The major accident at Fukushima

Seismic, nuclear and medical considerations

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17, avenue du Hoggar
Parc d'activités de Courtabœuf, BP 112
91944 Les Ulis Cedex A, France

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Report of working group *Solidarity for Japan*

Chaired by

Alain CARPENTIER, President of the Académie des sciences, with

Jacques FRIEDEL, former President of the Académie des sciences, for the part *Megaseisms and megatsunamis*

Édouard BRÉZIN, former President of the Académie des sciences, for the part *The nuclear accident*

Étienne-Émile BAULIEU, former President of the Académie des sciences, for the part *Consequences on health and the environment*

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SECOND PART The nuclear accident

PRESENTATION

Alain Carpentier, President of the Académie des sciences – Institut de France

"Although it is Japan government's global responsibility to overcome the Fukushima Nuclear Power Plant accident, we hereafter want to ask all academies in countries and regions around the world to support and cooperate with us".

Science Council of Japan

"On March 11, 2011, the North-East of Japan was struck by a huge earthquake followed by a major tsunami and a series of accidents that took place at the nuclear power site at Fukushima, with emissions of radioactive elements". This was the message addressed by Prof. KANAZAWA, President of the Science Council of Japan (SCJ), only a few days after the catastrophe, to his colleagues Presidents of the Science Academies, adding that he nourished the hope the "the academies would continue in the future to help with the necessary rehabilitation work". Coincidentally, some ten days later, a Japanese delegation from SCJ was welcomed by the Académie des sciences - Institut de France to a G8-G20 meeting organised this year by France. On this occasion, we were able to have an exchange of views about the situation at Fukushima and to envisage the aid that our country could offer to a friendly nation whose high repute in science generally and particularly in the nuclear field is long-standing. Consequently, the idea arose to set up an ad hoc academic Working Party, with the assigned mission to analyse the events that had taken place in Japan, to make a status report regarding seismic and nuclear risks both in metropolitan France and in our overseas territories and to draw conclusions and make recommendations as deemed appropriate to the situation, recognising nonetheless the limits of the exercise in a constantly evolving context which will continue to do so for several years to come.

This was not the first time that more or less serious accidents took place in the world, whether of natural origin or related to human activities, but generating, through the return on experience, the necessary analyses and, subsequently, to taking the measures most appropriate to forecasting such events, mitigating their effects or preventing them from taking place in the future. As far as seismic activities are concerned, geologists have carefully registered, localised and analysed accurately the more dramatic occurrences, with their spectre of several hundred thousand deaths, as happened in Lisbon in 1755 and at Sanriku in 1896, to mention but two of the most memorable earthquakes among hundreds on record. At Tohuku, on March 11, what was first observed was an earthquake of magnitude 9 that took place in a zone which, although certainly prepared for this risk, nevertheless had not foreseen an event of such a magnitude. Secondly and more important, there was an associated tsunami of exceptional size for that coastline. The cumulative effects of the earthquake and the tsunami led to thousands of deaths, wounded, displaced, homeless and lost persons. This disaster enabled us, notwithstanding, to observe that the GPS alert systems and the paraseismic constructions had proven reliable. If these had not existed, Japan would have had to record a far greater number of dead and wounded, inasmuch as the capital area of Tokyo was close to the earthquake's epicentre.

In contradistinction, where the nuclear events were concerned, the fact that the Fukushima power station was located in a risk area led to a cascade of events where the negative effects were additive. "When the earthquake took place, March 11, 2011 at 14h46, three reactors in service immediately went to outage status (as planned), but the site was cut off from its external electric power supply. The emergency diesel generators started and came on line, but those connected to reactors N°1 and N°4 stopped one hour later, given that their diesel fuel tanks had been swept away by the incoming tsunami." This is the verbatim wording in the report that the SCJ addressed on March 23 to the other science academies who had made known their solidarity with Japan early on. Their report and the numerous information briefs released on a regular basis, demonstrated that the SCJ had the clear intention to honour its earlier commitment to provide full, real-time information to the world's scientific community and the public at large, thereby countering the criticism, often justly levelled in the past, of secrecy that had previously too often surrounded nuclear activities in general and nuclear site accidents in particular. The desire to be transparent is but one of the aspects of the exemplary behaviour of Japan, whose population, faced with this terrible tragedy, remained dignified and self-controlled to a remarkable degree, eliciting our admiration. We witnessed scenes of courage, solidarity, humanity that will serve as examples to those who, under similar circumstances and submerged by the events and remorse, would have given up.

The academic Working Party (WP) we set up comprised three separate sub-groups, each dealing with one of the three aspects – seismic, nuclear and medical – of the drama as it unfolded. Although these events are, in many respects, interdependent, we felt they were sufficiently distinct to justify that we study them separately. Thus, each sub-group, chaired by a former president of the Académie des sciences - Institut de France, whose remit it was to guarantee high level debates, received information from both Japanese and French authorities as well as advice from numerous experts invited for hearings. The WP members had a constant concern to reply not only the questions the scientists were asking but likewise those of the public at large. In the same manner as there was a "before" Chernobyl and an "after" Chernobyl, there will be a "before" Fukushima and an "after" Fukushima. The after-Fukushima will stem from the analyses that must be conducted by the international scientific circles. It is in this spirit that the Académie des sciences - Institut de France has replied to the call by the Science Council of Japan, making its contribution both in the shape of a Report and with proposals for scientific cooperation. Readers should not expect to find answers to all their questions in the report. There are many uncertainties, notably in regard to treatment of water supplies, rehabilitation of contaminated soils, reintegration of the displaced populations, food chain safety measures, optimised organisation of health-care units and services and population movements under extreme conditions … However, despite the sheer avalanche of new information arriving each month and enriching the dossier, the enclosed reports are sufficiently advanced to allow their publication today. These documents are addressed to the international scientific community, and particularly to Japan, as a token of our solidarity.

FIRST PART

Megaseisms and megatsunamis

THE MEGASEISMS AND MEGATSUNAMIS WORKING PARTY, CHAIR AND MEMBERS

Jacques FRIEDEL	Président, ancien Président de l'Académie des sciences
Pierre-Yves BARD	Observatoire des sciences de l'Univers de l'université de Grenoble
Pascal BERNARD	Institut de physique du globe de Paris
Michel CARA	École et Observatoire des sciences de la Terre de l'université de Strasbourg
Vincent COURTILLOT	Académie des sciences
Jean DERCOURT	Secrétaire perpétuel honoraire de l'Académie des sciences
Claude JAUPART	Académie des sciences
Xavier LE PICHON	Académie des sciences
Raùl MADARIAGA	École normale supérieure
Jean-Paul MONTAGNER	Institut de physique du globe de Paris
Alain PECKER	Académie des technologies
Jean-Paul POIRIER	Académie des sciences
Jean SALENÇON	Ancien Président de l'Académie des sciences
François SCHINDELÉ	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Paul TAPPONNIER	Académie des sciences

Personalities invited for a hearing by the Working Party

Rolando ARMIJO	Institut de physique du globe de Paris
Robert DAUTRAY	Académie des sciences
John DOUGLAS	BRGM
Nikolaï SHAPIRO	Institut de physique du globe de Paris
Steve TAIT	Institut de physique du globe de Paris

Critical review assured by

Alain CARPENTIER	Président de l'Académie
Philippe TAQUET	Vice-président de l'Académie
René BLANCHET et Jean-Louis LE MOUËL	Membres de l'Académie

1 | Scientific data

Planet Earth has always been a theatre of internal movements that take place because of the significant differences in temperature and density existing between the Earth's surface and centre. This specific activity takes place between the Earth's crust and the metallic core that extends down more than 3 000 km to the limit of the metallic core. At this extreme depth, the Earth's mantle has a very high temperature and is continuously deformed by warping and creeping phenomena. On the contrary, at the higher levels, the temperatures are low and display an elastic, brittle behaviour, responding to mechanical stresses by sudden jolts, *i.e.*, as occurs in earthquakes.

1.1 Earthquakes in subduction zones

In a subduction zone, we can observe how an oceanic plate, denser and colder than the neighbouring mantle, drives itself, because of its weight, under another plate (which may be continental or oceanic, depending on the region) cf. Figure 1.1. This downward progression produces very significant deformation phenomena that release their energy in the form of earthquakes and non-seismic landslides. The largest earthquakes, known also as "megaseisms", have their origins at the frontier between the two plates at depths generally less than 50 km deep. A simple model that can be used to explain such earthquakes: that of the elastic rebound, initially proposed for the San Andreas Fault after the 1906 earthquake that struck the San Francisco area in 1906 and which was later been adapted to similar occurrences in subduction zones. In what is termed as the inter-seismic phase, between two earthquakes, the deep section of the subduction is sliding forward continuously, slowly but surely building up an accumulation of shear stresses in the upper section, in the so-called "seismogenic zone". This zone is normally blocked by the opposing friction forces that exist between the two plates. Occasionally, the accumulated stress is such that it exceeds the friction threshold value and leads to a brutal shift of the plates: *viz.*, an earthquake takes place. This model explains the jerking movement in a subduction zone, but it does not allow us to calculate the magnitude (or seismic momentum) to be assigned to any given earthquake. Earthquake magnitudes – a logarithmic energy function – depend not only on the distribution pattern of the cumulated stresses generated by movements of the deeper section of the advancing plate, but also on the history of previous earthquakes in the area.

Subduction zone earthquakes take place both inside the plates as well as at the frontier between plates. In Japan (and similarly in the French West Indies), the activity of the upper plate, with the emerged surface islands, is particularly

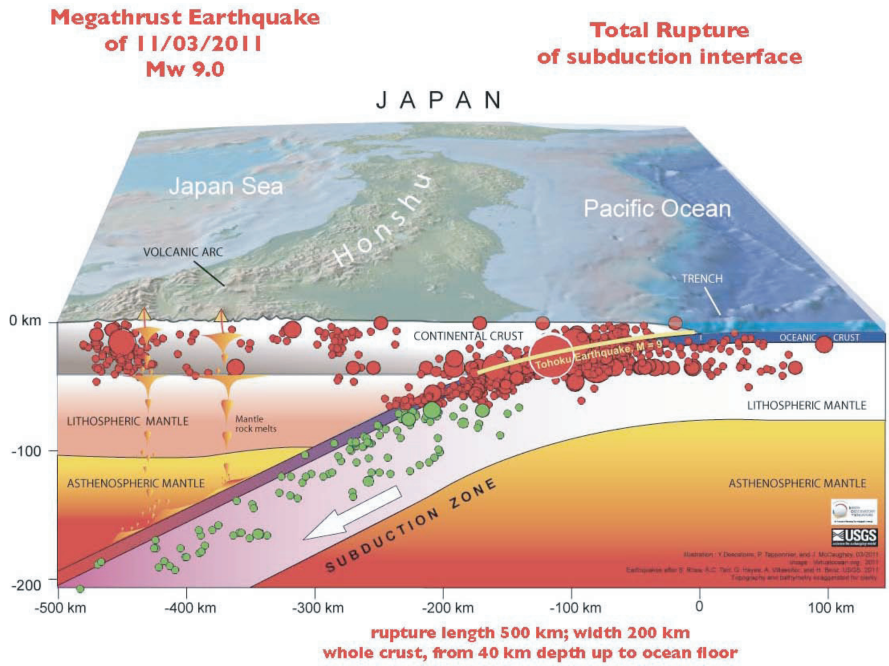

Figure 1.1
Rupture of the subduction zone, March 11 2011.

significant and leads to highly destructive earthquakes with a magnitude in excess of 8.0. These earthquakes become catastrophic when they occur in or close to inhabited areas. One such earthquake occurred in the "prefecture" of Iwate, North of the city of Sendai in Japan. Important earthquakes also take place inside the oceanic plate and can reach the magnitude of 8.0. Such earthquakes are common in South America and in the West Indies and Caribbean area. Beyond any doubt, the most dangerous earthquakes take place along the frontier between plates and can occasionally exceed the value 8.5; we then are faced with events in the category of *megaseisms*.

The seismicity of subduction zones complies with several empirical laws, the most important of which is Gutenberg-Richter's law which states that the number of earthquakes of a magnitude higher than a given value will decrease by a factor 10 when the magnitude is increased by one unit. Consequently, the seismicity of a given area depends on the value for the biggest earthquake possible in that subduction zone. In geophysics, this extreme event is called the reference earthquake for that region. However, in most subduction zones, we do not know the scale of *the reference earthquake*, given that the archives are too recent or are incomplete. This indeed is the case for North-East Japan (Tohoku) where the history of seismic events only goes back 500 years from the time Japan began building its nuclear power stations in the mid-seventies. In many subduction zones, the historic catalogues of events can be completed by paloeoseismic data: traces of old tsunamis in the estuaries, or marine ledges or shelves, etc., allow us to reconstitute old earthquakes.

In regard to the Tohoku region, one major paleoseismic event was identified some ten years ago and dated to year 869 AD. When the seismic history is well documented, as is the case in Chile, where megaseisms are more frequent than in Tohoku, we can identify zones where there is a high deficit of seismic slipping, called *seismic gaps*. These so-called gaps are areas where the short-term seismic risk is high. This particular analysis allowed us to identify the Maule Fault Gap in Chile where an earthquake of magnitude 8.8 took place on February 27, 2010. More recently – since 1990 approx. – our range of measurements and terrain observations has been augmented by data from space geodesics (using GPS satellites and radar interferometry) and this allows us to estimate the ratio of non-seismic slippage and the rate of accumulation of elastic deformations. Interpreting these data is not easy because the time allotted to a space-borne observation is short compared with the duration of a seismic cycle. Space data has shown that there are non-seismic episodes in the lower sections of a seismogenic zone. It is thought that these slow movements retard the occurrence of megaseisms.

1.2 Tsunamis

A tsunami originates in rapid movements of an ocean bed and the amplitude reached by the tsunami wave will be a function of the surface area set in motion, of the amplitude and the direction taken by the wave. It is the vertical movements that are the most dangerous. A tsunami originating in an oceanic basin will progress at a speed that is a simple function relating to the height of the water displaced. Approaching the coast and given the water gets shallower below the tsunami, its speed decreases rapidly and simultaneously the wave gets higher. Also, near the coast – where there is a complex configuration of sea-bed and coastline, with horizontal variations stretching over distances comparable with the depth of water – we observe other wave amplification phenomena that are not yet fully understood today, partly because our data on floor-bed shapes are not totally accurate.

Our knowledge therefore of the probability of a tsunami occurring still remains to be improved. For example, the previous cases December 26, 2004 on Sumatra and March 11, 2011 in NE Japan were well in excess of the amplitudes that most seismic specialists had expected given the magnitude of the earthquakes that are expected and fault slips that are largely under-estimated; it is above all, it is our knowledge of seismic sources that we need to improve with the perspective of such mega-events. The return cycle for events of this magnitude is certainly of the order of a thousand years. In numerous continents, however, the historically recorded period, either oral or in writing, only goes back some centuries, and often, in most cases, less. The available data are therefore very inadequate to correctly assess the definitive probability, all the lower so that the effects of a major tsunami impacts on most of the shorelines of the basin where it occurs and this can be felt up to 20 000 km from the origin. We must often look for the residual effects of a tsunami at a very great distance from its starting point on the globe.

In the case of an earthquake, the characteristic features of a tsunami allow us to work backwards to the initial break-zone and the displacement that takes place along the break. We can also calculate the tsunami characteristics from the estimations of the submarine earthquake. Combining these two approaches, scientists have been able to make significant progress in understanding these events.

1.3 The Tohoku earthquake, March 11, 2011

The Tohoku earthquake, among those measured by appropriate instruments over the past century, more or less, with its magnitude of 9.0-9.1 is ranked fourth in decreasing order, after Sumatra (2004, 9.1-9.2), Alaska (1964, 9.2) and the biggest earthquake recorded, in Chile (1960, 9.5). The break zone for Tohoku measured 600 km by 250 km, but the area with highest displacement (> 30 m and locally up to the enormous value of 60 m, was only 100 km by 50 km). Given that the plate convergence rate is estimated at 90-95 mm/yr in this region, the deformation that was relieved during this earthquake must have accumulated over at least the past seven centuries. One rather astonishing feature of this earthquake is that two thirds of the break occurred in the area close to the deep ocean trench, where the break plane is a less than 20 km below the bed. This extremely high break zone was the main source of the gigantic tsunami that built up after the quake. The 1896 earthquake that occurred in the Nord certainly had similar characteristics, the evidence being in the major tsunami that hit the coastline.

The “megaseism” and the “megatsunami”, March 11, 2011 hit the country that has the most dense network of geophysical observations in the world, with a rapid and highly sophisticate early warning system and the highest anti-tsunami barriers, a country where the population has the best earthquake training with a long history of acquired experience in these matters, where there is one of the highest levels of scientific achievement and where national disaster management policy based on knowledge acquired from previous events is a major source of concern. The tragic and unexpected consequences of this catastrophe were dramatic (and would have undoubtedly been much worse if the warning systems had not functioned properly, if the paraseismic quality of the buildings and the training of the populations had not been as good as they were).

The Japanese seismologists responsible for making predictions were convinced that the probability of an earthquake occurring could be calculated in a rational manner, using the definition of reference earthquakes for each region. The forecast map, therefore, had not made any provision for an earthquake of magnitude higher than 7.5 in the area closest to the Asian continent and 8.2 closer to the deep ocean trench. The Tohoku earthquake had a magnitude of 9.0-9.1. On the bases of these forecasts, the tsunamis accompanying the earthquakes were not predicted to exceed 4 to 5 metres on reaching the coast. The Tohoku triggered tsunami measured between 15 to 20 metres. The Fukushima nuclear power station site had been built to protect the infrastructures from tsunamis less than 5.7 m in height upon reaching the coastline, whereas this tsunami just off the reactor sites measured 14 m with respect to the sea's normal level.

