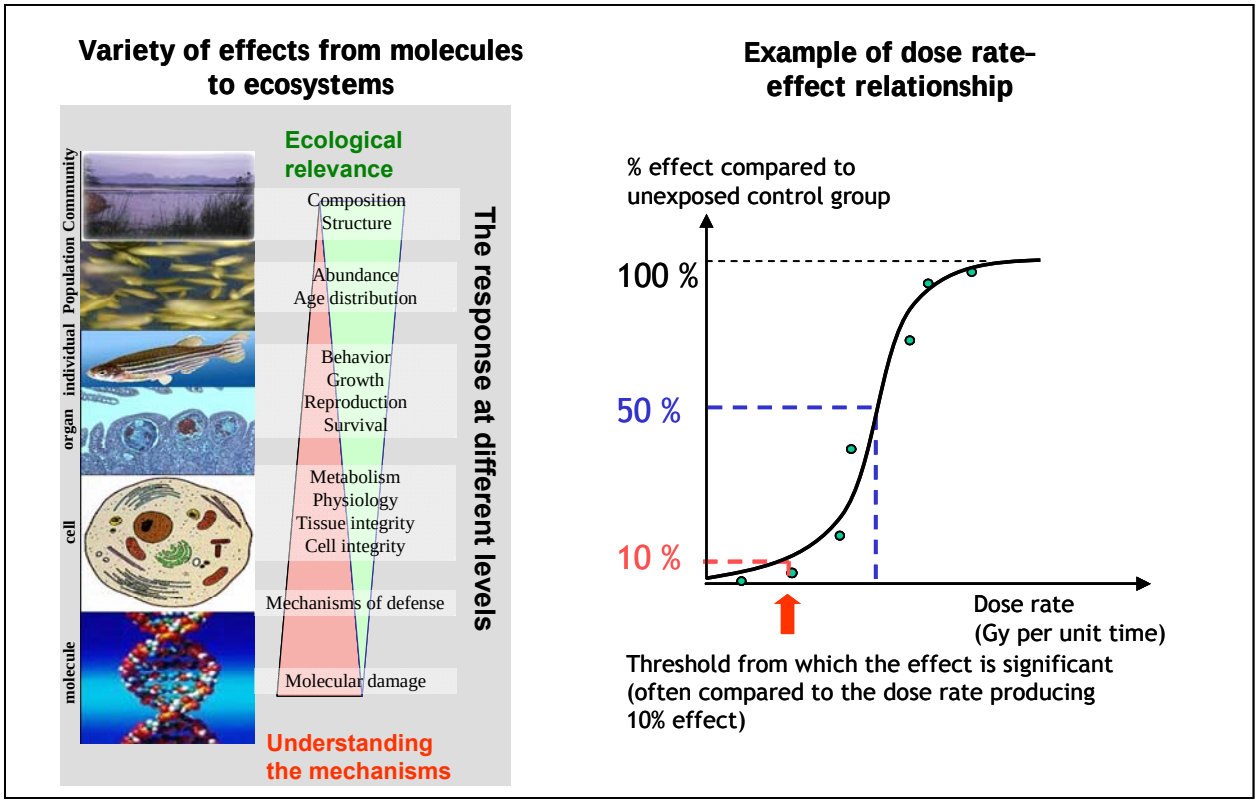
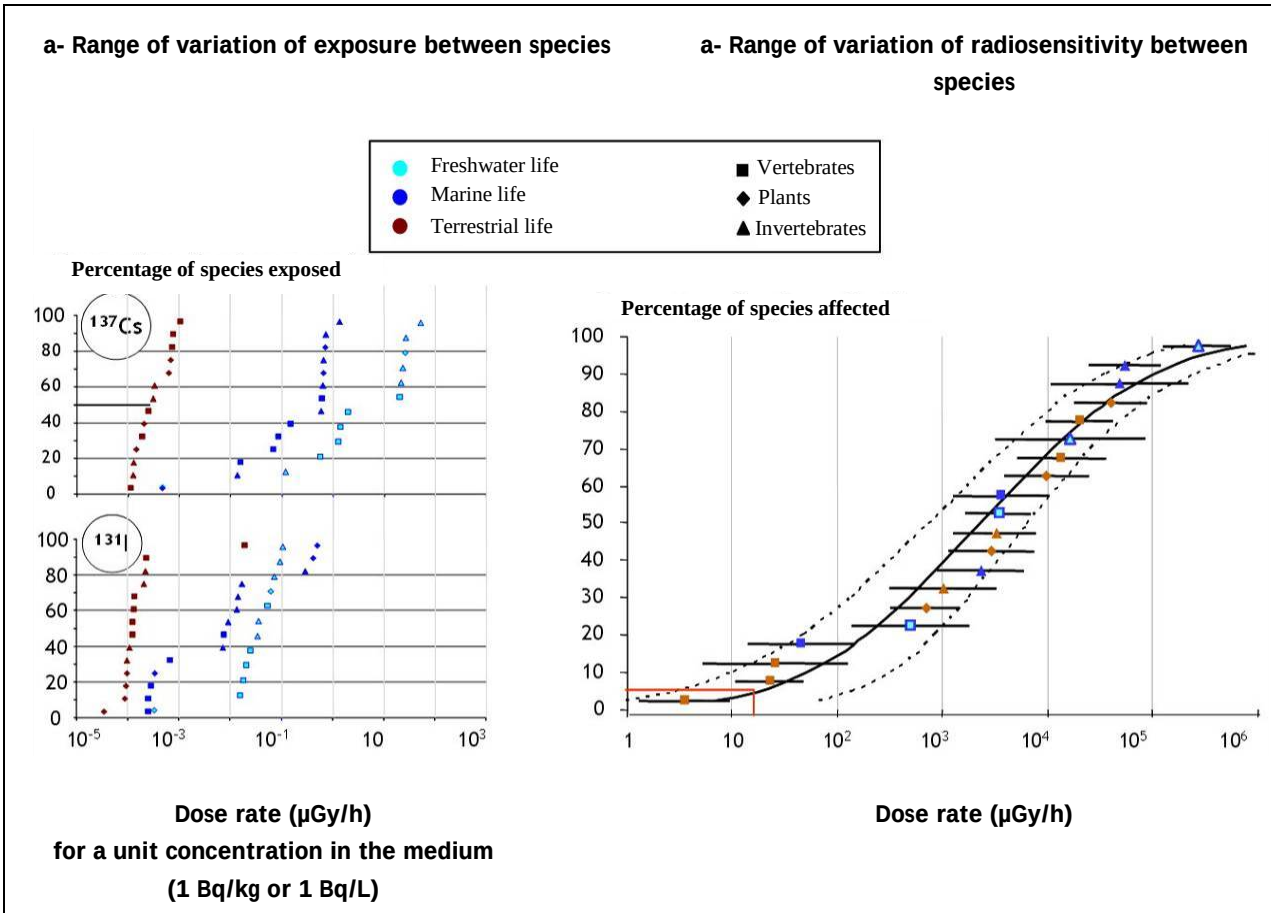


Figure 6-69 - Varieties of ecotoxic responses observed at different levels of organization of living things, and example of a logistical 'dose rate—effect' relationship. These relationships are used to determine the threshold beyond which the effect is significant.



- Reading example -

For 1 Bq of 137Cs in a soil, 50% of terrestrial species receive a dose rate below $3x10^{-4}$ µGy/h.

For the same concentration of ^{137}Cs in the water, the dose rate to marine organisms varies across four orders of magnitude.

5% of species have an ionizing radiation sensitivity threshold below 17 µGy/h.

Radiation sensitivity varies over six orders of magnitude between species.

Figure 6-70 - Ranges of variation between species (a) of the absorbed dose rate for a same unit concentration of the medium (example of ^{137}Cs and ^{131}I) and (b) of the radiosensitivity.

The method for evaluating the ecological impact is based on comparing the doses or dose rates to which living organisms are exposed during a given period to protection criteria. The protection criteria are defined for a specific taxonomic group or to maintain the structure and operation of an ecosystem. For example, the *recommended ecological protection criterion on completion of the European PROTECT project is 10 µGy/h (0.24 mGy/d): Below* that dose rate, no effect related to exposure to ionizing radiation is expected *for ecosystems*[27]. *In its publication No. 108*[28]*, the International Commission on Radiological Protection suggests dose rates for which certain types of effect are probable according to group of species (e.g. reduced reproductive success of birds*

[27] Garnier-Laplace, J. *et al.* (2010). A multi-criteria weight of evidence approach to derive ecological benchmarks for radioactive substances. J. Radiol. Prot. 30, 215-233.
[28] CIPR (2008). Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38, 4-6.

between 1 and 1000 mGy/day). Over the last ten years, many studies, largely guided and carried out by IRSN within the framework of European projects (ERICA, PROTECT) have been conducted to determine the numerical values of these protection criteria. On an international level, the method of evaluating the radiological risk to ecosystems and the associated criteria, which were developed in the framework of the ERICA project, are now recognized and will be applied in particular in the context of the UNSCEAR working group on evaluating the impact of the Fukushima Dai-ichi accident.

For non-human species, the biological effects of interest are essentially those that can be directly interpreted in terms of the demographics of the species populations: survival, growth, and reproduction. They are deterministic, appearing above a threshold according to a dose (or dose rate) / intensity of effect relationship, which is often logistical (Figure 6-70).

As in the case of the analysis of the ecological impact of the Chernobyl accident, it is (and will be) essential to distinguish three phases in the levels and type of exposure of living organisms to understand how the effects observed on fauna and flora unfold: acute exposure at a high dose (a few weeks), transient exposure at a medium dose (a few months), and chronic exposure at a low dose (years).

The acute phase extends throughout the initial weeks following the accident. This phase is characterized by the presence of a large quantity of short half-life radionuclides likely to generate high dose rates for living organisms, mainly by external irradiation with a significant proportion of the dose delivered by beta-emitting radionuclides. For organisms living on land, the main exposure pathways during that period are immersion in the plume, in addition to foliar deposit for plants and inhalation for animals. These three processes are almost simultaneous with the atmospheric release. For aquatic creatures, the exposure pathway is direct exposure to water, which is the receiving medium of the release, whether direct in liquid form or caused by the surface deposition of atmospheric release. During this phase, the so-called 'acute' effects are likely to be observed. 'Acute' effects include any notable biological modification occurring within a few days or weeks of absorption of a significant radiological dose, leading to irreversible damage and, eventually, death ('acute radiation syndrome'). For example, in the Chernobyl exclusion zone, dose rates of up to 20 Gy/day caused the appearance of the 'red forest', in which 90% of the pine trees *(pinus sylvestris L.)* died.

The transient phase covers the few months following the accident. It is characterized by the decay of the short half-life radionuclides and a redistribution of all the deposited radionuclides, which occurs to a greater or smaller extent in the various compartments of ecosystems (initiation of the processes of dispersion, erosion, runoff, and transfer within and between compartments). During this period of a few months, the internal contamination of living organisms becomes gradually predominant over the external irradiation. For example, during the three months following the Chernobyl accident, 80% of the total dose was delivered to the plants and animals, and more than 95% of this dose is due to β radiation. The effects that can potentially be observed during this phase are acute and appear as of a cumulative absorbed dose threshold. The feedback from the Chernobyl accident shows the absence of harmful effects on plants or animals for cumulative doses below 0.3 Gy[29]in the initial months after the accident.

The chronic phase, during which the contamination levels of the environments change much more slowly, takes place on a scale of many years. Long half-life radionuclides such as ^{137}Cs integrate into the biogeochemical cycles of their stable counterparts. For example, in the exclusion zone around the Chernobyl power plant, the exposure situation can be considered to have become chronic from the fall of 1986, when the dose rates were less than 1% of the initial values, with a variable contribution from ¤ and β radiation for each species, according to the location, way of life, and intensity of the internalization flows of the dominant radionuclides, which are ^{137}Cs and ^{134}Cs. The effects reported in the literature concerning that period are often contradictory or subject to scientific controversy because of a large number of potentially confusing factors. The reasons for these controversies are varied: the weakness or lack of a robust evaluation of the dose or dose rate (in qualitative and quantitative terms), the failure to allow for the extreme spatial heterogeneity of the exposure for 'mobile' wild species in the exclusion zone, the failure to take into account various environmental factors, such as seasonality, the lack of similar observations for true non-exposed

[29] UNSCEAR (2008) Vol. II. Sources of ionizing radiation United Nations Scientific Committee on the Effects of Atomic Radiation. Report to the General Assembly, with scientific annexe E. United Nations, New-York, 2011

control subjects, the unsuitable statistical methods used to interpret the data, and the uncertainties inherent in the extrapolations required to interpret the ecological significance of the effects observed at different levels of biological organization (e.g., what is the consequence on the population of an increase in cytogenetic abnormalities?).

6.5.2. IMPACT ANALYSIS FOR TERRESTRIAL ECOSYSTEMS AROUND THE FUKUSHIMA DAI-ICHI POWER PLANT

As far as IRSN is aware, to date no information concerning the effects observed on fauna and flora in the 20 km exclusion zone has been reported in the scientific literature. Very recently, Shozugawa et al. (2012)[30] published a few gamma spectrometry test results concerning samples of soil and plants collected on April 10th, 2011 within 5 km of the power plant. The radionuclide concentrations measured by gamma spectrometry in the three soil samples collected (values in Bq/kg read on a graph: $4.9x10^4$ for l'^{131}I, $5x10^3$ for each of the two cesiums (^{134}Cs and ^{137}Cs), 5 for l'^{110m}Ag, 100 for ^{132}Te, 10 for each of ^{140}Ba and ^{140}La, $5x10^3$ for each of ^{91}Sr and ^{91}Y, 7 for each of ^{95}Zr and ^{95}Nb), make it possible to estimate the order of magnitude of the associated dose rates for flora and fauna. At those levels of soil contamination, the maximum dose rates are obtained for mammals (20 µGy/h) and birds' eggs (1 mGy/h) that might be present in this zone.

Although the information currently available is very sparse, it highlights the existence of a potential ecological risk to the terrestrial ecosystem in the Fukushima Dai-ichi exclusion zone, particular for reproduction, which is the most radiation-sensitive criterion. *In situ* studies are required in order to refine this initial rough estimate, which is based on a very small number of spot measurements.

With regard to the Japanese terrestrial environment in the 100 km around the damaged power plant, it was possible to estimate the maximum dose rates outside the 20 km zone during the very first month following the accident, based on the deposits on the ground. That is how the IRSN published the first estimate of the potential impact on terrestrial ecosystems[31], which has been brought up again many times in the scientific literature[32,33]. This study focused on the forest ecosystem and the geographical area located 25-45 km north-west of the Fukushima power plant—one of the areas worst affected by atmospheric deposition. **The dose rate, estimated according to the European ERICA method[34], and taking into account the main radionuclides emitted (^{137}Cs, ^{134}Cs, ^{131}I, ^{129m}Te, ^{129}Te, ^{132}Te, ^{136}Cs, ^{132}I), extend in a range from 2 mGy/day for birds to 6 mGy/day for small mammals. These values are ten to one hundred times higher than the ecosystem protection criterion, taken to be 0.24 mGy/day in Europe, and are indicative of probably cytogenetic damage and altered reproduction in conifers and vertebrates (Figure 6-71). As with the observations made in contaminated territories outside the Chernobyl exclusion zone, no acute effect has been reported to date or to our knowledge concerning non-human species in the terrestrial ecosystems around the Fukushima site.**

[30] Shozugawa *et al.* (2012). "Deposition of fission and activation products after the Fukushima Dai-ichi nuclear power plant accident." Environmental Pollution 163 : 243-247.
[31] Garnier-Laplace J. *et al.* (2011). Fukushima wildlife dose reconstruction signals ecological consequences. Environ. Sci. Technol. doi:10.1021/es201637c
[32] Schmidt C. (2011) Scientists Estimate Radiation Doses To Wildlife Near Fukushima Nuclear Disaster: Animals and plants near the Japanese nuclear plant may have received unsafe doses. Chemical & Engineering News 10 juin 2011, ISSN 0009-2347 American Chemical Society
[33] Schiermeier Q. (2011) Wildlife threatened by Fukushima radiation. News published online 27 May 2011 | Nature | doi:10.1038/news.2011.326
[34] Brown, J.E *et al.* (2008). The ERICA Tool. J. Environ. Radioact. 99, 1371-1383.

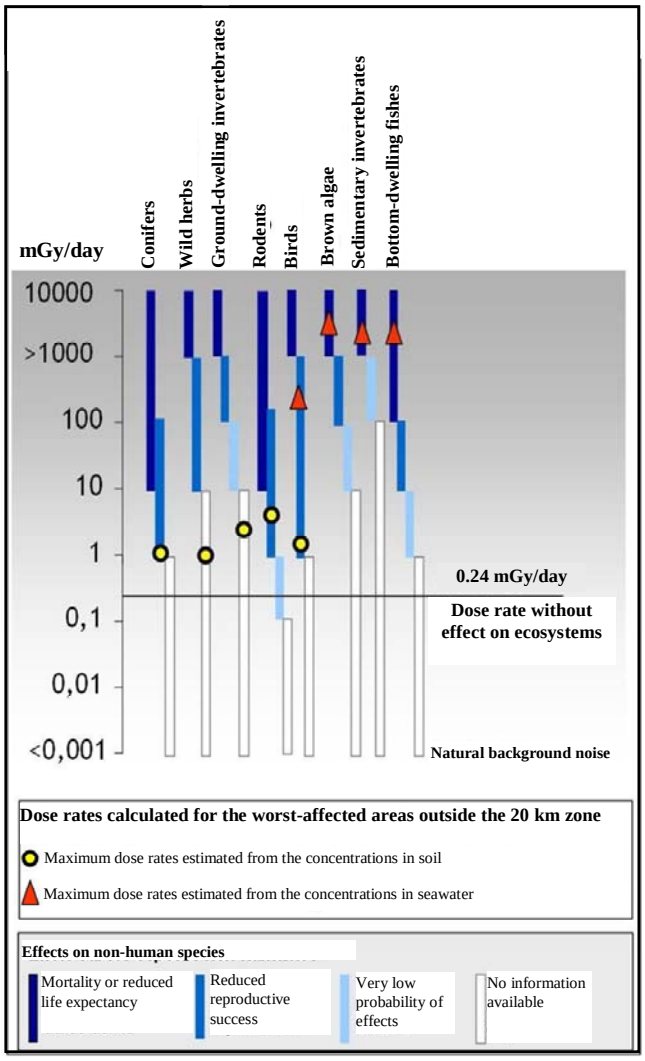


Figure 6-71 - Scale of potential effects on marine and forest fauna and flora (outside the exclusion zone) predicted based on the estimate of dose rates induced by exposure to the dominant radionuclides (^{131}I, ^{134}Cs, ^{137}Cs) the first month after the Fukushima Dai-ichi accident. The ranges of dose rates for the various taxonomic groups and effects are from the studies by the ICRP 108[35] (adapted from Garnier-Laplace et al., 2011).

For the exposed Japanese ecosystems, the transient phase started with the arrival of spring. It therefore coincided with the resumption of the biological activities of the species present, and covered the first post-Fukushima breeding season. To date, the analysis of the effects that appeared during this period for terrestrial ecosystems is mentioned in only one article, which appeared in the journal 'Environmental Pollution'[36]. It inventories the effects observed in fourteen species of bird sampled in July 2011 at 300 capture points in the Fukushima district. At each station, the total number of birds seen or heard was counted and the species identified. Based on statistical processing, the authors revealed that the bird community was significantly depleted in the most contaminated areas. Of the 14 species common to the Chernobyl and Fukushima regions, the negative correlation between ambient dose rate and abundance (number of individuals) is stronger in Japan: the birds in the Fukushima area would therefore seem to be more sensitive to ionizing radiation than their counterparts in Chernobyl, where the species have been exposed for 25 years. Going back over this analysis, and this time considering all species, including those that are specific to each of the regions, would show, on the contrary, a stronger correlation in Chernobyl. The authors explain this result by the disappearance of many species in the most contaminated areas of Chernobyl. These results would need to be

[35] CIPR (2009)- International Commission of Radiological Protection Environmental Protection Eds. The concept and use of Reference Animals and Plants. Annals of ICRP; Publication 108, 242 pages, 2009.
[36] Møller, A.P. *et al.* (2012) Abundance of birds in Fukushima as judged from Chernobyl. Environmental Pollution. 164 : 36-39.

confirmed, however, because of the lack of characterization of the dose rates received by the organisms, which are not specified in the article, and details concerning the statistical methods used to process the data.

From July 2011, because of the physical decay of the short half-life radionuclides, it is possible to consider as a first approximation that the exposure of living organisms was essentially due to soils contaminated by radioactive cesium (external and internal radiation from this secondary source term, whose concentration is considered to be stable over time). **Thus, ignoring the genetic adaptation processes that could take place over the course of several generations, and based on the data in Figure 6-23 adjusted for radioactive decay, and assuming that no remediation action is undertaken, the areas with $^{134+137}$Cs surface activity above 600, 1 000 and 3 000 kBq/m^2 are potential risk areas for biodiversity and terrestrial ecosystems respectively after one year, five years, and up to 30 years of chronic exposure (Table 6-XIII).**

Table 6-XIII - Change over time of the exposure dose rate ranges for fauna and flora according to the accumulated deposits of cesium 134 and 137. Prospects at one year, 5, 10, 20 and 30 years. The shaded areas indicate that a potential risk persists (value greater than the ecosystem protection criterion). The reference date is the date of the accident.

Depositions (kBq/m^2)	Range of variation of dose rates for terrestrial species (µGy/h)									
	1 year		5 years		10 years		20 years		30 years	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
<=10	0.03	0.20	0.02	0.16	0.01	0.09	0.01	0.06	0.00	0.04
30	0.09	0.6	0.07	0.5	0.03	0.3	0.02	0.2	0.01	0.1
60	0.2	1.2	0.1	1.0	0.06	0.5	0.04	0.4	0.03	0.3
100	0.3	2.0	0.2	1.6	0.1	0.9	0.1	0.6	0.05	0.4
300	0.9	6.0	0.7	4.8	0.3	2.6	0.2	1.8	0.15	1.3
600	1.7	12	1.3	9.7	0.6	5.1	0.4	3.6	0.3	2.6
1 000	2.9	20	2.2	16	1.1	8.6	0.7	5.9	0.5	4.4
>3 000	8.6	60	6.7	48	3.2	26	2.0	18	1.5	13

6.5.3. IMPACT ANALYSIS FOR MARINE ECOSYSTEMS

For the transient phase, the evaluation performed by a Russian team[37] reflects this drastic drop in concentrations in the water column, leading to overall dose rate estimates in the region of 2 mGy/day for fishes and marine mollusks, and remaining below 10 mGy/day near the shore. These values are, however, indicative of possible damaging effects on reproduction and embryonic survival in vertebrates. Buesseler *et al.*[38] , in their meta-analysis of radionuclide concentrations of seawater, also emphasize the effectiveness of the dilution caused by the local and regional hydrodynamics of the Pacific Ocean, and they suggest that, because of this, the dose rates to non-human species will remain very low from direct exposure and will be below the protection criteria for species. This estimate, **however, unlike that of Kryshev *et al.* (2011)[32], does not include the possibilities of bioaccumulation *via* the trophic networks, or the role of secondary release sources that can be played by sediments, particularly coastal ones.** Finally, the Pacific Ocean, whose waters had ^{137}Cs concentrations in July 2011 that were 10,000 time higher than the baseline levels measured in 2010, still receives terrestrial supplies from the erosion and runoff processes operating in the contaminated catchment basins of the Fukushima district.

Once again, the knowledge currently available does not allow the possibility of a radiological risk to the marine ecosystem to be ruled out. This knowledge is still very limited, which creates great uncertainly concerning the

[37] Kryshev A *et al.* (2011) Evaluation of the irradiation dose rate for marine biota in the region of the destroyed Fukushima reactor (Japan) in March–May 2011 Atomnaya Énergiya **111**: 41–45.
[38] Buesseler K *et al.* (2011) Impacts of the Fukushima nuclear power plants on marine radioactivity. Environmental Science & Technology **45**: 9931–9935.

results obtained. **Continued environmental monitoring and increased knowledge concerning accidental releases are therefore two key elements that will allow us to evaluate the ecological impact of the Fukushima Dai-ichi accident on the marine environment. Finally, any forecast of ecological risk in a context of multiple stresses (physical, chemical, radiological) is bound to be highly uncertain.**

6.5.4. PROJECTS INITIATED BY IRSN ON THE ECOLOGICAL CONSEQUENCES OF CHRONIC EXPOSURE TO LOW DOSES FOLLOWING A NUCLEAR ACCIDENT

An overall analysis of the work by Møller *et al.* as well as other review publications on the subject of the ecological consequences of the accident at Chernobyl[39], has recently led the IRSN to launch a research program **on the Chernobyl area** in order to:

- Specify the chronic exposure level due to the radionuclides present (external and internal exposure),
- Determine whether the species are or have been capable of adapting (effect on genetic diversity) to this new environment. This will particularly involve an examination of whether genetic and phenotypical differences between populations are observable according to the level of contamination;
- Specify the taxonomic differences in radiosensitivity in order to understand why certain authors reach the opposite conclusions from Møller *et al.* (*for example,* the work of Baker *et al.*[40] which shows, in micromammals, that populations increase in the exclusion zone and that the high exposure levels (of the order of mGy/h) do not cause any major abnormality, particularly on reproductive capabilities, growth, etc.),
- Evaluate the ecological condition of this zone *by applying* an integrated approach (the field of functional ecology), for example, by studying the degradation of bedding in the terrestrial and aquatic environments (an indicator of the material and energy flows), but also by developing models to understand and dissociate direct effects (e.g. exposure to radiation) from indirect effects (e.g. the prey/predator relationship). To date, these aspects have not been examined by any team.

In parallel, work has also begun in the Fukushima region. The Freebird project, selected by the National Research Agency in the context of the Flash Japan call for projects, aims to evaluate the effects of a radioactive contamination gradient on the bird populations inhabiting the area in a 100 km radius around the damaged power plant. The idea is to look into the effect of exposure to radioactivity on:

- The physiology of birds *via* (i) the quantification of oxidizing stress by the dosing of carotenoids, the pigments involved in the coloring of feathers and in anti-oxidant defense; (ii) genotoxicity, (iii) immunotoxicity, and (iv) the effects on hormones;
- Sexual signals and maternal commitment during the mating period, looking for a possible connection between the physiological status of birds and these two key selection processes (e.g., potential reduction of the quantity of carotenoids in feathers under the action of ionizing radiation can lead to consequences in terms of sexual attractivity).

[39] Geras'kin, S.A *et al.* (2008). Effects of non-human species irradiation after the Chernobyl NPP accident. Environ. Int. **34**: 880-897.
[40] Baker, R. J., Wickliffe, J.K., 2011. Wildlife and Chernobyl: The scientific evidence for minimal impacts. Bulletin of the Atomic Scientist. 14 April 2011. Web Edition.

APPENDIX 6-1: ATMOSPHERIC RELEASES FROM THE ACCIDENT RE-ASSESSED IN 2011 BY IRSN (SOURCE TERM MER5)

The tables below present the cumulative releases for the main isotopes of the source term. For iodine, the total corresponds to the sum of iodine in gaseous form (2/3 of the total) and particulate form (1/3 of the total). The cumulative release of all the isotopes is **7.18×10^{18} Bq**, of which 91% rare gases, 6% iodines, 2% tellurium, 0.8% cesiums and less than 0.5% of other isotopes. This source term has **73 released isotopes**, and 135 isotopes were dispersed when progeny were taken into account.