The main error made by the Japanese specialists was to consider that the past century of seismic events was representative of the continuous, ongoing subduction process. It is, however, known that subduction zones can produce earthquakes equal to or higher than magnitude 9, with lateral movements in excess of 20 to 30 metres, due to stress accumulated over several centuries, *i.e.*, a much longer period than the Japanese specialists had used for their forecasts. The fact that major earthquakes, magnitude 7.5 to 8 had relieved part of the elastic deformation did not preclude that a megaseisms could follow, and indeed this was the case on March 11, 2011. The seismic energy dissipated over the past century only represents 20% of the energy represented by the progressive dip of the Pacific plate sliding under the Japanese archipelago. In other words, seismicity over a span of one century only accounts for some 20 mm/yr progression, i.e., approximately one fifth of the total displacement expected. The hypothesis that there was a permanent regime therefore implied that 80% of the energy in the plate slipping process was evacuated via microseisms or via plastic slippage.

The geological and historic records show that very big tsunamis had hit the Tohoku coastline in years 1611 and 869, and the residual traces are much greater than those left by the earthquakes over the past century (although the lesser magnitude earthquake that occurred in 1896 did produce some really impressive damage). The cycle for major tsunamis occurring lies between 500 and 1 000 years.

The building of a dense GPS network (30 km between the stations) following the Kobe earthquake in 195 allows scientists to demonstrate that the elastic deformation observed in Japan as a result of the progressing Pacific Plate corresponded to a slip rate close to 80 mm/yr, *i.e.,* almost 100% of the subduction rate and not 20% as had been conjectured. Japan therefore acts as an efficient blocking system preventing, in essence, the continuous slippage of the Japanese Plate over the subducting Pacific Plate. This "blockage" along the coastline develops a steadily increasing elastic energy in Japan's crust layers, the accumulated energy of which will only be relieved and released when the energy built up exceeds the threshold value for friction between the two plates; Local relaxation may occur, in areas where there is a lower friction value, this explaining the medium magnitude earthquakes that have been observed over the past century. But a total relaxation along the complete subduction trench will occur if the accumulated stress is high enough. The order of magnitude of slippage we are referring to here is compatible with a large slippage of 60 m, as mentioned earlier, that accumulates every seven centuries at least, and this explains the amplitude and the rarity of megaseisms and the associate megatsunamis.

The Tohoku earthquake serves to show that any forecast based on recent data proves inadequate. We must therefore take both historic and geological data into account if we wish to characterise seismicity over a span of at least several centuries, better still over several millenaries. The Tohoku earthquake reinforces a recently proposed idea, that the maximum magnitude that can be attained by a subduction triggered earthquake is 9+, independently of the subduction progression rate (maximum accumulation of elastic displacement 30 m approx.). Such a conjecture, as we shall see below, has considerable importance when it comes to assessing the risk factor for seismic activities in the French West Indies.

2 | France

2.1 French West Indies (Antilles islands)

The recent examples provided by earthquakes in Sumatra and Japan have led us in France to reconsider the levels of risk of seeing megaseisms or tsunamis in France. To be precise here, the only area where this might occur is around the French West Indies, with the advancing North American Plate diving below the Caribbean archipelago at a speed of 2 metres per century. The island of Guadeloupe in 2004 experienced a surface earthquake, with magnitude 6.3, leading to a certain amount of destruction in the nearby Saintes archipelago and one death. The island of Martinique in 2007 felt the effects of a deep-lying earthquake, magnitude 7.3; there was no damage or deaths.

Had that particular earthquake occurred at another location, the effects could have potentially been very serious indeed. We can note, for the record, that these two earthquakes in the French West Indies are considered the two most violent earthquakes on French territory for the past century.

In year 1843, but this was before appropriate instruments existed, a major earthquake, no doubt of a magnitude close to 8 destroyed the town of Pointe-à-Pitre on the island of Guadeloupe, but there was no accompanying tsunami. The return cycle for such an event is of the order of several centuries. The recent Japanese (Tohoku) earthquake shows that the Caribbean zone could also be the site of a future megaseism with an extremely long cycle, no doubt exceeding a millenary. In the French West Indies the most ancient chronicles only date from 1492 (Christopher Columbus). It is therefore important to pursue investigations, both on land and at sea in terms of full geological and geophysical analyses (with cooperation throughout the Caribbean Arc) and draw benefit from high resolution space measurements to reconstitute the history of earthquakes and possible tsunamis that may have occurred in this region over several thousand years. Numerous buildings, even those that house public administrations, on both Guadeloupe and Martinique islands do not comply with paraseismic standards that would allow them to resist an earthquake of magnitude 8, even less so one of magnitude 9. Finally let us bear in mind that, on top of seismic risks, there are also risks of strong volcanic activities

2.2 Mainland ("metropolitan") France

Mainland or "metropolitan" France has a very different seismic profile than the French (and other) islands in the Caribbean area. The general context is that of the two European and African tectonic plates moving towards each other at an approx. speed of 70 cm/yr, with a deformation largely absorbed north of the Maghreb countries. It is therefore plausible that an earthquake of magnitude 7.5 in the Maghreb region could lead to a 1-3 m tsunami reaching the Riviera coastline. Correlatively, large scale earthquakes are few and far-between in metropolitan France. History however tells us that earthquakes of a magnitude between 6 and 7 are possible. Their cause would lie mainly in interplay of old, existing faults-lines and a largely unknown deformation field surrounding them. In France, the tectonic context and the influence of significant ground profile variations and their associate stresses are not accurately known as yet. The areas that are seismically most active are the Pyrenean mountain range and the Alps and also France's North-East border region. The Ligurian rim, off the coastline at Nice on the French Riviera is a special case where compression earthquakes can take place below the sea-bed. This indeed is probably what happened when certain towns on the coastline East of Nice were shaken in 1887 and when a 2 m tsunami hit the Mediterranean coast at Cannes and Antibes. Moreover, a vast and somewhat diffuse seismic zone extends from the Massif Central up to the Brittany area known as the Massif Armoricain. The strongest historically recorded earthquakes in France probably never exceeded the magnitude of 7, but the example just seen in Japan, where the megaseism was bigger than any historically known event in that area, should invite us to reflect on this with caution. We have never recorded any major tsunamis on any of France's coastlines.

Some further geological analyses and accurate dating of seismic markers in the recent quaternary era are definitely needed. On the scale of the millenary, we know that about 10 earthquakes of magnitude 6 or more struck France. There is a famous, historically recorded example, in the city of Basel, where an earthquake in 1356 had a magnitude retrospectively estimated as being between 6 and 7. This sort and scale of earthquake can be highly destructive in a country with a high population density as is the case in France. We need only recall the example of the Lambesc earthquake (not far from Aix-en-Provence, in South France near the Mediterranean), where an earthquake estimated of magnitude 6.2 occurred on June 6, 1909 and killed 46 people in a low-density (at that time) area. Today that earthquake would lead to several hundred dead.

Either through damage to major industrial sites or collapse of older buildings in certain city areas, an earthquake of magnitude 6 can produce many victims and have very serious economic consequences, all then more so if the earthquake's epicentre is close to the surface and to an urban, hence heavily populated, area.

2.3 Ground response factors

We now know (and indeed have known for a long time) that local geographic features (nature of the surface layers and of those at lower levels) can modify to a large extent the characteristics of seismic movements and their potential to damage or destroy artefacts. A striking example is provided by the Kashiwasaki-Kariwa nuclear power station site in Japan, where highly heterogeneous three-D effects, moreover variable is strength, depending on the compass direction of the quake, have been duly noted.

The local ground response to seismic quakes are still undergoing lots of research, combining investigations and in situ measurements, with theoretical progress and "heavy" digital simulations. The progress, in fact, has been quite significant, but still remains insufficient since we lack accurate knowledge as to the nature of the lower ground levels beneath most of our major urban cities and our industrial sites. These stumbling blocks will only be removed if we resolutely engage *in situ* instrumentation and underground reconnaissance.

The most recent progress – taken into account at face-value – in paraseismic regulations for "normal risk levels" has been recorded thanks to the enormous efforts in terms of instrumentation and research commitments taken by the Japanese scientists after the Kobe earthquake (Jan. 17, 1995). All the earth movement recording positions have been systematically described thanks to geological and geophysical reconnaissance (drillings, measurement of seismic wave propagation speeds). The seismic community agrees that this is indeed a good example to be followed elsewhere round the world, but regrettably we also note that the funding is missing, notably in Europe. This heavy trend towards total disinterest in soil and terrain recognition has often led to some disagreeable surprises and to significant building over-costing.

3 | Socio-economic considerations

3.1 Governance

Establishing an operational observation system requires a lasting commitment. In most developed countries, it is in the remit of the Home Office to finance surveillance systems. In France, this undertaken lies solely with the Ministry for Higher Education and Research. Most probably, we should be looking for a compromise between the two sorts of organization. If there is no connexion with the research services, the surveillance services can be degraded and ignore the often rapid scientific progress in the area of natural risks. Without funding from the national Home Office, the responsibility carried by the Research ministry is too heavy, and this indeed is the case in France. The State authorities should acquire a systemic organization that would enable them *to coordinate* various actions taken in respect to major telluric risks (earthquakes, tsunamis, volcanic eruptions, land-slides). After the Soufrière volcano erupted on the island of Guadeloupe in 1976 a High Council for Assessment of Volcanic Risks [CSERV] was appointed (however the CSERV was recently disbanded) and the experience gained served to demonstrate that this body was not functioning properly. There were questions about the competency of the ministry to which the CSERV reported, and indeed of certain public servants who were monitoring the work done. Following the earthquake in 2004 on Sumatra, a "delegate for tsunami alerts" was appointed in the prime minister's office. Unfortunately, Government did not follow through in supporting this position. After an initial investment phase the running costs were cut off and the delegate in essence ceased to exist. It would appear necessary to this Working Party that a body should be re-appointed, *reporting to the Prime Minister*, with an organisation that would assure co-ordination of

Government actions should a major telluric event occur, with participation of those ministerial departments in charge of civilian security matters (Home Office), of Higher Education and Research and of the Environment.

We can, however salute the initiative of the French Government to have the CENALT (Alert Centre for Tsunamis) funded by both the French Home Office and the Ministry for Ecology.

The actions to be undertaken without delay in the French West Indies (the Caribbean plate and its Northern and Southern limits), the Lesser Antilles Arc, subduction zone) in respect to mega seisms and the degree of mechanical coupling, should associate high level research and routine observation and surveillance, combining historic, geological, seismological, volcano data, GPS, both inland and at sea. These recommendations are addressed to the ministry in charge of Higher Education and Research, plus the universities and major research establishments, the CNRS notably its Institut national des sciences de l'Univers whose responsibility it is to overview work engaged by the OSU (observatories for studies of the Universe, and certain University research units). INSU is an agency that allocates funding means to the scientists, is in charge of studies of natural milieus (in liaison with the other CNRS Institutes). INSU also provides for supervision and support to the Institut de physique du globe de Paris, and the OSU. Several establishments carry out research in the Caribbean: IPGP notably ensures surveillance of natural phenomena in Guadeloupe and Martinique. The scientific and operation functions of the volcanological and seismological observations in the French West Indies should be underscored.

The funding as needed should be planned and scheduled. Responsibility and budgetary allocations should be clarified (between the ministry for Higher Education and research the CNTRS-INSU, but also the French Home Office where civilian safety is concerned. It was the Institut national des sciences de l'Univers (under a previous statute) that directed the observatories, allocating their funding and personnel appointments on behalf of the Ministry for Higher Education and Research. The statute of the INSU should be reviewed. Under the new CNRS statutes (that also cover the CNRS Institutes), this organizational link has been quashed and the CNRS deems that it is no longer in a position to fund the observatories, considered as operational units.

3.2 Regulations applicable to seismic events and nuclear installation safety

In France, seismic regulation is written into the Code known as the Basic Safety Rules, which goes back to 2001 and relies on a deterministic assessment of seismic event probabilities.

In order to meet the demands of the French Nuclear Safety Authority, the IRSN/BERSSIN (French Bureau for Assessment of Seismic Risks to Safety of Installations - Bureau d'évaluation des risques sismiques pour la sûreté des installations) develops expertise in respect to probability computation thanks to leading-edge research work, of recognised international standing in association with competent academic research laboratories. The operator has developed an extensive programme of collaborative research, with numerous research laboratories and similar bodies, collaborating in the European SIGMA Programme *(Research and Development Programme on Seismic Ground Motion).* The investigations into seismic probabilities have been subcontracted to private concerns.

Despite the policy statements issued by the IRSN to guarantee transparency (its assessments are made public), we could envision adopting the American practice, based on expert panels and who carry out very in-depth analyses, both by research scientists and operators, dealing precisely with the governance issue and its acceptable forms and with the role of experts in assessing probabilities (cf. for example, the documents produced by the *"Seismic Hazard"* Panel of the NRC and by the SSHAC Committee (National Regulatory Commission the Senior Seismic Hazard Analysis Committee).

3.3 Paraseismic protection for installations

The best protection for the installations lies in the application of paraseismic construction standards and prescriptions. Indubitably, recent experience teaches us that when buildings are erected in conformity with modern standards (*viz.,* later than the decade 1970-1980 approx.), earthquake damage is limited. In all recent major earthquakes, the older buildings brutally collapsed whereas modern buildings, if they comply with paraseismic designs, remained standing.

Correct paraseismic construction calls for special attention at each stage, from the drawing board to the finished structure. If stress is often laid on the dimensional phase, the early design phase and application of appropriate building phase rules are equally important. The aim here is to avoid fragile breaks occurring in certain structural areas that lead to chain reaction breaks (domino effect) and a rapidly progressive collapse sequence. Dimensioning implies that the structural elements are chosen with an adequately high resistance factor.

The "art" of paraseismic protection lies in the capacity of the building to resist forces that are higher than those included in the dimensioning calculations. The level of the external impacting forces can only be defined using probabilistic forecasting: we can thereby accept that this level be exceeded with a probability all the lower, if the building is large or presents a risk vis-à-vis the environment. However, is of prime importance that if and when this level is exceeded there will not be an ensuing catastrophe. The answer here seems to be forthcoming in the principle of "capacity dimensioning", akin to using a fuse in an electric circuit. The designers plan energy dissipation areas where the non-elastic deformations are concentrated, with acceptable damage to the building but not its collapse, and other areas which are over dimensioned. This procedure is written into all modern regulations and in particular in the recent Eurocode collection of European standards.

Implementing the concepts set out above is a sensitive process, especially in France. As we know, France has a low seismic history; consequently our civil engineers and builders do not benefit from adequate training in paraseismic techniques. This is all the more evident in SMEs in the construction sector. The problem is less acute in the major public works enterprises who have invested in special training schemes and efforts to make their personnel aware of the underlying issues.

Conclusion

The cataclysm that struck the North-East coast of Japan on March 11, 2011 constitutes a major earthquake event on Earth, major in both intensity and size of the land-area impacted and by the fact that it was accompanied by a huge tsunami.

This megaseism hit a country which has not only the densest geophysical network of sensors in the world, plus a rapid seismic and tsunami alert system using the latest technologies, with the highest anti-tsunami barriers that exist, in a country where the population has the experience of past events and the best earthquake training imaginable, and finally where the scientific excellence of the engineers and research workers has enabled the Japanese to manage properly recent disasters, thanks to the knowledge acquired over the past century. The tragic consequences of this event encourage us to seek out their causes.

Clearly the direct aftermath of the earthquake was correctly handled, both in terms of the Government instructions issued to the population, the good paraseismic design of the main buildings and the automatic reactions of the alert system. Nonetheless, the scale and the extent of the earthquake took the Authorities by surprise.

Neither was the megatsunami predicted by the Japanese Authorities and this was both the cause of tremendous physical damage, notably to the nuclear reactors built near the coast-line and of considerable loss of lives. The Japanese example also throws light on certain questions and issues that should be addressed by France.

RECOMMENDATIONS

– All studies regarding natural risk factors (earthquakes and tsunamis) should be carried out over periods of time that are sufficiently long to integrate the high degree of irregularity needed to gain valid return data from experience. It is very important that we take account of both historic and geological records. Geological analyses should be developed, notably along the known major fault lines still in activity, in sensitive areas of Metropolitan France, the French West Indies and in the French Pacific territories.

– In the world's major subduction zones (and notably in the Caribbean area), France should participate in the international development of studies into, and protection against, megaseisms and associate tsunamis, through collaboration via the permanent measurement and alert networks that can measure seismicity and ground movement as well as variations in sea level and issue warnings in the case of detected and impending tsunamis.

– In this field research activities as well as surveillance and paraseismic standards should integrate the rapidly evolving knowledge base of earth sciences and associated technologies. This work should lead to regularly updated, common standards. Where basic research is concerned, the interactions between the various research teams working in these fields in different research establishments should be encouraged and vitalised. In particular, reflection should be forthcoming in involve the IRSN, the operators and the academics, and should be conducted with the aim to improve, if deemed necessary, the fundamental safety regulation (RFS in French) for nuclear installations, in order to integrate new assessment methodology for probabilistic events.

– Paraseismic construction standards must be complied with whenever builders begin to design a new structure and the completed building must be certified by a qualified authority independent of the prime contractor. Paraseismic construction standards for major infrastructures and industrial sites must be established at a pan-European level, notably when the sites are prepared for nuclear power generation equipment and structural housing or for chemical production plants, with active participation of IRSN, CEA and operators.

– Research and surveillance activities should receive regular financing from varied sources, guaranteed by the State both for the medium and long-terms. Studies conducted in relation to natural event probabilities in an operational context, such as assessing faults close to industrial plant that carry a risk factor, *e.g.*, large dams, chemical industrial sites and nuclear power stations, should be carried out directly by the industries concerned.

– The regional "Prefects" (nationally appointed authorities with extensive State delegated powers for certain local and regional affairs), who are responsible for civilian protection and for their delegated administrative powers need to be fully aware of the main characteristics and consequences for natural catastrophes. Specific training should be provided in these matters. Moreover, natural probabilistic events should be addressed in school programmes and be integrated into all citizens' education and cultural backgrounds.

– Research into natural probabilistic events and development of prevention schemes must be seen as being in the general interest and the Japanese example demonstrates clearly that such studies should concentrate equally on governance and pure research aspects of the issues addressed. A National Council for Natural Risks, placed under the authority and reporting to the Prime Minister should be instated and provided with funding from those ministerial departments concerned (Environment, Home Office, Higher Education and Research). Public research and academic representatives sitting on this Council should constitute a majority.

SECOND PART

The nuclear accident

THE NUCLEAR ACCIDENT WORKING PARTY, CHAIR AND MEMBERS

Édouard BRÉZIN	Président, ancien Président de l'Académie des sciences
Sébastien BALIBAR	Académie des sciences
Yves BAMBERGER	Électricité de France (EDF), Académie des technologies
Bertrand BARRÉ	Areva
Sébastien CANDEL	Académie des sciences
Catherine CÉSARSKY	Académie des sciences
Marie-Pierre COMETS	Autorité de sûreté nucléaire (ASN)
Robert DAUTRAY	Académie des sciences
Denis GRATIAS	Académie des sciences
Robert GUILLAUMONT	Académie des sciences
Guy LAVAL	Académie des sciences
Yves QUÉRÉ	Académie des sciences
Michel SCHWARZ	Institut de radioprotection et de sûreté nucléaire (IRSN)
Bernard TISSOT	Académie des sciences
André ZAOUI	Académie des sciences
avec la collaboration de Yves BRÉCHET	Académie des sciences

Personalities invited for a hearing by the Working Party

David BAUMONT	Institut de radioprotection et de sûreté nucléaire (IRSN)
Philippe BILLOT	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Bernard BOULLIS	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
François GAUCHÉ	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Gilbert GUILHEM	Institut de radioprotection et de sûreté nucléaire (IRSN)
Philippe JAMET	Autorité de sûreté nucléaire (ASN)
Xavier POUGET-ABADIE	Électricité de France (EDF)
Jacques REPUSSARD	Directeur général de l'Institut de radioprotection et de sûreté nucléaire (IRSN)
Alan ZAETTA	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)

Critical review assured by

Alain CARPENTIER	Président de l'Académie
Jean-Claude DUPLESSY et Denis JÉRÔME	Membres de l'Académie

The short text that follows is a summary statement of the findings and conclusions the Working Party reached, on three points:

– How should we understand the major nuclear accident at Fukushima Daiichi?

– What is the status of nuclear installations in France post-Fukushima?

– What potential is there for nuclear energy generation in the future?

This text was drafted in reference to the analyses we conducted and to the debates and hearings we held, that led to the writing of far-more complete appendices, either by members of our Working Party or by personalities it had invited for hearings.

1 | Sequence of events at the Fukushima Dai-ichi nuclear power stations

Among the appendices there is a detailed description of the sequence[1] of events that took place at the Fukushima nuclear power station. The following text simply summarises the main phases recorded. We present a preliminary analysis on the basis of data we have to date, but there are uncertain areas. It will probably take a few more years before we fully understand what really happened at Fukushima, distinguishing clearly, for example, the consequences we can attribute on one hand to the earthquake, and those resulting from the tsunami, in different areas of the power station. New data will become available, and it will prove opportune to resume our analyses, perhaps within an international framework.

It will also take some time to deduce and identify the errors to be avoided in the future, as well as the safety measures to be implemented in respect to currently operational nuclear reactors. Moreover in June 2011, at Fukushima the situation remains fragile and is at the mercy of another violent earthquake replicate.

Nevertheless, we can assert in all probability that the earthquake that happened on March 11, 2011, 14h46, despite being of a magnitude in excess of 9, *i.e.,* beyond the threshold limits used for the design calculations of the Fukushima[2] power station, would not have created too serious damage to the environment and to the health of the inhabitants, had there not been the tsunami. For the time being, the analyses are as yet dubious. It is possible, *e.g.,* that the depressurisation valves that connect the confinement bodies to the flue chimneys that release effluent gases directly to the atmosphere, may have been damaged by the earthquake. One consequence here could be that if these taps and valves were damaged they could have been the cause of the hydrogen explosions that took place in the reactor buildings and thereby endangered the spent fuel pools, which incidentally were not cooled. Our analysis on this point is uncertain and depends on making further in-depth investigations on the real state of the reactors today – this will necessarily take a lot of time.

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[1] Several web sites allow Internauts to follow the evolution in time of the six Fukushima Dai-ichi reactors: notably the official site of the Japanese Safety Authority [NISA] http://www.nisa.meti.go.jp/english/ ; the French Institut de Radioprotection et de Sûreté Nucléaire http://www.irsn.fr/FR/Documents/home.htm; the operator TEPCO's site – http://www.tepco.co.jp/en/press/corp-com/release/index-e.html
Appendix 1 contains details about the sequence of initial events at Fukushima.

[2] The building design called for a resistance capacity for an earthquake of magnitude 8: readers will note that one point on the Richter scale corresponds to a 30-fold increase in the energy released. Nevertheless, it is possible that the acceleration produced by the earthquake at the reactor sole did not exceed the limit value set by the building design engineers.

The paraseismic devices did come on line and reactors N°1, 2 and 3 were automatically shut down (reactors N°4, 5 and 6 were already in outage for maintenance), the external electric power supply had been cut, but the back-up generators needed to power the reactor cooling circuit pumps did start up normally. Despite the fact that the reactors had shut down, there was still the problem of evacuating the considerable amount of residual heat that originated in the radioactive products that accumulated in the nuclear fuel load during normal operation just prior to shut-down: we are talking about several tens of Megawatts (MW) in, a few seconds after shut-down and another fifteen or so MW only 24h later on. As we understand the information provided to date, it would appear that neither reactor core vessels nor the cooling pools in which the spent fuel cell arrays taken from the reactors[3] for replenishment, were cracked and it also appears that the hydraulic circuits, *viz.*, those used to cool the plant parts were intact and ready for use. Obviously, it is very difficult to ascertain the exact state of the equipment immediately after the earthquake, and before the tsunami hit the coast, given the level of damage that the site then suffered.

The reactors (vessel, core …) themselves had been properly designed to respond to an earthquake and to a break of the external power supply. Unfortunately, they had not been designed to last long enough for this case where the back-up electric supply and the cold coolant source were also knocked out by the tsunami. The latter hit the station 55 minutes after the earthquake, submerging the emergency electric generators of reactors N°1, 2, 3 and 4[4] and damaging the sea water intake devices as it travelled inland.

For each reactor, there still remained the emergency turbine generators. The cooling of reactor N°1 should have been assured by a passive system drawing on a water reservoir positioned directly above the reactor vessel (known as the "Isolation Condenser") and by a high pressure water injection system depending on a turbine driven pump that uses steam produced in the reactor core (known as the "High-Pressure Coolant Injection system". The passive system – that had started up and ran automatically before the emergency generators failed – stopped and could not be restarted later in a continuous mode. The turbo-pump failed to start. The exact reasons for these failures

[3] There still is a doubt as to the status of the cooling pool at reactor N°4 – which contained the reactor's full load of fuel, given that the reactor was in outage for maintenance purposes. Did this fuel load become uncovered by water because of a fault in the cooling circuits or because of a leak in the pool walls consequent to the earthquake? A fire broke out near the pool the origins of which have not yet been ascertained. Following a reconnaissance tour made by robots, the fuel assemblies were deemed to be intact.

[4] Reactors N°5 and 6 had been built respectively in 1978 and 1979 and were erected about 10 metres above sea-level (reactors N°1, 2 and 3 dated 1970-1973) and their cooling circuits were doubtless flooded by the tsunami. At the date April 18, 2011 the site situation seems under control. One of the four diesel generators was operational and proved adequate to the needs.

(human factor, material failure, and due, for example, to failed emergency battery) are not as yet known with precision. It therefore would seem that there was in fact no cooling of the reactor core for a period of approximately 14h.

For reactors N°2 and N°3, the cooling function was momentarily ensured by pumps driven by turbines themselves driven by steam from the reactor cores (known as the "Reactor Core Isolation Cooling system"). These pumps enabled cold water to be circulated from the reservoirs through the annular torus rings in the lower part of the reactor buildings. The high pressure water injection system also started up automatically in the case of Reactor N°3. For various reasons, that remain to be elucidated (battery failure, instrumental high water line in the reactor vessel, loss of pressure in the vessel), these emergency systems failed. It therefore would seem that there was in fact no cooling of the reactor cores N°2 and N°3 for a period of approximately 7h.

Since the cold source could not effectively be restored, these emergency systems would not have enabled long-term cooling for the reactors cores. Injection of cold water *via* a complementary system would have been needed, and was indeed finally found an implemented, but far too late given the situation.

With the absence of appropriate cooling, the heat released by the radioactivity of the fuel in the core slowly vaporises the water in the vessel, then heats up the resulting steam; the pressure inside the vessel rises. And when the temperature rises above 800-900 °C, the oxidation reaction metallic sheathes made of zirconium alloy, Zircaloy, that encapsulate the nuclear fuel[5] tends to accelerate strongly thereby freeing enormous quantities of gaseous hydrogen and associate energy inasmuch as this particular reaction is highly exothermic[6]. All this sequence probably took place in less than one hour.

When a system such as this type of reactor sees its coolant circuits dry up, then nuclear fuel is no longer immerged in the surrounding liquid water; at a temperature around 900 °C, the control bar structures (boron carbide in a steel sheath for boiling water reactors (BWRs) starts to melt, then at 1 800 °C the fuel cells (and their assembly encasements in the case of the BWR design) made of Zircaloy also melt; beyond 2 300 °C, the fuel itself starts a melt-down, it being notably dissolved by already molten structural matter and forms a magma, the so-called "corium" at a very high temperature.

[5] They are made from zirconium which is a neutron transparent metal, which at 1 200 °C in presence of water vapour reduces the water to form zirconium oxide and gaseous hydrogen.

[6] The free enthalpies for the oxidation reactions of Zr by H_2O and O_2 are respectively -459 kJ/mol Zr and 6 -755 kJ/mol Zr.

To decrease the internal reactor vessel pressure[7], the operators released steam, but when this came into contact with the metallic roofing over the reactor buildings, the mixture of hydrogen and steam exploded, in fact literally blowing off the metallic roofs first at reactor N°1 then at reactor N°3 (the level of damage being even more severe in the latter case). We can note that the reactor N°3 was partly loaded (a low fraction in fact) with MOX fuel[8] but that did not induce any significant change in the nature of the radioactive matter ejected, given that the compounds formed by the transuranian elements are scarcely volatile.

When a water intake was established via the fire protection circuit and used to inject sea water, the continuous heating and rising temperatures of the reactors were stopped. But, as of March 17, a new source of worry came when it was conjectured that in cooling pools, where spent fuel is stored (and especially for reactor N°4) the fuel cell structures could emerge and find themselves in direct contact with the ambient air above the pools. In this case the heat released by the radioactivity of the fuel would be sufficient – if the pool cooling circuit failed – to "uncover" a pool in, anything from one to ten days, depending on the number and the level of radioactivity of the fuel cells in the pool. Had the mechanical effects of the earthquake spilled a large quantity of water outside the pool or was the pool itself cracked? We still do not know the answer to this question. The potential danger her is quite serious since we would be faced with the equivalent of a core melt-down in the open air [9] without any confinement for the fission products released, since the pool designers had not included such protection barriers for these storage and cooling pools[10]. The fuel cell structures have not a priori been damaged, and this has been confirmed by measurements of the level of radioactivity round the Fukushima site[11] and reconnaissance sorties carried out by mobile robots. On April 23, the operator TEPCO announced that the pool temperature for the

[7] Placed in the torus, in principle separate from the confinement barrier, at 8-09 bar it appears in the case of Reactor N°1, whereas the nominal specified limit is only guaranteed to 5 bars. The steam release takes place through the torus water which retains part of the radioactivity, but subsequently can enrich the vapour with hydrogen when the steam condenses. Release of steam from the confinement volume exits in principle through the flue chimney. A very violent explosion took place at Reactor N°3 with a leak of radioactive water into the turbine hall.

[8] MOX : Mixed Oxide Fuel composed of plutonium from the retreatment process of spent fuels at 7% and depleted uranium ^{238}U, which is a "residue" from the enrichment process at 93%. 32 fuel cells out of 548 in the core were MOX fuel models.

[9] With a notable difference : there was practically no further 131 iodine emissions, but we note that there were 1 300 spent fuel cells from Reactor N°4, *viz*. The equivalent of several full reactor loads.

[10] Exception made of the external metallic structure. The explosion of these barriers doubtlessly allowed the fire lances to refill the spent fuel cooling pools for reactors N°1 and 3.

[11] It is now estimated that the caesium emissions would have been ten times higher than those resulting from damage to the reactors, therefore with radiological effects much more serious than those observed at this time.

reactor N°4 pool was still at 90 °C, *i.e.,* higher than the normal 40 °C, but below the boiling point of water.

At the date of August 25, 2011, it would appear that the situation is coming under control (provided of course that there is no new violent earthquake, but the ground nonetheless continues to shake) and that only small amounts of radioactive matter released. Reactors N°1, 2 and 3 are now constantly cooled by injection of soft water, directly into the confinement vessels (flow rate approx. 15 m^3/h)[12].The highly contaminated water that this flow produces after circulation in the vessel is taken from the turbine halls, treated in three installations, as of June 2011 and then after desalination is reinjected back into the vessels. Moreover, nitrogen gas is also injected into the three confinement vessels to maintain an inert atmosphere and avoid any risk of hydrogen catching fire (and/or exploding).

However the control phase will only be complete when the reactor cores are cooled down with a closed circuit coolant system in operation. The radioactivity measurements for matter released by this major nuclear accident, ranked level 7 on the INES[13] scale, *i.e.,* the highest level possible, indicate that the emissions into the atmosphere are approximately ten times less than at Chernobyl Notwithstanding, given that the radioactive particles rose to a far lower altitude, this led to radioactive deposits near the power station in a highly populated area on a level comparable with that around Chernobyl. The fact that the evacuation of the 20 km zone round the station (with approx 170 000 inhabitants) was ordered and organised before the major emissions of radioactivity took place, no doubt decreased the impact of the local radiation but for the moment we do not have an accurate estimation of the doses received by the inhabitants or the local radiation rates.

Moreover, due to especially unfavourable weather conditions, when the March 15 and 16 particle releases occurred (with a wind blowing inland and accompanied by heavy rain and even snow), the result as a strip of land North-East of the Fukushima area, 60 km long and 20 km wide which received high level deposits of radioactive iodine and caesium isotopes. The evacuation of 70 000 inhabitants was ordered by the Japanese Authorities two months after the accident in order to reduce their exposure to caesium 137 still present. The very existence of this new exclusion zone, together with the initial radial 20 km zone was probably the most serious result of this catastrophe.

It is sometimes imagined that a nuclear reactor out of control will become an "atomic bomb". Let us immediately clarify this – an apocalyptic scenario such

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[12] The first calculations related to hwo the accident unfolded show that the confinement vessel of reactor N°1 must have been pierced by the melted corium, releasing part of this radioactive, molten 'magma' onto the reactor's concrete floor base.

[13] International Nuclear Event Scale.

as this can, fortunately, be ignored. Nuclear accidents in the past, even the most serious ones, were caused by "classic" increases in temperature and pressure and not to any runaway, explosive chain reaction. The fuel used for a nuclear reactor, composed of uranium (^{238}U) and less than 5% of the fissile ^{235}U isotope, plus the 239Plutonium produced in the reactor, simply do not allow you to trigger a nuclear explosion, whatever the sequence of events[14].

The explosion that occurred at Chernobyl was due to a very rapid rise in water pressure as the power level of the reactor went off scale. In the case of Fukushima, the explosions were caused by hydrogen leakage – the reactors had been shut down immediately after the first effects of the earthquake were sensed.

A somewhat improvised process called for large volumes of contaminated water to be used to cool both the reactors and the fuel storage pools – decontamination of the water has just begun, following a procedure set out in an appendix to this report. Decontamination of soils and waste management will take place in a later phase.

Some complementary questions:

- Reactors buildings N°1-4 were built by digging, practically at sea-level, into the coastline cliff witch rises some 40 m above sea-level. Maybe the intention here was to use a rock base that would prove more stable in the event of an earthquake occurring, or maybe to facilitate pumping operations. Whatever the reason, the exposure of the station to tsunamis would not have happened if the station had been erected on the cliff-top. Obviously, the construction engineers realised the danger and changed their position, installing Reactor buildings N°5 and 6 are positioned some 10 m higher than the others[15].
- We can appreciate how important it is to protect diesel generators against the effects of flooding.
- The fact that the emergency backup systems used to control the turbines in the reactor failed (they are designed to keep the reactor under control in the case of simultaneous loss of both the external electric supply and the cooling sources, was an aggravating factor. We can only be surprised in regard to the possible causes for such a loss (it took place at reactor N°1 after just two hours of loss of power supply). Nevertheless, there being no cold source due to the tsunami, the cooling process could not have been assured for any length of time because the temperature of

[14] In order to make a nuclear weapon, you need to have access to almost pure ^{235}U, or at least enriched 80%. Dispersion of ^{235}U in the ^{238}U in a reactor totally precludes production of any "atomic explosion".

[15] Reactors N°5 and 6 are in cold outage status, as of March 20, 2011.

the water in the reactor vessel torus would have reached boiling point and led inevitably also to loss of systems.