Rare gases (period)	Total (Bq)
Kr-83m (1.83 hours)	6.37×10^{14}
Kr-85 (10.8 years)	3.26×10^{16}
Kr-85m (4.48 hours)	4.39×10^{15}
Kr-87 (76.3 minutes)	4.28×10^{13}
Kr-88 (2.84 hours)	2.16×10^{15}
Xe-131m (11.8 days)	3.92×10^{16}
Xe-133 (5.24 days)	5.94×10^{18}
Xe-133m (2.19 days)	1.32×10^{17}
Xe-135 (9.14 hours)	3.71×10^{17}
Xe-135m (15.3 min)	1.73×10^{16}
Xe-138 (14.1 min)	6.26×10^{03}
Total rare gases	**6.54×10^{18}**

Iodines (period)	Total (Bq)
I-131 (8.02 days)	1.97×10^{17}
I-132 (2.29 hours)	1.68×10^{17}
I-132m (1.39 hours)	2.70×10^{10}
I-133 (20.8 hours)	4.20×10^{16}
I-134 (52.5 minutes)	5.01×10^{11}
I-135 (6.57 hours)	2.20×10^{15}
Total iodines	**4.09×10^{17}**

Tellurium (period)	Total (Bq)
Te-127 (9.35 hours)	9.51×10^{15}
Te-127m (109 days)	2.14×10^{15}
Te-129 (69.6 min)	7.97×10^{15}
Te-129m (33.6 days)	1.22×10^{16}
Te-131 (25.0 min)	8.36×10^{14}
Te-131m (30 hours)	3.71×10^{15}

Cesiums (period)	Total (Bq)
Cs-134 (2.06 years)	2.78×10^{16}
Cs-134m (2.9 hours)	1.49×10^{12}
Cs-136 (13.2 days)	9.80×10^{15}
Cs-137 (30.17 years)	2.06×10^{16}
Cs-138 (33.4 min)	1.08×10^{09}
Total cesiums	**5.82×10^{16}**

Te-132 (3.20 days)	$1.08x10^{17}$
Total tellurium	**$1.44x10^{17}$**

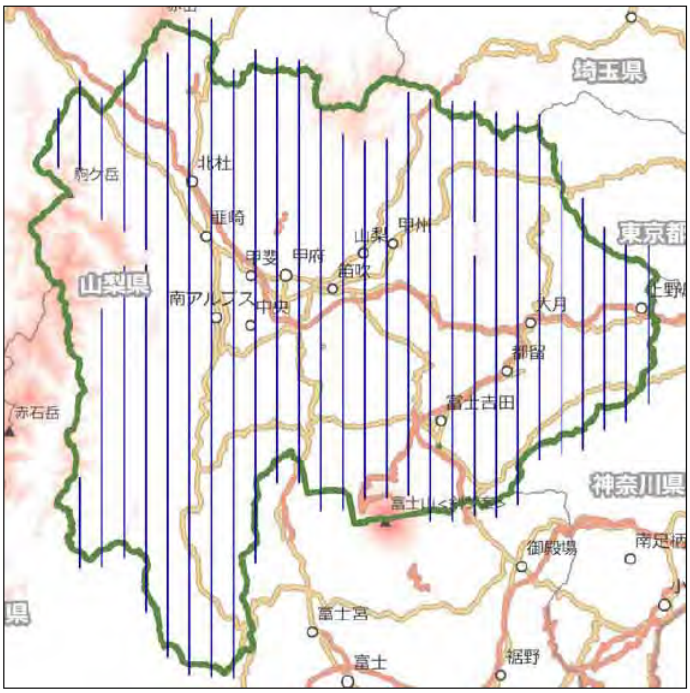
Other radionuclides (period)	Total (Bq)
La-140 (1.68 days)	$1.66x10^{13}$
Ba-140 (12.8 days)	$1.12x10^{15}$
Nb-95 (35.0 days)	$1.08x10^{13}$
Sr-89 (50.5 days)	$4.33x10^{13}$
Sr-90 (28.8 years)	$3.27x10^{12}$
Pu-238 (87.7 years)	$2.43x10^{09}$
Pu-239 (24110 years)	$4.07x10^{08}$
Pu-240 (6564 years)	$5.08.10^{08}$
Pu-241 (14.4 years)	$1.40x10^{11}$
Pu-242 (375000 years)	$1.65x10^{06}$

APPENDIX 6-2: PRESENTATION OF AIRBORN MEASUREMENT CAMPAIGNS PERFORMED IN JAPAN

Since April 2011, MEXT has organized several airborne measurement campaigns in collaboration with the Japan Atomic Energy Agency (JAEA) and the Nuclear Safety Technology Center (NUSTEC). As of December 1st 2011, 22 districts had been mapped.

The measurements were obtained using on-board instruments in privately-owned helicopters, emergency helicopters, or military helicopters. The flights were carried out at an altitude from 150 m to 300 m according to the terrain, where high reliefs were not mapped (during the first campaign performed with the DOE, the flight altitude went as high as 700 m).

The measurements were performed on rectilinear routes, with the flight paths spaced as far apart as 3 km (see figure below). According to the site to be mapped, the spacing of the flight paths could be reduced. Thus, in the 80 km zone around the facility, this space was between 1.8 km and 2 km.



Example of a measurement map for the Yamanashi district

To obtain a cartographic representation, the measurements performed were integrated spatially on disks with a radius of 300 m to 600 m according to the flight altitude.

The measurements taken concerned the dose rate equivalent 1 m from the ground (without subtracting the natural ambient dose rate) and the surface activity in cesium 134 and cesium 137. The airborne measurements were then correlated with measurements carried out *in situ* by the Japan Chemical Analysis Center for validation.

After analyzing the results, MEXT compiled them before publishing them on its website. They were published approximately three weeks to one month after each measurement campaign. The results were published later in English. The results were occasionally corrected, and new maps put online. The corrections were due to errors of interpretation of the raw results, or better correlation with the *in situ* measurement campaigns.

According to the size of the district, each campaign lasted from one week to several weeks. The following airborne measurement campaigns were carried out in 2011:

- April 6 → April 29 : 80 km around Dai-ichi
- May 18 → May 26 : 80 km to 100 km around Dai-ichi
- May 31 → July 2 : 80 km around Dai-ichi
- June 22 → June 30 : Miyagi district
- July 12 → July 16 : Tochigi district
- August 9 → August 15 : Yamagata district
- July 26 → August 2 : Ibaraki district
- August 16 → August 28 : Fukushima district
- August 23 → Sept. 8 : Gunma district
- August 30 → Sept. 23 : Niigata district
- Sept. 14 → Sept. 28 : Akita district
- Sept. 14 → Oct. 13 : Iwate district
- Sept. 23 → Sept. 30 : Shizuoka district
- Sept. 24 → Oct. 7 : Nagano district
- Sept. 30 → Oct. 4 : Yamagata district
- Oct. 5 → Oct. 12 : Gifu district
- Oct. 7 → Oct. 9 : Toyama district
- Sept. 8 → Sept. 12 : Saitama district
- Sept. 8 → Sept. 12 : Chiba district
- Sept. 14 → Sept. 18 : Kanagawa district
- Sept. 14 →Sept. 18 : Tokyo district
- Oct. 7 → Nov. 1 : Aomori district
- Oct. 16 → Oct. 20 : Aichi district
- Oct. 17 → Oct. 24 : Ishikawa district
- Oct. 17 → Oct. 20 : Fukui district

7. ACTIONS TO PROTECT POPULATIONS AND POST-ACCIDENT MANAGEMENT IN JAPAN

The accident at Fukushima led the Japanese authorities to initiate actions to protect the populations, firstly from the immediate consequence of the releases (exposure to the radioactive plume) and then concerning the radioactive deposits formed by the atmospheric dispersion of these releases (external exposure to radiation emitted by the deposits and risk of internal contamination by ingestion of contaminated foodstuffs).

Moreover, during the past year, in addition to radioactivity measurements aiming to characterize the environmental contamination (mapping the deposits) or monitor the contamination of foods and the dwelling-places of persons (see Section 6), post-accident management actions were carried out by the government bodies or local authorities to reduce contamination and prepare for a gradual return to the evacuated territories.

7.1. EVACUATION OR PROTECTION

The information sources available to IRSN, most notably the report from the Japanese government concerning the Fukushima accident, sent to the IAEA on June 7th[41], provide a record of the sequence of main population protection decisions taken from the start of the accident.

7.1.1. EMERGENCY PROTECTION ACTIONS

On March 11th 2011, because of damage caused by the tsunami, on the Fukushima Dai-ichi power plant in particular, the Prime Minister declared a nuclear emergency situation at 7:03 pm local time, and requested the setting up of a emergency cell.

The same day, at 8:50 pm, the Governor of Fukushima District ordered the evacuation of the towns of Futuba and Okuma, located within a 2 km radius of the Fukushima Dai-ichi power station. At 9:23 pm, the Prime Minister instructed the relevant local authorities to evacuate the area in a 3 km radius around the facility and to shelter any persons outside this 3 km radius but within a 10 km radius. On March 12 at 5:44 am, the evacuation was extended to a 10 km radius.

In parallel, the problems encountered in the other nuclear power plant, Fukushima Dai-ini, located a dozen kilometers south of Fukushima Dai-ichi, led the Japanese authorities to decide, on March 12 at 7:45 am, to evacuate the population living within a radius of 3 km around the facility and to shelter the population beyond that radius and within a 10 km radius. On March 12th at 5:39 pm, the evacuation was extended to 10 km (subsequently, on April 21, this radius was reduced to 8 km, which in practice made it the same evacuation area as the 20 km one set up in the meantime around Fukushima Dai-ichi.

On March 12 at 6:25 pm, following the explosion in Reactor Building 1, the evacuation zone around the Fukushima Dai-ichi site was extended to 20 km (affecting approximately 78,200 persons, including those within a 10 km radius of Fukushima Dai-ini), and then a shelter zone in a radius from 20 to 30 km around the site was set up on March 15th at 11 am (concerning approximately 62,400 persons).

On March 15th at 11:30 pm, NISA announced that the evacuation of inhabitants in a 20 km radius around Fukushima Dai-ichi and a 10 km radius around Fukushima Dai-ini had been in effect since that day at 7 pm.

[41] Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety - The Accident at TEPCO's Fukushima Nuclear Power Stations.

The table in Figure 7-1 summarizes the emergency protection actions decided upon in Japan from 11th to 15th March 2011.

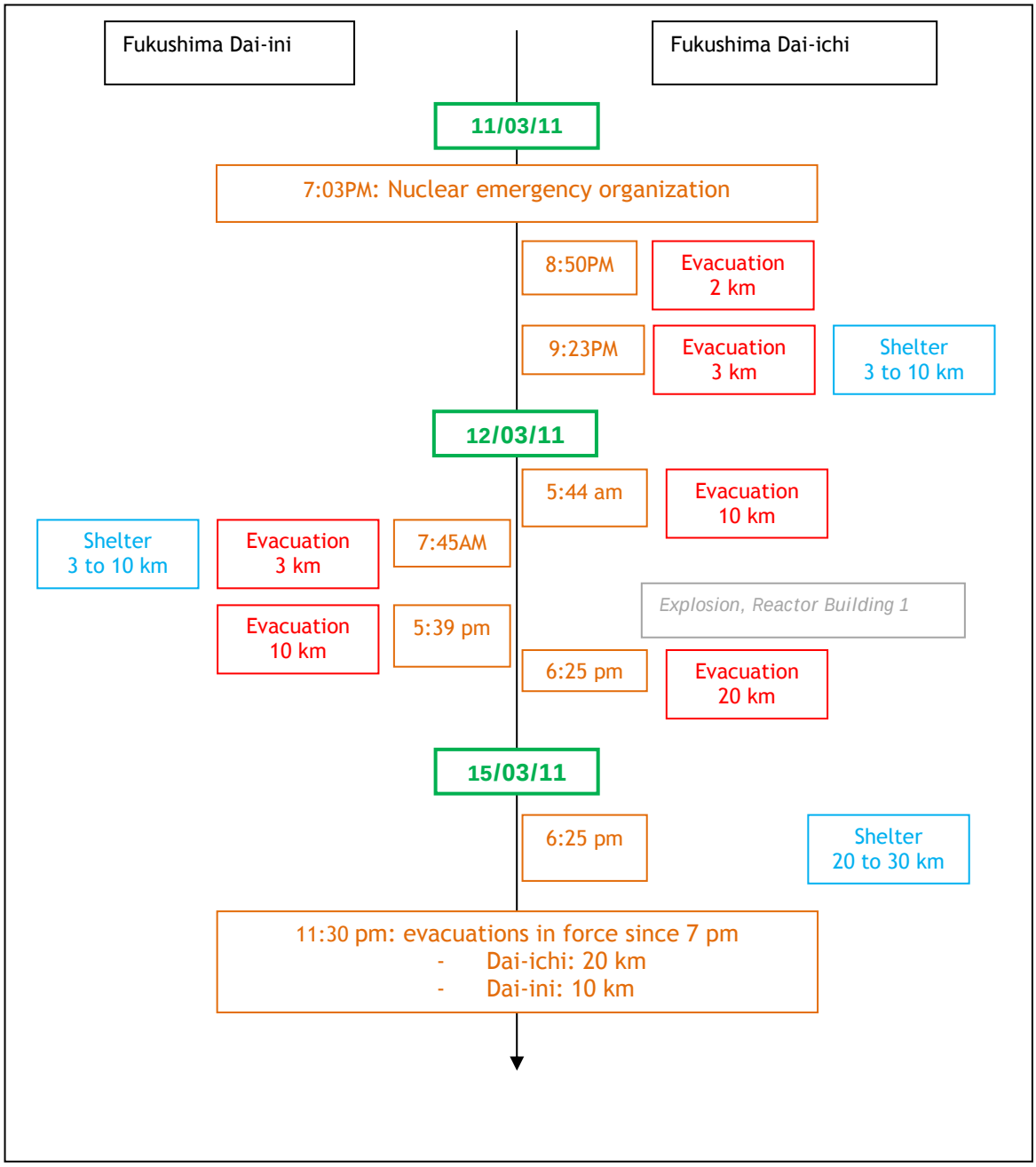


Figure 7-1– Chronology of the protective actions decided on in Japan from March 11th to March 15th 2011 around the Fukushima Dai-ichi and Fukushima Dai-ini power plants.

7.1.2. ADDITIONAL PROTECTIVE ACTIONS IMPLEMENTED FROM APRIL 2011

At the end of March, while the major atmospheric releases occurring between the 12th and 25th of March had dissipated, the results of the initial measurement campaigns revealed significant dose rates beyond the 20 km evacuation zone, and particularly toward the north-west. Moreover, certain inhabitants located between 20 and 30 km, where the shelter instruction still remains in force because of the precarious condition of the damaged facilities of Fukushima Dai-ichi, started to evacuate that area voluntarily because their economic and social life was becoming increasingly difficult to sustain. In this context, local initiatives and new decisions by the government authorities were implemented to supplement the emergency protective actions taken in March.

For example, on April 7th, the Mayor of Iitate took the initiative of advising pregnant women and children under the age of 3 (50 persons) to go to the neighboring town of Fukushima within one week.

On April 11th, the first announcement extending the initial evacuation zone was made: the residents of Katsurao, Iitate, Namie, and part of Kawamata and Minamisoma were asked to leave within one month (first announcement).

On April 21st, the 20 km evacuation radius became a 'Prohibited Area'. Unauthorized entry into this area became subject to a fine of 100,000 yen (approximately €835).

On April 22nd, the residents of Katsurao, Iitate, Namie, and part of Kawamata and Minamisoma were again asked to leave within one month. Those areas then constituted the 'Planned Evacuation Zone' or 'Extended Evacuation Zone'. In parallel, taking shelter in the 20-30 km area was lifted around the Fukushima Dai-ichi power plant, and that area became an 'Emergency evacuation preparation area'. This concerned the municipality of Hirono, part of Minamisoma, part of Tamura, and part of Kawauchi. In those municipalities, the population may remain, but must be prepared for a possible emergency evacuation in the event of a new problem arising on the Fukushima Dai-ichi site. The map in Figure 7-2 illustrates the protective zoning in force at that time.

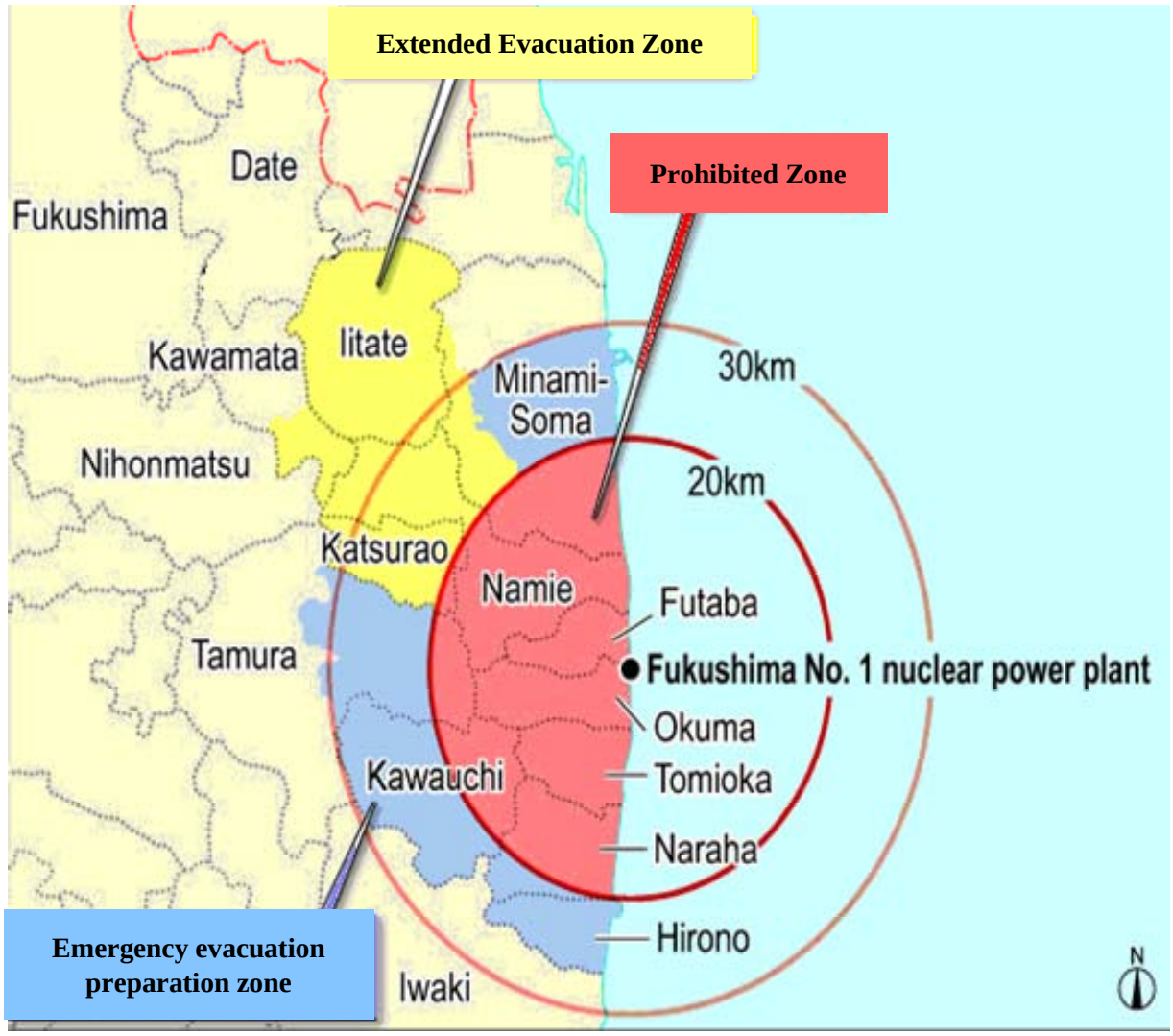


Figure 7-2 - Population management zones.

On May 15th, 4000 residents of Iitate and 1100 from Kawamata (municipalities located in the extended evacuation zone decided on in April) were re-housed in neighboring towns.

On 16th June, the Government recommended the evacuation of persons residing in 'hot spots' (dose greater than 20 mSv/year) located outside the Prohibited Zone: this concerned 113 homes in the municipality of Date.

On July 21st, the government recommended the evacuation of 59 homes in the municipality of Minamisoma, and on August 2nd and 3rd, 72 homes and one home respectively in the towns of Minamisoma and Kawauchi.

On August 18th, the evacuation of residents from the extended evacuation zone was almost totally complete.

In parallel, in order to limit the exposure of children in schoolyards, MEXT indicated that schoolyards were only accessible subject to the dose rate at 1 m in primary schools or 50 cm in nursery schools being less than 3.8 µSv/h.

7.2. MANAGEMENT OF FOODSTUFFS IN JAPAN

With regard to the mechanism for monitoring foodstuffs, Japan relies on the standards for sale or consumption defined by the MHLW on March 17th 2011 and validated by the FSC (Japanese food safety commission) on March 29th (Table 7-I). Exceeding these standards leads to the implementation of bans.

Table 7-I – Standards for sale or consumption instituted in Japan following the Fukushima accident

(Bq/kg)	Baby food	Milk and dairy products	Vegetables	Cereals	Meat, eggs, fish
iodines	100	300	2,000	-	-
Pu and transPu alpha	1	1	1	10	10
uranium	20	20	20	100	100
cesiums	200	200	500	500	500

This mechanism is not comparable to a zoning system. In Japan, it is not implemented via the definition of a perimeter in which actions are applied. The controls and bans are applied on a case-by-case basis according to the specific strategy implemented by each local government concerned by the consequences of the accident.

MEXT however issued certain general rules. The system of bans and lifting of restrictions thus operated in the following way during the past year:

- Marketing authorization is granted *a priori*; restrictions are not implemented unless *a posteriori* tests reveal values outside the limits of the standards,
- Testing is performed by sampling, but the exact protocol is never disclosed; some doubt therefore remains concerning the representative nature of the samples on the scale of the farms, municipalities, or districts concerned,
- The procedure for lifting bans appears to be strict:
    - Select several sampling points,
    - Perform weekly tests on foodstuffs products at those points,
    - When the measurement results for three consecutive weeks are within the limits, it is possible to lift the ban.

This management mechanism was applied to many product categories in Japan, but the dates, duration, and areas in which it was applied were variable, as the example of spinach illustrates in Figure 7-3.

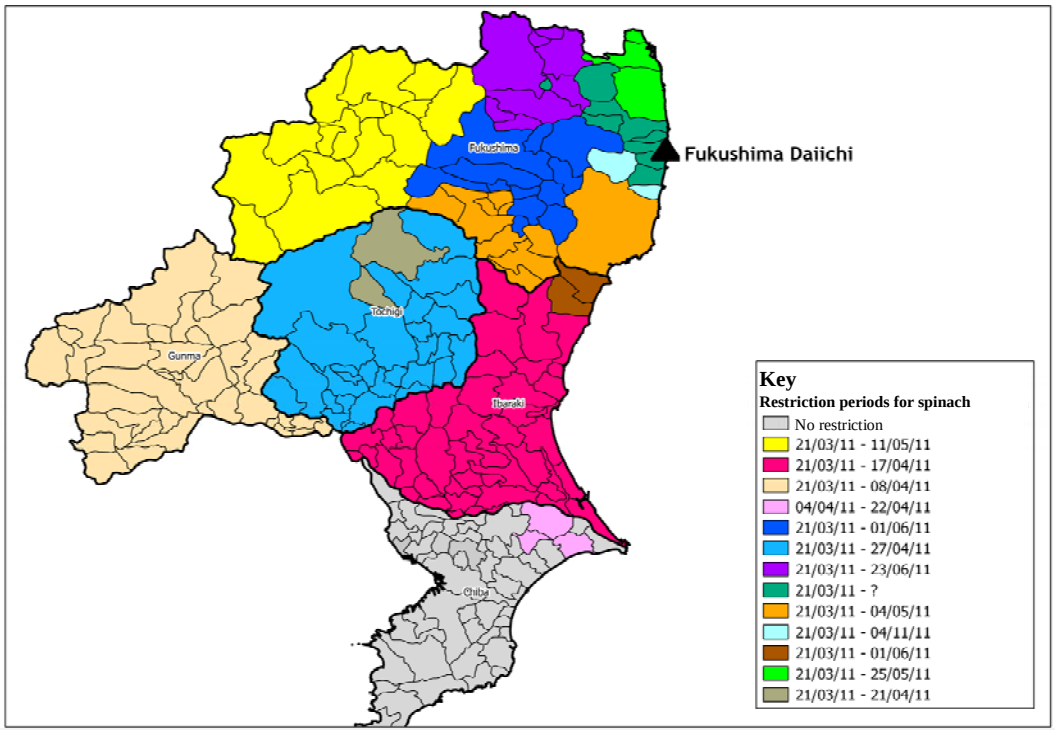


Figure 7-3- History of restrictions on the sale of spinach

The information currently available does not enable IRSN to fully evaluate the effectiveness of the food contamination management mechanism in Japan. In particular, it seems that the restrictions are sometimes implemented rather late and non-exhaustively, which has led to part of the Japanese population losing confidence in this mechanism. A few observations cast doubt on the effectiveness of the system implemented:

- Certain restrictions were implemented very late, after measurement results exceeding the limits had been obtained; for example:
    - For bamboo shoots, the results from samples taken on April 27th 2011 in Iwaki (Fukushima district) exceeded the limits set by Japanese standards, but the restriction on sale did not take effect until May 9th 2012,
    - For tea leaves, the first sample found to have exceeded the limits was taken on May 9th 2011 in Kanagawa district, but the sale restriction order was not issued until June 2nd 2011; however, the leaves picked in early May 2011 might not yet have been ready for processing.
- Certain types of produce underwent sampling whose results exceeded the limits without giving rise to restrictions on a national level, and products whose contamination exceeds the limits were detected on the Japanese market (tea leaves, algae and mussels, loquat);
- Certain municipalities were subject to restrictions although no samples were taken there or the samples all produced results within the limits;
- The marketing restriction is not always associated with the consumption restriction,
- There is no systematic application of the three tests before release, or the information concerning the representative nature of the tests performed is very patchy.

These observations do not allow us to assess whether there were major food-related health risks in Japan. The doses received in Japan by ingestion of contaminated foods are difficult to estimate (see Chapter 8). It is important, however, to remember that the occasional consumption of foods with contamination levels slightly exceeding authorized threshold limits does not pose a significant health risk. Only the regular consumption of strongly contaminated foods could have led to significant doses, particularly in the initial weeks following the accident.

7.3. PREPARATION FOR THE RETURN OF POPULATIONS AND DECONTAMINATION ACTIONS

7.3.1. POPULATION RETURN STRATEGY ANNOUNCED IN JAPAN

On July 20th 2011, the Japanese government announced that it hoped to allow residents to return to the evacuation zones outside the 'Prohibited Zone' and eliminate the 'Prohibited Zone' in the coming months.
On August 9th, the government announced that it had established the plan to be implemented to re-evaluate the extension of the zones.
On August 26th, the first temporary visits to the 3 km zone were organized.
On September 30th, the emergency evacuation preparation zone status was lifted. On the 58,500 persons concerned, approximately 28,500 had chosen to leave altogether rather than live in a constant state of alert.
On January 3rd 2012, the Japanese authorities announced that they could cancel the 20 km Prohibited Zone as of April 2012, and create three new areas with different statuses according to radioactivity level.

The government then plans to create:

- A return preparation zone, which concerns the areas where the annual dose potentially received by external exposure related to deposits is between 1 and 20 mSv/year. This area would be decontaminated as a priority, to achieve a dose level as close as possible to 1 mSv/year, corresponding to the legal limit for the exposure of populations to nuclear activities under normal operation. To make the area habitable, however, the infrastructures and economic activities would have to be restored, after nine months lying idle and because of the damage caused by the earthquake and the tsunami. The decontamination work in this area is paid for by the municipalities and district governments;
- A **'Limited Habitation Zone'**, concerning the areas where the annual dose is between 20 and 50 mSv/year. Decontamination would be carried out there to return the level below 20 mSv /year and allow residents to return later. The decontamination work in this zone is paid for by the Japanese government;
- A **'Difficult Return Zone'** where the annual dose exceeds 50 mSv/year. This is essentially a strip going north-west from the power plant, It will remain totally deserted for at least a decade. The State should offer to buy back the abandoned land from inhabitants.

7.3.2. DECONTAMINATION ACTIONS

- **Government decontamination plan**

In the territories where exposure is between 20 mSv/year and 10 mSv/year, the aim is to implement actions to reduce the contamination and reach a dose lower than 10 mSv/year at the end of 2012. In these areas, for schools, the target figure is maximum exposure of 5 mSv/year (or 1 µSv/h).

Wherever the annual dose is between 10 mSv and 5 mSv, the aim is to reach annual doses less than 5 mSv/year in March 2013, and close to 1 mSv/year (i.e. 0.23 µSv/h) from the end of 2014.

To train the participants, public meetings were organized, local companies were created, and a Ministry of the Environment field office has now been set up in Fukushima.

To carry out these actions successfully, the government has created a guide to decontamination best practices, which was published in late November. These practices were defined after several months of experimentation, carried out by the JAEA, amongst others, on the initiative of the government.

- **Decontamination pilot sites**

In the summer of 2011, actions were undertaken by the municipalities as well as by institutes such as JAEA to decontaminate schoolyards, public swimming pools, squares, etc. The work carried out by JAEA led to the creation of manuals for private individuals and municipalities.

Municipalities such as Date City and Fukushima City have set up their own initiatives to conduct cleaning campaigns in certain neighborhoods[42].

JAEA, with support from the government, set up two pilot sites in 2011, covering about 7 or 8 acres (3 ha) each, in Minamisoma City and Date City, near 'hot spots'. These pilot sites were used to test different cleaning methods in different environments (buildings, forests, agricultural, etc.).

Another project, supported by the government and managed by JAEA, was set up in late 2011. Its aim was to create pilot decontamination sites in 12 municipalities of the evacuated zone. There are 16 pilot sites in all, and they include neighborhoods, parks, schools, industrial buildings, etc. The total surface to be decontaminated is 221 ha (over 500 acres). The decontamination period is estimated at approximately three months.

The pilot sites are divided into three groups. Each group is in charge of defining the actions it will carry out. More than twenty companies are involved in this project. The various actions being tested include pressure jet cleaning, cleaning using sponges with cesium-absorbent properties, spray-on films that trap radionuclides after polymerization, using vacuum sweepers,

To better evaluate the effectiveness of the various actions undertaken, a precise mapping of the site is made before and after the actions are carried out. Finally, to reduce the quantity of waste, various reduction measures are applied before storage. These actions are, for example, are treating the water used for decontamination, crushing plants, and sorting masses of earth according to their level of contamination.

- **Example of decontamination actions**
  - **Decontamination action in a school**

In April, certain municipalities decided to implement decontamination actions on schools where the dose rate levels were above 3.8 µSv/h at 1 cm.

To limit the exposure of children in the town of Koriyama, the municipality stripped the surface of the playground or grass to a depth of 3 cm on April 27th (see Figure 7-4). The effectiveness of this action was evaluated during the operation (see Table 7-II). Following on from this experiment, two surface stripping campaigns were carried out between April 27th and May 2nd, and May 24th and 28th, in all schoolyards where the dose rate was greater than 3.8 µSv/h at 1 cm. The dose rates measured before and after surface stripping are presented in Table 7-III. The removed soil was stored and then sprayed with a fixer product to make it less prone to returning into suspension.

[42] Actions implemented in Date City (in Japanese) http://www.jaea.go.jp/fukushima/pdf/decon_j_11.pdf

Figure 7-4 – Stages of surface stripping in schoolyards

Table 7-II – Effectiveness of soil stripping carried out on April 27th

	Height from ground	Dose rate in µSv/hr		
		April 7	April 27 (before removal)	April 27 (after removal)
School 1	1cm	5.5	4.1	1.9
	50cm	4.5 (measured at 1m)	3.3	1.9
School 2	1cm	4.7	4.5	0.9
	50cm	3.4	3.1	0.9

Table 7-III – Effectiveness of soil stripping campaigns of April 27th to May 2nd and May 24th to 28th

	Average dose rate in schools (µSv/h)					
	Measurements 1 cm from the ground			Measurements 50cm from the ground		
	Before removal	After removal	Efficiency (%)	Before removal	After removal	Efficiency (%)
Mean	2.1	0.7	65.3	1.7	0.7	59.1
(min-max)	(1.4 - 4.5)	(0.2 - 1.9)	(35.0 - 90.5)	(1.1 - 3.3)	(0.2 - 1.6)	(25.0 - 88.2)

- **Decontamination of the Watari district[43]**

An initial cleaning campaign was carried out in the Watari district (Fukushima). This was done to study the effectiveness of the actions to then apply them to other neighborhoods. This campaign was carried out on July 24th. Town employees and private individuals participated in the cleaning work. The Fukushima town website indicates that 3400 persons took part in this action.

The actions carried out included the cleaning of roads, sidewalks and ditches using sweepers and pressure jets, as well as the cleaning of flower beds and certain administrative buildings open to the public. The dose rate and dose

[43] http://shinsai.city.fukushima.fukushima.jp/?p=3182

were checked before and after cleaning. In the coming weeks, new actions will be undertaken to clean the public parks. Provisional results are given in Table 7-IV and Table 7-V.

Table 7-IV : Effectiveness of the cleaning of school access routes, campaign of July 24th[44]

	Average dose rate on school access routes (µSv/h)					
	Measurements 1 cm from the ground			Measurements 50cm from the ground		
	Before cleaning	After cleaning	Efficiency (%)	Before cleaning	After cleaning	Efficiency (%)
Mean	2.25	1.8	20.55	1.65	1.35	18.9

Table 7-V : Mean effectiveness of the cleaning of a house, campaign of July 24th

	Dose rate (µSv/hr)		
	Before cleaning	After cleaning	Efficiency (%)
Guttering	6.8	1.6	76.5
Entry	0.9	0.8	11.1
Garden	1.5	1.2	20
Interior	0.5	0.4	20

In general, the contamination reduction actions on buildings reduce the ambient contamination only slightly, unless carried out in the initial weeks following the deposition, i.e. before the radionuclides have become fixed. Cleaning and removal of vegetation that had accumulated in eavestroughs or gutters, however, eliminates a significant proportion of the radioactivity accumulated in these hot spots. Figure 7-7 shows that, on average, the cleaning of guttering reduced the dose rate at the deposition points approximately by a factor of four.

- **Waste processing plan**

In parallel with the decontamination plan, the Ministry of the Environment has presented a plan to dispose of and store the waste obtained from the decontamination process.

The planned storage method would be scalable over time.

For all the waste generated by the decontamination process, the decision was to set up a temporary, but monitored, storage system for a maximum period of three years.

For longer periods—from three to 30 years—the government plans to set up temporary storage centers.

Finally, thirty years from now, the government plans to set up long-term underground storage facilities.

In any case, regular or continuous checks are planned to ensure that no contamination of the environment is caused (Figure 7-5).

The waste generated by the decontamination process that is considered to be contaminated, is waste whose activity exceeds 8000 Bq/kg for waste other than soil.

For certain categories of waste (e.g., agricultural waste), the plan is to incinerate it and then store the contaminated ashes.

[44] http://shinsai.city.fukushima.fukushima.jp/?p=4325

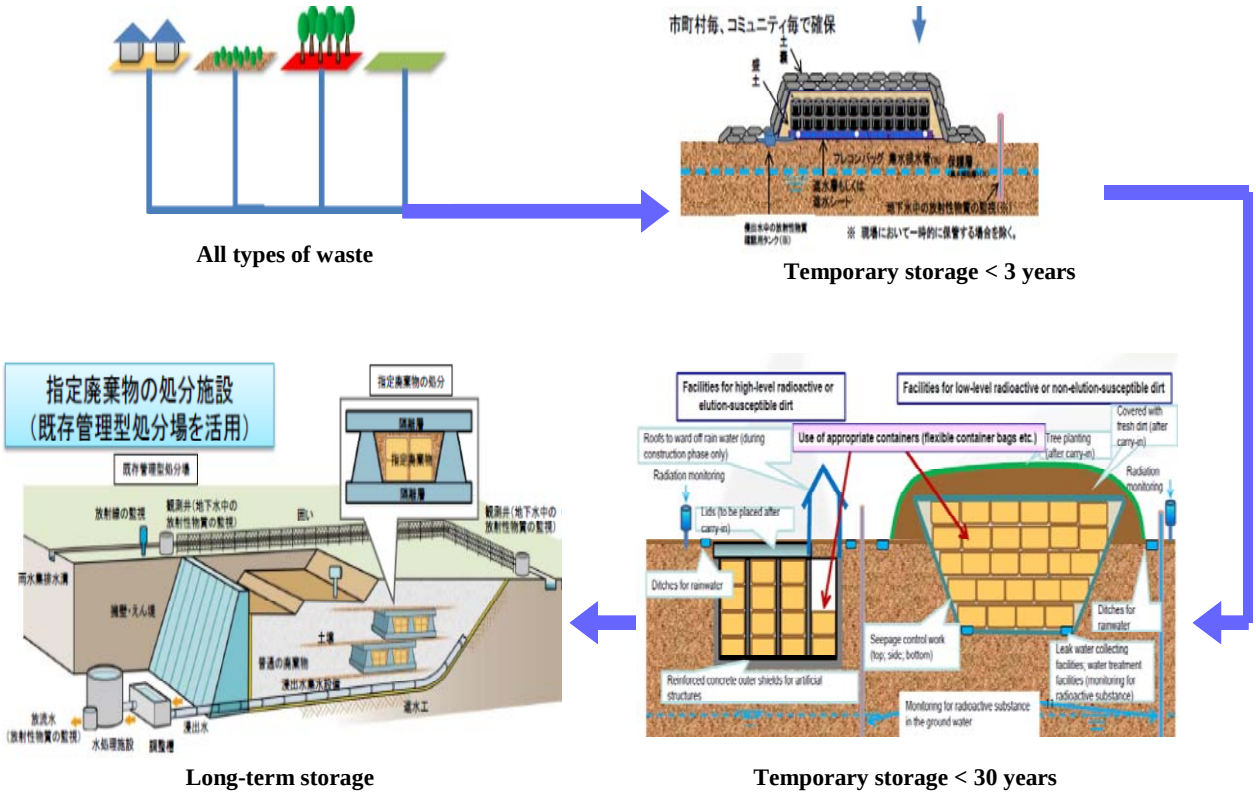


Figure 7-5 – Steps in the storage of contaminated waste.

- **Contamination of the urban environment**

In urban areas, the deposition is heterogeneous. Meteorological disturbances due to the effects of buildings cause accumulation points in locations where air recirculates. In addition, there is more or less deposition according to the urban surfaces. A dry deposit will become better fixed on a rough surface, and a wet deposit will run off better from a smooth surface. In addition, as for an accumulation of snow, the deposition areas of the eavestroughs are locations where radioactivity can particularly accumulate, creating hot spots.

The different measurements published by the Japanese authorities revealed these deposition disparities in the urban environment.

Figure 7-6 presents measurements taken in late July on paths toward a school in the Watari area of Fukushima before and after cleaning the sidewalks. Different dose rates are observed on either side of the road. The sidewalk on the right always has a higher dose rate than the one on the left.

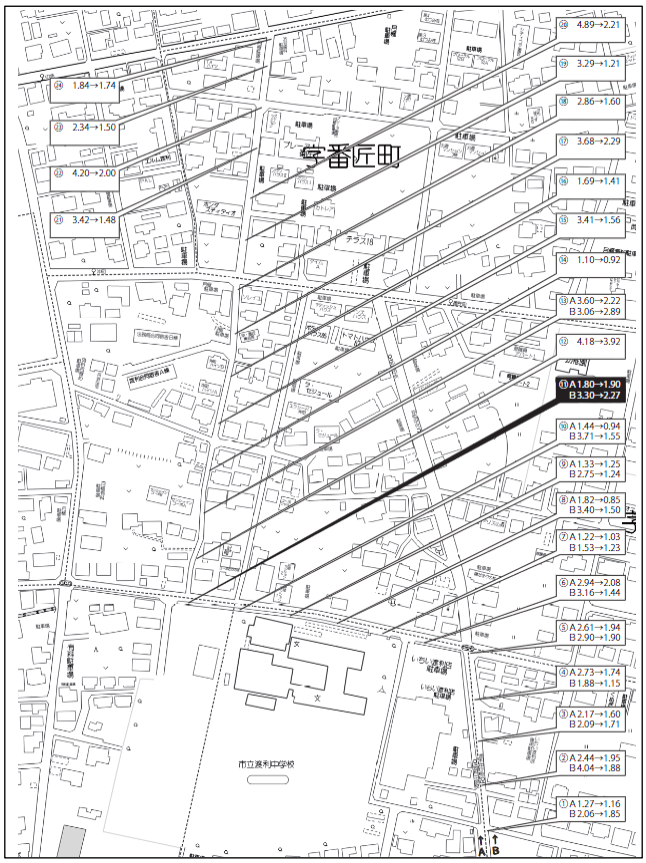


Figure 7-6 – Dose rate measurements taken before and after decontamination at 1 m along the school path

Figure 7-7 presents the dose rates measured near a house in the Watari neighborhood before and after contamination reduction actions. The maximum dose rates are measured at the eavestroughs, i.e. at the deposition points of the runoff from the roof.

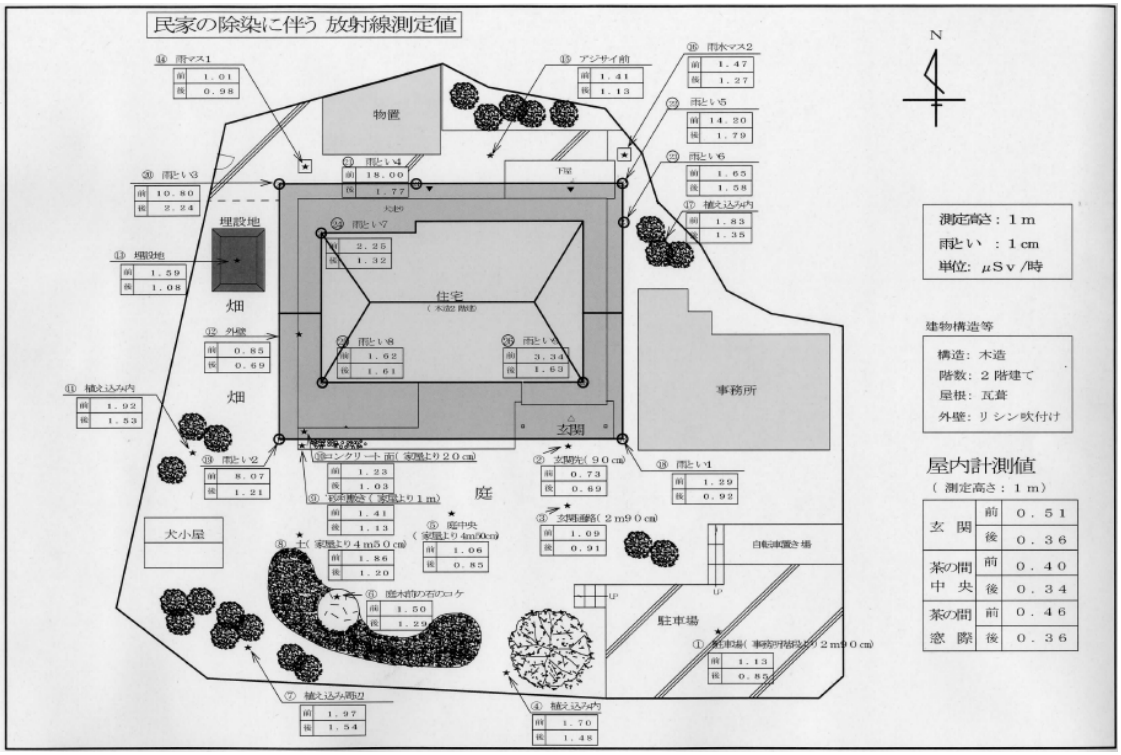


Figure 7-7 – Dose rate measurements taken before and after decontamination

8. DOSIMETRIC AND HEALTH IMPACT IN JAPAN

Following the earthquake and tsunami that occurred on the east coast in northern Japan, the Fukushima nuclear power plant was badly damaged, and a large quantity of radioactivity was released into the atmosphere and the sea. The surrounding populations were evacuated, while others, who lived in more remote areas, were placed under shelter. The countermeasures taken with regard to the exposure of the population in Japan included temporary restrictions on drinking water and certain foods produced in several districts, ordered by the Japanese authorities. During emergency operations undertaken in the power plant, workers and other participants were exposed to significant levels.

The health risks to persons exposed in Japan at the time of the Fukushima accident and in its aftermath depend on the level of the radiation doses received.

Exposure to the radioactive releases caused by the accident largely depended on where the persons were located, their way of life (activity, food, travel, etc.) and compliance with the protective actions implemented by the authorities, most notably emergency or delayed evacuation, or the taking of stable iodine tablets.

The doses actually received by different categories of person remain very difficult to estimate, even one year after the accident, because they depend on the number and quality of the radioactivity measurements available (in the environment or on individuals) and the information collected concerning the conditions of exposure. Work is currently underway under the auspices of UNSCEAR *(United Nations Scientific Committee on the Effects of Atomic Radiation)* in order to assess, in particular, the dosimetric and health consequences in Japan. IRSN participates actively in this work.

Thus, at its annual session in May 2011, the United Nations Scientific Committee on the Effects of Atomic Radiation decided to start writing an initial report on the accident at the Fukushima Dai-ichi power plant and its consequences on the health of persons exposed to the radioactive fallout.

In order to accomplish this task, UNSCEAR called upon all governments to nominate experts, who would be appointed to write this report on a voluntary basis. A total of nearly 60 experts, from Europe, Japan, Canada, the USA, Brazil, Korea, Russia, Belarus, Ukraine, and Australia, were appointed. There are nine experts from France: five from IRSN and four from the CEA.

The experts have been divided into four working groups:

- The first group, led by an American delegate, is responsible for collecting measurement data and checking its quality. IRSN is represented by an expert in charge of one of the three sub-groups of this working group,
- The second group, led by a German delegate, is responsible for evaluating the atmospheric and marine dispersion of the radioactive discharge. IRSN is represented by one expert in this working group,
- The third group, led by an Australian delegate, is responsible for assessing doses and risks to the population and non-human species. IRSN is represented by two experts in this working group,
- The fourth group, led by a French delegate from IRSN, is responsible for assessing doses and health effects to workers.

Moreover, a coordination group consisting of the Chairman of UNSCEAR, the Chairman of the Japanese delegation to UNSCEAR, the leaders of the four working groups, and the Scientific Secretary of UNSCEAR and his colleagues, ensures the smooth progress of the report drafting process.

A first interim report will be presented at the 59th annual session of UNSCEAR in May 2012, and the final report, whose publication is expected at the end of 2013, will be presented at the 60th annual session of UNSCEAR in May 2013.

This UNSCEAR report will also benefit from contributions by the main international organizations, most notably the World Health Organization and the World Meteorological Organization.

To assess the dosimetric impact and health risks affecting persons exposed in Japan, IRSN collected information or performed evaluations for three categories of the population in Japan:

- Workers (including outside workers) present on the site during the accident and in the phase of restoring control over the facilities on the site, which is still ongoing,
- The Japanese population residing in the areas most exposed to accidental releases and radioactive deposition,
- French nationals returning from Japan and checked by IRSN.

8.1. GENERAL CONCEPTS

Overall, the risks expected after a nuclear accident of this magnitude essentially consist of an increased probability of the occurrence of certain types of cancer in the most exposed segments of the population, particularly thyroid cancer in small children. The two indicators used in this report to assess these risks are the effective dose and the equivalent dose to the thyroid.

The effective dose accounts for the doses delivered to each organ of the human body exposed to ionizing radiation, the nature of that radiation, and the inherent sensitivity of each of the organs to this radiation. It is expressed in a unit called the *sievert* (Sv) or divisions thereof: millisievert (mSv, thousandths of a sievert), microsievert (µSv, millionth of a sievert), or nanosievert (nSv, billionth of a sievert). The equivalent dose to the thyroid is the dose delivered specifically to the thyroid, particularly by the radioactive iodines.

The assessment of the dose received by an individual following incorporation of a radioactive substance involves a complex approach. It requires knowledge of how the activity in that substance will evolve in the organism, and a calculation of the dose received by the various tissues and organs. The determination of incorporated activity depends on retention measurement (whole-body and pulmonary in particular), of the radionuclides and their urinary and/or fecal excretion (radiotoxicological analysis).

Whole-body countings (i.e. in vivo measurements) involve determining the activity of the radionuclides incorporated in the organism by detecting the x-rays and gamma rays they emit outside the organism. This technique requires no biological sampling, and it can identify the radionuclide(s) concerned according to the energy of their emissions, quantify the activity at a given instant, and use it to estimate the initial intake.

The radiotoxicological analysis of excreta (i.e. in vitro bioassays) consists of determining the activity of the radionuclides eliminated in urine or in feces following the intake of radioactive substances. These tests are less demanding than whole-body countings (WBCs) with regard to the nature of the radiation that can be detected. They allow all types of radioactive emission to be measured, but nonetheless require the implementation of more extensive logistics. In fact, given the sample volumes required and in order to take fluctuations in daily excretion into account, they require 24-hour resting times for the urine, and this can rise to three days for feces. The samples must then be taken to a radiotoxicological testing laboratory and processed according to the nature of the radionuclides to be measured.

When a nuclear accident occurs, the main radionuclides likely to be detected in the exposed persons are the isotopes of cesium and iodine. These can equally well be detected by whole-body counting and by urine bioassays.

8.2. EXPOSURE OF WORKERS AND OTHER PARTICIPANTS ON THE FUKUSHIMA DAI-ICHI SITE

The only information currently available concerning doses received by the workers involved in the operations carried out at the Fukushima Dai-ichi power plant are those provided by the TEPCO company, which has been publishing a monthly report since April 2011. This information concerns employees of TEPCO and its subcontractors only. No precise information concerning the other categories of worker exposed (firemen, police officers, municipal employees, civilian security personnel) has yet been obtained, even though at least some of those workers have undergone dosimetric monitoring.

The last report published on February 29th 2012 concerned 3,340 TEPCO employees and 16,775 employees of companies subcontracted by TEPCO. The mean dose received by those workers between March 11th and 31st January 2012 was 24.72 mSv for TEPCO employees, and 9.35 mSv for subcontractor employees. Note that a comparison with the data supplied by TEPCO on January 31st 2012 indicates an unexplained discrepancy of 66 workers. If the information given in the report dated January 31st 2012 is compared to the information in the report dated February 29th 2012, the February 2012 month-end report should have mentioned 3,405 TEPCO employees and 16,776 employees of subcontractor companies.

Table 8-I – Summary dated February 29th 2012 of doses recorded by TEPCO for its own workers and those of its subcontractor companies

Cumulative dose	TEPCO	Contractors	Total
> 250 mSv	6	0	6
200 – 250 mSv	1	2	3
150 – 200 mSv	22	2	24
100 – 150 mSv	117	17	134
50 – 100 mSv	409	347	756
20 – 50 mSv	646	2,078	2,724
10 – 20 mSv	494	2,667	3,161
< 10 mSv	1,645	11,662	13,307
Total	3,340	16,775	20,115
Maximum (mSv)	678.80	238.42	678.80
Mean (mSv)	24.72	9.35	11.90

As at February 29th 2012, six workers, all employed by TEPCO, had received a dose exceeding 250 mSv. According to TEPCO, 85% of the dose received by those six workers was caused by inhaling iodine 131 due to not wearing suitable protective masks. The maximum recorded dose was 678.80 mSv.

Note that very little precise information is available concerning the methods used to evaluate the doses received by the workers, in particular for those who were not wearing dosemeters in the days immediately following the accident. Requests for additional information were recently sent to the Japanese authorities by the United Nations Scientific Committee on the Effects of Atomic Radiation.

8.3. EXPOSURE OF THE JAPANESE POPULATION

8.3.1. THE VARIOUS POPULATION EXPOSURE PATHWAYS FOR RADIOACTIVE SUBSTANCES RELEASED INTO THE ENVIRONMENT

The radioactive releases into the atmosphere as a result of the accident had the most immediate and significant impact in terms of local population exposure. Although there were also substantial direct releases into the sea, these could only have had an indirect impact through possible consumption of contaminated fish and seafood products (algae, coastal fish, shellfish, etc.).

The exposure pathways, the rate at which doses were accumulated (dose kinetics) and, ultimately, the magnitude of the doses received largely depend on the timeline of the accident and of course on a person's location.

At the time when the releases were dispersed in the air, in the form of a radioactive plume, the population may have been exposed via two main pathways (Figure 8-1):

- *external exposure* by radiation emitted by gamma-emitting radionuclides dispersed in the atmosphere (in the form of gas or fine particles in suspension, called "aerosols"), including those present above ground level;
- *internal exposure by inhalation* of radioactive gas or aerosols present in the ambient air at ground level. The radionuclides inhaled cross the pulmonary barrier into the bloodstream relatively easily and then distribute throughout the body. Some radionuclides tend to concentrate in specific organs, e.g. radioactive iodine in the thyroid. The radionuclides incorporated irradiate surrounding tissues and organs and continue to do so for as long as they remain in the body, even after the person concerned is no longer exposed to contaminated air. The residence time in the body depends on the radioactive half-life of the radionuclide and how fast it is eliminated by natural bodily functions.

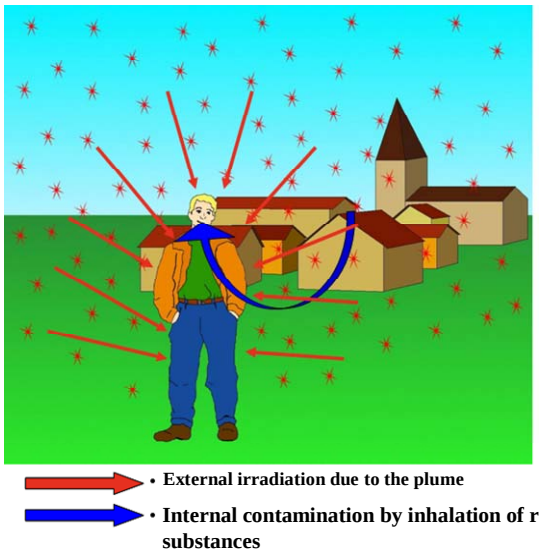


Figure 8-1 - Main exposure pathways to contaminated air caused by accidental radioactive release.