- Absence (or inefficiency) of the hydrogen collecting and recombination equipment locate in the roof space above the reactor confinement vessel caused the explosions that took place above reactors N°1 and 3. In reactor N°2, the explosion took place in the vessel torus. We can note at this point that passive hydrogen recombination units (RAPs in French for passive auto-catalytic recombination devices) were installed, by the end of yr.2007, on all nuclear reactors in service in France (cf. below).
- The question is: did the operator TEPCO have all the means to hand, to adequately face emergency operations in radiating premises? Likewise, the other question is why it took so long for appropriate sized auto-pumps to be brought to the site and engaged in the cooling process. It will be recognised that damage to the road network round Fukushima and the sensitive questions of how to allocate means to various local situations did produce delays; nonetheless, these delays and their causes should be analysed in detail. It would also prove interesting to see if the robots supplied by the French Group INTRA[16] would have been capable of intervening efficiently.
- Absence of a confinement barrier above the cooling pools may lead – should the cooling process be down for several days – to a really serious danger, given that to date there is no system designed to limit the radioactive emissions that could occur[17]. In this light, we can understand readily how important it is to limit the number of spent fuel elements that are stored in cooling pools located on the same premises as the reactors.

2 | Nuclear power generation in France, post-Fukushima

The accident at Fukushima revealed that an extremely improbable event – *e.g.,* simultaneous loss over a long time span for both the electric power sources and the cold sources – leading to serious damage to three nuclear power generation units on a single site – did in fact happen. We must, consequently, re-assess the safety certification of our nuclear power generating units in France and take into account as ‘not impossible’ certain very low probability events, and include the possibility of several rare events occurring simultaneously, even though considered a priori to be independent of each other.

[16] A robot accident intervention group set up in 1988 by EDF-CEA-COGEMA.

[17] In the case of the EPR design, the cooling pool is located within the “aircraft-proof shell”, offering a high degree of resistance in the case of a large scale crash, but it will be noted that the shell offers no confinement role in respect to loss/emission of radioactive elements.

All past incidents recorded in nuclear industries and a fortiori those classified as serious or major, have led to a stringent re-assessment of safety factors in design and in operating nuclear power production plants. On each such occasion, appropriate modifications have been introduced and further research engaged with the aim to improve safety levels and operational security. It is thus fundamental that we draw all the lessons from the events at Fukushima.

2.1 French nuclear power stations

France today produces 78% of its electricity in 58 nuclear power reactors, operated by EDF (the French national electric utility operator), and these reactors can be classified as follows:

– 34 reactors, each 900 MW, average operational life to date* - 29 years;

– 20 reactors, each 1 300MW, average operational life to date - 23 years;

– 4 reactors, each 1 450 MW, average operational life to date - 13 years.

(*These average operational lives are calculated starting at the time the reactor diverged, up to a reference date, December 2010). We note that an EPR (European Pressurized Reactor) 1 600 MW reactor is currently being assembled at Flamanville (on France's Northern coastline, bordering the English Channel).

All 58 reactors in service at France are of a PWR design (pressurized water), used to both moderate the neutron emissions and evacuate heat, whereas the technology at Fukushima is BWR (Boiling Water Reactors). Readers interested will learn some basic operational features of the various reactors designs, and details for both[18] PWR and BWR plant. Water-cooled and water moderated reactors do have the advantage that in the case of loss of water (by transfer, leaks or by boiling), the number of fission reactions decreases: this is an intrinsic feature of their core designs and is of highest importance in terms of meeting safety requirements. These reactors use 3,5% enriched uranium[19] for fuel loads and in the case of over 20 of the 58 reactors, a Mixed OXide, so-called MOX fuel (cf. Appendix 14).

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[18] There are also so-called heavy reactors, where a fraction of the water molecules consists of oxygen and deuterium (the hydrogen isotope twice as heavy as hydrogen alone).

[19] cf. Appendix 1: glossary.

Design, construction, operation and dismantling of nuclear power generation plant (nuclear reactors per se, workshops for assembly, dismantling of fuel elements) obviously are all dictated by absolute safety standards. The responsibility for ensuring overall safety of nuclear power generation plant lies with the operator, *viz.,* EDF in France. Modifications leading to improvement of safety levels happen when:

– there is a return on experience, through incidents and/or accidents;

– the 10 yearly full inspections of each nuclear power plant.

Incidents do occur, indeed in all industrial sectors including nuclear, and we can cite the example of the flooding of the French Blayais station in 1999, or the serious accidents such as occurred in 1979 at Three-Mile-Island (TMI), Pennsylvania, USA or the major accidents such as at Chernobyl in Ukraine in 1986, led to deep-reaching analyses and to subsequent and significant improvement in terms of plant safety, not only from a technical standpoint, but also in terms of operations organisation and human factors. In France, this is one of the R&D and engineering missions assigned to EDF and IRSN also does research in this area. The accident at Fukushima will certainly lead to a full review of similar risks elsewhere and then to the implementation of remedial measures if deemed necessary by local authorities.

The building permit on a nuclear power plant does not include any *a priori* reglementary provision as to life expectancy of the installations, but does require that the operator carry out an in-depth safety inspection every ten years[20]. Bring the reactor back on line can only be done with approval from the French Nuclear Safety Authority (ASN). The oldest French plant installations are consequently going through their third ten year inspection, beginning with Tricastin N°1 and Fessenheim N°1. The ASN in November 2010 issued its approval for continuing operation of Tricastin N°1 following 30 years of previous operation. ASN will likewise issue its decision in respect to the capacity for Fessenheim N°1 to continue to be operated for a further ten years, *i.e.,* till the next full inspection. Fessenheim N°2 is currently in its ten-year outage for routine inspection.

Continuous surveillance of reactors, modifications introduced to account for return on experience and progress recorded in safety research, plus the ten yearly inspections carrying the prerequisite of an ASN approval before being brought back on line; all tend to notably reduce any potential risks due to ageing of the French nuclear power generation plants.

[20] The Working Party did wonder what could the justification of a ten year inter-inspection period, and why this is not 5 years, for example? The answer is that several years of preparatory work are needed before each 10 year full; inspection. In addition, there are continuous spot checks and routine inspections.

The accident at Fukushima does not constitute a reason for stopping France's older nuclear power stations[21]. Notwithstanding, it does imply that an in-depth inspection be carried out on all similar sites (whether recent or old) inasmuch as nuclear plant is an intrinsically complex technology system, and special attention must be given to the control and failsafe sub-systems, the ancillary equipment and the spent fuel storage pools. We need to re-assess all the existing storage pools used to store radioactive nuclear wastes while awaiting to be vitrified and placed in repositories.

In addition, we need to look into the consequences of a severe dry spell (weather-wise) that could in essence jeopardise the plant's external cooling systems. However, the danger level here is not of the same nature inasmuch as it can readily be seen as it develops and in this case the reactors can be closed down; this would lead to a loss of electricity for the national grid but would be nowhere near the damage level incurred by a tsunami or brutal flooding of the site.

We can note that on each nuclear power production site in France, there are cooling water reservoirs for the reactor vessel and for ancillary equipment, and these are planned as of design phase. In certain cases, they have been improved where deemed necessary in terms of return of experience. Return of experience on the Fukushima accident must also be taken into account, for the purpose of introducing further improvements.

2.2 How France's national nuclear safety is ensured and organised

2.2.1 Regulations

French law (June 13, 2006) appertaining to transparency and safety of nuclear plant and its operation, led to the establishment of the ASN, which is an independent administrative authority, responsible for controlling all civilian nuclear activities in France. ASN, on behalf of the State by its remit, ensures the control and inspection of nuclear safety equipment and protocols, radioprotection for workers in the nuclear industries, hospital patients, then public at large and the environment faced with risks arising through use of nuclear reactions[22] and ionising radiation. ASN is headed by a group of

[21] The NRC (Nuclear Regulatory Commission of the USA) has examined requests from the reactor license holders to extend the service life from 40 to 60 years. This extension has already been granted to over 100 reactors.

[22] Nuclear safety includes nuclear safety, radioprotection, prevention and the fight against terrorism and similar attacks, as well as civilian security in case of a serious or major accident occurring.

irrevocable commissioners, each appointed for a ten year term of office by the President of the French Republic and by the Presidents of the two Parliamentary houses (MPs and Senators). The same law June 13 institutionalised local Information Commissions[23] that liaise with each nuclear power generation site.

Insofar as we can ascertain, ASN is indeed an independent authority when it come to controlling operations at nuclear plant – indeed, it demonstrated this by ordering the stoppage of Bugey N°3 reactor until such times as the operators had replaced the steam generators, following suit to the discovery that there was extensive corrosion on one of the existing generators. The reactor was in an outage status for twenty months.

We can also note that since 2001 there is a Delegate for Nuclear Safety and Radioprotection for all activities and plant that reports to the Defence authorities; the Delegate reports to the Minister of Defence and to the Minister for Industry.

Both ASN and the Delegate rely on the technical expertise provided by the French Institute for Radioprotection and Nuclear Safety (IRSN).

2.2.2 Research in nuclear safety matters

The IRSN Institute (supra) was established by law May 9, 2001 and housed some 1 000 specialists of these fields, research scientists, engineers, technicians, physicians, highly competent in issues related to nuclear activities and radioprotection. The research programmes conducted in nuclear safety questions by the Institute, for the benefit of public authorities, are carried out in the IRSN laboratories located in France, on eleven 11 different sites, often in partnership agreements with the CEA[24], the CNRS and numerous international laboratories[25]. IRSN disposes of a 90 M /yr budgetary expenditure for nuclear safety research programmes, carried out mainly in the IRSN laboratories and those of its partners. IRNS also conducts research in radioprotection matters (for human beings and the environment) and its results here were used for the events at Fukushima. Readers are invited to consult Appendix 9 describing the contribution of IRSN to accidents involving a core melt-down.

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[23] cf. The site of the Association nationale des comités et commissions locales d'information : www.anccli.fr

[24] Commissariat à l'énergie atomique et aux énergies alternatives [Commissariat for Atomic Energy and Alternate energy sources].

[25] Numerous references to IRSN programmes are found at the site www.irsn.fr. The document authored by Mr Schwarz « Recherche à l'IRSN sur les accidents de fusion de cœur [ISRN research on core melt-down occurrences] is attached in appendix and give a situation status as of April 2011.

2.2.3 French programmes for nuclear safety research

The main objective when designing, sizing and operating nuclear power generation plant (reactors, fuel cell workshops) is to ensure overall plant safety by taking into account, as of the drawing board stages, those devices, procedures, etc., intended to prevent certain potential accidents. In the case of a reactor the most feared accident, of course, is a core melt-down which would lead to emission of large quantities of radioactive particles into the atmosphere and impact the environment.

Research into the chain of events that leads to accidental particle emission and their consequences on the environment are vital to the process of producing energy from nuclear fission. For France, it is the IRSN and the CEA who engage in such research, in liaison with the operators (EDF for the reactor installations) and Areva for the fuel cycles and the CEA for experimental reactor designs and prototypes and other basic nuclear infrastructures and equipment. Both IRSN and CEA participate in numerous European and international research programmes and are programme leaders in some cases. The research work carried out by the IRSN is essential to development of the Institute's capacity to exercise its independent expertise. The operators themselves have their own research and development teams.

Additional research has often been engaged following incidents or accidents in nuclear reactors or other parts of the cycle. Each accident reveals new situations and circumstances and leads to progress in terms of safety factors. For example, after the accident at TMI-2 (1979) and at Chernobyl (1986), the research programmes and return on experience led to major modifications in certain safety related components (or are currently being developed) for the currently operated second generation reactors as well as development of systems to limit the consequences (hydrogen recombination units, pressure relief valve design and filers for the confinement vessel barriers). New reactor operating protocols were drafted and implemented. All the lessons learned together with the result of research have contributed to the design of the 3rd generation reactors, such as the European Pressurised Reactor (EPR).

Research programmes in nuclear safety for 2nd and 3rd generation plant relate to two sorts of accident:

– Dimension related accidents the consequences of which are integrated into design stages for later reactors. The challenge here for the scientists and engineers is to counter such accidents and prevent them from degrading into serious accidents. There are two categories here: loss of the primary coolant (should for example the primary circuit fail, leak or break) and reactivity accidents (instant power level rise when a control bar is suddenly removed leading to a rapid rise in temperature of the fuel in the reactor or a very rapid loading of the fuel cell assemblies.

– Serious operational accidents or outwith design reasons (*i.e.,* not due to design errors) where the challenge for the operators is to control and limit the consequences. The risk here is losing the confinement consequently to a part or a total core melt-down and to avail of devices that will limit further effects (using so-called mitigation technologies). Such accidents (*viz.,* with core melt-down) were not taken into account when designing the 2nd generation reactors; this research programmes are aimed at reducing where possible this risk and limiting its consequences should it take place.

  A demand issued by the French national Safety Authorities, dated 1993, called for integration in design stage of any new reactor, all categories of serious accident. In particular, devices and arrangements that permit containment of the consequences of such events within the reactor confinement barriers have been taken into account for the design of the 3rd generation reactors, such as the EPR.

The problem with safety research lies in the extreme complexity of the phenomena interacting. The scientific aims are to gain a better understanding as to the physical and chemical processes that lead to a break in the confinement barriers (sheaths for the fuel cells, primary cooling circuit and the confinement walls) and to characterise the subsequent emissions of radioactive nuclide particles (identification, quantities, dispersion diagrams, terrain measurements *in situ*). We must be in a position to develop models and tools for simulation. They must notably be capable of predicting *in extenso* how a given accident is going to evolve and to assess and identify the means that need to be used to limit the consequences.

The CEA research programmes, supporting efforts to improve safety levels of the electronuclear industries, are mainly funded by the operators, but also receive grants from the State and in certain instances from the IRSN.

It is vital that scientists have the means to carry out research in the public's interest, even beyond the research work carried out for funded by the industrial sectors involved.

Experimental work in the field of nuclear safety calls for considerable ways and means, in certain cases of a remarkably high standard, notably in respect to studies of fuel cells, on premises and with installations that allow you to handle highly radioactive material, which requirement today, can only be dealt with accordingly on the CEA premises. These experimental means for safety issue research need renewing and new installations are currently being assembled.

We know that the behaviour of an uncooled reactor allows us to understand what happened at Fukushima. The Fukushima accident, when analysed, shows that the knowledge base needs to be improved in-depth, and even that new forms of research have to be initiated. The CEA, IRSN and the industrialists are already examining how to upgrade and/or redirect some of their research programmes and to establish priorities and make estimates for funding.

Whatever the circumstances that lead to emission to the atmosphere and environment of radioactive particles, it is important to be able to rapidly characterise the extent of the contamination and its nature. This is an area of research that needs to be addressed by a wide-spread and numerous scientific community, inasmuch as environmental issues are concerned. Operational procedures have to be improved, with operational simulation models and also studies into chemistry and transportation of radioactive elements contained in the nuclear fuels when transiting in various environments, should be engaged.

Research into nuclear safety is a priority issue and should be written into clearly defined and publicised programmes. In particular, public research in safety matters must be considerably revamped and developed beyond what is already done by the industrial sectors. It must take into consideration, not only the physicochemical aspects of accidents but also management of serious crisis situations and the implementation of mitigation processes to diminish the consequences of the latter. Scientists as a corporate body should be associated with these challenges, beyond the research commitments of specialist establishments such as the CEA or IRSN.

Some questions and research in regard to hydrogen

Hydrogen explosions represent a real danger if there is also a core melt-down, and this seems to have been inadequately handled in the case of Fukushima. The hydrogen explosion risk is perfectly identified in various studies that exist in France and elsewhere in the world. So-called passive recombination devices for hydrogen have been installed in all the French nuclear power stations; the aim is to consume (adsorb) hydrogen as and when it is released and to prevent it from accumulating should it be produced accidentally. Generally speaking, the recombination is ensured by catalytic adsorption which is a slow process compared with the rate at which hydrogen is produced in the case of a core melt-down; we need to verify that the various measures taken allow you to limit the quantity of hydrogen that is temporarily present in the reactor’s confinement volume.

It would likewise prove useful to assess the behaviour of the gas release and filter devices that exist on currently operated reactors to ensure depressurisation and thus limit the pressure in the confinement volume. Although the primary objective is not to evacuate the hydrogen produced, an ignition of the gas is always possible after a venting pressure release operation. The arrangements needed to avoid this happening consist of adding a high relative concentration of water vapour to inert the vented mixture and to place other devices that preheat the mix to prevent condensation of the vapour in the pipes, thereby maintaining the mix's inert characteristic. These devices and their operation should be re-examined in the light of what happened at Fukushima. More generally, it is important to pursue ongoing research efforts as to the risks associated with the presence of the hydrogen in the confinement vessels.

3 | Nuclear fuel cycle and future possibilities

3.1 A comparison of safety equipment: EPR - Generation II reactors

Readers will find in appendix a detailed description of improvements incorporated in the EPR design[26] which, in essence, is a PWR with improved safety equipment with respect to the other (2nd generation) reactors in service today. The improvements cover a real decrease of the probability of the core melting, thanks to a provision to stock much greater qualities of cooling water and a series of back-up, emergency electric generators, a paraseismic architectural design which can also resist an aircraft impact, a "spread zone" for a hypothetical corium being formed in the case of a serious accident. The EPR generation has effectively drawn from the return on experience of the TMI and Chernobyl accidents. In contradistinction, there is no provision to confine radioactivity losses that would occur in the event of an accident in the cooling pools where the spent fuel cells are stored.

3.2 Beyond the EPR

Readers will find in an appendix a very full description of then operations that appertain to fuel handling, from the point the uranium oxide is mined, to the ultimate waste stage when completely spent. Let us note that the French electronuclear industry has taken several specific policy decisions here:

– the spent fuel is retreated to extract plutonium and to durably store the ultimate wastes;

[26] European Pressurized Reactor.

– a new fuel mixture, named MOX, is made incorporating the plutonium;
– the highly radioactive ultimate wastes are vitrified;
– studies engaged to identify possible deep geological repositories for long-life ultimate wastes.

The current strategy, i.e., with extraction of plutonium from the initial fuel load after its operational service time and its re-composition to become a MOX[27] fuel is coherent with the French policy vision that calls for the building and commissioning of high speed neutron so-called breeder reactors (Generation IV) in the second half of this century. Naturally, these options could be reassessed if another radically different stance were to be adopted.