For a given person and radionuclide, the higher the radionuclide concentration in the air and the longer the air is contaminated, the larger the dose. Consequently, a similar dose may be received after brief exposure to a high concentration or prolonged exposure to a lower concentration.

When the person exposed is inside a permanent building with the doors and windows closed, internal exposure by inhalation may be temporarily delayed and reduced (the time taken for the radionuclides in the outside air to penetrate into the rooms). Furthermore, the gamma radiation emitted by the radionuclides present outside the building is attenuated by the construction materials (the effectiveness of attenuation depends on the type used and the size of the building), which can help to lower the doses received, typically by about 30%.

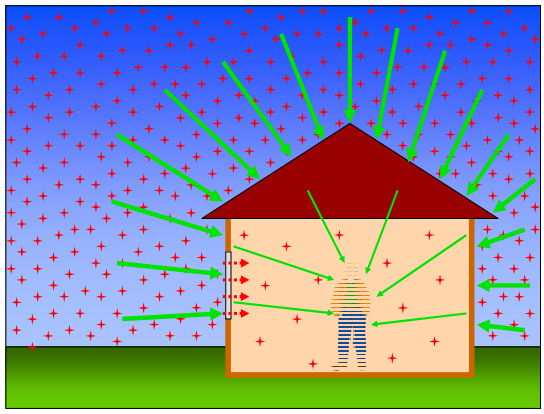


Figure 8-2 - Protection provided by a building against radioactive contamination of the outside air: the construction materials attenuate the gamma radiation and delay the penetration of radioactive particles into the building.

Emergency evacuation of areas likely to be exposed to the plume prevents population exposure if evacuation can be carried out before any releases start. This is the most effective protective measure in the event of a high level of ambient air contamination or prolonged radioactive releases (longer than about ten hours), but is difficult to implement and is not without risk (emergency protective measures during the accident cf. 7.1.1).

Taking stable iodine tablets reduces the dose to the thyroid from exposure to radioactive iodine, especially iodine-131. This treatment, which is particularly appropriate for children and pregnant women, must be administered just before the radioactive releases occur or shortly after initial exposure; for maximum effectiveness, the recipients must also take shelter.

The Japanese authorities are reported to have issued instructions to take stable iodine on March 16, 2011 during evacuation of the area within a 20 km radius of the damaged power plant. No evacuated residents seem to have taken any tablets, since the evacuation was apparently over by the time the instructions were made public. According to the SPEEDI information system[45] set up by the Japanese authorities, no dose rate higher than the limit of detection of 0.2 µSv/h (equivalent to a thyroid dose of 100 mSv for a 1-year-old child) was measured during a screening program carried out on 1,149 children between March 26 and 30, 2011.

[45] System for Prediction of Environmental Emergency Dose Information

Radioactive aerosols and gases gradually sink to ground level. The radioactive deposits thus formed will contribute to the exposure of people located in the contaminated areas, via the following main pathways:

- *external exposure from the gamma-emitting radionuclides deposited*. The intensity of exposure mainly depends on the extent of the radioactive deposition, the topology of the areas contaminated, and individual lifestyle (time spent outdoors);
- **internal exposure from ingestion of contaminated foodstuffs harvested in these areas**. As with internal exposure by inhalation, the radionuclides incorporated cross the digestive barrier and remain in the tissues and organs for a varying amount of time, leading to exposure of the body to ionizing radiation;
- **internal exposure from inadvertent ingestion of radioactive particles**. This exposure pathway, which is usually of secondary importance, exists when someone touches a surface that has unstable deposits (radionuclides not fixed on the surface) or loose contaminated materials (soil) then puts their hand to their mouth. Young children are at particular risk unless precautions are taken.

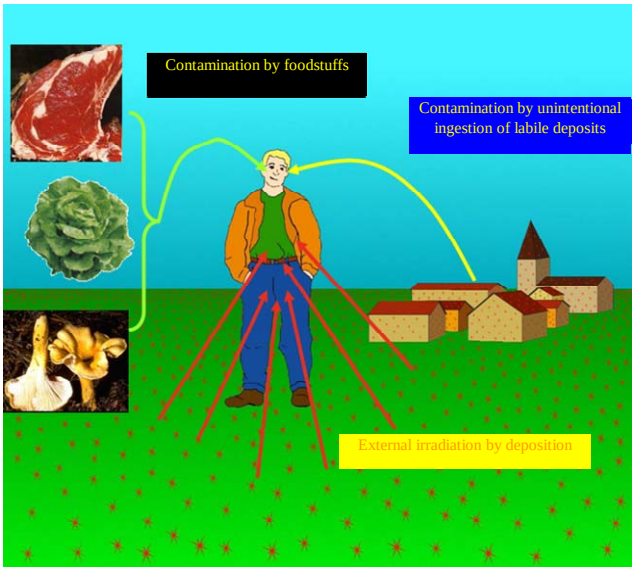


Figure 8-3 - Main exposure pathways to radioactive deposits in a post-accident situation

On a secondary level, there is a risk of exposure by inhalation of suspended radioactive particles from deposits, particularly in windy conditions or as a result of human actions (vehicles passing by, for example). The corresponding doses are usually low compared with those due to other exposure pathways. Nevertheless, this risk must be taken into consideration for people carrying out dirty work in heavily contaminated areas.

As we shall see in the next section, the doses due to exposure to the radioactive plume may be high in the vicinity of the damaged nuclear plant and may be received over a short period, ranging from a few hours to several days, as was the case in the Fukushima accident. The doses due to deposition are received more gradually but may become significant over time. Taking into account the presence of radionuclides with a short radioactive half-life in the deposits and phenomena specific to contamination of the food chain (see Chapter 6), the doses likely to be received from external exposure to deposition or from ingestion of contaminated foodstuffs may be particularly significant during the first month following formation of the deposits. **This is why, even though protecting the public from exposure to the radioactive plume must always be a priority in the most affected areas, initial preventive measures in relation to radioactive deposits must be implemented as soon as possible, especially in areas that are further away, where these deposits may have a significant short-term impact on food chain contamination**.

It is important to stress that in the case of the Fukushima accident, radioactive deposition started to become significant in Japan from March 15-16, 2011, whereas significant radioactive releases continued until March 25 (see Chapter 6). This means that during the release phase (from March 12-25), the public could have received a dose from both the plume and the radioactive deposits. After March 25, in the absence of new significant releases into the

environment, only persistent deposits continued (and still continue) to expose people who stayed (or still remain) in the contaminated areas, resulting in a gradual increase in the doses received.

8.3.2. ESTIMATE OF THE DOSES LIKELY TO HAVE BEEN RECEIVED BY THE LOCAL POPULATION DURING THE ATMOSPHERIC RELEASE PHASE

Within the context of work carried out in 2011 to evaluate atmospheric releases and simulate their dispersion over Japan (see Chapter 6), IRSN assessed **the doses potentially received by a 1-year-old child assumed to have remained in the same location from March 12 (when the releases began) until midnight on March 25 (when the phase of significant releases ended), without any protection (i.e. outdoors).** This exposure scenario is obviously not realistic but makes it possible to conservatively identify what are likely to have been the most exposed areas, i.e. those where emergency protection issues needed to be given priority attention. This conservative approach is one that IRSN commonly adopts in the event of an emergency to predict the potential dosimetric impact of an accident in progress, in order to recommend reasonably cautious protective measures to the authorities at a time of heightened uncertainty. The "1-year-old child" category is used because young children are most vulnerable to exposure to radioactive releases, especially iodine (in terms of thyroid doses received).

To assess these doses, IRSN considered the three main exposure pathways during this release phase:

- external exposure to gamma radiation emitted by the radioactive plume;
- internal exposure by inhalation of radionuclides present in the air;
- external exposure to gamma radiation emitted by the radioactive deposits on the ground, which are gradually formed according to the trajectories of the radioactive plume and the rain.

The dose likely to have been received by ingestion of contaminated foodstuffs is not taken into account here, as it is not a determining factor in the emergency protection strategy (sheltering or evacuation, administration of stable iodine). Moreover, in the case of the Fukushima accident, IRSN does not have sufficient data to make a reliable estimate of this dose.

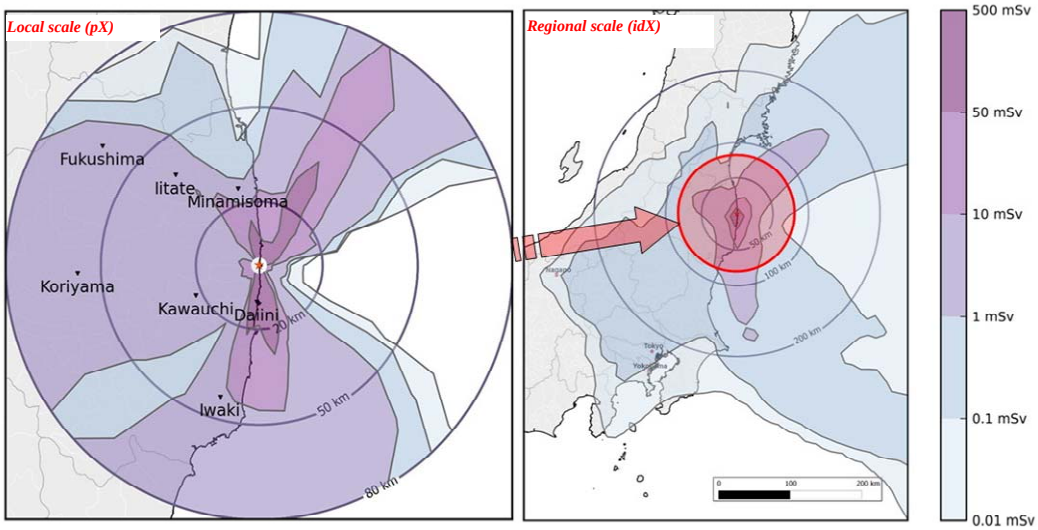
The maps in Figure 8-4 and Figure 8-5 represent, respectively, the cumulative effective dose and equivalent dose to the thyroid at the end of the release phase (midnight on March 25, 2011), based on the assumptions described above and calculated on a local scale (using model pX) and on a regional scale (using model ldX).

As expected, the doses likely to have been received were highest at local level. Whatever the scale, these estimates show that the marine environment suffered the greatest impact from the atmospheric releases. This obviously refers to virtual doses, because there are no full-time human inhabitants of that environment (especially not a 1-year-old child). Moreover, in the absence of any direct environmental measurements at the time of the releases, dose estimation is particularly inaccurate in this sector.

On land, the highest doses during the release phase could have been received in the coastal areas, to the north and especially to the south of the Fukushima Dai-ichi power plant. According to this simulation, effective doses above 10 mSv could have been received, assuming the people concerned continuously remained outdoors, up to 40 km to the south; the effective doses calculated exceed 50 mSv([46]) inside a 20 km radius, corresponding to the emergency evacuation zone on March 12. Concerning the equivalent doses to the thyroid, theoretical values above 50 mSv[47] could have been received as far as 60 km to the south of the power plant, in Iwaki. These correspond to a release from Reactor 2 on March 15 between midnight and 5 am, when the wind was blowing towards the south.

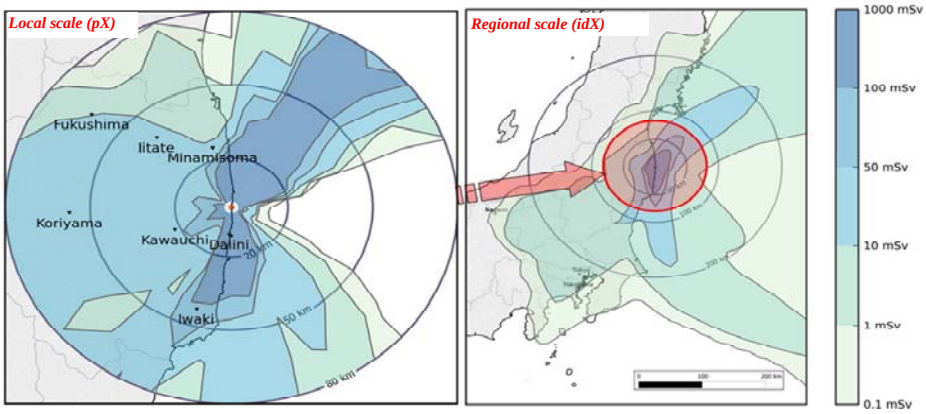
[46] An effective dose of 50 mSv corresponds to the intervention level in France for emergency evacuation of populations exposed to an accidental atmospheric release.

[47] A 50 mSv equivalent dose to the thyroid corresponds to the intervention level in France for the administration of stable iodine tablets in the event of exposure to an accidental release of radioactive iodine. In Japan, the intervention level is 100 mSv, in compliance with IAEA recommendations.



Effective dose likely to have been received by a 1-year-old child who remained without protection (outdoors) from March 12 to midnight March 25, 2011

Figure 8-4– Maps of the effective doses potentially received by an unprotected 1-year-old child during the release phase of the Fukushima accident. The doses on the regional scale map are only representative more than 100 km from the release point, taking into account the IdX modeling conditions. Within a shorter distance (area inside red circle), the doses on the local scale map, which was obtained using model pX, are representative.



Equivalent dose to the thyroid likely to have been received by a 1-year-old child who remained without protection (outdoors) from March 12 to midnight March 25, 2011

Figure 8-5– Maps of the equivalent doses to the thyroid likely to have been received by an unprotected 1-year-old child during the release phase of the Fukushima accident. The doses on the regional scale map are only representative more than 100 km from the release point, taking into account the IdX modeling conditions. Within a shorter distance (area inside red circle), the doses on the local scale map, which was obtained using model pX, are representative.

It should be emphasized that there is some uncertainty concerning the position of the radioactive plume in the southern sector because of the imprecise nature of the data and the modeling of meteorological conditions on a local scale, particularly for the release event occurring on March 15 and 16, 2011 (cf. 6.1.2.2). The plume heading south might therefore have passed more over the marine environment.

Further away, the doses received during the release phase, in the absence of protection, would have been significantly lower:

- below 10 mSv for the effective dose more than 40 km to the south, and of the order of 0.1 mSv in the Tokyo metropolitan area;
- below 50 mSv for the thyroid dose more than 40 km to the south, and of the order of 1 mSv in the Tokyo metropolitan area.

It should be noted that the doses determined from the individual measurement results for French citizens living within a 60 km radius of the Fukushima Dai-ichi power plant at the time of the releases (see 8.4) seem significantly lower than the conservative ones derived from the model.

It is interesting to note that the areas most affected by radioactive deposition, located to the north-west of the Fukushima power plant, are not the areas where the doses due to exposure to the plume were highest. This can be explained by the strong influence of rainfall or snowfall, which caused these deposits during the night of March 15-16, whereas in the areas most exposed to the plume, the deposits consisted mainly of dry deposits in a lesser quantity.

On the local scale, for equal levels of dose potentially received, there is a large disparity from one location to another concerning the contribution of the various exposure pathways and the dose kinetics during the release phase from March 12 to 25, 2011 (Figure 8-6).

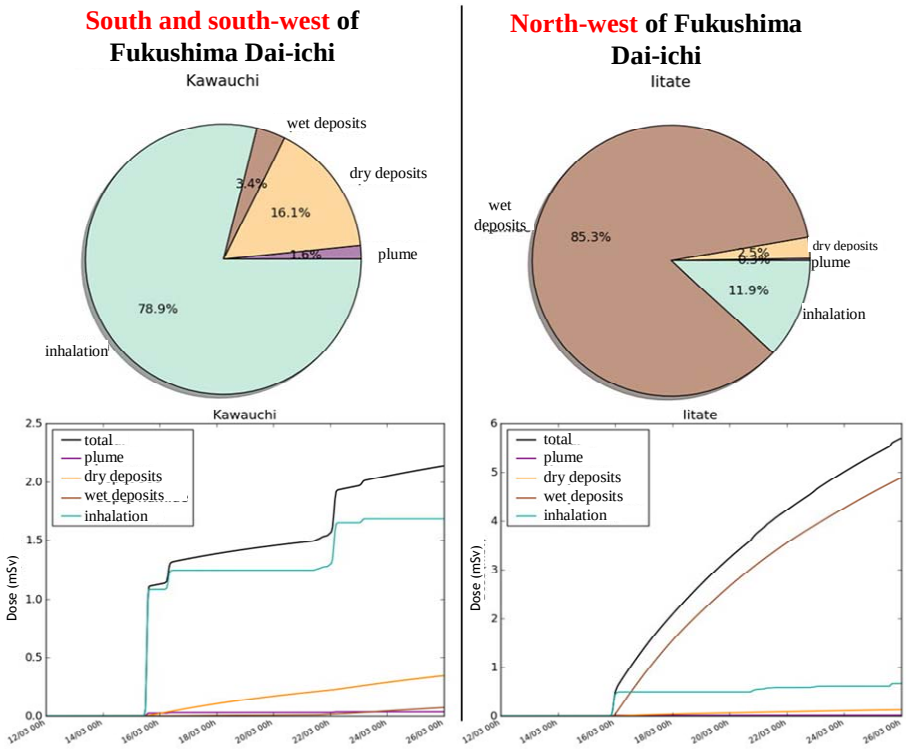


Figure 8-6 - Contribution of the exposure pathways and dose kinetics (effective dose, without protection) during the release phase (March 12-25, 2011) in two different locations (Kawauchi and Iitate, shown in Figure 8-4) within 40 km of Fukushima Dai-ichi (cumulative doses calculated using model pX).

The example of Kawauchi is representative of the exposure situation during the release phase in the areas situated to the south-west and south, and on the coast north of the damaged power plant (Minamisoma):

- the effective doses received between March 12 and 25 were due primarily (70-80%, depending on the location) to internal exposure by inhalation of radioactive substances and secondly (15-20%) to external exposure to dry deposits;
- these doses were received over brief periods (in stages), mainly around March 15-16 (except in the north, where first exposure occurred on March 12 and 13) then around March 22-23;
- after the release phase, exposure continued at a more moderate level.

The example of Iitate is characteristic of the exposure situation during the release phase in the areas situated to the north-west, heading towards the town of Fukushima:

- the effective doses received between March 12 and 25 were due primarily (about 85%) to external exposure to wet deposits and secondly (about 12%) to internal exposure by inhalation of radioactive substances;
- these doses were received gradually from March 15, 2011 onwards;
- after March 25, exposure persisted because of significant deposition.

Whereas the effective dose levels were of the same order of magnitude in the two examples mentioned (a few mSv received in 14 days), these significant differences in dose kinetics and respective contributions of the exposure pathways to the dose received are the result of differences in the intensity of rainfall at the time of the releases, which was concentrated in the north-west during the night of March 15-16, leading to high levels of radioactive deposits (see 6.2). In these areas, external exposure to radioactive deposits quickly became the main exposure pathway, and persisted well beyond the release phase.

These differences in contribution of exposure pathways and dose kinetics can be analyzed retrospectively in terms of population protection strategy:

- in areas where internal exposure by inhalation of airborne radionuclides accounted for the largest contribution, with rapid dose kinetics, emergency protective measures such as sheltering, evacuation or administration of stable iodine were most appropriate (cf. 8.3.1);
- in areas where external exposure due to radiation from radioactive deposits accounted for the largest contribution, with slower but long-lasting dose kinetics, protective measures considered in a post-accident situation were most appropriate, in particular short-term withdrawal (albeit less urgent than emergency evacuation in the event of exposure to the plume) for people living in areas with the highest levels of radioactive deposition.

8.3.3. ESTIMATE OF THE DOSES LIKELY TO HAVE BEEN RECEIVED BY THE LOCAL POPULATION FROM EXTERNAL EXPOSURE TO RADIOACTIVE DEPOSITS

On April 8, 2011, IRSN made an initial estimate of the doses likely to have been received by people living in the contaminated areas in Japan as a result of external exposure to gamma radiation emitted by radioactive deposits; it did so by interpreting aerial dose rate measurements obtained by the American DoE/NNSA and published on its website on April 7, 2011. On that date, IRSN had no measurement data concerning the isotopic composition of the radioactive deposits, and the forecasts of doses potentially received during the first year following the accident used the isotopic composition of the source term estimated by IRSN at the time (see 6.1) and the analysis of the decay profiles of the dose rate measured at various points in the areas affected. In late April 2011, MEXT published new maps showing dose rates and caesium-134 and caesium-137 deposits, as well as a map of estimated doses due to external exposure to deposits during the first year (see map in Figure 8-7). MEXT then updated this dose forecast

map periodically, following new measurement campaigns, but without any significant changes from the first map published at the end of April 2011. As expected, the highest dose levels concerned the areas that had received the largest deposits, formed between March 15 and 16, 2011 over an area covering several tens of kilometers north-west of the Fukushima Dai-ichi power plant, during heavy rainfall and snowfall at the time of the atmospheric dispersion of a release from Reactor 2.

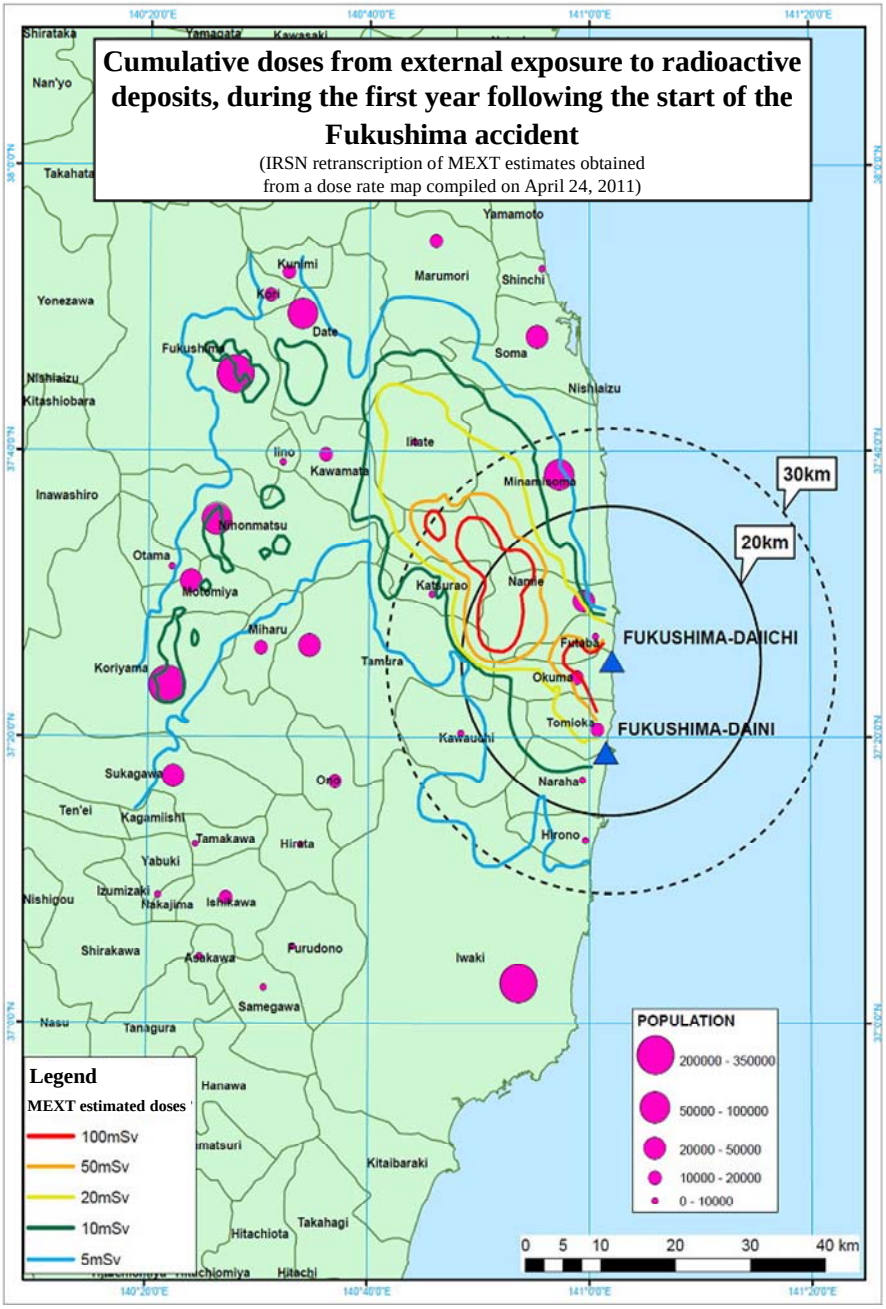


Figure 8-7 – Map of predicted cumulative doses during the first year after the accident (from March 11, 2011 to March 11, 2012), received from external exposure to radioactive deposits (based on the MEXT map compiled on April 24, 2011).

The estimate of the doses likely to have been received from external exposure to radioactive deposits over a given period (one month, three months, a year, etc. after the start of the accident) takes into account several factors:

- the rate of decrease of the ambient dose rate resulting from the radioactive deposits, which depends on the their initial isotopic composition. In its first assessment, IRSN had overestimated the barium-140/lanthanum-140 ratio in the deposits, which meant that it underestimated the dose potentially received after a year by a factor of 2.5 compared with the MEXT estimates. The latter take into account measurements of radionuclide activity in the deposits, which revealed that the deposits initially contained short-lived radionuclides (iodine-131 and tellurium-132/iodine-132) and then, once these had disappeared due to radioactive decay, mainly caesium-134 and caesium-137 (cf. Chapter 6);
- the assumptions about the time spent outdoors and about the shielding factor (SF) of buildings (dose rate lower indoors than outdoors; see 8.3.1). The values used by IRSN (12 hours a day spent outdoors and SF = 0.3) were different from those used by MEXT (8 hours a day spent outdoors and SF = 0.4), but combining these two parameters ultimately produces an equivalent result (a dose reduction by a factor of 0.65 for IRSN, and 0.6 for MEXT).

These estimates are indicative and do not consider the variability of factors taken into account, related mainly to the local heterogeneity of the radioactive deposits (presence of "hot spots"; see Chapter 6) or to people's lifestyle (time spent outdoors, shielding provided by various types of buildings, movements, etc.). For example, spending only four hours a day outdoors in the contaminated areas can reduce the dose received by about 20% (or even more, depending on the shielding effect of the buildings) compared to the value estimated by MEXT.

By comparing the dose map published by MEXT with the map of cumulative deposits of caesium-134 and caesium-137, it is possible to derive a conversion factor relating the cumulative dose from external exposure to deposits over the first year to the surface activity of caesium-134 and caesium-137: 16.6 mSv per MBq/m^2 of $^{134+137}$Cs. Moreover, using the demographic data concerning the Fukushima prefecture provided by the Statistics Bureau, Ministry of Internal Affairs and Communications, Japan (http://www.stat.go.jp/), IRSN deduced that, **outside the emergency evacuation zone 20 km around the Fukushima Dai-ichi power plant, close to 70,000 people living in areas with $^{134+137}$Cs deposition exceeding 600,000 Bq/m^2 were likely to receive a dose greater than 10 mSv in the first year due to external exposure to the deposits.** If the most contaminated areas (annual dose exceeding 20 mSv) had not been evacuated, as the Japanese authorities decided to do on April 22, 2011, this dose could even have been higher than 50 mSv for approximately 5,300 people. **Inside the 20 km exclusion zone, even higher doses, in excess of 200 mSv, could have been reached, according to the maps published by MEXT. These estimates confirm that it would have been unthinkable to allow the return of the people urgently evacuated from this zone at the time of the accident**.