Decisions concerning the future of France's electronuclear industry lie exclusively in the hands of out fellow citizens through application of the democratic process by which we live. We simply wish to situate those potential possibilities of nuclear power generation we should bear in mind before the political decisions are taken:

– Using so-called fast neutrons for the fission process[28] enables us to fully exploit the potential energy of the uranium (or thorium) and thereby we can increase the availability of energy for the future to several thousand years, even though this would involve a complete overhaul of the current nuclear industry and its power production sites.
– The existing stock of depleted uranium, as it results from today's enrichment processes, together with the plutonium that has already been extracted through retreating spent fuel loads, gives France huge energy reserves, with zero emission of greenhouse gases (GHGs).
– The ASTRID prototype will be commissioned in the 2020s and will constitute an important stage for the development of a breeder reactor using sodium as the coolant. This new breeder design will possess a higher level of safety resulting from ongoing studies notably with a reactor core that has pre-designed intrinsic stability that enhances the safety factor probability to a level that does not exist in any breeder FNRs[29] reactors currently in service. Designers and building engineers involved in this project will certainly, when ready, make proposals for complementary safety features to ASN and the latter will naturally make known its position in this respect.

[27] It should be noted that spent MOX fuel assemblies are not retreated.
[28] We recall that the fissile isotope ^{235}U represents only 0.7% of naturally existing uranium. If we use the ^{238}U isotope, which is 140 more abundant, the energy procurement horizon goes from several centuries to thousands of years.
[29] Fast Neutron Reactor aka breeder reactors; in French RNR for Réacteur à neutrons rapides.

Other concepts under study in the laboratories certainly merit further, long-term, investigation; as examples we could cite very high temperature reactors, molten salt cooled thorium reactors, hybrid fission-fusion reactors, magnetic and inertial fusion, etc.

The major nuclear accident at Fukushima led the Academy (Académie des sciences - Institut de France) to undertake this report. A considerable amount of investigation will be necessary if the Academy wishes to issue long term recommendations about alternate paths for future reactors and current fuel cycles.

RECOMMENDATIONS

The major accident that occurred at Fukushima throw emphasis on the fact that not only is it vital to maintain some form of cooling system for both the reactors and the cooling pools containing spent fuel loads but also a need to contain radioactive matter whatever the circumstances. Studies must be resumed in respect to natural risks, whether they be seismic or climatic, including possibilities that a site risks being flooded (i.e., the back-up emergency electric equipment must be made totally waterproof), a study of the dangers presented by the cooling pools and the possibility to build confinement barriers round the cooling pools and organisation of emergency services should an accident occur. All accidents in the past have demonstrated the importance of recruiting highly skilled personnel, including among the adjunct temporary technical staff.

Nothing can gainsay a safety requirement, but there again no human activities are exempt of a degree of risk. Examples that readily come to mind are in the worlds of aviation, oil industries and automobiles. Previous accidents have enabled us to progress; research on safety issues identified in the aftermath of Fukushima have only just begun.

The paraseismic devices at Fukushima did operate satisfactorily, at least a priori; the catastrophe that hit Japan so severely was caused by the tsunami that followed the earthquake.

The fact that reactors N°1 to 4 were erected on the coastline, practically at sea level, shows that the tsunami wave-height had been seriously underestimated.

The safety measures had not foreseen concomitant loss of all the electric sources (internal and external), plus the loss of the cold sources for both reactors and the cooling pools for any length of time.

- **Concerning French reactors today**

1. The danger of residual heat from the core with the reactor down and from the cooling pool must no doubt be reassessed. Precautionary measures need to be taken in regard to the quantity of last-stand water supplies.

2. We must reassess the case of cooling pools. Ensuring that cooling of the fuel cells stored must be guaranteed under all circumstances, using appropriate means is one of necessary measures that must be taken in terms

of safety and radioprotection with the return on experience from Fukushima. Industrialists will make proposals and the national authority for nuclear safety (ASN) will be required to make its position known.

3. As far as is possible, the quantity of spent fuel cells in cooling pool storage must be limited.

4. Dangers represented by natural accidents, earthquakes, flooding and possible concomitant occurrence should be reconsidered.

5. We should also make provision for external circuit connections to be added to the reactor, to be used with external mobile cooling units; the time needed for passive safety devices to come on line in the case of 3rd generation reactors should be reconsidered in the light of the Fukushima accident.

- **For the future**

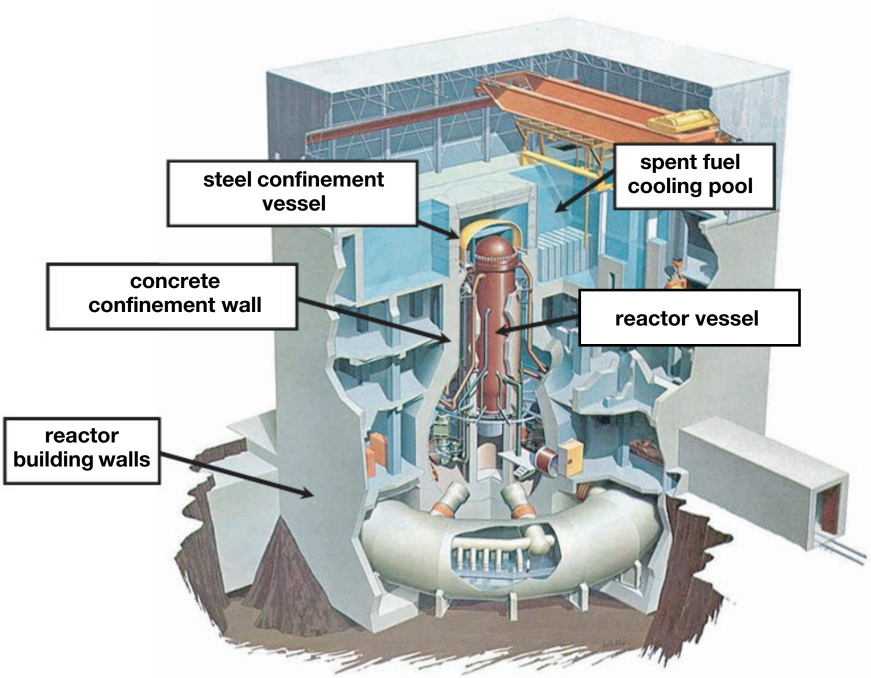
6. These events at Fukushima have shed new light on risk factors for reactors and spent fuel storage. We must not lose sight of the fact that the safety requirements outlined here concern all nuclear activities up to and including the definitive disposal of the ultimate radioactive waste matter.

7. Public research in the field of safety must be developed considerably (research into critical situation management, ways and means to prevent radioactive wastes getting into the atmosphere and environment, core melt-down and corium behaviour. Scientist must be associated with such work over and above commitments in the industrial sector research laboratories (EDF) and those of specialist establishments such as the CEA and ISRN. Academic/CNRS/engineering schools/universities' research should be reinforced, thereby enabling an increase in the number of points of view and possible options.

8. Beyond research engaged by the operators, who are legally responsible for the safety of their plant and infrastructures, the ISRN and CEA should be able to dispose of the means needed to carry out their own research in regard to innovation in safety issues and for novel nuclear installation design.

9. Design and operation of a possible future generation of nuclear power stations must be framed in such as way as to minimise transportation of radioactive matter.

10. The future of nuclear electric power generation lies with citizens and democratic process and not in the hands of the experts alone. However, this assertion implies that we need to explain clearly what the issues are and identify the various options possible, bearing in mind at all times the prime requirement for safety, not isolating the nuclear industrial sector from other sectors, not forgetting the general context of global warming in which this debate will necessarily be conducted.



Nuclear power plant of Fukushima Dai-ichi.

THIRD PART

Consequences on health and the environment

THE WORKING PARTY ON CONSEQUENCES ON HEALTH AND THE ENVIRONMENT, CHAIR AND MEMBERS

Étienne-Émile BAULIEU	Président, ancien Président de l'Académie des sciences

Sub-Section I – Radio-exposure and radioprotection

Bernard LE GUEN (coord.)	Électricité de France (EDF)
Roland MASSE (coord.)	Académie des technologies
André AURENGO	Académie nationale de médecine
Agnès BUZYN	Institut de radioprotection et de sûreté nucléaire (IRSN)
Edgardo D. CAROSELLA	Académie des sciences
Anne FLÜRY-HERARD	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Pierre LAROCHE	Service de protection radiologique des Armées
Michèle MARTIN	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Henri MÉTIVIER	Professeur émérite à l'Institut national des sciences et techniques nucléaires (INSTN)
Denis SAFRAN	Réanimation et traumatologie, Hôpital Européen Georges Pompidou
Jean SALENÇON	Ancien Président de l'Académie des sciences
Maurice TUBIANA	Académie des sciences
Alain-Jacques VALLERON	Académie des sciences

Sub-Section II – General Sanitary Consequences

Alain-Jacques VALLERON (coord.)	Académie des sciences
Michel SETBON (coord.)	CNRS, École des hautes études en santé publique, sociologue
André AURENGO	Académie nationale de médecine

Humbert BOISSEAUX	Hôpital Interarmées du Val-de-Grâce, service Psychiatrie
Pierre CARLI	Académie nationale de médecine
Marie-Lise CHANIN	Académie des sciences
Marc GENTILINI	Académie nationale de médecine
Michel LE MOAL	Académie des sciences
Denis SAFRAN	Réanimation et traumatologie, Hôpital Européen Georges Pompidou

Sub-Section III – Rehabilitation of soils and housing

Henri MÉTIVIER (coord.)	Professeur émérite à l'Institut national des sciences et techniques nucléaires (INSTN)
Jean-Marc PÉRES	Institut de radioprotection et de sûreté nucléaire (IRSN)
André AURENGO	Académie nationale de médecine
Pierre CHAGVARDIEFF	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Jean-Jacques LEGUAY	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)

Personality invited for a hearing by the Working Party

Monique SENÉ	Vice-présidente de l'Association nationale des comités et commissions locales d'information (ANCCLI)

Critical review assured by

Alain CARPENTIER	Président de l'Académie
Yves AGID	Académie des sciences
Jean-François BACH	Secrétaire perpétuel de l'Académie des sciences
Édouard BRÉZIN	ancien Président de l'Académie des sciences
Laurent DEGOS	Académie des sciences
Jacques FRIEDEL	ancien Président de l'Académie des sciences
Daniel RICQUIER	Académie des sciences

Introduction

The sanitary consequences of the major nuclear accident at Fukushima-Daiichi, Japan, are closely tied in with the natural catastrophe resulting from the giant Tohoku earthquake and the megatsunami, March 11, 2011. Firstly, because the nuclear accident was the direct result of the tsunami, secondly because the tsunami destroyed the infrastructures of the area, and this alone disturbed the authorities when taking urgent decisions relative to the local installations and the implementation and enforcement of measures to protect the populations against ionising radiation.

The consequences of the earthquake and the megatsunami are now well documented.

Observers have been able to see the important progress achieved in paraseismic building design, thereby considerably limiting loss of lives when the earthquake occurred. A useful comparison in this sense can be made with recent earthquakes in Chile and Haiti.

As far as the tsunami is concerned, we also underscore the importance of Japan's forecasting systems and the admirable role played by the organisation and discipline of the Japanese people. Again, a stark comparison can be drawn with the Sumatra tsunami that hot the coast December 26, 2004: loss of lives in Japan albeit horrendous, was ten times less than on Sumatra.

The impact of the nuclear accident is more difficult to evaluate, and for this reason, the French Académie des sciences has decided to focus its analysis on the consequences of being exposed to ionising radiation – both in terms of humans and on the environment – widening the scope of its studies to the psychosociological effects of exposure, in the overall context of sanitary consequences of large-scale destruction due to the tsunami waves and flooding.

With the data available to date, at the close of 2011, our purpose is to draft a status report and also give a forecast as to the evolution of risk factors following direct risk due to the Fukushima nuclear accident in the light of experience gained through previous catastrophes. In concluding our Report, we shall frame some recommendations that we deem applicable to France.

From a sanitary point of view, the earthquake and the tsunami and the damage that resulted to several reactors of the Fukushima-Dai-ichi power stations also produced attested sanitary effects that may carry the implication of certain potential consequences:

- the dramatic and immediate loss of lives (23 000 dead or missing) following the earthquake and tsunami; on the Fukushima nuclear site, two workers were reported missing after the tsunami had passed through the plant buildings;
- consequences related to ionising radiation, whether through external exposure given the proximity of the radioactive sources, or contamination by radioactive particles and matter, classified external if occurring on the skin surface, or internal if they are ingested (contaminated food-stuff) or inhaled (radioactive gases or aerosols). These potential consequences can be rapid and proportionate to the level of the radioactive dose received (for high doses), such as those impacting the workers who were sent into the reactor area after the accident, or relatively delayed, and which apparently affected plant workers and local populations in a haphazard distribution, with a higher probability as the dose received increased;
- consequences that can be attributed to the difficulties surrounding the inspection/repair visits to the reactors and ancillary equipment (pumps, …) at Fukushima, in particular during the initial weeks after the accident; stress, fatigue, working under extreme heat in a devastated industrial site (25 wounded, 2 deaths, one because of a fatal heart attack while another died due to a collapsing crane…);
- consequences to public health, related to post-accident trauma, following suit to the natural catastrophe (earthquake and tsunami) and the nuclear accident, related also to faulty communications and to the evacuation orders, whether justified or not, and finally to temporary accommodation for the survivors. These various factors can induce a high morbidity including depression syndromes, suicides, addictive pathologies (tobacco, alcohol) and worsened existing pathologies due to disorganisation of the medical care services. Moreover, apprehension of the future can lead to a drop in fecundity and an increase in voluntary termination of pregnancy;
- severe environmental consequences: soil contamination disturbed the agricultural production of the entire area of the Fukushima prefecture (approx. 500 km^2) to the point that large scale civil engineering equipment and operations will be needed to be deployed to ensure adequate decontamination, after identification and specific treatment of "hot spots". Quality and speed of the rehabilitation process will

determine the main characteristics of the nuclear accident aftermath and of the final effects of the accident on people's health.

The management principles adopted by the Japanese authorities dealing with the Fukushima accident comply with the recommendations of the International Commission for Radiological Protection (ICRP). The approach implemented calls for an "emergency phase" followed by a phase specific to long-lasting radiation exposure. The objective of the protection measures is to prevent immediate effects and to reduce delayed effects to the lowest reasonably attainable level, given the prevailing circumstances.

For emergency levels of exposure, evacuation is enforced if the populations concerned risk receiving radiation levels of 100 mSv/yr or more, and not recommended if the level is below 20 mSv/yr. During this initial emergency period, *viz.*, with a risk in the range 20-100 mSv/yr, the objective is to protect the populations from radioactive fallout and to make preparations for their return to certain exclusion areas[1]. The measures taken include evacuation and sheltering of the displaced populations, food-stuff management, precise cartography and monitoring of the contaminated areas, primary decontamination (tarmac cover, showering, sealing and equipping buildings used to shelter children, in particular school congregation areas …) that can enable a gradual return of the populations after six to nine months to the least contaminated zones.

This initial emergency phase was transitory, *i.e.*, the time needed to deal with the crisis situation. As soon as the situation at Fukushima was stabilised, the management policy moved to the stage called "existing exposure" and the value recommended by the ICRP[2] for this sort of situation must fall between 1 and 20 mSv/yr, depending on the circumstances. The objective is to bring the level below the level of 1 mSv/yr after several years. The decision to move from the emergency phase to "existing exposure situation), to use the ICRP denomination, was only taken end September 2011 by the Japanese Government. The long-term management of the 'stable' contamination is based on a single radionuclide: caesium 137. After the local populations have returned to the least contaminated areas, appropriate soil treatments and crop selections will have to be implemented.

This demonstration of the will of the Japanese authorities to control exposures aims at avoiding any long-term sanitary impact (with the objective of a

[1] ICRP 109: Application of the Commission's Recommendations to the Protection of People in Emergency Exposure situations Ann. of ICRP, 39 (1), 2009.

[2] ICRP 111: Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas After a Nuclear Accident or a Radiation Emergency. Ann. of ICRP, 39 (3), 2009.

cumulated dose "around 100 mSv" over several years) and setting up a 30 year sanitary monitoring programme for a population estimated at approximately 400 000 persons. The accident at Chernobyl showed that in Belorussia, 25 years after the events, the annual average dose for one million inhabitants of a territory that are still considered to be contaminated by the Administrations is approximately 0.1m Sv/yr. Only a few thousand persons are exposed today to doses of the order of one millisievert. This result was obtained through both the gradual natural decrease in the levels of radioactivity and the continuous work by the public authorities and other actors, including the populations themselves, especially the agricultural workers, to control residual contamination. The authors of this Report present the direct sanitary consequences of the accident at Fukushima-Dai-ichi and draw a comparison with those associated with the accident at Chernobyl (cf. Section 1.1). We shall then refer to some general sanitary consequences, over and above the specific effects of radioactivity (cf. Section 1.2). Lastly, we shall analyse both the environmental consequences and the decontamination measures to be taken (cf. Section 2). Throughout the Report, and in particular in our Recommendations, we evoke what the consequences might be if ever such an accident were to occur in France and what steps could be used to mitigate them.

The main concepts related to radioactivity (characteristic features of a radioactive source, dosimetry, effects of ionising radiation on living organisms, radio-induced cancers, prevention measures using stable iodine) are recapitulated in the Appendices.

We based our findings largely on communiqués issued by MEXT[3], by the IAAE[4] and the French IRSN[5], by the Japanese company TEPCO and the UNSCEAR Report, dated April 2011[6] and on the consequences of Chernobyl and by the Japanese Government to the IAAE (June 2011).

We must insist on the fact that the data we were able to access in relation to Fukushima must be seen as provisional and may well be revised significantly, as a function of progress in clinical, dosimetric and environmental studies, in Japan. The data we have used dates from November 2011.

3 Japanese Ministry of Education, Culture, Sports, Science and Technology.
4 International Agency for Atomic Energy.
5 French Institut radioprotection et de sûreté nucléaire.
6 United Nations Scientific Committee on the Effects of Atomic Radiation.

1 | Sanitary consequences of the accident at Fukushima-Dai-ichi

The Tohoku earthquake and subsequent tsunami that hit Japan so badly on March 11 caused 22 626 dead or missing persons[7] due to the earthquake and the tsunami, according to the WHO SITREP35 Situation Report, dated July 5, 2011. Before Japan even begins to clear the disaster area for future reconstruction programmes, the Government already is faced with a bill evaluated initially at 297 billion $US, to which sum must be added the costs of dismantling six reactor buildings and equipment, of rehabilitating the areas contaminated by radionuclide fallout from the Fukushima-Dai-ichi reactors N°1, 2 and 3, from the cooling pool of reactor N°4, and for creation of a definitive exclusion area of ground that has been permanently contaminated. A further evaluation was issued May 31 by the President of the Japan Centre for Economic Research placing the costs between 70 and 245 billion $US. The result in financial budget terms will be to decrease by 50% the national GDP growth figure for yr. 2011 and will also incur a sanitary cost because of the choices to be made that will necessarily diminish the well-being of Japanese citizens.

But what about the sanitary consequences of the nuclear accident alone? We could readily imagine that they are high because of the dramatic media coverage. It is still early days to draw a definitive conclusion but nonetheless, we can relate to the effects of Chernobyl, April 26, 1986. According to the assessment issued in August 2011 by the Fukushima nuclear plant operator TEPCO, the total qualities of radioactive matter ejected from these two nuclear accidents is as follows:

	Quantity of radioactive matter released at Fukushima	Quantity of radioactive matter released at Chernobyl
Iodine 131	130 000 TBq[a]	1 800 000 TBq
Caesium 137	11 000 TBq	85 000 TBq
INES Equivalence[b]	630 000 TBq	5 200 000 TBq

[a] TBq = terabecquerel, *i.e.,* 10^{12} Bq. The Becquerel is the unit used to measure radioactivity and represents 1 nuclear disintegration per second.
[b] International Nuclear Event Scale (INES); cf. Appendix 1.

[7] NB – 11th August 2011, the police reports gave a slightly lower figure: 15 689 dead and 4 744 missing.

Iodine 131 and caesium 137 are the two nuclides that produce the highest contribution to the radioactive doses received by the local populations. Other radio nuclides do, however, play a more or less important role, notably certain rare gases such as tellurium 132 and iodine 132, for external exposure factors and caesium 134 for internal contamination. The contribution of some other fission products is low to marginal and we need only mention for the record ruthenium-rhodium 103, barium-lanthanum 140 and niobium 95. The refractory matter used at the reactor site was not raised to a sufficiently high temperature to contribute in any significant manner to the radioactive cloud release. Some traces of strontium, present on the Fukushima site, were detected up to values of 250 Bq/kg of soil, to the North-West of the evacuated area; low trace amounts of plutonium were likewise detected. Their level however is equivalent to that left by the above-ground open nuclear tests of the 1960's and this is probably the origins for most detection cases here.

Total fall-out at Fukushima is therefore about 10% of that released from Chernobyl; however, in terms of the quantities released these figures correspond to the maximum level of the INES scale, which we feel should also be adapted to reflect sanitary risks. It will be noted, nonetheless, that local deposits of radioactive matter reached comparable levels for both situations, although the area of land contaminated was very different.

1.1 Effects of radioactivity

1.1.1 The clean-up operatives and workers

Some 400 site operatives were present on the Fukushima Dai-ichi site when the tsunami reached the coast. On March 15, the IAAE at Vienna announced that 150 of those present had been contaminated with fission products at levels between 500 and 1 500 Bq, which called for an immediate decontamination but did not present any significant sanitary risk. It turned out later, however, that a far larger number of workers might have been subject to internal contamination after the discovery end May that there were two cases of thyroid fixation, the workers showing respectively values of 9 800 and 7 700 Bq of iodine 131 more than 2 months after they had been decontaminated like their colleagues. This assessment of internal exposure could only be carried out six weeks after the accident notably because there were no appropriate apparatus available to conduct the measures in the immediate following days. Indeed, the evolving situation led to identification of new cases of "mixed" internal and external exposures, and a new assessment July 13, 2011, as follows.

Total personnel having received internal and/or external contamination doses during March and April at Fukushima Dai-ichi (source TEPCO):

Range of the dose	Number of site workersexposed in March	Number of site workers exposed in April
Over de 250 mSv	6	0
From 200 to 250 mSv	3	0
From 150 to 200 mSv	14	0
From 100 to 150 mSv	88	0
From 50 to 100 mSv	301	10
From 20 to 50 mSv	813	96
From 10 to 20 mSv	917	279
Less than 10 mSv	1 396	2 869

The number of site workers who have been exposed on a daily basis since the accident took place in March has varied from 50 to 250 at Fukushima Dai-ichi and approximately 600 at the second site Fukushima Daini, the back-up zone … All told, some 10 000 workers were assigned to these clean-up operations.

Two workers were contaminated when their legs were exposed to contaminated water but at a level that did not cause any radiological burn effect (2 to 3 Sv at skin surface); these two workers were admitted to hospital up to March 28. The efficient doses remained below the prescribed limit of 250 mSV[8]. Since August 30, the Japanese Government has decided to lower the acceptable limit to 100 mSV.

The immediate serious consequences for the workers were essentially accidents: 1 died because of a malfunction of a gantry crane, 2 were drowned, 1 had a fatal heart attack, 25 were wounded and treated between March 11 and 25. There are no recorded observations of early health consequences that relate to overexposure to ionising radiation, and this agrees with the prescribed doses evaluated for the workers.

[8] In emergency radiological situations, ICRP 103 recommends not to exceed 33 mSv.

In terms of delayed health consequences – *taking into consideration all the personnel assigned to clean-up operations and the associate levels of the radioactive doses received by the workers – there is no cause to indicate any measurable increase in their risk of developing cancer.* It is noteworthy to mention the precautions with which the Japanese radioprotection authorities managed the operations, thereby avoiding any doses that would have led to serious syndromes. In the face of the risk, however, it was proposed that a stem-cell bank be constituted for these workers.

1.1.2 Local and regional populations

Despite the disaster created by the earthquake and the tsunami, the evacuation orders for the zones concerned by possible radioactive fallout were issued and implemented rapidly. According to the communiqué[9] of Japanese Nuclear and Industrial Safety Agency (NISA), dated April 4, the declaration of a radiological emergency alert was decided March 11, at 19h03, and the Prime Minister issued the Directive to evacuate an area radius 3km around Fukushima Dai-ichi, then a at 21h23, a 10 km radius, finally at 18h25 on March 12, an area 20 km radius after transitory confinement at home measures. Stabilised iodine tablets (1 500 000) were made available to the evacuees as of March 15. The number of inhabitants living in the 20 km radius is approximately 30 000. A zone of radius 10 km was also evacuated around the second site Fukushima Daini and as of March 25, confinement zones, evacuation preparedness orders were issued, and for volunteers the evacuation procedure within the 20 km radius around Fukushima. Body contamination checks were carried out during the evacuations; the levels published were low.

To a large extent, the prevailing winds immediately following the accident spared the land areas and the cloud was pushed seawards, which nonetheless created a lasting problem of contamination of sea resources, aggravated by the decision to eliminate the contaminated site cooling water to sea. The releases into the atmosphere dated March 15 and 16 did affect land up to distances greater than had been forecast in the contingency plans, beyond the 30 km radius, to the North-West of Fukushima. Rural countryside was seriously contaminated by iodine and caesium, notably in the zone surrounding the village of Iidate. The levels of contamination led the IAAE to propose that this zone be evacuated but in fact the decision to do so was taken slowly and incompletely. In its June 14 communiqué, the Japan Atomic Industrial Forum (JAIF) indicated that there were some high level points approximately 60 km to the north-West (Date, Ryo-Zen) where the limit of 20 mSv/an was exceeded.

[9] http://www.nisa.meti.go.jp/english/files/en20110404-5-1.pdf

The caesium fallout pattern shows maximums in an angular sector of some 30° towards the North-West from Fukushima Dai-ichi, up to and beyond 30 km, with measured values between 0.02 and 3.7 MBq/m². The IAAE at Vienna estimates that the corresponding quantities of iodine represent between 0.2 and 25 MBq/km². These figures are comparable with those in the area evacuated round Chernobyl.

The food-chains were also screened efficiently, in association with numerous measurements taken for radioactivity in the atmosphere, water and soils. Out of 4 218 measurements made by the Japanese Ministry for Health between March 19 and May 31, only 318 values measured were in excess of the limits allowing sale of foodstuffs in the zones peripheral to the evacuated areas, essentially in the Fukushima Prefecture zone. The levels of contamination reported were confirmed by the IAAE. Temporary interdict orders were largely issued for sale and consumption by the populations of vegetables, mushrooms, meat and local fish catches.

The acceptable levels (for Japan) were 300 Bq/litre for water (100 Bq for children) for iodine 131 and 200 Bq/litre for caesium 137; for dairy products, 300 Bq/lg for iodine and 200 Bq/kg for caesium; for meat and eggs 500 Bq/kg for caesium whereas the level of 2 000 Bq/kg was temporarily considered as acceptable for fish. These limits are clearly set out in the following table:

Regulatory limits for concentration levels of certain radionuclides in Japan's food-chain:

Radionuclides	Drinking water	Food for babies	Milk and dairy products	Vegetables	Cereals	Meat, fish, eggs, etc.
Iodine 131	300 Bq/kg	-	300 Bq/kg	2 000 Bq/kg	-	-
Radioactive caesium	200 Bq/kg	-	200 Bq/kg	500 Bq/kg	500 Bq/kg	500 Bq/kg
Uranium	20 Bq/kg	20 Bq/kg	20 Bq/kg	100 Bq/kg	100 Bq/kg	
Alpha transuranian elements (Pu 238, 239, 240, Am 241, Cm 242, 243 and 244)	1 Bq/kg	1 Bq/kg	1 Bq/kg	10 Bq/kg	10 Bq/kg	10 Bq/kg

The figures above are given as guide-line values that enable the authorities to avoid excessive contamination of the populations, taking into account the national 'normal' diets and various international recommendations. The figures differ from the guide-line values used in Europe to regulate sale of foodstuffs (cf. *codex alimentarius*). The restrictions regarding use of urban water supplies were all abolished on May 10.

Despite the organisation used to avoid contamination of the food-chain, some loopholes were identified. In July, 1 400 cows that had eaten straw contaminated beyond the accepted limits were dispatched to the abattoir for later consumption. The contaminated bovine meat came from eleven (11) Prefectures, including Fukushima, Miyaga and Iwate. Rice straw, dried in the open air, had adsorbed large amounts of caesium before being distributed throughout Japan. Following this discovery, the Government identified the beef and rice straw distribution circuits, took corrective measures such that there will not be any consequences for the consumers. The Government prohibited the slaughtering of cows in the Prefectures of Fukushima, Tochigi, Miyagi and Iwate. The measures were abolished August 25.

The Ministry of Education, Culture, Sports, Science and Technology (MEXT) published, May 24, a detailed map of the external doses integrated since the accident took place, outside the evacuated areas. The highest levels of contamination were to the North-West, just beyond the 30 km radius, with values between 6 and 30 mSv/yr. These figures lead us to conjecture that the annual doses will reach worrying levels, higher than 100 mSv and will require long duration evacuation measures or a decontamination programme for the soils.

Beyond the specific radioactive fallout areas, other radionuclide deposits were temporarily detected throughout Japan and in particular in the Tokyo region, showing that the radioactive cloud could have significantly raised the contamination levels in the air. These sporadic bursts did not and will not have any sanitary effect inasmuch as the levels recorded are well within the limit fluctuations for natural radioactivity.

Regarding medical and sanitary consequences, the overall situation is dominated by daily problems and anxiety, in the immediate aftermath of the crisis. These problems take on major proportions when faced by the evacuated populations. The policy choice of whether to displace populations are especially difficult for elderly persons: at Iidate, the eldest villager committed suicide to avoid leaving his home. The 78 000 persons displaced were authorised to return to the 20 km area for a few hours with the proviso that they submit to radioprotection monitoring. In contradistinction, the levels prevailing in the 3 km radius area prohibited the 6 000 evacuees from doing the same.

In regard to thyroid tests, some 1 200 children were screened[10]; the results revealed doses from 1 to 2mGy[11] maximum. In France, it can be noted that stable iodine is prescribed whenever the estimated thyroid received dose reaches or exceeds 50 mSv.

Given the speed with which the evacuations were organised – and the restriction orders issued prohibiting consumption of locally produced foodstuffs, plus the rapid distribution of stable iodine (in an already highly iodine impregnated population) – it can be assumed that the levels of internal contamination of these populations are low. No data published to date lead to supposing that there will be any serious contamination of children by the iodine 131. Nonetheless, we do not, at this time, have enough data to be conclusive in this respect concerning the populations living in the non-evacuated areas, notably to the North-West.

On July 26, the Japanese Food Safety Commission estimated that a cumulated dose of 100 mSv over several years would have no adverse effects on health and considers, on this basis, that the currently observed levels of contamination of the food-chains are acceptable, and there is a general international consensus on this conclusion.

The total population of the Fukushima prefecture is estimated at 2 million inhabitants and it has been proposed that there be a continuous follow-up screen for thyroid pathologies for the 360 000 persons aged under 18 at the time of the accident. Moreover, the 200 000 persons evacuated, as well as the children of some 20 000 pregnant women at the same time will be able to benefit from extensive medical check-ups.

At the end of May, the Government announced an epidemiological monitoring programme over the coming 30 years. The principle adopted here is to select the screening sample through interviews that will be organised during the summer recess and to adapt the screening process proper as a function of the results of this enquiry.

An aid programme for the inhabitants concerned by possible environmental consequences of the accident at Fukushima Dai-ichi has been launched and includes a continuous monitoring process. The programme consists of:

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[10] Wakeford R. And Now Fukushima. *J Radiol Prot* 2011, 31, 167-176.

[11] Which corresponds to 0,05 to 0,1 mSv (effective dose). The gray (symbol: Gy) is an SI unit, designating the dose of ionising radiation absorbed by a person (or animal) and representing an ingestion of 1 joule per kilogramme (mass of human tissue). Again in the SI system, the millisievert (mSv) is defined as “the natural radiation level cumulated on average absorbed by a person over a one year period, not including the gas radon”.

- a re-evaluation of the contamination levels in the evacuated areas;
- a search for temporary housing (by August 8, 13 949 units had been identified out of the objective of 15 200 needed);
- organization of visits to the evacuated areas, including the innermost 3 km radius zone;
- an administrative control of the evacuated areas beyond the 30 km radius (where the population had the choice to stay or move); elimination of the main "hot spots";
- law and order operations and control in the evacuated areas;
- setting up of a reimbursement fund for health expenses incurred by the populations;
- elimination of the main wastes;
- decontamination of the school premises;
- continuous monitoring of the background radioactivity and of the food-chain;
- setting up of an information and pedagogically enlightened communication system for the local populations;
- setting up of a housing rehabilitation programme.

A decontamination programme was made public on August 26, with the aim to reduce by half the level of contamination detected in the residential areas close to the power station site over the next two years.

The preliminary actions began in September with the announcement intimated to the populations that the risk zones will most certainly remain prohibited for a long time to come.

The Japanese Government announced early October that the restrictions placed on the inhabitants of five townships, beyond the 20 km radius round the Fukushima power station site, were cancelled, subsequently to the decreased risk levels estimated for these areas.

This decision is primordial since the quality and the rapidity of rehabilitation of these areas determines the main aspects of the aftermath of the crisis period and the impact of the accident on the health of the local populations.

Moreover, the Government announced that the evacuation order would be cancelled for other regions after the 2nd stage of the plan has been finished (planned for 2012).

In preparation for this gradual cancellation of restrictions, the operator TEPCO has already scheduled training for 4 000 persons by the end of 2012 to help assess the radiological impact measurements in the different zones monitored.

1.1.3 Populations outside Japan

Every State took steps to protect their populations by prohibiting import of contaminated foodstuffs from Japan. For other products, April 22, the Japanese authorities published directives aimed at Japanese ports, explaining the purpose and procedures of the radiological inspections to be implemented before the ships left port and allowing for the issue of non-contamination certificates, if needed (source ASN).

Regarding the extension of the radioactive cloud, the levels recorded were very low in all the countries and do not raise any sanitary problems, in Asia, America or Europe. The USA were affected March 19 and France March 24 by circum-planetary particles.

1.1.4 Comparison Chernobyl / Fukushima

Although both nuclear accidents were classified at the same, maximum level (7 on the INES international scale), Fukushima will definitely have less sanitary consequences.

Among the 600 liquidators who were assigned to cleaning the Chernobyl site in April-May 1986, 237 showed acute radiation syndrome (ARS) and 134 had a confirmed diagnosis with received doses between 1 and 16 Sv. Twenty-eight – among those most exposed – died in the early weeks after the accident, most of whom had very serious, deep and extensive radiological burns. In this ARS sub-group, 19 patients died in 2006, some because of their exposures, others not. Fourteen deaths due to miscellaneous causes were observed in the non-confirmed ARS group. The follow-on the skin burns are severe but there has been no observation of cancers on burns during the 25 years of monitoring after-Chernobyl.

Among the 59 patients in the ARS Ukraine group there were 4 cancers, 2 leukaemia and 3 cases of myelodysplasia.