As in the release phase, the dose kinetics due to radioactive deposition were not constant over time. Immediately after formation, during the night of March 15-16, 2011, the surface deposits were composed primarily of short-lived radionuclides (^{131}I, ^{132}Te/^{132}I); after a month, due to rapid decay of these radionuclides, the total activity of the residual surface deposits represented just 15% of the initial activity, and the ambient dose rate measured in the same areas over the same period had decreased accordingly (see 6.2.3.4). The maps in Figure 8-8 therefore represent the cumulative doses for the first month (from March 15 to April 15, 2011) of external exposure to the deposits, and the cumulative doses for the subsequent 12 months (from April 15, 2011 to April 15, 2012). IRSN obtained these by interpreting the iso-dose rate map for April 24, 2011, as published by MEXT, assuming an isotopic composition of the deposits, deduced from the source term estimated by IRSN. The doses were calculated for a person assumed to spend half of his time outdoors (12 hrs/day) and the other half in a building with a shielding factor of 0.3.

The estimates made show that the doses potentially received during the first month from external exposure to the deposits represent approximately one-third of the cumulative doses over the subsequent 12 months. These results confirm the importance of taking action to protect the population as promptly as possible, by removing people from the most contaminated areas because they could be exposed to significant doses in the initial months following the formation of deposits. As an illustration, the area (excluding the 20 km exclusion zone) where a dose exceeding 10 mSv could have been received between March 15 and April 15, 2011 is represented on the map in Figure 8-9, deduced from the left-hand map in Figure 8-8; in this area, the doses could have been higher than 25 mSv, without counting doses due to exposure to the radioactive plume between March 12 and 25 (cf. 8.3.2) or doses due to possible consumption of contaminated foodstuffs (cf. 8.3.4). This area includes part of the municipalities of Minamisoma (south-west), Iitate, Namie, and Katsurao (east).

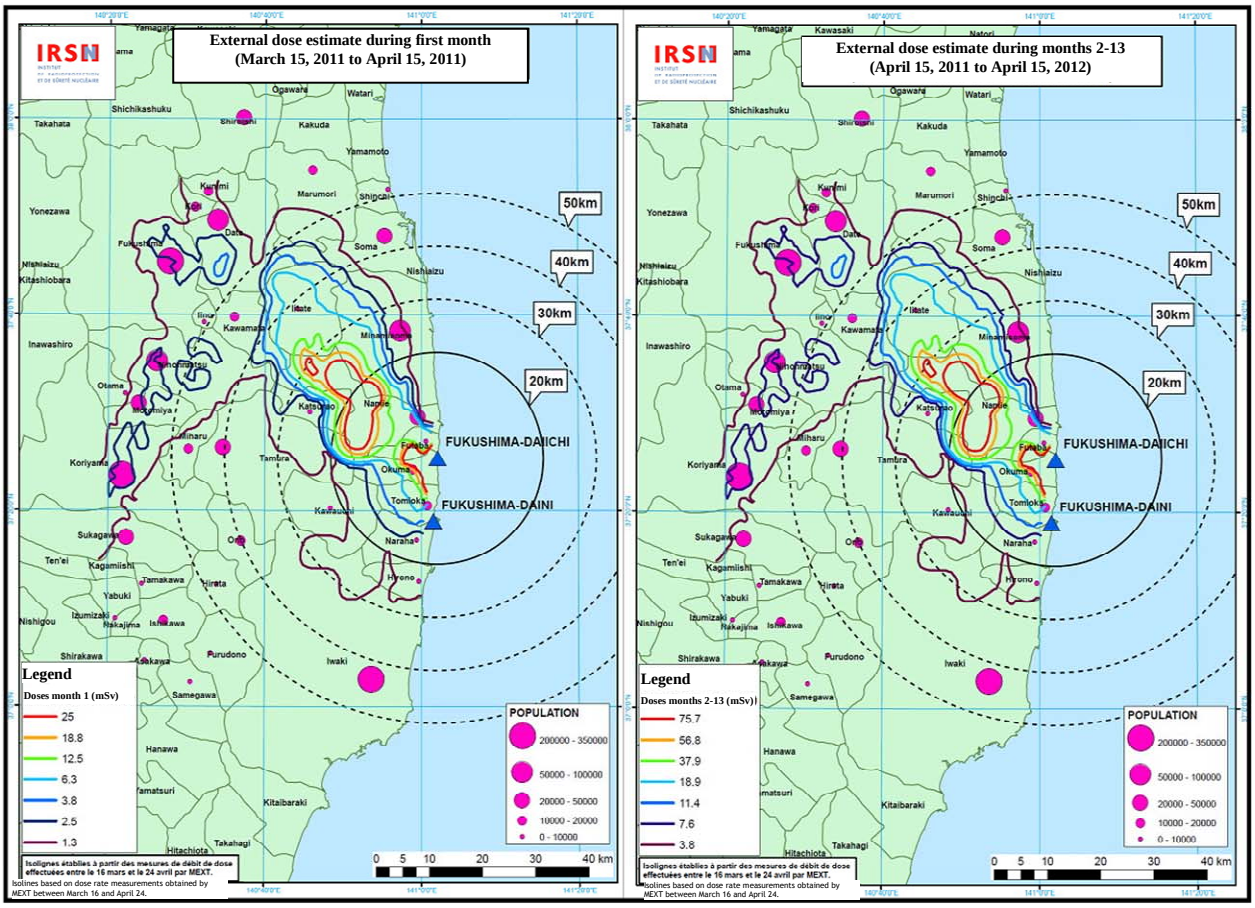


Figure 8-8 – Maps representing the doses from external exposure to radioactive deposits likely to have been received by the end of the first month (left-hand map) and during months 2-13 following the formation of the deposits in the Fukushima prefecture (IRSN estimate deduced from the MEXT iso-dose rate map for April 24, 2011).

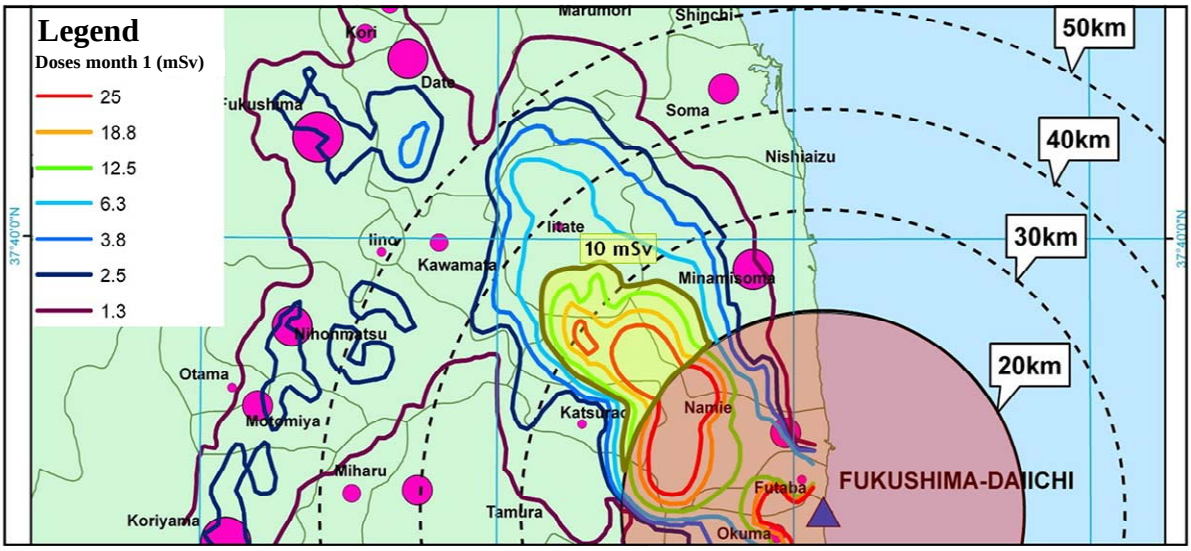


Figure 8-9 – Area (in yellow) where the doses from external exposure to radioactive deposits are likely to have been higher than 10 mSv at the end of the first month following the formation of the deposits in the Fukushima prefecture (based on the left-hand map in Figure 8-8). The circular area shaded red corresponds to the 20 km zone urgently evacuated at the time of the accident.

Likewise, the area (excluding the 20 km exclusion zone) where a dose exceeding 10 mSv could have been received between April 15, 2011 and April 15, 2012 is represented on the map in Figure 8-9, deduced from the left-hand map in Figure 8-8. This area is larger than the previous one and corresponds approximately to the planned displacement zone set up on April 22 by the Japanese authorities (except for a small sector in the municipality of Date), which includes the municipalities of Iitate, Namie, and Katsurao as a whole (in addition to the parts of the latter two municipalities that had already been urgently evacuated on March 12) as well as part of the municipalities of Minamisoma and Kawamata (district of Yamagiya). In the most contaminated parts of this zone, the doses that could have been received during this period if evacuation had not taken place are estimated at more than 75 mSv, in addition to the doses already received during the first month following the formation of deposits or via other exposure pathways (inhalation, ingestion of contaminated foodstuffs, inadvertent ingestion).

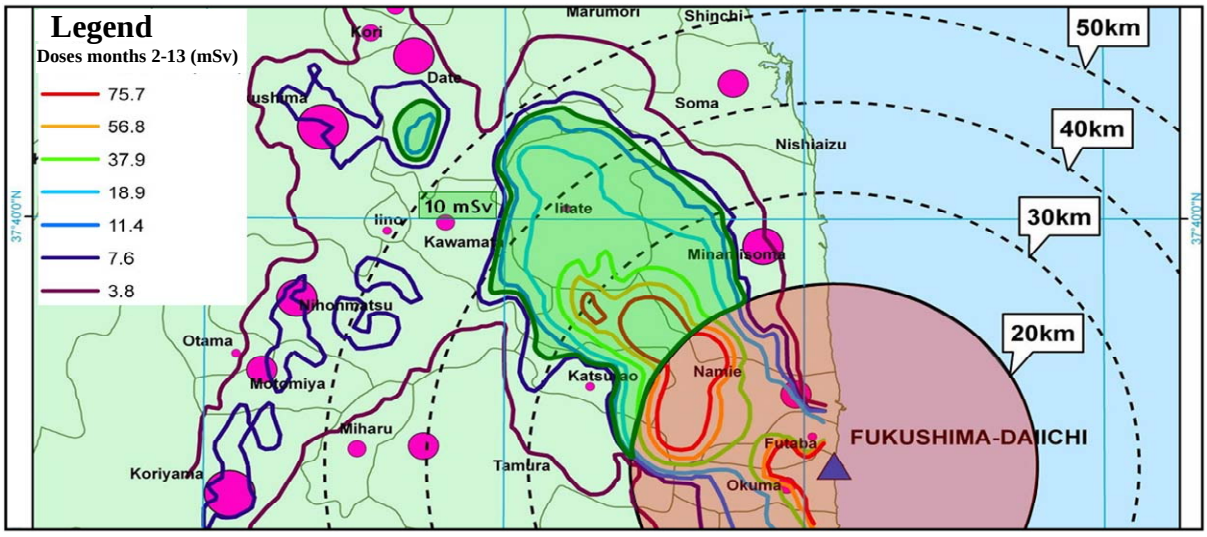


Figure 8-10 – Area (in green) where the doses from external exposure to radioactive deposits are estimated to be higher than 10 mSv between April 15, 2011 and April 15, 2012 in the Fukushima prefecture (based on the left-hand map in Figure 8-8). The circular area shaded red corresponds to the 20 km zone urgently evacuated at the time of the accident.

As before, these dose estimates are indicative and do not take into account any specific radiological characteristics that might lead, locally, to dose levels being significantly adjusted up or down.

8.3.4. RISKS ASSOCIATED WITH INTERNAL EXPOSURE FROM INGESTION OF CONTAMINATED FOODSTUFFS

IRSN does not yet have sufficient data to make a reliable estimate of the doses received in Japan from ingestion of contaminated foodstuffs, especially during the weeks following the accident, for people living in the areas that received the highest levels of deposits on the ground. Estimating these doses does in fact depend not only on the level of contamination of foodstuffs produced in these areas, which is partly known from published measurements (see 6.3), but also on having information about the food intake of the people concerned and their degree of compliance with the restrictions imposed by the Japanese authorities.

In order to determine the level of risk to which part of the Japanese population could have been exposed, without giving an opinion on the actual risk in Japan, IRSN calculated the doses received in a scenario involving ingestion of foodstuffs contaminated at levels observed in certain areas of Japan. Immediately after dispersion of the radioactive releases, two foodstuff categories were particularly sensitive to the radioactive fallout and therefore posed a significant risk to consumers in Japan:

- leafy vegetables, such as spinach, which were found to be contaminated with several tens of thousand Bq/kg of iodine-131, caesium-134 and caesium-137, a hundred kilometers from the Fukushima Dai-ichi power plant. Theoretically much higher contamination levels, over a million Bq/kg, could have been reached in the most contaminated areas outside the 20 km exclusion zone but there is no evidence of this from the measurements carried out in Japan, perhaps because the accident happened at the end of the winter, before any crops were ready for harvesting in these areas;
- cow's milk, which was found to be contaminated with several thousand Bq/l of iodine-131 and several hundred Bq/l of caesium-134 and caesium-137 for about a week, especially in Iitate and Kawamata. Theoretically much higher contamination levels, in the region of 100,000 Bq/l for each of these three radionuclides, could have been reached in the most contaminated areas of Iitate during the same period (cf. 6.3.2.2), but once again there is no evidence of this from the measurements carried out in Japan, probably because the accident happened at the end of the winter, when the livestock were being fed fodder that had been harvested the previous year and was therefore only relatively lightly contaminated (except possibly if it had been kept in the open air).

Calculations were performed based on the measurement data available for milk and some vegetables (Tables 8-II and 8-III), assuming that these had been consumed by children aged between 1 and 5. It should be noted that the bulk of the milk and vegetables for which radioactivity levels are shown in the tables below were not sold on the market.

Table 8-II – Iodine and cesium concentrations measured in milk sampled (but not sold on the market) at the end of March 2011 in the prefectures of Fukushima and Ibaraki

Prefecture	Sector	Sampling date	Measurement date	I-131 (Bq/l)	Cs-134 (Bq/l)	Cs-137 (Bq/l)
Fukushima	Kawamata-machi	03/20/11	03/20/11	5,300	9	11
Fukushima	Iitate-mura	03/19/11	03/20/11	5,200	210	210
Fukushima	Kawamata-machi	03/22/11	03/23/11	2,600	24	30
Ibaraki	Kawachi-machi	03/19/11 – 03/21/11	03/22/11	1,700	64	
Ibaraki	Mito-shi	03/19/11 – 03/21/11	03/22/11	1,700	15	
Fukushima	Kawamata-machi	03/17/11	03/19/11	1,510	ND	ND
Fukushima	Kunimi-machi	03/19/11	03/19/11	1,400	13	23
Ibaraki	Kawachi-machi	03/19/11 – 03/21/11	03/22/11	1,300	54	
Fukushima	Kawamata-machi	03/20/11	03/20/11	1,200	9.5	8.7
Fukushima	Kawamata-machi	03/16/11	03/18/11	1,190	ND	18.4
Fukushima	Iitate-mura	03/22/11	03/23/11	1,000	25	28
Ibaraki	Kawachi-machi	03/19/11 – 03/21/11	03/22/11	1,000	38	
Fukushima	Iwaki-shi	03/19/11	03/19/11	980	ND	6.6
Fukushima	Kawamata-machi	03/18/11	03/19/11	932	ND	ND
Ibaraki	Kawachi-machi	03/19/11 – 03/21/11	03/22/11	900	68	

ND: not determined

Table 8-III – Iodine and cesium concentrations measured in vegetables sampled (but not sold on the market) at the end of March 2011 in the prefectures of Fukushima and Ibaraki

Prefecture	Sector	Vegetable	Sampling date	Measurement date	I-131 (Bq/kg)	Cs-134 (Bq/kg)	Cs-137 (Bq/kg)
Ibaraki	Hitachi-shi	Spinach	03/18/11	03/20/11	54,100	1,931	
Ibaraki	Hitachi-shi	Spinach	03/18/11	03/20/11	25,200	1,105	
Ibaraki	Kitaibaraki-shi	Spinach	03/18/11	03/20/11	24,000	690	
Fukushima	Kawamata-machi	Shinobuhuyuna	03/21/11	03/22/11	22,000	14,000	14,000
Ibaraki	Hitachioomiya-shi	Spinach	03/18/11	03/20/11	19,200	1,040	
Fukushima	Tamura-shi	Spinach	03/21/11	03/22/11	19,000	20,000	20,000
Ibaraki	Hitachioomiya-shi	Spinach	03/18/11	03/20/11	17,800	908	
Fukushima	Iitate-mura	Broccoli	03/21/11	03/22/11	17,000	7,000	6,900
Ibaraki	Naka-shi	Spinach	03/18/11	03/20/11	16,100	911	
Fukushima	Hirata-mura	Spinach	03/21/11	03/22/11	16,000	1,000	1,100
Ibaraki	Takahagi-shi	Spinach	03/18/11	03/19/11	15,020	524	
Fukushima	Motomiya-shi	Kukitachina	03/21/11	03/22/11	15,000	41,000	41,000

In the absence of any sufficiently detailed information about these children's diets, it was assumed that their consumption of milk and vegetables was similar to that of young children in France, on average. The calculations then show that, for a given level of contamination of these foodstuffs, a 1-year-old child receives the highest doses.

The average effective dose calculated for a 1-year-old child who has consumed the contaminated milk shown in Table 8-II is 0.07 mSv, mainly due to iodine-131. The maximum value obtained for the most contaminated milk is 0.22 mSv/day. The average effective dose for the vegetables is 0.14 mSv, with a maximum of 0.35 mSv. Using the same assumptions, the equivalent doses to the thyroid would be 1.5 and 4.5 mSv/d respectively for milk, and 2.6 and 6.9 mSv/d for the leafy vegetables in Table 8-III. However, it cannot be ruled out that concentrations 10 to 100 times higher than the average values were reached in the most contaminated areas. The associated doses would then have to be multiplied accordingly, i.e. committed effective doses possibly exceeding about 10 mSv per day.

It should be noted that these dose estimates do not take account of the other radionuclides likely to be present. The simulation shows that the estimated doses might be increased by about 10-30% if all the radionuclides present in the releases were to be taken into consideration.

The following comments can be made concerning these estimates: the calculations were carried out for daily food consumption at the end of March, i.e. when food contamination was highest. They cannot be extrapolated beyond this period. In fact, given the rapid decrease in the concentrations found in these foodstuffs between March 20 and April 20 (by a factor of 100 to 1,000) due to the combined effect of radioactive decay (for iodine) and dilution of the initial level of leaf deposition as a result of biomass growth (for both iodine and cesium), the daily committed doses from the end of March onwards would have been much lower. Furthermore, the calculations do not take into account any loss of activity between sampling and consumption of the foodstuff, particularly because of the way in which it was prepared. Lastly, the food contamination checks and consumption bans implemented by the Japanese authorities most likely contributed to reducing the doses actually received.

Ingestion of soil

The dose due to inadvertent ingestion of contaminated soil can be estimated from the specific activity data given in Table 6-III. Assuming that a 1-year-old child ingested 0.1 g[48] of soil on March 31, 2011, the effective dose received is 0.002 mSv. Assuming the date of ingestion was March 15, when deposition was thought to be at its highest level, gives a dose of 0.007 mSv. The equivalent dose to the thyroid is 0.03 mSv and 0.13 mSv respectively for ingestion on March 31 and March 15, 2011.

8.4. RESULTS OF CHECKS CARRIED OUT BY IRSN ON FRENCH NATIONALS

Within 48 hours of the accident, IRSN began receiving enquiries from occupational health physicians responsible for monitoring French employees returning from Japan, aircrew members, and journalists who went to Japan to cover the events, and also from French expatriates in Japan planning to return to France either temporarily or permanently. All of these people contacted IRSN to find out whether or not they had been contaminated by radioactive elements during their stay in Japan.

In response to the concerns of these French nationals, IRSN offered to perform whole-body countings at its Le Vésinet site near Paris to detect the presence of any radioelements that might have been incorporated and to quantify their activity. The data obtained could then be used to calculate the internal dose received by the individual concerned. Each person underwent an in vivo γ-ray spectrometry including 2 measurements: a whole-body counting (duration: 20 minutes) and a thyroid counting (duration: 15 minutes).

By the end of 2011, IRSN had carried out 280 in vivo γ-ray spectrometries on 268 people: 95 journalists, 62 company employees working in Japan, 36 aircrew members and 75 private individuals (Figure 8-11). The number of in vivo γ-ray spectrometries is higher than the number of people measured, as some were measured several times, either because they went to Japan a few times or because they were employees who were checked before their departure and upon their return.

[48] This quantity of soil is regarded as a guideline for dose assessment. For information, it is the value recommended in the *Guide méthodologique – Gestion des sites potentiellement pollués par des substances radioactive* (Methodological guide for management of industrial sites potentially contaminated by radioactive substances), French Ministry of Ecology, Sustainable Development, Transport and Housing – IRSN – ASN, December 2011.

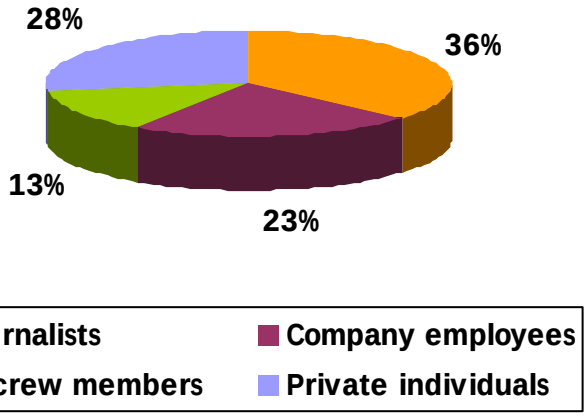


Figure 8-11 – Breakdown of people undergoing in vivo γ-ray spectrometries between March 14, 2011 and December 19, 2011

Table 8-IV shows that of the 84 in vivo γ-ray spectrometries revealing the presence of radioactivity in the person measured (i.e. 30% positive results), none concerns Air France aircrew members. The airline actually very quickly decided to ground its aircraft and personnel in Seoul, with Tokyo's Narita Airport temporarily serving as a stopover to disembark and embark passengers. Following this decision by Air France, the physician responsible for monitoring aircrew limited his requests for in vivo γ-ray spectrometries to those employees who were in a particularly heightened state of anxiety.

Figure 8-IV – Breakdown of in vivo γ-ray spectrometries performed and positive in vivo γ-ray spectrometries obtained between March 14, 2011 and December 19, 2011, by category of people measured

	No. of people measured	No. of in vivo γ-ray spectrometries performed	No. of positive in vivo γ-ray spectrometries
Journalists	95	99	62 (62.6%)
Company employees	62	70	4 (5.7%)
Flight personnel	36	36	0 (0%)
Private individuals	75	75	18 (24%)
Total	268	280	84 (30%)

Figure 8-12 indicates that 77% of the in vivo γ-ray spectrometries on journalists were performed during the first three weeks following the accident. As regards private individuals (expatriates and students), the measurements were essentially concentrated in two waves, with one-third carried out during the first two weeks and two-thirds during the July-September 2011 vacation period. As for company employees, the timing of the measurements corresponded with their business trips to Japan.

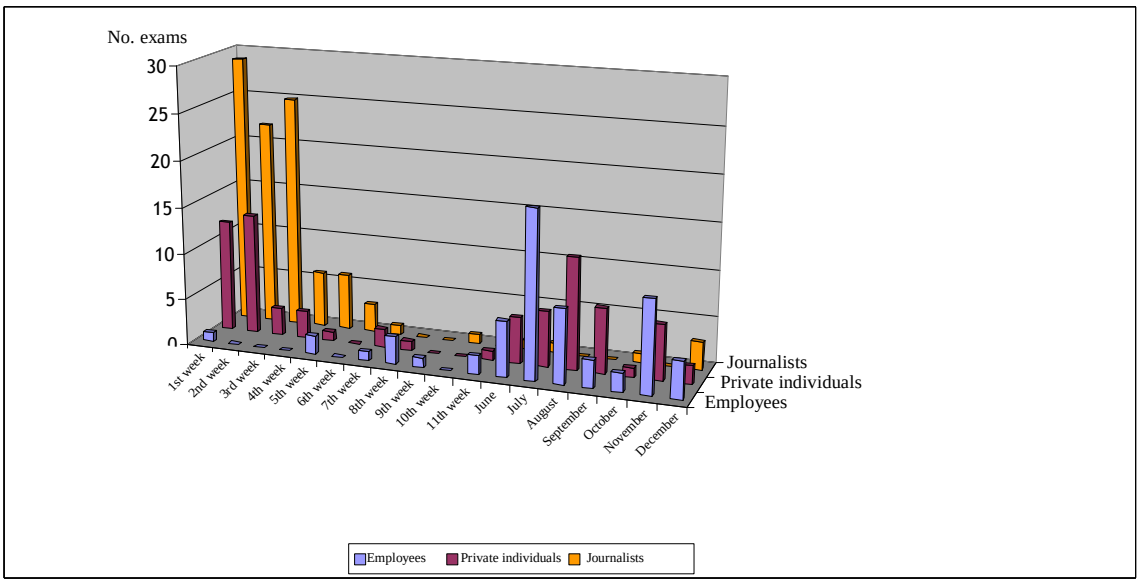


Figure 8-12 – Trends in the number of in vivo γ-ray spectrometries performed on journalists, private individuals and company employees between March 11, 2011 and December 19, 2011

The effective dose and the equivalent dose to the thyroid were calculated for each person who tested positive for the presence of radioactive elements. Iodine-131 was the isotope most frequently detected, though iodine-132 and tellurium-132, and much more rarely caesium-137, were detected in a few people.

Figure 8-13 and Figure 8-14 respectively show the distribution of effective doses and equivalent doses to the thyroid calculated for people who tested positive in their in vivo γ-ray spectrometry.

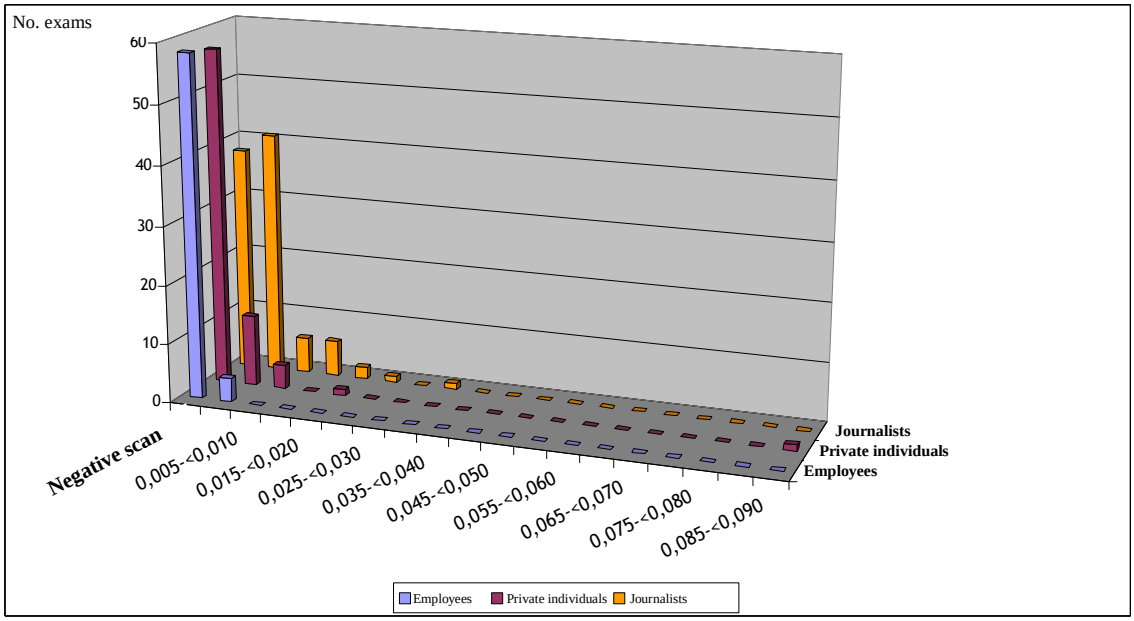


Figure 8-13 – Distribution of the effective doses received by the different categories of people measured (in mSv)

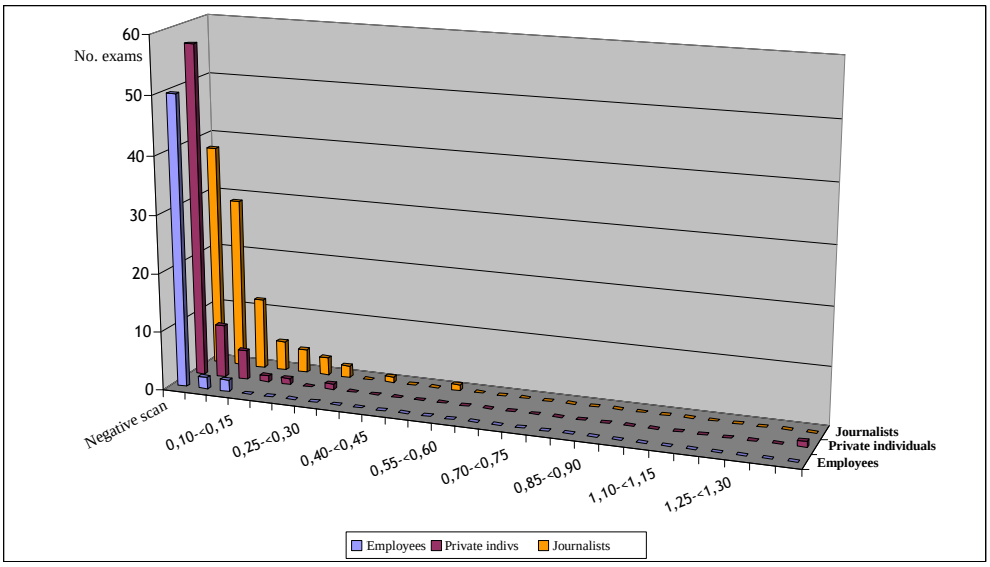


Figure 8-14 – Distribution of the equivalent doses to the thyroid received by the different categories of people measured (in mSv)

For the most exposed person, the effective dose is less than 0.1 mSv, and the equivalent dose to the thyroid less than 1.4 mSv. For the purposes of comparison, the regulatory dose limit for the public is an effective dose of 1 mSv/year (compared with the calculated maximum dose of 0.1 mSv for the French nationals measured) and the equivalent dose to the thyroid that triggers the process of administering stable iodine is 50 mSv (compared with the calculated maximum dose of 1.4 mSv for the French nationals measured). At these levels of exposure, the French nationals measured have no cause for concern in terms of health effects.

Figure 8-15 shows the geographical distribution of private individuals staying in Japan, in the cities of Sendai, Iwaki, Koriyama, or Fukushima, during the most significant release events, i.e. between March 15 and 16, or in Tokyo (March 15 and 16 and between the afternoon of March 20 and March 23), who had a positive result in the in vivo γ-ray spectrometry performed upon their return to France.

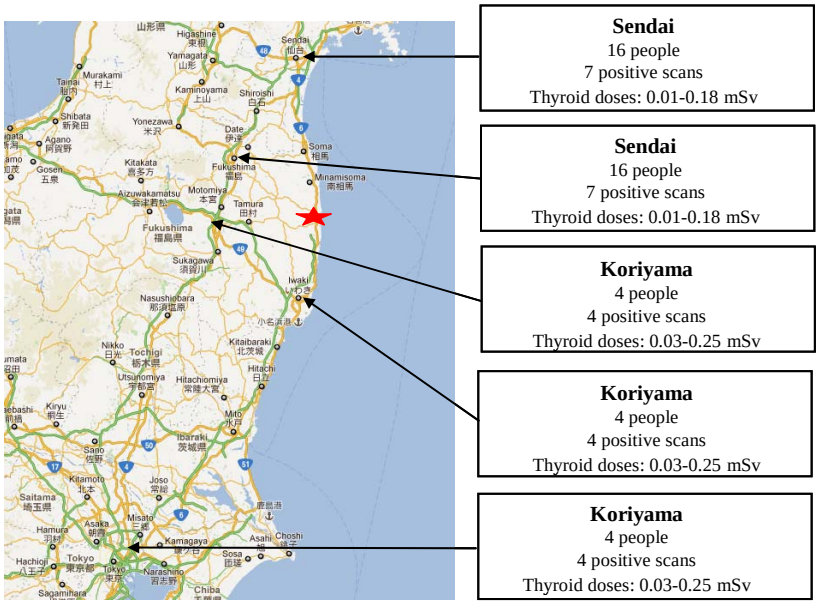


Figure 8-15 – Geographical distribution of private individuals staying in Sendai, Fukushima, Koriyama, or Iwaki during the releases on March 15-16 or in Tokyo (releases on March 15-16 and March 20-23, 2011), whose in vivo γ-ray spectrometry produced a positive result

Figure 8-16 shows the geographical distribution of journalists present in Tokyo, Soma, or Sendai during the most significant release event, i.e. between March 15 and 16, who had a positive result in the in vivo γ-ray spectrometry performed a few days later upon their return to France.

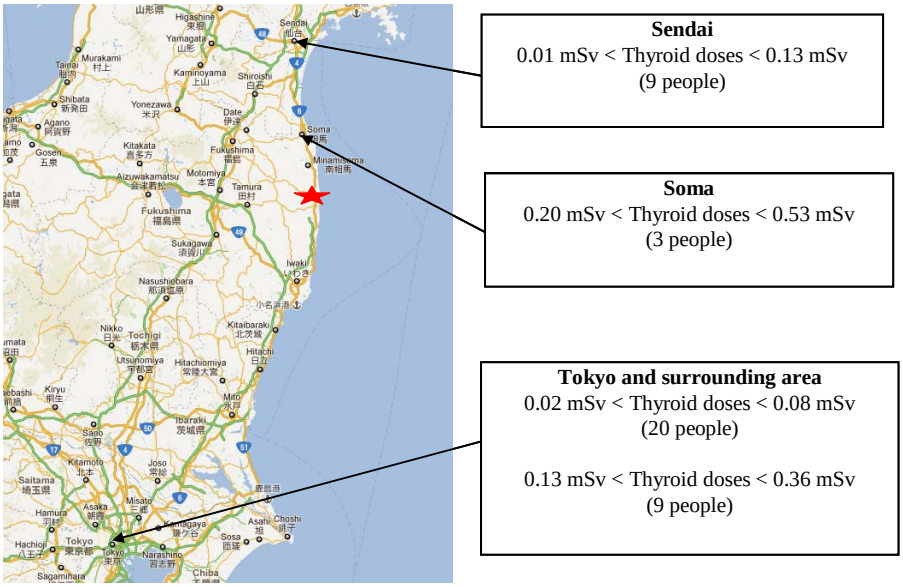


Figure 8-16 – Geographical distribution of journalists present in Sendai, Soma, or Tokyo during the releases on March 15-16, whose in vivo γ-ray spectrometry produced a positive result

These results show that the contamination of people at the time of the releases and in the days that followed essentially depended on their behavior (especially the time they spent outdoors) and their precise location while they were in the contaminated areas, the influence of local weather conditions being the dominant factor. These results cannot be generalized to everyone staying in a given city, but do give an indication of the possible dose range to which people may have been exposed on those dates and in those locations.

8.5. HEALTH EFFECTS AND MEDICAL MONITORING OF EXPOSED WORKERS

8.5.1. HEALTH EFFECTS

According to the information provided by the Japanese authorities, no health effect attributable to exposure to ionizing radiation has been observed to date in the workers involved in operations conducted at the Fukushima nuclear power plant. However, according to statements made by physicians at the National Institute of Radiological Sciences (NIRS), in view of the nature of the operations remaining to be carried out, the appearance in the coming months of effects on workers' health directly related to radiation exposure cannot be ruled out.

To date, the deaths of six workers have been recorded. Apparently, none of these deaths could be attributed to exposure to ionizing radiation. According to the Japanese authorities:

- two workers died on March 11, 2011 as a direct result of the tsunami and the earthquake,
- two workers died of heart failure, one on May 14, 2011 and the other on January 9, 2012,
- one worker died of acute leukaemia in August 2011,
- one worker died of septic shock on October 6, 2011.

Moreover, hyperthermia (increased body temperature) has been observed in 43 workers, probably due to insufficient cooling of their work clothing.

8.5.2. MEDICAL MONITORING

A database to contain all the information concerning the monitoring of workers' health is currently being set up. Every worker, including those no longer involved in the operations underway at Fukushima Dai-ichi, will receive a basic medical check-up including tests of their eyesight, hearing, lungs, cardiovascular system, and digestive system, as well as biological tests and an evaluation of the person's psychological and psychiatric condition.

In addition, workers who have received a dose exceeding 50 mSv will receive special monitoring aimed at detecting the formation of cataracts, and those whose dose exceeds 100 mSv will undergo additional tests to monitor the onset of thyroid disorders and certain types of cancer (lung, stomach, and colon).

Based on the observations recorded, the medical monitoring could be reviewed in three years' time.

8.6. EPIDEMIOLOGICAL MONITORING OF EXPOSED POPULATIONS IN JAPAN

8.6.1. PRINCIPLE OF THE STUDIES CONDUCTED

In late June 2011, the Japanese health authorities devised and set up epidemiological studies to evaluate the health of individuals exposed to the radioactive releases and to monitor changes in their state of health over time. Depending on the group concerned, these studies are based on a questionnaire, to be supplemented in certain cases by medical examinations. The results of these epidemiological studies will provide information concerning the base rate of occurrence of certain pathologies in the Japanese population (cancer, leukaemia, psychological disorders, thyroid problems, liver or kidney disease, diabetes, etc.) and allow an evaluation of any health effects on the population due to exposure to radioactive fallout. The planned duration of these studies is 30 years, and they are conducted under the leadership of Fukushima Medical University in collaboration with other Japanese medical centers.

These studies consist of the following tasks:

- Conducting a basic survey of all persons present in the Fukushima prefecture during the release phase. The aims of this survey are to estimate the external dose received by the individuals exposed, to gather information concerning the administration of stable iodine tablets and the consumption of food products and drinking water, and to identify those people for whom long-term medical monitoring might be necessary. This survey is to be carried out on 2,057,053 people.
- Thyroid screening of all children under the age of 18 who were present in the Fukushima prefecture during the release phase. The main aim of this study is to reveal any increase in the occurrence of thyroid cancer,

as observed in children exposed to radioactive fallout from the Chernobyl accident. This study will concern approximately 360,000 children born before March 1, 2012.

- Monitoring any genetic or congenital abnormalities that might appear in children born of women who declared their pregnancy between August 1, 2010 and July 31, 2011. This study will include approximately 20,000 women and will supplement an earlier study launched in 2010 in a dozen regions of Japan by the Japanese Ministry of the Environment, concerning approximately 100,000 pregnant women. The aim of the latter study (JECS: Japan Environment and Children's Study) is to evaluate the consequences of exposure to chemical and physical environmental toxins in children born of those mothers. From the time it was implemented, the JECS study included places near the Fukushima Dai-ichi nuclear power plant (Fukushima, Minami Souma, Namie). In August 2011, the Japanese authorities decided to include in this study a group of 6,900 women from some of the towns and cities most exposed to radioactive fallout (Kawamata, Koori, Date, Kunimi). All the children born of mothers recruited into the JECS study will be monitored until the age of 12.
- Special medical check-ups for people who were evacuated from the areas most exposed to radioactive fallout. This study will concern approximately 210,000 people and will provide information concerning lifestyle (smoking, alcohol consumption), psychological condition based on a questionnaire, the basic rate of occurrence of pathologies such as cancer, leukaemia, diabetes, or liver and kidney disorders, and any radiological examinations carried out that could affect the external dose received (particularly CT scans). Moreover, special additional monitoring over a ten-year period of psychological disorders in approximately 30,000 people from the prefectures of Fukushima, Iwate, and Miyagi will be implemented by the Japanese Ministry of Health.

8.6.2. PROGRESS AND INITIAL RESULTS

Dosimetric questionnaire

Since late June 2011, 29,097 questionnaires have been sent to people who were in the towns of Namie, Iitate, and Kawamata at the time of the radioactive releases. As at January 20, 2012, the response rate was 50.2%. The lowest response rate concerned people aged between 21 and 30 (36.5% of questionnaires filled in), and the highest was from people in the 61-70 age group (63.1% of questionnaires filled in).

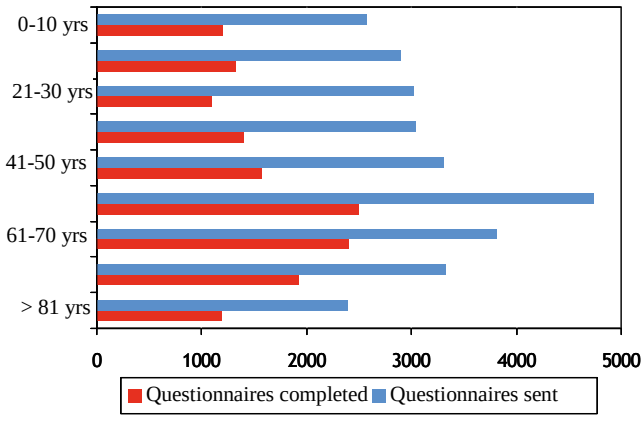


Figure 8-17 – Summary (as at January 20, 2012) of responses to questionnaires sent to people who were in Namie, Iitate, or Kawamata at the time of the releases

Based on the completed questionnaires, the external doses received were calculated, using special software developed by the NIRS, for 1,589 people from Namie, Iitate, or Kawamata: for 62.1% of them, the external dose calculated was below 1 mSv, and the maximum dose calculated was 14.5 mSv for one person.

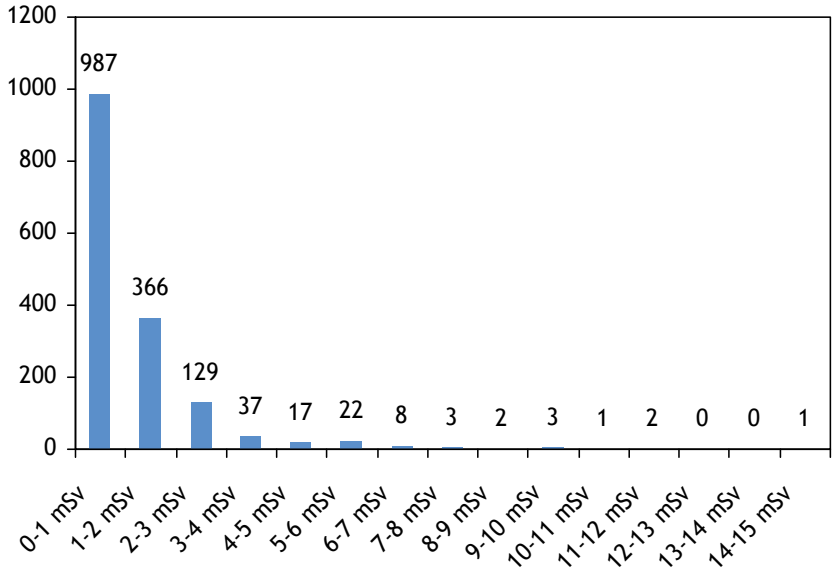


Figure 8-18 – Initial results of the calculations of external doses received by people who were in the Fukushima prefecture at the time of the releases

From the end of August 2011, questionnaires were sent out more widely, to all 2,057,053 people who were in the Fukushima prefecture at the time of the radioactive releases. As at January 20, 2012, the overall response rate was 20.8%.

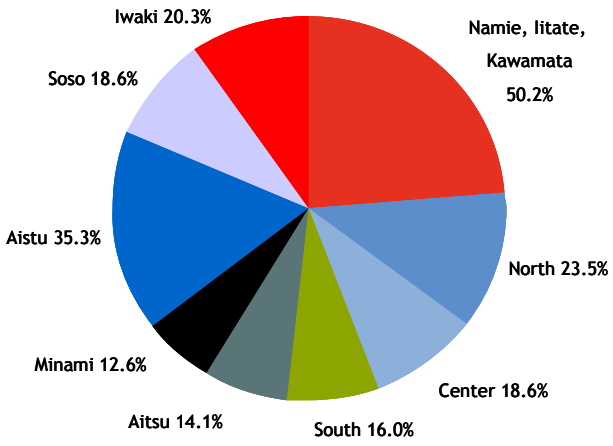


Figure 8-19 – Summary (as at January 20, 2012) of responses to questionnaires sent to people who were in the Fukushima prefecture at the time of the releases

Evaluation of thyroid disorders in children exposed to the radioactive releases

Between October and December 2011, 19,715 children who were in Namie, Iitate, or Kawamata at the time of the radioactive releases were invited for thyroid screening: 4,908 children were tested at Fukushima Medical University, and 14,807 at other medical centers in the Fukushima prefecture.

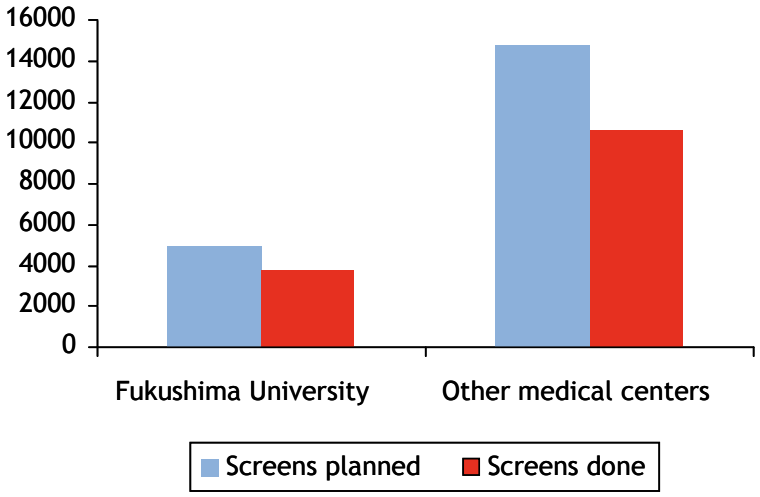


Figure 8-20 – Progress of thyroid screening of children at all of the medical centers involved

As at December 31, 2011, 14,442 children had undergone initial thyroid screening, consisting essentially of an ultrasound examination of the thyroid, possibly supplemented by biological and histological tests if any pathological abnormality was detected. Of the children screened, 23.7% were aged from 0 to 5 years, 27.3% from 6 to 10 years, 29.6% from 11 to 15 years, and 19.4% were older than 16.

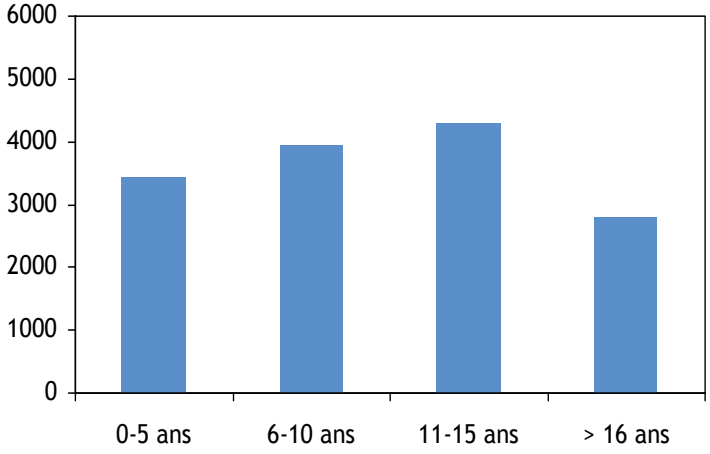


Figure 8-21 – Breakdown by age group of children who had undergone thyroid screening at Fukushima Medical University as at December 31, 2011

Of the 3,765 children screened by Fukushima Medical University, the thyroid ultrasound produced normal results for 69.6%. At least one fluid-filled cyst considered as subnormal (diameter less than 20 mm) was detected in 28.8% of the children, while 1.5% had at least one nodule, again considered as subnormal (diameter less than 5 mm). At least one nodule with a diameter greater than 5 mm was found in 0.7% of the children screened, but without any additional tests being necessary in the opinion of the physicians. Finally, no fluid-filled cyst larger than 20 mm in diameter was found.

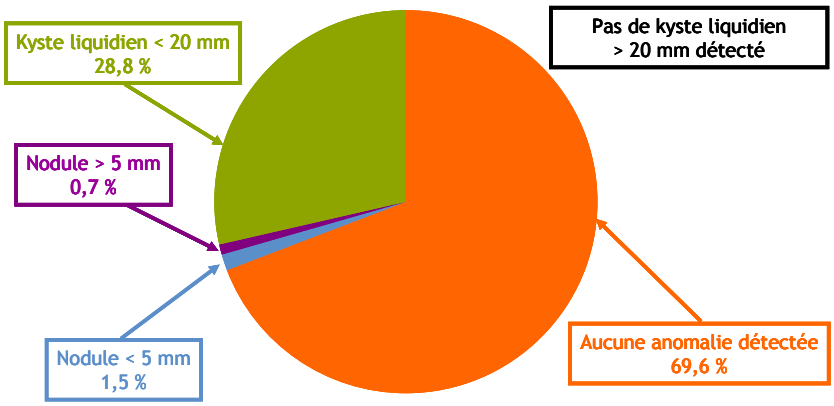


Figure 8-22 – Observations made on 3,765 children who have had a thyroid ultrasound

Between January and March 2012, 27,467 children who were in Date, Tamura, Hirono, Naraha, Tomioka, Kawauchi, Okuma, Futaba, or Katsurao at the time of the radioactive releases were invited for thyroid screening. The remainder of the children involved in the study will receive invitations sequentially between April 2012 and March 2014.

Starting in April 2014, follow-up thyroid screening will be performed on the 360,000 children concerned at a rate of once every two years until age 20, and then every five years above the age of 20.

No information is currently available concerning the progress of the studies planned for pregnant women and evacuees.

9. VERY LONG-RANGE IMPACT

Although located a long way from the site of the accident, France and its overseas departments, regions and collectivities in the northern hemisphere were nonetheless affected by masses of slightly contaminated air. Very long-range calculations were used to predict the arrival dates of these contaminated air masses and the expected levels of activity. IRSN implemented an enhanced radioactivity monitoring plan in March 2011 covering the whole of France and its overseas territories. This involved stepping up vigilance with IRSN's traditional monitoring equipment, combined with deployment of additional resources to monitor ambient radioactivity and undertake environmental sampling.

9.1. IMPACT IN FRANCE AND IN FRENCH OVERSEAS DEPARTMENTS, REGIONS AND COLLECTIVITIES

The Institute has published a report[49], which is available on its website, providing a scientific analysis of the results of these enhanced monitoring efforts. The report collates and interprets more than 5,700 measurement results obtained by IRSN on some 1,400 samples and approximately 3,000 results submitted by nuclear operators.

The key points to note are as follows:

- in France, the various measurement results relating to air, rainwater and land-based products revealed that no traces of radionuclides attributable to the Fukushima accident were detected prior to March 24, 2011. Monitoring detected trace levels of the main radionuclides released into the atmosphere during the accident (iodine-131, cesium-134 and cesium-137, and smaller quantities of tellurium-132) and enabled changes to be tracked until May 2011. For example, the maximum iodine-131 levels detected were of the order of a few millibecquerels per cubic meter of air, approximately 10 becquerels per kilogram of plant matter, and a few becquerels per liter in rainwater or milk. At no time did these concentrations pose any environmental or health risk;
- the various observations revealed that all French regions were affected to the same extent, albeit with some geographic and chronological fluctuations due to the movements of the air masses. These levels are consistent with the forecasts based on modeling by IRSN in association with the French meteorological institute, Météo-France. These concentrations were between 500 and more than 1,000 times lower than those measured in France in early May 1986, following the Chernobyl accident.
- the maximum exposures by inhalation and by ingestion of iodine-131 were calculated, based on significant iodine measurements obtained over the period. The maximum dose by inhalation was 2 microsieverts (µSv) for 1-year-old infants, and 0.03 µSv for adults. The doses by ingestion were 43 µSv and 0.17 µSv respectively. These estimated doses are very low and confirm that at no time did the concentrations of radionuclides of artificial origin (iodine-131, cesium-134, and cesium-137) measured in the various compartments of the environment in France and its overseas departments, regions and collectivities pose an environmental or health risk.

[49] Report: *Analyse de l'impact de l'accident de Fukushima en France (métropole et DROM-COM) à partir des résultats de la surveillance renforcée de la radioactivité dans l'environnement* (Analysis of the impact of the Fukushima accident in France and in French overseas departments, regions and collectivities, based on the results of enhanced environmental radioactivity monitoring) http://www.irsn.fr/FR/expertise/rapports_expertise/Documents/environnement/IRSN_Analyse-impact-Fukushima-France_012012.PDF (in French with an English abstract)

It should be noted that six months after the accident, the ambient level of cesium-137 (less than 0.4 µBq/m^3), the only artificial radionuclide still measurable, was only double the pre-accident background level.

9.2. ATMOSPHERIC CONTAMINATION IN EUROPE

Simulations were carried out on a global scale (Figure 9-1) using Météo France data and show that the plume began passing over the North American continent on March 16. French overseas territories (St Pierre and Miquelon) and northern Scandinavia were affected from March 19 onwards, the West Indies from March 22, and other European countries from March 23.