Concerning the delayed health symptoms, the count for Chernobyl stands at 7 000 thyroid cancers for an estimated population of 2.5 million children lacking natural stable iodine and who were exposed to high doses of radioactive iodine[12]. There will doubtless be no such events for Fukushima because of the low number of children exposed to radioactive iodine at a level considered to be worrying, in this in every scenario envisaged. This results from both the measures taken to protect the populations, among which the interdict on contaminated dairy produce and a rapid, high level distribution of stable iodine as a food-supplement to the entire Japanese population …

In regard to worrying levels, *i.e.*, those beyond which epidemiological studies reveal a higher than expected frequency of cancers, *viz.,* 100 mS and for a short period, Chernobyl was characterised by an on-site population of 530 000 so-called liquidators who received an average 120 mSv. If we refer to the collective dose, *i.e.*, the sum of the individual doses received, the figures represent 60 000 men.Sv. Nothing of this order happened at Fukushima, where the only populations at risk were the 110 (approx.) who indeed received over 100 mSv and those populations invited to remain in their homes in contaminated areas. In one IRSN scenario, this decision led to the equivalent of 4 400 men.Sv, *i.e.*, less than 10% of the collective dose received at Chernobyl.

Evaluating the real level of cancer risk for these populations comes down to making extrapolations. After 25 years of monitoring of the Chernobyl populations by UNSCEAR, the measurements made in 2011 did not reveal any significant increase in cancers other than thyroid cancers in persons exposed when children. This, however, does not preclude some excess cases of leukaemia notably for the liquidators, and some possible related breast cancers, but these excess values are not validated for all the liquidators, although they appear in certain sub-groups; if such observations are confirmed, they will be qualitatively low. It is an observation that is compatible with what we have learned about excess cancers in the population of Japanese who survived Hiroshima and Nagasaki, 60 years after the events.

We can recall that as far as hereditary effects are concerned, no genetic change has been observed in the human populations under observation and that effects on foetuses only appear for doses above 100 mSv; such occurrences have not been observed in the case of Chernobyl.

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[12] These levels and ratios correspond to an increase of a factor of almost 100 for younger populations (aged less than 5 years of age in 1986) compared with the average reference values.

Sanitary consequences, other than radiological

We now have to analyse the consequences of this nuclear accident in terms of public health. The anxiety created was quite considerable: the UN in the declaration by the Secretary General Kofi ANNAN, in 2000: *"Chernobyl is a word we would all like to erase from our memory; more than 7 million of our fellow human beings do not have the luxury of forgetting. They are still suffering, everyday, as a result of what happened'',* then the OCHA (Office for the Coordination of Human Affairs) drew the same conclusion and the Chernobyl Forum published in 2006 and finally the UNSCREAR in 2011 sought to establish the causes of the poor sanitary state of the populations affected by severe anxiety and disarray without finding any factors other than poverty insufficiencies, and a permanent chronic post-traumatic stress due to the level of residual contamination of soils, and a loss of confidence in the authorities deemed responsible.

Over and above the fact that the consequences not specifically caused by radiation sources, but by the accident itself generate unending pseudo-scientific fantasies, the price to be paid for poor crisis management is undoubtedly very high. What will the case be for Fukushima? Among the post-accident measures, those that relate to the compensation of the ruined populations and the implementation of soil rehabilitation procedures such that they can one day be returned to the collectivities for future use are specially awaited.

1.2 General sanitary consequences

Assessment of the consequences of a nuclear accident, in terms of impact on public health is not just a question of analysing pathologies mechanically related to the radiation (cf. Section 1.1). The assessment must also take into account the indirect effects, such as disorganisation of the region's health services, impacts on health as perceived by the population including on "objective" factors but seen as such by the populations concerned an likewise, effects on mental and physical conditions[13]: development of mental disorders (post-trauma stress, depression …) and associate clinical syndromes.

[13] It would be a mistake to consider as "caused" only the "specific" medical consequences (radio-induced cancers) of a nuclear accident for the purpose of assessing the sanitary impact: let us imagine a person who had a heart-attack after the events at Fukushima; let us further suppose that the person's transfer to hospital was delayed by the local state of disorganisation and that, finally, the person died for lack of immediate hospital intensive care. The death here was not caused directly by radiation but we can attest that the nuclear accident was the cause. This is what we call "counter-factual evidence" (had the accident not occurred, the person would not have died).

In this section, we shall examine the non-specific sanitary consequences of radiation resulting from a nuclear accident. By "non-specific", we are referring to the impact effects that are not direct, mechanical consequences (wounds, trauma in the cleaning-up operations, radio-induced cancer).

The situation as it resulted from Fukushima over the months that immediately followed the accident is summarised below; however, extrapolation of this situation to other nuclear accidents, in terms of non-specific sanitary events, is very complicated because Fukushima was not only a nuclear accident but also involved in/caused by an environmental disaster (the Tohoku earthquake and subsequent tsunami) that led to enormous consequences in terms of immediate (and future), local health conditions.

We shall nonetheless make a brief analysis of the "nuclear" accidents at Three Mile Island (TMI) and Chernobyl, recognising that it will prove very difficult to draw any generally applicable lessons should another nuclear accident occur, using just the analysis of the few accidents that have happened in the past. The reasons are that they were of different magnitude and hit populations whose base-line health status were very different at the time and lastly because they took place at dates distant from each other. Faced with this heterogeneous picture, it is very important to consider the organisational responses to the situation and the epidemiological methods put in place to assess the impacts of a non-nuclear environmental disaster, for which a much greater amount of experience is available and which lead to a directly useable "model" in the area of non-specific consequences of nuclear radiation. It is clear, for example, that if France were one day to face up to a nuclear accident, the past experience of France with catastrophes such as AZF fertilizer factory explosion at Toulouse in 2001, would probably prove more useful than the response of the Ukrainian authorities or even the Japanese response at Fukushima; in like manner, the response to the attacks on the World Trade Center, September 11, 2001 (cf. Appendix 6) is also an important source of return on experience inasmuch as (a) there a much greater population (Manhattan) at risk; (b) there were many in-depth and extensive studies including the risks for mental and physical health (and therefore in regard to development of methodologies than could be transposed to other situations); (c) it happened in our information-intensive age in a country with technical and financial means for assessment and population monitoring much higher than those available at the time of TMI and Chernobyl, and comparable to those on which France could call if ever confronted with a similar catastrophe.

Lastly and alongside the non-specific sanitary consequences of accidents and catastrophes, this section is also focussed on perception of risk by the general public concerned. This degree of perception obviously has a large impact in terms of subjective health assessment and objective examinations (notably in the area of mental disorders) and also in terms of attitude in regard to the health care system: the perceived risk probably is a stronger driving force than "objective" risk that makes the population turn (or not) to the health care system.

1.2.1 Lessons learned from the nuclear accidents at Fukushima-Dai-ichi, TMI and Chernobyl

2011- Fukushima: the events

By July 5, 2011, i.e., 4 months after the catastrophe March 11, the tsunami was recorded as having caused 15 534 deaths (1 600 of which were resident in the Fukushima prefecture at the time of the event) and 7 092 persons declared missing [1].

The nuclear accident led to many population evacuation orders: on April 22, the area within a 20 km radius of Fukushima was prohibited to access. In the next ring, between 20 km and 30 km radius, planned evacuation order were issued, for certain zones (where the annual exposure estimated was 20 mSv/year) while others were designated as "emergency evacuation prepared zones". The precise qualification of these zones will be reviewed on an annual basis, as a function of recorded exposure levels. Evacuation of the planned evacuation zones was almost completed by June 30 (the reasonable hypothesis made was that the short delay before evacuation would not have any significant consequences on the health of the last populations evacuated).

On June 16, the Japanese Government decided to identify possible "hot spots" outside the planned evacuation ring, spots supposed to have an annual exposure level of 20 mSv/yr. However, by June 30 it was recognised that the potential hot spots identified would not attain the limit figure for the received dose.

Following the tsunami, the number of persons moved to evacuation centres rose to 440 000 (March 15). Three months after the catastrophe, more than 110 000 persons had been displaced, but 30 000 "only" were housed in the evacuation centres. This exceptional situation arose in a highly developed country that not only had the capacity to handle the disaster but also the means to analyse it. The demonstration was made that the management of the displaced persons, the provisions made for correct sanitary conditions and the organisation of re-housing all relied on five factors:

- rapid, efficient distribution of drinking water and of a correct system to evacuate waste water and effluents;
- the existence of natural leaders (before the catastrophe struck) in the Japanese community;

– the existence of a strong "community" bond linking the displaced persons;

– more efficient operations in the "small", compared with the "large" centres;

– the importance of the role played by "public health nurses" (a category still to be identified in France).

Fukushima: impact on equipment

The tsunami and the Tohoku earthquake seriously damaged the gas supply-lines, the water supplies and the electric networks. They caused considerable damage to transport facilities, in particular through the massive destruction of police and fire brigade vehicles, and likewise trains and buses. Cell phones stopped working because the relay antennae were down and largely destroyed. The situation was therefore one of extremely serious damage in which the proportion due to the nuclear accident is obviously impossible to quantify, but was in fact low.

The country's health system was severely impaired: the tsunami hit many hospitals directly and paralysed others through destruction of the electric and water supplies.

Fukushima: actions and public health studies launched immediately

– The problems related to transmissible diseases: the base here is the epidemiological routine monitoring that in fact existed prior to the accident (the same applies incidentally in France). However, this routine monitoring broke down through lack of doctors and "sentry alert" laboratories, etc. Specific monitoring, for example, on illnesses arising from use of low quality water sources was set in motion.

– Mental health issues: the interpretation of data related to mental health, collected during the catastrophe, cannot be carried out properly without some basic information of the Japanese population's state of health generally (*i.e.*, prior to the accident). In many countries this is simply not possible but in the case of Japan which is a highly developed country, it was feasible. Thus in the prefectures of Iwate and Miyagi there were higher, known, rates of suicide compared with the national average (0.25‰), *viz.* 0.34‰ and 0.28‰. Information of this order is primordial when it comes to analysing the cases of suicide after the catastrophe.

Evaluation of post-trauma stress disorders (PTSD) was a priority from the start for the authorities after Fukushima and the monitoring systems were launched for such an evaluation immediately. "Psychological support (PSCs) cells" were opened for the public at large. The WHO report dated June 2011pointed out that the separation of these PSC units from the other medical teams in the field was not an ideal situation and that, on the contrary, it was advised that multidisciplinary teams should be prepared, capable of offering integrated care, therefore including for mental health disorders.

- Non transmissible diseases: the risk factor for such illnesses increases during times of catastrophe. The Japanese authorities used a 3 tier classification, dividing the population into 3 groups, each corresponding to a specific level of action and intervention:
  - Group 1 includes patients benefiting from dialysis, type 1 diabetes, patients fitted for respiratory assistance, transplant patients and those under stringent medical control and treatment because of critical heart conditions;
  - Group 2 includes type 2 diabetes, asthma, cancer, chronic bronchitis and other cardiac disorders;
  - Group 3 includes high-blood pressure patients, patients with hypercholesterolemia syndromes and certain patients at risk in respect to non-transmissible diseases – for example, people undergoing tobacco and/or alcohol weaning and who run the risk of interrupting their programme because of the events.
- Long-term monitoring:The Fukushima authorities immediately set in motion a long-term monitoring programme of the health situations of the prefectural residents (including information on demography, health, radioactive doses received and estimated for coming years). A first preliminary questionnaire was used as of June 30 for residents in the planned evacuation area, *i.e.*, covering some 26 to 28 000 persons. Special monitoring was also set up for those who has received high doses during and immediately after the accident and for those who had been resident in the prohibited access zone (201 831 persons).

Fukushima's authorities also studied the cases of 194 371 residents. Complementary enquiries were organised; for example, a random sample of 120 persons were invited to take a full-body scan.

Epidemiological research

A large-scale epidemiological enquiry was decided in August 2011: on July 25; 2011 the Diet (Japanese Parliament) voted a 1.2 billion $US part of which was earmarked for the epidemiological monitoring of the entire Fukushima prefectural population (over 2 M residents) [2]. As of June 2011, a 12-page questionnaire had been distributed to all the inhabitants of the Fukushima prefecture, in order to assess the individual radiation dose levels; it was also planned that the 36 000 youngsters (the under18s) would have a thyroid checkups and that the 20 000 pregnant women at that time and their as yet unborn children would be monitored before and after birth. The tie scale for the studies is 30 years; the target set by the organisers of the studies is framed both in terms of public health (to ascertain needs better) and scientific (since the extensive data base that will be collected and archived may lead to new results relating to low radiation exposure risks.

Fukushima: action taken by the French InVs in respect to French citizens living in Japan

The international division of the French national Institute for Sanitary Monitoring, or InVs (cf. Appendix 9 for a detailed description of InVs organisation), organised an enquiry using an unprompted questionnaire that was to be distributed to "all" French citizens present in Japan on March 11. The InVs web-site informs us that some 9 000 French visitors/residents were concerned, several hundred of whom were in the area of Sendai [first coastal city hit by the tsunami]. The questionnaire will serve to build a data base for possible later analysis, since it also geo-location of the persons identified (enabling dosimetric positioning) and to obtain some information as to their "attitudes" faced with the impeding risks (seeking safe shelter, taking iodine tablets).

1979: Three Mile Island (TMI), Pennsylvania, USA

The Three Mile Island accident took place on March 28, 1979. TMI was classified "5" on the INES scale, caused a low level contamination of the immediate milieu[14], a priori not likely to lead to any fatal casualties. And yet the level of emotion generated in the public at large was high, both at the time of the accident and afterwards (cf. Appendix 7). More than 140 000 women and children were evacuated from the area. Under such conditions it became very necessary for an epidemiological study to be instated, not only to provide scientific insights and knowledge but also because it was the only way open to proving to the public at large what the reality was (in other words, demonstrating absence of long term radiation consequences). The rapid and efficient launching of the enquiry by the American CDCs (Centers for Disease Control and Prevention), by the national Bureau of Census) and by the

[14] It has been estimated that the average dose received by the 2 million inhabitants who lived in the Three Mile Island region was 1 millirem and that the maximum dose received was 100 millirems (natural background radiation is 100-125 millirems for the region). US Nuclear Regulatory Commission, 2009.

Pennsylvania State Department of Public Health remains today a perfect model of organisation (described in detail in Appendix 7).

An important lesson learned from TMI was the impact that such an accident can have on the health care system generally (deprogramming of care schedules in the hospitals of the area, changes in emergency case flow lines and use of intensive care units, absenteeism of medical and nursing professionals, etc.).

1986: Chernobyl, Ukraine

The Chernobyl nuclear accident happened on April 26, 196 and was classified at level "7" on the INERS scale (cf. Appendix 8). A detailed status report was published in 1997 Epidemiologic Reviews, which is an international bench-mark in terms of epidemiological studies [3] and then there was the "Chernobyl Forum" [4], convened twenty years after the catastrophe, under the auspices of international organisations, notably the WHO. According to the findings of this report, in mid-2005, less than 50 fatal casualties could be directly attributed to radiation resulting from the accident and most of these deaths were personnel severely exposed during the clean-up operations and it has been conjectured that close on 4 000 persons risk dying from cancer subsequently to the accident. The figure were (and still are) controversial and much higher figures are in circulation and accessible to the general public [5]. Unfortunately, figures forthcoming from a large number of the world's best experts working under the control of international organisation are often placed on the same level (at best) in innumerable Internet postings as those put forward by miscellaneous organisations or even individual self-appointed experts who lack the means and the technical knowhow of the real experts.

1.2.2 Sanitary impacts of environmental catastrophes

1.2.2.1 Post-traumatic stress disorder (PTSD), depression and other long-term psychological consequences of catastrophes

Post-traumatic stress disorder (PTSD) has been defined since 1980, when it was introduced DMS-III[15]. Its epidemiology is well described in [6], an overview of some 192 papers on the subject. Five of these papers related to nuclear accidents (one is specific to TMI and four to Chernobyl). Nevertheless,

[15] Diagnostic and statistical manual of mental disorders III (1980).

these are "old" accidents when the PTSD cases were not really recognised for what they were and when means were lacking to undertake such studies. Indeed, it is accidents other than nuclear that provide the lessons about method and results appertaining to psychological sequels of environmental catastrophes. Thus, Galéa *et al.* [7] sought, one year after the September 11, to identify the determining factors of PTSD and occurrence of depression in the populations concerned; it is clear now that all or part of their methodology could be re-used in the event of a future nuclear accident.

1.2.2.2 Non-specific clinical syndromes observed at a distance from the catastrophe

Often, after a series of natural and/or technological catastrophes, certain varied clinical syndromes (therefore not psychological) appear – they are called *"medically unexplained physical symptoms"* (MUPS). Van den BERG and his colleagues in [8] analysed attentively 57 papers on this subject, 10 of which related to earthquakes, 7 to floods and 8 to nuclear accidents (4 for TMI and 4 for Chernobyl). Concerning nuclear accidents, the enquiries took place 4 months and 11 years after TMI and between 6 years and 11 years for Chernobyl.

1.2.2.3 Impact of catastrophes on 'perceived' health conditions

We recall that "perceived" health conditions (also known as "subjective" health) is a reality that scientist must take into account on a par with "objective" health considerations; not only is it is a "measure", in essence, of what persons feel about their health, and even if we take the "ice-cold" standpoint of a health economist, we can understand that it really is the subjective perception that becomes the driving force for the attitudes people adopt when it comes to using the health system and services, or measures of prevention.

The impact of Chernobyl on health perception was studied, for example, for young persons born close to the date of the accident (aged less than 15 months or still *in utero*), when they reached the ages 11 and then 19. The study was carried out with adolescents from the city of Kiev, with 262 from Chernobyl compared with 261 non evacuated friends of the same age-group and then to a third group of 325 youngsters chosen on a random basis from among the population of Kiev.

The study showed that the evacuated children had a subjective health assessment that was poorer than that of the adolescents of the two other groups and that one factor of risk of poor health was the perception they had of the Chernobyl risk and also the perception their mothers gave of the same risks.