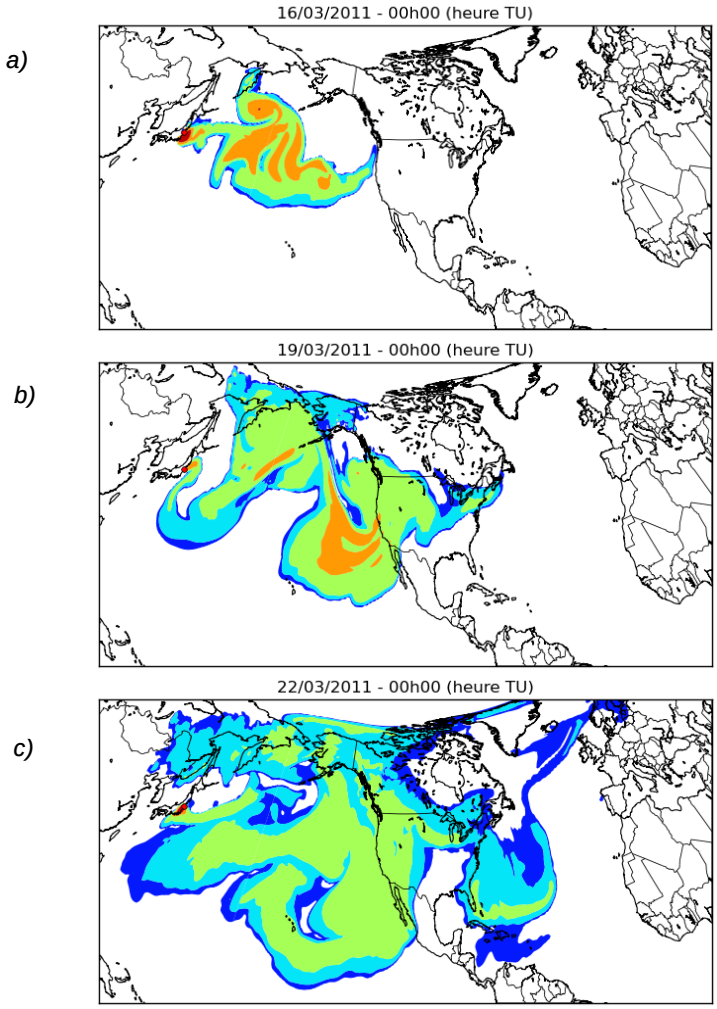


Figure 9-1 - Dispersion of the plume on a global scale on three separate dates: 03/16 (a), 03/19 (b), and 03/22 (c)

In Europe, the measurements obtained by the national airborne radionuclide monitoring networks were analyzed[50] and compared with the predictions made by IRSN's calculation code LdX.

[50] O. Masson et al. (2011) *Environ. Sci. Technol.*, **45**, pp. 7670-7677

9.2.1. SCOPE OF THE ANALYSIS

As indicated in Chapter 6, radioactive emissions into the atmosphere began on March 12. Isotopes of xenon, chiefly Xe-133 (^{133}Xe; $T_{1/2}$ = 5.2 days), were the main contributors to the source term (approximately 6.10^{18} becquerels). Only five sampling stations in Europe had the capability of quantifying airborne levels of ^{133}Xe. Most of these are operated under the auspices of the comprehensive nuclear-test ban treaty organization (CTBTO) and the results were not available outside this organization. Of the various radionuclides released in large quantities and of major importance for assessing the long-range health impact, iodine-131 (^{131}I; $T_{1/2}$ = 8.0 days), cesium-134 (^{134}Cs; $T_{1/2}$ = 2.1 years), and cesium-137 (^{137}Cs; $T_{1/2}$ = 30.1 years) were easily detected. Other short-lived radionuclides, such as tellurium-132 (^{132}Te; $T_{1/2}$ = 3.2 days) and iodine-132 (^{132}I; $T_{1/2}$ = 2.3 hours), were also measured in trace amounts. All were carried across the Pacific towards the North American continent and reached Europe, despite dispersion and deposition occurring along the route of the contaminated air masses.

Most European countries have developed airborne radionuclide monitoring programs since the 1950s. More than 150 sampling points are distributed throughout Europe and operate continuously as part of the networks set up to detect trace levels of airborne radionuclides. These stations are equipped with high-volume air samplers for specific radionuclides and some also have adsorbers for collecting gaseous iodine. The sampling periods were reduced to provide an overview of the daily variations in ^{131}I, particularly in its particulate form and – to a lesser extent – in its gaseous form. Most of the data was passed on by the participating laboratories to the "Ring of Five (Ro5)" network, which is an informal group set up in 1983 with the aim of ensuring rapid data exchange in the event of any increase in the concentration of artificial radionuclides likely to be found in trace amounts in the atmosphere (typically between 1 and 10 micro-becquerels per cubic meter of air). In addition to "measurement laboratories", other partners were involved, including national meteorological services, university staff and International Atomic Energy Agency (IAEA) personnel.

9.2.2. AIR MONITORING STATIONS

The sampling stations located in Europe are equipped with various types of aerosol collectors that operate at different flow rates. In every case, the particulate fraction is collected on filters, made from fiber glass or polypropylene fiber. Traps, usually filled with activated carbon, were also used to sample gaseous radioiodine. After sampling, the activity levels were measured by gamma spectrometry (usually on high-purity germanium detectors). During the period studied (from March 20 to April 13), isotopes of cesium and iodine were detected above their detection thresholds. A correction for summation effects was made to the determination of ^{134}Cs in order to obtain the true ^{134}Cs/^{137}Cs ratio. In the aftermath of the Chernobyl disaster, it was found that there was considerable variation in this ratio, probably because this correction had not commonly been made. The midpoint of the sampling period was chosen as the reference time for all the stations. For short-lived ^{131}I, a correction for decay was made in accordance with this reference. For the purposes of quality control, the level of ^{7}Be of natural origin was used as internal standard. The range in natural variation of the specific activity of ^{7}Be is well known for each station, making it possible to validate the sampling and measurement procedures.

9.2.3. RESULTS AND DISCUSSION

After the initial releases on March 12, contaminated air masses arrived on the North American continent on March 17[51]. As regards Europe, ^{131}I was first detected between March 19 and 20 in Iceland, between March 19 and 21 in northern Scandinavia, and between March 23 and 24 for most other European countries. Rising levels were generally recorded over the next 10 to 12 days, up to March 28 or 30, for western and central Europe, and up to April 3 for Belarus (Figure 9-2). A second peak of a similar amplitude was also observed between April 3 and 5. The falling values in between these peaks coincided with the occurrence of an event marked by precipitation over most of Europe and may also be explained by the air masses being scavenged in transit, dry deposition, the decrease in the atmospheric source term, and the half-life of ^{131}I. Throughout the measurement period, the peak values ranged from less than 1 mBq/m^3 up to 6 mBq/m^3 for the particulate fraction of ^{131}I, and up to 11 mBq/m^3 for the gaseous fraction. These values are three to four orders of magnitude lower than the activity levels recorded in western Europe after the Chernobyl accident, in April 1986. On a European scale, the average values for ^{132}Te and ^{132}I were 0.032 and 0.043 mBq/m^3 respectively, with a maximum of 0.12 mBq/m^3. For a given location, the ^{132}Te and ^{132}I levels were approximately in equilibrium. After the second week in April, they were no longer quantifiable above detection thresholds.

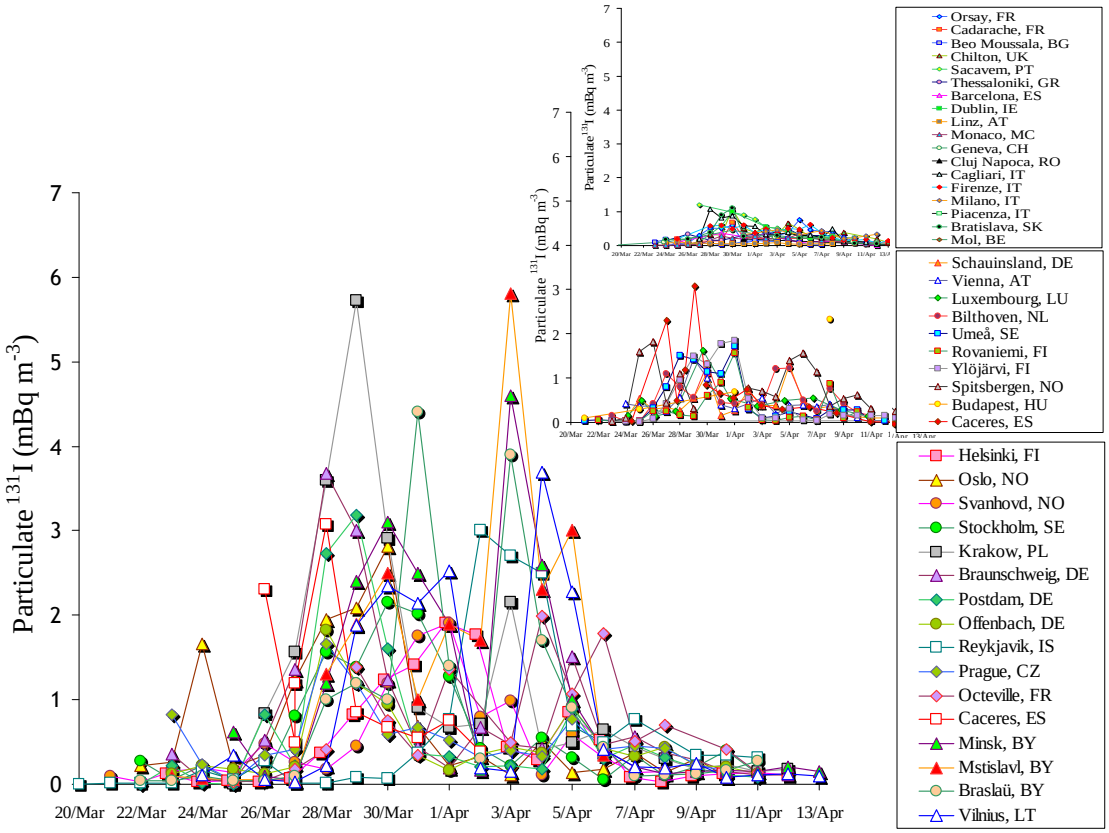


Figure 9-2 – Time series of activity levels of airborne particulate ^{131}I (mBq.m^{-3}) in northern and central Europe (bottom graph), and in western and southern Europe (middle and top graphs), due to releases caused by the accident at the Fukushima nuclear power plant (O. Masson et al, 2011, Environ. Sci. Technol., 45, pp. 7670-7677)

[51] Diaz Leon, J.; Jaffe, D.A.; Kaspar, J.; Knecht, A.; Miller, M.L.; Robertson, R.G.H.; Schubert, A.G.; Arrival time and magnitude of airborne fission products from the Fukushima, Japan, reactor incident as measured in Seattle, WA, USA. *J. Environ. Radioact.* Article in press.

During the last couple of weeks of March, weather conditions in Europe led to the formation of a “corridor”, within which higher activity levels were recorded (Figure 9-3). This corridor lay along a north-west/south-east axis, stretching from Scandinavia through eastern Germany, Poland, the Czech Republic and Belarus. Activity peaks for particulate ^{131}I, of about 6 mBq/m^3, were thus recorded in Krakow (Poland), Braslaw and Mstislaw (northern Belarus), and also in Brunswick (northeastern Germany). Countries in western and southern Europe (Ireland, the UK, Belgium, Switzerland, France, Italy, Portugal, and Greece) measured peak levels typically less than 1.5 mBq/m^3. The arrival dates of the contaminated air masses and the corridor of higher values were in fact predicted by the simulations carried out using the Eulerian LdX dispersion model developed by IRSN and integrated into the Polyphemus modeling platform. Figure 9-4 shows the simulations for ^{137}Cs, arbitrarily calculated at 12:00 UTC so as to simplify day-to-day comparisons. The contamination footprint is broadly similar for ^{131}I, since the ratio of ^{131}I to ^{137}Cs levels remained relatively constant. The model took into account the fact that the air masses were gradually depleted by deposition. Dry deposition of ^{137}Cs was modeled using a simple diagram, at a constant deposition rate (V_d = 2.10^{-3} cm/s). With regard to wet deposition, the parameters used in this study were of the form $\Lambda=aP_0^b$; with a=5.10^{-5} h/mm/s, b=1 and rain intensity (p_0) in mm/h. This model used the meteorological data obtained from Météo-France's Arpège model, with a resolution of 0.5°.

Many uncertainties persist regarding the assessment of the source term, the weather conditions encountered by the air masses in transit, the parametrization of the efficiency of scavenging, and the long-distance atmospheric dispersion between Japan and Europe. The comparison between the values measured and the simulation cannot therefore be used to calculate absolute values, but does demonstrate the ability of simulations to identify those regions where levels were higher, and also hot spots. For example, the relatively high value measured over the Iberian peninsula, on March 29, was actually predicted by the LdX model.

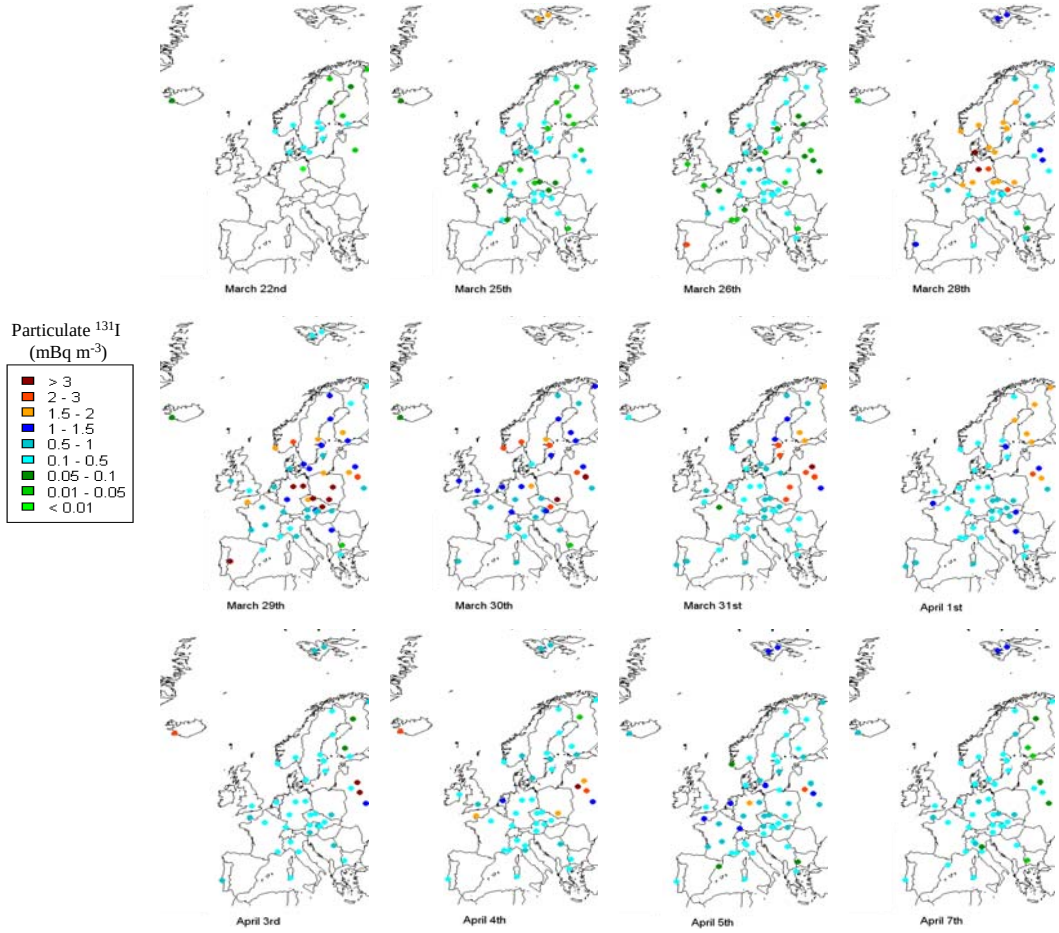


Figure 9-3 - Daily activity levels of particulate ^{131}I measured between March 22 and April 7, 2011 (O. Masson et al, 2011, Environ. Sci. Technol., 45, pp. 7670-7677)

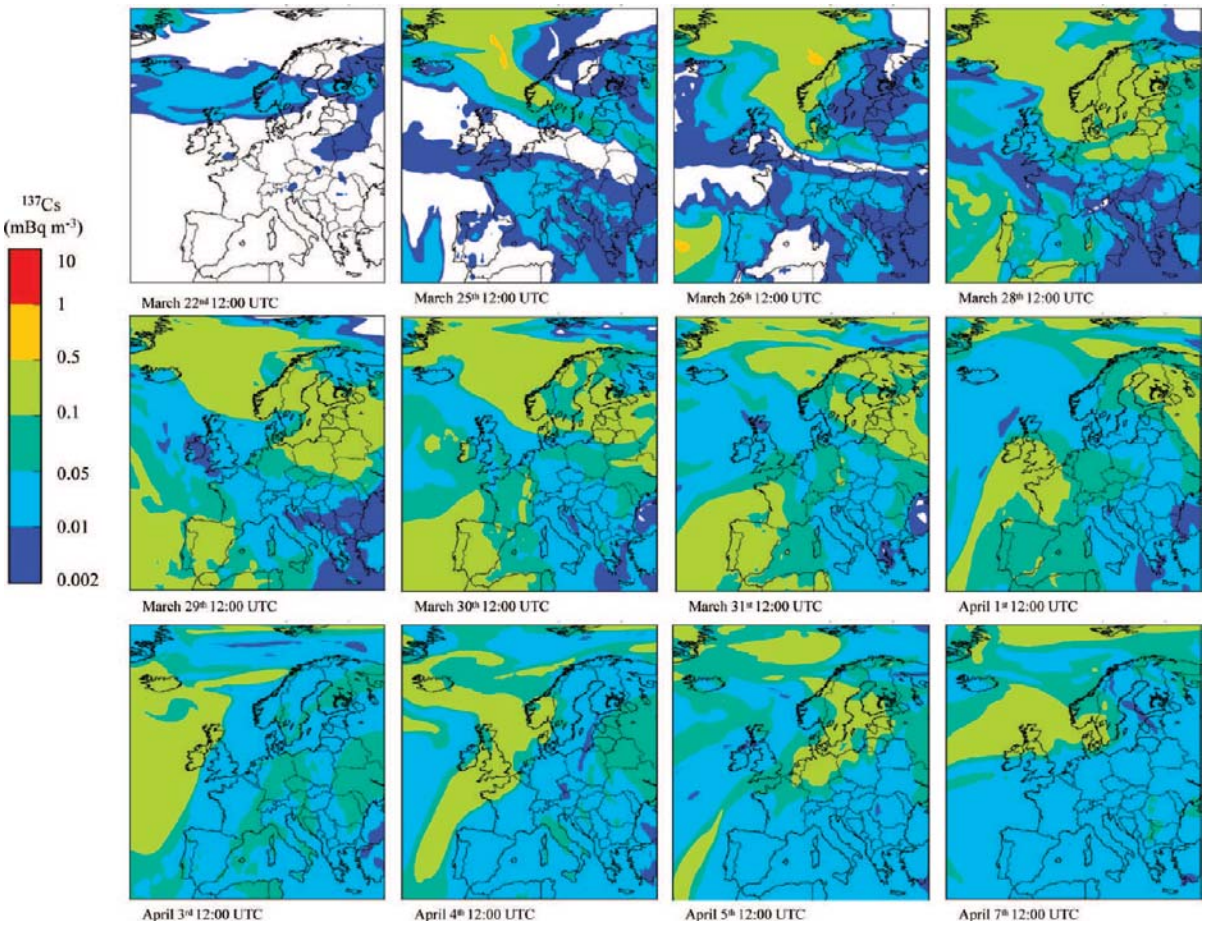


Figure 9-4 – Simulations of airborne activity levels of ^{137}Cs in Europe between March 22 and April 7, 2011 (O. Masson et al, 2011, Environ. Sci. Technol., 45, pp. 7670-7677)

Characterizing airborne iodine levels is complex, as this element co-exists in two forms, particulate and gaseous, requiring different types of samplers. At the time of the Chernobyl accident, relatively few measurements of the gaseous ^{131}I fraction were conducted. Subsequently, many sampling sites were equipped with activated carbon samplers to collect gaseous iodine, which means that it is now possible to obtain more detailed information about this fraction and also about the gaseous/particulate ratio, in terms of both spatial distribution and variation over time. Based on around 210 pairs of values acquired up to April 12, the average gaseous/total ^{131}I ratio obtained is 77.2% ± 13.6% (Figure 9-5). This is identical to the average ratio found after the Chernobyl accident[52]. The greater variability of this ratio can be explained by higher measuring uncertainties for the low levels of total iodine. This ratio also varies over time, since the particulate fraction is particularly sensitive to wet deposition. For example, the gaseous/total ratio on a given site varied between 0.79 and 0.90, and even up to 0.96 over a few days. Another source of uncertainty may stem from the adsorption properties of the adsorbent used for the gaseous fraction and, in particular, its collection efficiency in moist conditions. Apart from the capture characteristics, overall uncertainties probably reflect different aerosol washout/scavenging conditions as well as effects related to the chemical reactivity of the two fractions, while in transit. Consequently, the predicted estimate of the gaseous iodine concentration based on values for the particulate fraction must be treated with caution.

[52] Cambray, R.S.; Cawse, P.A.; Garland, J.A.; Gibson, J.A.B.; Johnson, P., Lewis, G.N.J.; Newton, D.; Salmon, L.; Wade, B.O. Observations on radioactivity from the Chernobyl accident. Nuclear Energy. 1987, 26, issue 2, 77-101.

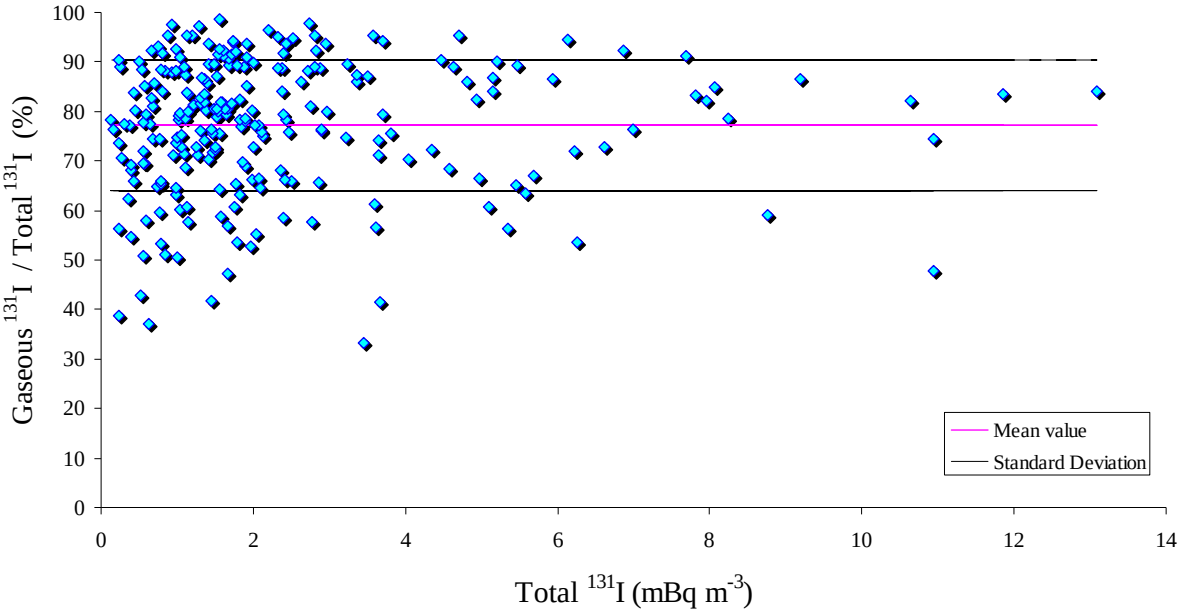


Figure 9-5 - Gaseous ^{131}I / total ^{131}I ratio in the atmosphere in Europe after the accident at the Fukushima nuclear power plant (O. Masson et al, 2011, Environ. Sci. Technol., 45, pp. 7670-7677)

As a first approximation, it can be assumed that there is a gradual transfer of gaseous iodine into the particulate form, as if gaseous ^{131}I were acting as a reservoir for the latter. According to the measurements conducted on the site of the Fukushima Dai-ichi power plant between March 22 and April 4, the average particulate ^{131}I / gaseous ^{131}I ratio was 0.46 ± 0.17, i.e. a gaseous ^{131}I / total ^{131}I ratio of 71% ± 11%. This is identical to the value observed in Europe (Figure 9-5), indicating that ^{131}I remained mainly in its gaseous form in transit. Consequently, the transfer of gaseous iodine into its particulate form, if it occurs, is not sufficient within the space of two weeks to counterbalance the decrease associated with the deposition of particulate ^{131}I, mainly by rain. In fact, the gas-particle conversion time for ^{131}I is typically two to three weeks[53]. In this respect, it can be seen that the temporal variation in the gaseous ^{131}I / total ^{131}I ratio shows a slight upward trend over time on average (Figure 9-6). This probably corresponds to a faster decrease in the particulate form.

As was the case after the Chernobyl accident, ^{134}Cs and ^{137}Cs were detected. While tracking the air masses originating from Fukushima as they passed over Europe, these isotopes were usually detected three or four days after ^{131}I, their concentrations having exceeded the metrological decision threshold at a later point in time. In Europe, ^{134}Cs had not been measured in the atmosphere since the mid-1990s due to its relatively short half-life (2.06 years). Conversely, ^{137}Cs was still measurable in trace amounts before the Fukushima accident: less than 1 µBq/m^3 in central Europe and less than 0.3 µBq/m^3 in northern and southern Europe taken as a whole. Its persistence in the atmosphere can be explained partly by its longer half-life (30.1 years) and partly by the fact that soil particles containing traces of old deposits (originating from Chernobyl fallout and/or global fallout from atmospheric nuclear testing) are regularly resuspended. Another source is the emission of ash during biomass fires. Unlike iodine, which is mainly in gaseous form, cesium isotopes bond rapidly with aerosols and are therefore easily scavenged by rain. The temporal and spatial averages of cesium values recorded from March 20 to April 12 in Europe were 0.076 and 0.072 mBq/m^3 for ^{137}Cs and ^{134}Cs respectively, with a first activity peak of 0.75 mBq/m^3 in Lodz (Poland) between March 28 and 30, and a second peak of 1.0 mBq/m^3 in Vilnius (Lithuania) between April 3 and 4. Compared with the situation in the aftermath of the Chernobyl accident, the ^{137}Cs airborne activity levels in Europe after the Fukushima accident were

[53] Uematsu, M.; Merrill, J.T.; Patterson, T.L.; Duce, R.A.; Prospero, J.M. Aerosol residence times and iodine gas/particle conversion over the North Pacific as determined from Chernobyl radioactivity. Geochem. Journal, 1988, 22, 157-163.

at least 10,000 to 100,000 times lower. Irrespective of the radionuclide considered, activity levels remained low enough not to pose any public health risk in Europe.

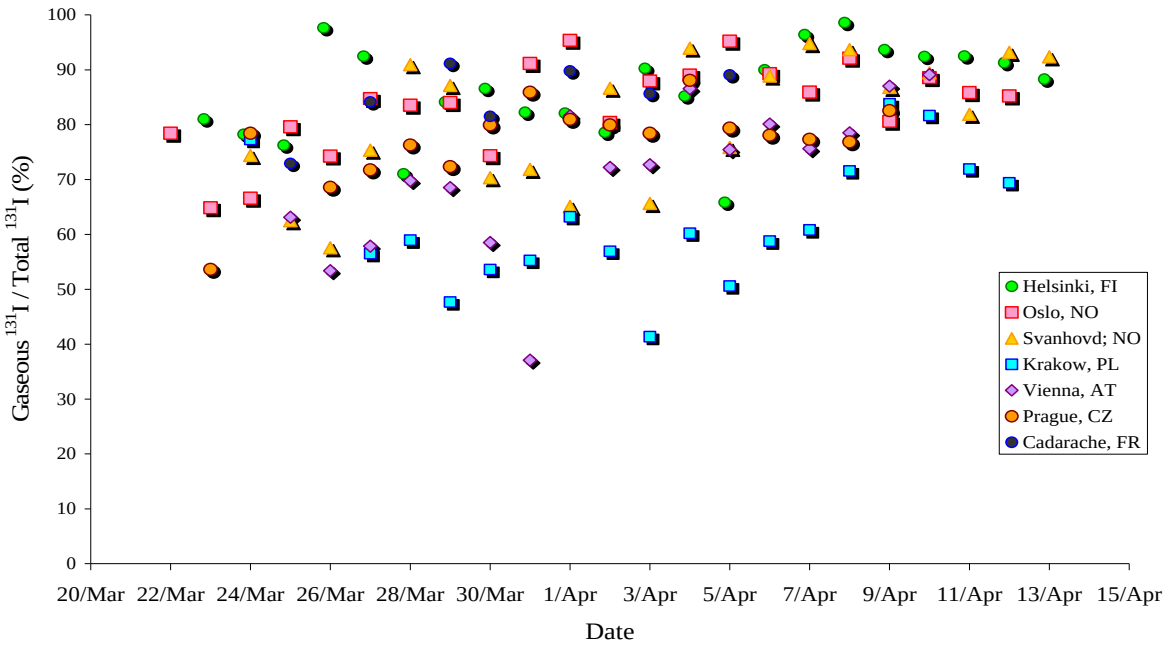


Figure 9-6 – Temporal variation in the gaseous ^{131}I / total ^{131}I ratio in Europe after the accident at the Fukushima nuclear power plant (O. Masson et al, Environ. Sci. Technol., 45, pp. 7670-7677)

The $^{134}Cs/^{137}Cs$ ratio in the Chernobyl fallout in 1986 was between 0.5 and 0.6[54], but remained close to 1 in the Fukushima fallout (Figure 9-6). This ratio was relatively constant over time during the first three weeks of the study period. Figure 9-8a shows the relationship between ^{131}I (particulate fraction or total fraction) and the values for ^{137}Cs. It is known that dry deposition of the gaseous fraction of ^{131}I was substantial and significantly higher than that of cesium[55]. The value range of the $^{137}Cs/^{131}I$ ratio found in this study is consistent with the deposition values observed in the United Kingdom[56] after the Chernobyl disaster. The variations had been attributed to the amount of rainfall in different places.

[54] De Cort, M. et al. Atlas of cesium deposition on Europe after the Chernobyl accident (Office for Official Publications of the European Communities, ECSC-EEC-EAEC, Brussels-Luxemburg, 1998.
[55] Tschiersch, J.; Shinonaga, T.; Heuberger, H. Dry deposition of gaseous radioiodine and particulate radiocesium onto leafy vegetables. Sci. Total Environ. 2009, 407, 5685-5693.
[56] Clark, M.J.; Smith, F.B. Wet and dry deposition of Chernobyl releases. Nature. 1988, 332, 245-249.

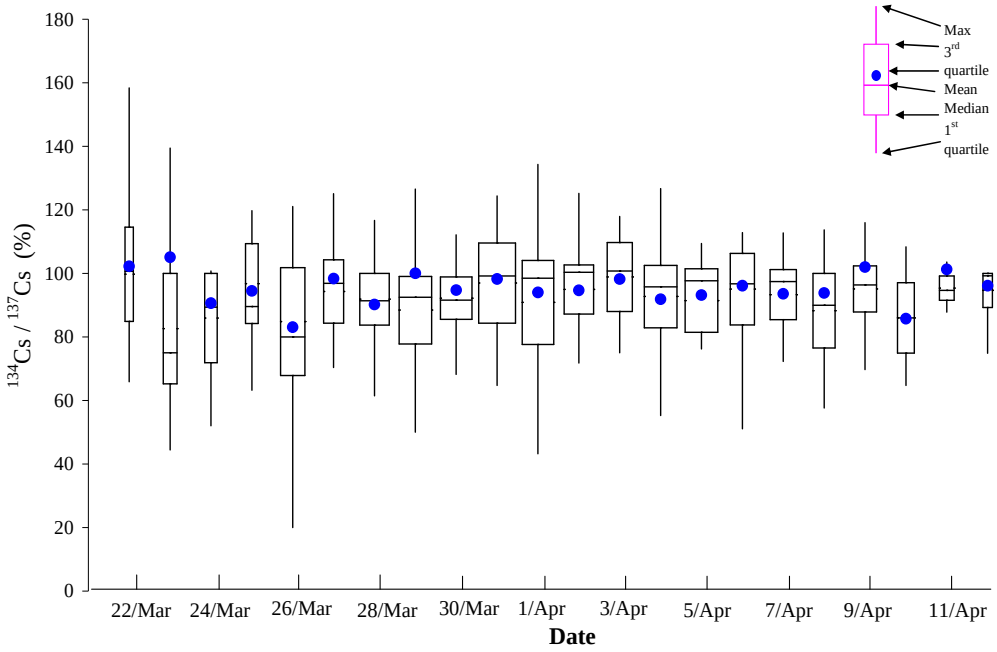


Figure 9-7 – Temporal variation in the $^{134}Cs/^{137}Cs$ ratio in Europe after the accident at the Fukushima nuclear power plant (O. Masson et al, 2011, Environ. Sci. Technol., 45, pp. 7670-7677)

Between March 19 and April, the measurements carried out near the nuclear power plant by the operator show that the ^{137}Cs/particulate ^{131}I ratio increased from 0.35 to 11%. This means that the radioactive plume contained more iodine at the start of the accident, which is consistent with the fact that iodine is more volatile than cesium. In Europe, from the time when ^{137}Cs began to be detected (March 22 onwards), this average overall ratio varied little Europe-wide (between 4.6% and 6.5%) up to March 27 but then increased due to the arrival of more concentrated air masses (Figure 9-9b). This may indicate adsorption of gaseous ^{131}I on non-contaminated aerosols situated on the edge of the contaminated air masses. This interpretation may corroborate the significantly lower $^{137}Cs/^{131}I$ ratio observed at the Jungfraujoch alpine station (Switzerland, 3,450 m), i.e. at an altitude approximately corresponding to the upper limit of the planetary boundary layer[57].

To check whether any parameters other than the radioactive decay of ^{131}I might explain the increase in this ratio with time, the average values were corrected for radioactive decay of iodine-131 (triangles in Figure 9-9b) and extrapolated back to March 11, corresponding to the emergency shutdown initiated when the earthquake was detected. It can be clearly demonstrated that the radioactive decay of ^{131}I is primarily responsible for the increase in this ratio. Consequently, it can be assumed, as a first approximation, that the scavenging coefficient for cesium is also applicable for particulate ^{131}I and that the transfer of particulate iodine from the gaseous fraction, if it occurs, is of negligible importance in view of the long distance travelled in the atmosphere from Fukushima.

[57] Colluad, Coen M.; Weingartner, E.; Furger M.; Nyeki S.; Prévôt A.S.H.; Steinbacher M.; Baltensperger U.; Planetary boundary influence at the Jungfraujoch analyzed by aerosol cycles and synoptic weather types. Atmos. Chem. and Phys. Discuss. 2011, 11, 985-1024.

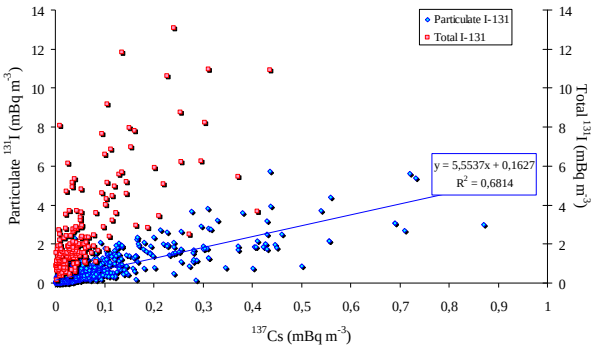


Figure 9-8 a - Particulate ^{131}I and total ^{131}I, as a function of the ^{137}Cs levels measured in Europe after the Fukushima accident (O. Masson et al, Environ. Sci. Technol., 45, pp. 7670-7677)

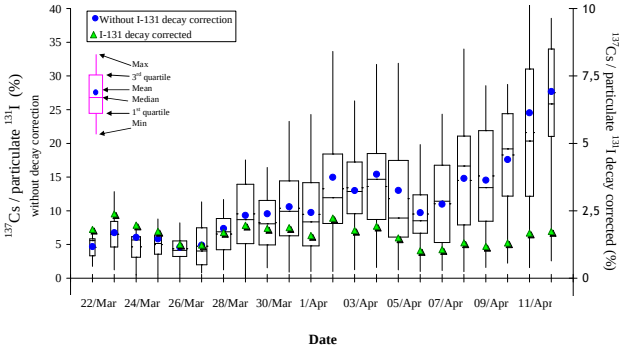


Figure 9-9 b – Temporal variation in the average $^{137}Cs/^{131}I$ ratio in Europe after the Fukushima accident (O. Masson et al, Environ. Sci. Technol., 45, pp. 7670-7677)

The highest concentrations of ^{131}I measured in Europe based on samples taken at ground level persisted for about 10 days. The average concentrations in the higher activity corridor were approximately 1 mBq/m^3 for particulate ^{131}I and 4 mBq/m^3 for the two fractions. There is little data available on the vertical distribution of ^{131}I in the troposphere; nevertheless, the activity levels seem to be fairly homogeneous in the vertical plane in Europe. In fact, samples taken at the Jungfraujoch alpine station (3,450 m) showed ^{131}I activity levels of up to 0.9 mBq/m^3, while high-altitude samples collected by aircraft on March 30 over Switzerland (at up to 8,000 m) indicated a level of 2.3 mBq/m^3, and a few mBq/m^3 over northern Germany (at up to 10,000 m). It is therefore reasonable to assume that ^{131}I was well mixed from ground level right up to the upper part of the troposphere. Assuming a representative average concentration of 10 days (i.e. 240 hours), that the air masses moved at an average speed of 50 km/h, and that the corridor with the highest concentrations was 3,000 km wide with a mixing height of 5.5 km, a volume of about 3,000 X (240 X 50) X 5.5 km^3 is obtained. If an average iodine-131 concentration of 4 mBq/m^3 is used, it can be estimated that approximately 10^{15} Bq of ^{131}I passed over Europe, i.e. less than 1% of the amount released into the atmosphere at the Fukushima nuclear power plant.

10. CONCLUSION

The accident at the Fukushima Dai-ichi nuclear power plant has revealed the vulnerabilities of some nuclear facilities, even in a highly developed country with advanced technical skills such as Japan.
Awareness of the need for continuous progress in enhancing nuclear safety around the world has led to numerous initiatives at the national and international levels. These initiatives are part of multiple objectives, which include assessing the vulnerability of nuclear power plants in light of lessons learned from the accident, assessing the health and environmental consequences of the accident, eventual improvements in preparing and conducting response efforts in case of an emergency as well as safety standards, and the constant need to improve knowledge through research efforts.

10.1. AT THE INTERNATIONAL LEVEL

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

At its annual session in May 2011, UNSCEAR began writing an initial report on the accident at the Fukushima Dai-ichi nuclear power plant and its consequences on the health of persons exposed to radioactive fallout.

In order to accomplish the task, UNSCEAR called upon all governments to nominate experts, who would be responsible for writing the report on a voluntary basis. A total of nearly 60 experts from Europe, Japan, Canada, the USA, Brazil, Korea, Russia, Belarus, Ukraine, and Australia were appointed. There are nine experts from France: five from IRSN and four from the French Alternative Energies and Atomic Energy Commission (CEA).

The experts have been divided into four working groups:

- the first group, led by an American delegate, is responsible for collecting measurement data and checking its quality. IRSN is represented by an expert in charge of one of the three sub-groups in this working group;
- the second group, led by a German delegate, is responsible for evaluating atmospheric and marine dispersion of radioactive releases. IRSN is represented by one expert in this working group;
- the third group, led by an Australian delegate, is responsible for evaluating doses received by the population and the consequences on the persons exposed and on non-human species. IRSN is represented by two experts in this working group;
- the fourth group, led by a French delegate from IRSN, is responsible for evaluating doses received by workers and the consequences on their health.

In addition, a coordination group consisting of the Chairman of UNSCEAR, the Chairman of the Japanese delegation to UNSCEAR, the leaders of the four working groups, and the Scientific Secretary of UNSCEAR and his colleagues, ensures the smooth progress of the report drafting process.
A first interim report will be presented at the 59th annual session of UNSCEAR in May 2012, and the final report, whose publication is expected in late 2013, will be presented at the 60th annual session of UNSCEAR in May 2013.
The UNSCEAR report will also benefit from contributions by major international organizations, including the World Health Organization and the World Meteorological Organization.

International Atomic Energy Agency (IAEA)

The general public and many governments have expressed a strong desire to increase the role and powers of the IAEA in the area of nuclear safety, including

- more rigorous application of the IAEA's safety standards for the design and operation of nuclear reactors, as well as the organization of inspection bodies;
- expanding the possibilities for IAEA to verify application, especially with expert assessments;
- strengthening the role of the IAEA in the area of information management in the event of a nuclear accident.

The IAEA's General Conference in September 19-23, 2011 adopted an extensive plan of actions, which includes the following twelve measures:

- assess safety vulnerabilities of nuclear power plants in light of lessons from the recent accident;
- step up reviews by IAEA experts to maximize benefits for its member States;
- step up preparedness and organization for emergency operations;
- step up effectiveness of national inspection organizations;
- step up effectiveness of operator organizations in the area of nuclear safety;
- examine and step up the IAEA's safety standards and improve application;
- improve effectiveness of the international legal framework;
- facilitate implementation of infrastructure required by member States for starting a nuclear power program;
- step up and maintain skill creation;
- ensure continuous protection of people and the environment from ionizing radiation after a nuclear emergency;
- increase transparency and effectiveness of communications and improve the sharing of information;
- use research and development efficiently.

This plan proposes means for action and levers to create international dynamics and pressure that will result in progress in safety, since incentives in this area are often more effective than legal obligations.

The IAEA's Ministerial Conference following the accident, held on June 20-24, 2011, as well as the General Conference in September 2011, also stressed the need to develop coordination among technical safety organizations (TSOs)[58], particularly through the TSO Forum (TSOF). This upholds the conclusions at the International Conference on Challenges Faced by Technical and Scientific Support Organizations in Enhancing Nuclear Safety and Security held in Tokyo, Japan in October 2010, which concluded that "The IAEA should foster the establishment of a forum dedicated to nuclear safety infrastructure development issues related to scientific and technical support."
The objective of the TSOF, whose terms of reference were defined in July 2011, is to encourage open dialogue and sharing of scientific and technical information among TSOs worldwide, as well as the harmonization of practices. It also aims to consolidate worldwide assessment and research ability and make it more available. Involvement of IRSN and the European organization ETSON[59] as members of TSOF will be stepped up.

[58] *A technical safety organization (TSO) is a technical and scientific organization that carries out independent assessments and analyses of nuclear facility safety and radiological risks. Its activities comply with best practices in the field of risk assessment and meet internationally accepted and applicable scientific baselines and standards.*

[59] The members of the European Technical Safety Organisations Network (ETSON) agree to abide by a charter of principles for action and values intended to ensure the highest level of expertise and foster the development of research in nuclear safety and top-down harmonisation of their respective pratices, including a shared training platform for their newly recruited staff members.

Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD)

For its part, the NEA led a discussion during the forum held on June 8, 2011 to advance its work in the fields of nuclear facility safety and emergency response management. This primarily concerns three of its committees:

- Committee on Nuclear Regulatory Activities (CNRA);
- Committee on the Safety of Nuclear Installations (CSNI);
- Committee on Radiation Protection and Public Health (CRPPH).

Each of the committees has mobilized its working groups in recent months to make decisions on changes to be made to established work programs. Closer coordination should be established between CNRA and CSNI, as well as with CRPPH.

CSNI's planned work program covers the following topics:

- external and internal hazards;
- accident management (sharing operating experience feedback on management of the Fukushima accident);
- severe accidents;
- improving robustness of nuclear reactors;
- emergency management.

In parallel, CNRA has created the CNRA Task Group on the Impacts of the Fukushima Dai-ichi Accident and identified the following actions to be taken up by its working groups:

- WGRNR (regulation of new reactors): impact on site selection;
- WGOE (operating experience): increased sharing of international operating experience feedback on hazards;
- WGIP (inspection practices) inspections involving severe accidents and related equipment;
- WGPC (public communication): international aspects;
- Task Group on Long Term Operation: impact on extending service life of existing reactors.

World Association of Nuclear Operators (WANO)

WANO fosters mutual support, information exchange and good practices among nuclear operators to improve the performance and safety level of nuclear power plants.

Beginning in March 2011, WANO released an initial document on immediate verifications to be performed by operators in light of the Fukushima Dai-ichi accident. It issued another document on cooling of spent fuel pools in July 2011.

During the NEA forum, WANO committed to applying the lessons of the Fukushima Dai-ichi accident and strengthening its peer-review programs. WANO's changes to programs and organization are based on five measures:

- extend its field of activities to accident prevention and mitigation;
- develop an integrated strategy to respond to events, detailing the responsibilities of the installation involved, WANO's regional centers and the London office if another severe event occurs;
- take a series of measures aimed at improving its credibility and the quality of its products and services;
- become more visible to the public and recognized as the organization that represents nuclear operators worldwide. Closer coordination with IAEA and regulatory agencies is planned to favor interaction and encourage members to publish the results of peer assessments;
- make efforts to improve internal consistency.

World Health Organization (WHO)

Following the Fukushima Dai-ichi accident, WHO requested that an expert from IRSN provide support to the technical team of the radiation protection program set up in its department of public health and the environment in order to improve its response to the nuclear emergency at the Fukushima Dai-ichi nuclear power plant. IRSN provided support to the WHO in implementing a dose assessment methodology and defining a work plan for assessing the health consequences for people exposed to radioactive releases from Fukushima Dai-ichi.

European initiatives

On March 25, 2011, the European Council sought to submit nuclear power plants in Europe to additional safety assessments. ASN and IRSN made significant contributions to defining specifications of these analyses on the French and European levels in a manner that is consistent in terms of content and scheduling. According to the specifications prepared and proposed by WENRA[60] on May 7, 2011, these stress tests consist of:

- a targeted reassessment of behavior and safety margins of nuclear power plants in the event of extreme natural events that jeopardize safety functions and lead to a severe accident: (a) assessment of responses from nuclear power plants and (b) verification of prevention and mitigation measures;
- defense-in-depth tests: (a) analysis of loss of lines of defense in succession, (b) deterministic approach and (c) identification of weak points, cliff-edge effects, etc.;
- a report on initiating events: (a) earthquake, (b) flooding and (c) other extreme natural events;
- an assessment of a significant loss of safety functions: (a) loss of electrical supply and (b) loss of ultimate heat sink;
- a report on protection and management resources: (a) loss of core cooling function, (b) loss of cooling function in the spent fuel pool and (c) loss of containment integrity.

Reports from various countries were submitted in late 2011 to European bodies. Peer reviews by experts from various European countries have been organized. Conclusions from European stress tests will be submitted in June 2012.

In addition to the stress tests, the European Commission has encouraged several initiatives in response to the accident at the Fukishima Dai-ichi nuclear power plant, including setting up a working group within the European Nuclear Energy Forum (ENEF), with significant participation by industry members of Foratom/Eniss who plan to harmonize European standards at the top level. As part of the Sustainable Nuclear Energy Technology Platform, all stakeholders defining research programs on nuclear fission have also produced a document describing the consequences of the accident in this area.

[60] Western European Nuclear Regulator's Association

10.2. AT THE NATIONAL LEVEL

Complementary safety assessments

Eight months after the Fukushima accident, complementary safety assessment have helped define an approach for supplementing existing safety measures to improve facility robustness. This approach consists of implementing a "hardened safety core" to ensure the availability of equipment that plays an essential role in controlling safety functions and emergency management.
It will be supplemented by targeted changes to certain baselines, without waiting for ten-year reviews (determination of contingencies for earthquake and flooding, protection from fire, combinations of hazards to be taken into account, etc.).

Beyond this initial step, IRSN has identified the need for a long-term effort on three main fronts:

- analysis and stabilization of the safety reference base, so that it includes the notion of "hardened safety core" (the hardened core includes a set of structures, systems and components whose availability, in all scenarios considered, will ensure the three basic safety functions: control of the nuclear reaction, removal of heat produced by the reaction and confinement of radioactive materials); the principles have been defined, but must be applied both in terms of consequences for modifications to installations and its role and the change it brings to the general safety demonstration for installations. In addition, emergency management measures must be re-examined;
- analysis of proposals by industrial firms to modify equipment and/or operating and emergency procedures and general operating rules for installations that result from implementing the "hardened core" concept;
- finally, in parallel, further expert analysis of the Fukushima accident.

Call for a research project on nuclear safety and radiation protection

After IRSN and other research organizations underlined the importance of such a project in the first months after the Fukushima disaster, the French president announced at a press conference on June 27, 2011 his decision to release significant additional resources to step up research in this field where France is acknowledged as a leader. He used the research budget from the Investment for the Future that is part of a major national loan (which includes €22 billion for research and higher education out of a total of €35 billion) coordinated by the Commissariat Général aux Investissements d'avenir (CGI), which has asked the French National Research Agency (ANR) to organize a call for research projects on nuclear safety and radiation protection ensuing directly from an initial study of the Fukushima accident. The initial analysis was part of a presentation on the points of view of IRSN and CEA during the July 20, 2011 meeting of the Atomic Energy Committee. The analysis contributed to defining the scientific framework for the call for projects. Assembling these details, and those from other stakeholders, CGI defined a budget (€50 million), a deadline (April 26, 2012) and topics for research focusing on the following:

1. draw lessons from conditions leading up to major nuclear accidents, especially the one that occurred in Fukushima on March 11, 2011, and take into account initial conclusions from ASN's supplemental safety assessments;
2. study methods of operators and public authorities for managing all major nuclear accidents to date;
3. study the impact of these accidents in terms of releases and radioactive materials, impact on health and the environment and conditions for recovering contaminated regions;
4. application of these lessons on current and future French installations to increase operation safety, resistance and the effectiveness of emergency mechanisms in the event of extreme events.

IRSN stresses that in addition to improvements through regulations, inspections, changes in safety baselines, it is crucial that the lessons of Fukushima give rise to an intensive effort of questioning and knowledge creation, which must be encouraged in France—as illustrated by this call for projects—but also more generally through international cooperation.

10.3. NEED TO CHANGE RESEARCH PRIORITIES

The operation of nuclear power plants worldwide has been marked by three major accidents that affected nuclear facilities at Three Mile Island in the United States in 1979, Chernobyl in the Ukraine in 1986 and recently Fukushima Dai-ichi in Japan. Only the latter two accidents resulted in significant releases of radionuclides into the environment.

The accident at the Fukushima nuclear power plant was caused by an earthquake of very large magnitude that generated high intensity mechanical stresses and a tsunami of exceptional size. These two external natural hazards, with a causal connection, separately exceeded the limits considered in the design basis of the installation, and their combination was also not considered. Together, the result was loss of core cooling in several boiling water reactors resulting in partial core meltdown. Loss of cooling also affected fuel in the site's spent fuel pools, raising fears over criticality risks and meltdown in the spent fuel pool that had not been considered until present. The accident resulted in significant releases of radioactivity into the environment at low altitude, which were however limited by maintaining a certain level of protection offered by the reactor containments. The low-altitude releases contaminated a zone over a moderate distance. According to IRSN's current knowledge, relative confinement of fission products likely limited worker exposure to levels that were lower than those of the Chernobyl accident. For the general population, regional contamination was similar to that of Chernobyl, but over a smaller surface area.
For the sequence of the accident at the installation, operating experience feedback shows the need to increase research on accident prevention. First, characterization of natural hazards (earthquakes and risks of flooding whether or not caused by the earthquake) resulting in the accident must be improved and consideration of these hazards in probabilistic safety assessments must be done more systematically in order to identify weak points in these installations confronting these hazards. Probabilistic studies developed after the TMI accident and their application for postulated accident studies on the basis of internal failures led EDF in France to implement, as part of safety reviews, countermeasures (procedures and/or equipment) that supplemented those issued from the deterministic approach of the initial design. IRSN considers that the development of a comparable approach including external hazards is necessary.

It is also important to improve identification of weak points of installations that could result from aging or operating mode from the standpoint of human and organizational factors.
Operating experience feedback also demonstrates that the phenomenology of severe accidents is now relatively well known. This result must be credited to past ambitious research programs coordinated by IRSN, particularly the Phebus Fission Products program (conducted at a CEA research facility). Significant uncertainties still remain, however, concerning certain phenomena relating to the sequence of core meltdown accidents and still more relating to pool dewatering. Research priorities concern in-depth analysis of the accident sequence and research targeted at the most obvious gaps: **thermohydraulic and thermomechanical behavior of fuel assemblies in loss of cooling conditions, effectiveness of emergency cooling makeup since partial meltdown of core elements affects geometry, criticality risks, production of hydrogen while overheated fuel is cooling and related explosion risks, transient behavior of core meltdown debris in the vessel bottom head and reduction of radioactive releases.**

This leads to the conclusion that beyond short-term measures to verify or, if appropriate, restore the safety margin at sites, it is necessary to pursue major research programs like those in the past to continue to improve the resilience of power reactors to phenomena that can lead to significant radioactive releases into the environment. In this regard, IRSN considers that it must pursue experimental in-reactor research programs on issues related to reactivity excursion and loss of cooling, as well as research on improving the resistance of confinement barriers (especially the

corium/concrete interaction) and protection systems, including passive ones. Experience has shown that for thirty years that such programs, conducted as a general rule as part of international cooperation to which the industry contributes, are a key factor in progress both in knowledge and risk evaluation, and improving technology.

A third concern from the accident experience feedback involves environmental aspects and those related to emergency management and intervention. In this regard, **IRSN wishes to stress that, if was able to provide relevant information earlier to decision-makers, and also to make it available to the public in a manner that was quick, intelligible and yet still accurate, this is because it had the scientific knowledge and tools from past research in the area of severe accidents, experience within its emergency response center from nuclear accident exercises held nationally over many years, and finally the results of its strategic commitment for several years of an approach characterized by openness to society and transparency.**

Nevertheless, there are some discrepancies between the regional contamination predictions made by IRSN and the in-situ measurements, suggesting that these predictive models need improvement. This is why IRSN deems it necessary, in light of the operating experience feedback, to increase certain research and development work in the area of radionuclide transfer (in the atmosphere or as a liquid) and the impact of this transfer to various environments, improve the installation section of emergency management tools and re-examine the regional radiological monitoring system. The effectiveness of the emergency plan, and in particular the choice of decision to make for optimal protection of the population as well as rapid collection of reliable data are essential, especially for densely populated areas. The goal of this work is not to develop academic knowledge in these fields, but to develop knowledge that is strictly necessary for developing operational tools for emergency management to supplement the panoply of forecasting resources that IRSN uses for its technical support to public authorities responsible for managing a nuclear emergency.

Finally, for aspects related to the radiation protection of the population near nuclear sites, the Fukushima accident confirms the plausibility of accident scenarios that include significant releases, particularly over the long term. This accident, unlike Chernobyl, can become a reference model of a severe accident with releases following partial confinement failure. Taking into account operating experience feedback for the Fukushima accident thus also appears essential from a perspective of changing policies concerning radiation protection of populations. Research needs in this area relate to

- development of techniques for rapid and robust large-scale assessment of individual doses in a concerned population;
- stepping up research on the effects of low doses received over time that affect the relevance of measures to protect the public. This research would require developing appropriate experimental platforms.

ooOoo