A similar study was conducted with mothers of young children, 11 years after the date of the catastrophe [9]. It showed that the mothers of the displaced "group" had a less good subjective health and had a larger number of days of sick-leave than the mothers of the control group.

Studies like these serve to identify possible action and prevention paths (for example, by showing the importance of relevant information as to the state of our knowledge when we address questions of objective radiation risk factors).

1.2.2.4 Impact of catastrophes on health care systems

An editorial in the American Journal of Public Health [10] recalled that as of 1982, public health specialists should work on preparatory work for the sanitary handling of a possible future nuclear accident.

The possible sanitary effects (some of which have already been observed) are very diverse: in environmental health, caused by the fact that the evacuated populations were regrouped at certain stages (drinking water, disease vectoring animals, waste effluents, …); food supplies and availability; supplies in general; treatment of chronic illnesses (high blood pressure, diabetes, etc.); management of mortuaries, etc. [11]. These sanitary impacts relate to the entire hospital system, because of the inaccessibility/unavailability of equipment, the difficulty to balance dealing with emergency cases and pre-existing patients in hospital at the time of the events, and finally the availability factor for medical staff at all levels.

1.2.3 The sociological approach to "real" and "perceived" risks

If as it is true today, we do not as yet have large data bases for Fukushima in terms of cross-checked data as to the psychosocial situation of the exposed population (and likewise of the population that has perceived itself as have been exposed); for this reason, we can raise certain questions, raise some hypotheses or make some assertions, but it they can only be verified/ invalidated correctly by conduction enquiries with the populations concerned. These hypotheses and assertions are partly based on existing literature about risks and catastrophes and on a more specific set of papers that address questions of perception of nuclear risks after serious accidents. We can however note that the nature of the risks, their duration in time and the multiple areas that are involved (environment, health, foodstuffs, housing, etc.) tend to compose a totally new framework of thought and analysis in the population of one of today's highly developed countries.

1.2.3.1 Some questions raised by the tsunami catastrophe and the Fukushima nuclear accident and their consequences

Are we faced with a natural catastrophe or was it is due to human activities?

The question of causality lies at the heart of all investigations, opinions, judgements after any event that leads to loss (of life, of material goods). The fact that the cause is perceived as being of nuclear origin or of natural origin will have serious consequences as to how the responsibilities lie, but also will contribute to how Japan (and others) judge nuclear power generation industry and its future. Certain people will assert that the nuclear accident would not have occurred if the very high-amplitude earthquake-tsunami had not taken place, while others will be adamant that nuclear risks and consequences of accidents would not exist if nuclear generation sites did not exist. This debate is impossible to resolve but it will, nonetheless, structure the protestations and the political decisions in respect to civilian nuclear power.

Why does Fukushima create such a high level of perceived risk?

This nuclear accident associates two well-known and identified parameters that can lead to a high level perception of risk [12]: on one hand, the novel nature of a nuclear power accident, on the other, its insidious, horrifying, invisible characteristics. It is new for a Japanese population that has no previous experience of nuclear dangers and effects (except for the elderly who survived either the Hiroshima or Nagasaki bombings in WWII) although they are aware of such potential dangers. Here they discover the problem but do not themselves have any solutions to offer: it is new, *i.e.*, uncontrollable since it is unknown. It is frightening to the extreme through the sheer number of possible risks (unknown), without any precise indications as to who will be affected and to what degree … and for how long.

Studies (public, published enquiries) relating to risk perception after several nuclear incidents (relatively minor) demonstrate clearly that there are today significant changes in risk perception with respect to civilian nuclear power. T. Katsuya [13] shows how, after an incident in a nuclear power station at Tokai, Japan, with local environmental contamination and radioactive radiation of 3 site workers (1 of whom subsequently died):

- confidence and acceptability of civilian nuclear power generation have decreased;
- the perceived probability of nuclear accident increased;
- the fraction of adversaries to civilian nuclear power has increased to a large extent, while that of the partisans has decreased moderately.

Post-Fukushima: a situation unprecedented in all human history?

Fukushima was a compound catastrophe, the origins of which were part natural part man-made, and as such it cannot be simply reduced to its human and material consequences: certain other recent catastrophes caused far more damage and deaths (the earthquake in Pakistan in 2005 led to 75 000 victims and millions of homeless, displaced populations; the hurricane Katrina, also in 2005, killed more than 2 000 persons and devastated complete cities, etc.) but the destructive nature of the events disappeared as soon as the events stopped. In the case of Fukushima, the risks continue to hang over the Japanese populations. The residual risks can even be perceived as higher than those of the catastrophic events themselves. Not perhaps in terms of deaths to come and discoveries of radio-induced cancers, but in terms of the continuing existence of a hostile environment, which remains hostile to man and rendered unfit for any human use. Duration of radiation, associated with the fact that it is an invisible threat that extends to all milieus (land, water, air, foodstuffs, fauna, flora), in essence, has produced a new era: one in which risk has become consciously permanent and ubiquitous. The question is: can life resume its normal course in such a changed context? How will the populations (exposed and perceived as exposed) react from this point on?

Which brings us to the next question: what can be done to reduce the incommensurable residual risk and the perception the population entertains of it?

In general, faced with a new risk, the first question is: what can we do to face up to it on an individual level and on a collective level? In the case of Fukushima, risk factors are different: they existed before any answer could be forthcoming, and this alone leads to a greater feeling of disarray and abandon (which characterises unforeseen catastrophes when they occur).

Part of the population living close to the Fukushima site can choose to quit the area and set up home again elsewhere, thus definitively leaving this threatening, enduring, environment. For the rest of the population, either by choice or because of an impossibility, will not leave and therefore will have to face up. The most important action, of course, will be to rapidly decontaminate the site. However, that will only be done on a long, incomplete and gradual basis. Above all other considerations, there will be a prime necessity to account for progress in this area, in order to demonstrate the reversibility of the consequences of the catastrophe and to lend credit to the idea that the task will be finished within a human time-scale. If the long range objective will be the observed return of the area to the state of a natural and neutral environment, an interim target will be to show that the task is indeed feasible and to make the various stages significantly clear to all.

It is important to bear in mind that the impact of Fukushima on the perception of nuclear risks extends far beyond the strict geographic context, *viz.*, the contaminated ground and facilities. Not only will there be an impact already (and which will continue) on the entire Japanese population, but the perception will expand to all countries that possess nuclear power plants and even those who envisage adopting nuclear power.

In other words, the stakes and future of civilian nuclear power generation will depend on the capacity we have to lend credibility to the possibility of achieving a gradual reduction of residual risks. And this is where we move to a totally new paradigm.

1.2.3.2 Foreseeable changes in the demand for care/treatments

Not only will new sanitary problems arise, but also the existence of a lasting, diffuse threat due to the radioactive environment will affect the perceived health assessments, of the exposed populations. In other words, like most catastrophes and traumatic situations (war, terrorist attacks, etc.), we shall see the development of a pernicious relationship between perception of residual risk, self-perception of consequences on health and a set of symptoms that will take many forms and with no return on experience available. There is therefore a risk that the demand for care/treatments the scale of which will be a function of many factors and for which management decisions imply that the authorities do not deny or refuse the demand.

1.2.3.3 Faced with a unique problem, can there be innovative solutions?

It is very important to observe, analyse and follow the self-perception phenomena expressed by the populations who are going to continue to reside in the sensitive area round Fukushima, in order to better understand how and why certain social groups (which one precisely?) and going to adapt to the new situation and those who are going to discover new difficulties, whether they be psychosomatic, psychological or even existential. By discovering the factors leading to fragility or resilience is a primary cognitive aim that must precede any form of innovation (a practical, relational or communication innovation) that has as its objective to mitigate the risk perception. It will be through a patient, accessible confrontation between two forms of knowledge (one about the perceived risks, the other about observed, objective, real risks) that we may see the arrival of new shared representation of "possible life conditions" after and around Fukushima.

1.2.3.4 How might we prevent such a catastrophe in Japan or elsewhere and how can we prepare for such an event?

The dilemma when it comes to preventing a major nuclear accident from happening is that prevention is hardly compatible with a programmed reduction of the consequences should such an event occur (so-called *mitigation*). The first aim (prevention) serves to reassure the populations that might be impacted ("we have taken every step conceivable for it never to happen"), while the second aim (programmed mitigation) in fact admits explicitly that there is a possibility of an accident, a sort of admission of not being totally in control of events and therefore it becomes a source of anxiety *per se*. Here we can see clearly the difference with the occurrence of a natural catastrophe (earthquakes, tsunamis, hurricanes, etc.) where the maximum efforts must be deployed *to mitigate the damage and destruction*, given that the catastrophe cannot be avoided.

The dilemma above leads on to a vital question: how should we communicate about nuclear risks in developed industrial countries that draw part of their energy requirements from nuclear power plants? Should it be, for example, a communication mode that excludes risks of a catastrophe, or again, should it be a communication mode that readies populations for a hypothetical event? The first option – that Fukushima will make highly "incredible" tends to widen the gap between the plant operators and the population they serve and supply, the second aims at implying the populations, bringing them together in a consensus as to how the management, mitigation of a catastrophe will be conducted.

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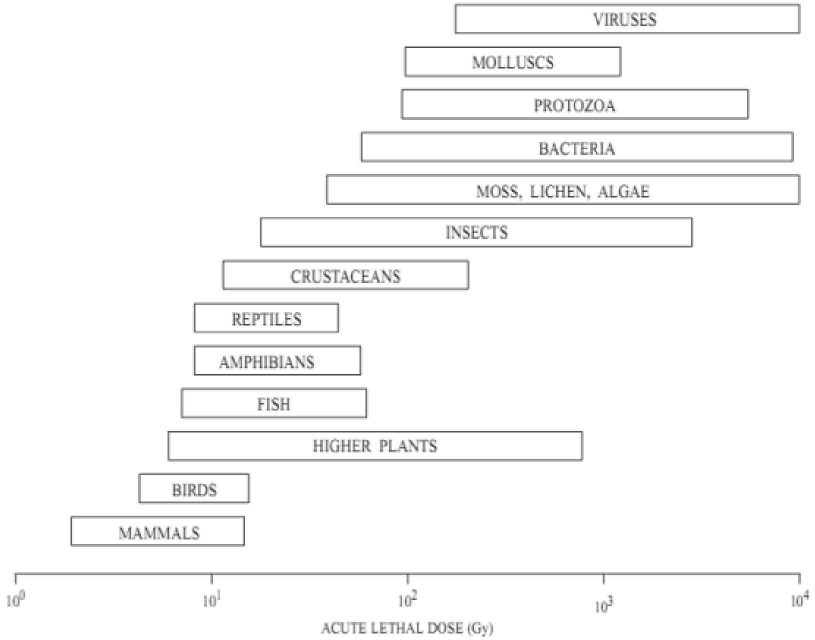
2 | Environmental consequences

Two points need consideration: on one hand, the consequences of radioactive matter released on fauna and flora, on the other, consequences of contamination of local produce. The latter point is important because the impact of the radioactive fall-out and releases seriously damages the local economy inasmuch as it becomes difficult to sell local produce even when there is compliance with existing safety standards.

2.1 Impacts of exposure to nuclear radiation on land fauna and flora

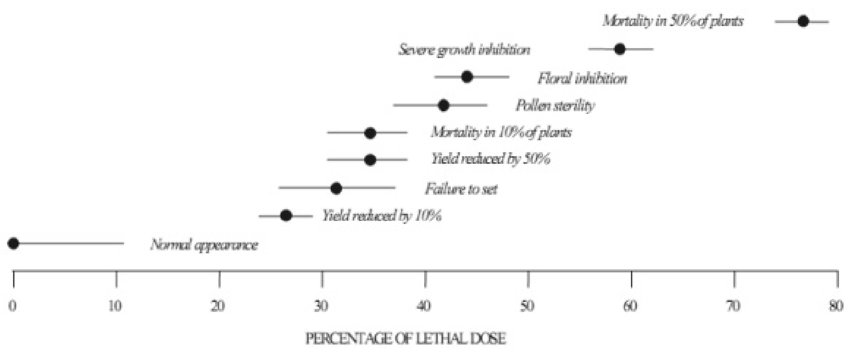
2.1.1 General observations

Although it is impossible to measure all the effects of radiation on known species, the figure below (source UNSCEAR) allows us to see that the sensitivity to ionising radiation differs between and plant species, and micro-bodies.



The data established by UNSCEAR lend weight to a position held by the ICRP in some of its earlier recommendations *"The environment is protected through the protection of mankind."* Despite certain protests, the reverse has not yet been proven.

Where plants are concerned, for example, it is now possible to measure the effects on various biological functions expressed as a percentage of the known lethal dose for the species, cf. Figure below.



Using the consequences of Chernobyl, it is also possible to have a clear description of ionising radiation impact on flora and fauna living in the ecosystem round the Chernobyl nuclear power plants.

2.1.2 Impact near Chernobyl

- The high level of ionising radiation received after the Chernobyl accident, measured on deposits of 0.7-3.9 GBq/m^2, led to severe detrimental effects in an area of several tens of kilometres in diameter (the evacuated zone round the power plants was set at 30 km radius).
- An increase in mortality in the area was observed for animals, surface invertebrates and pine trees which represent the most sensitive plants (hence the expression "red forests" heard in the media reporting on the aftermath of the accident). A lower reproduction rate was also observed, both for plants and wild-life (mammals, birds, etc.).
- After this sudden change in the ecological balance of most species previously present in the area, lasting several years, the abandoned fields and forests, in the 30 km radius zone evacuated round Chernobyl, became refuges for many plant and wild life species who took over the abandoned ecological niches and began to reproduce again.

– Surface invertebrates in the 30 km zone, following a drastic decrease in population (by a factor 30); have recovered their previous size and diversity.

The following set of lessons can be drawn from the observations made over more than 20 years since the accident:

– For land surface plants, the most sensitive (pine-trees), chronic doses around 400 microGy/hr (10 mGy/day) have low level consequences, and no effect at all on other plants.
– For most fresh water species, chronic doses lower than 400 microGy/hr (10 mGy/day) for those specimens most exposed does not appear to have any detrimental effects.
– For land animals that are the most sensitive (mammals), chronic doses of 40 microGy/hr (1 mGy/day) do not seem to impede their reproduction. Likewise, birds, reptiles and land invertebrates are in general less radiologically sensitive than mammals.

Genetic or somatic changes that can occur even with low exposure levels may not have any (or if any, very low) effects on bioceonoses, following the process of natural selection or through exchanges with populations in the neighbouring non contaminated habitats.

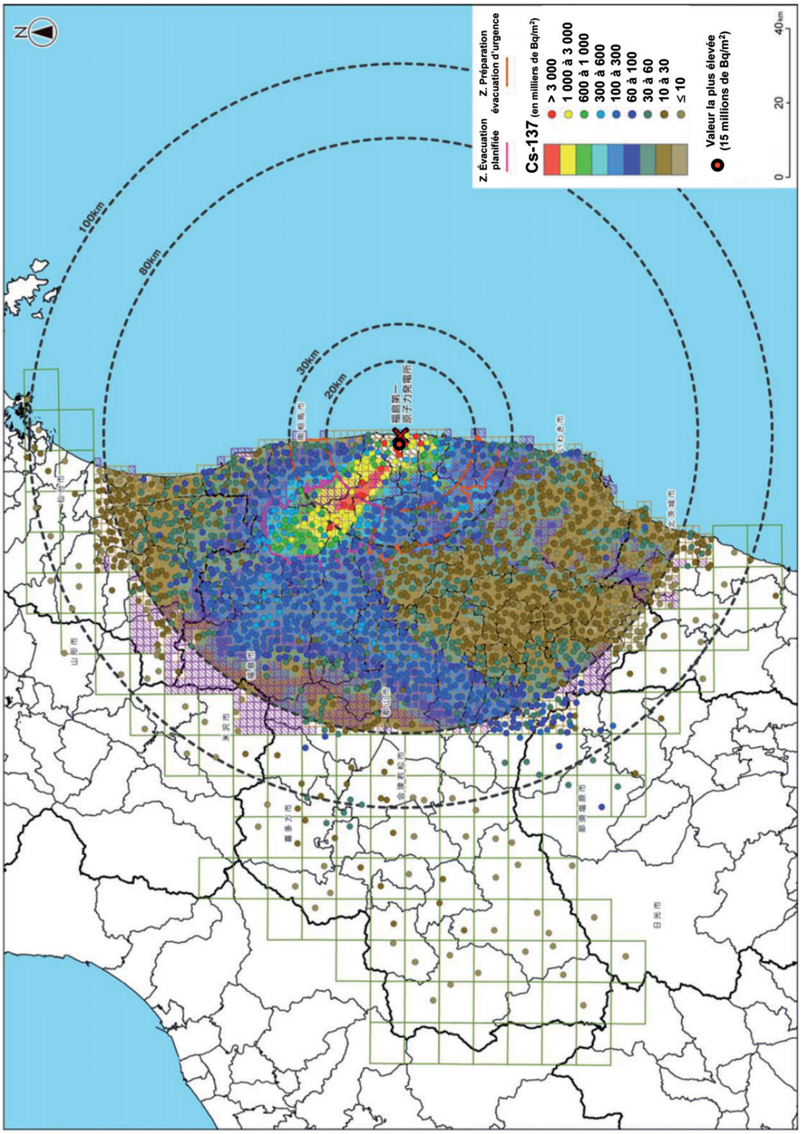
2.1.3 The situation around Fukushima

Although globally the radioactive matter released through the accident events is only 10% of that released at Chernobyl, the levels of radioactivity measured in the soil in the most contaminated areas is comparable to that found round Chernobyl. The same impacts therefore may be expected, even though the two accidents are in differing categories. In the case of Fukushima, the matter was composed solely by volatile elements released when the reactor core melted down and there was no dispersal/release of nuclear fuel. Nonetheless, we can expect that the solubility of contaminant radionuclides may prove to be of a higher level than that for the same radionuclides trapped in/with fuel particles.

2.2. Impact on vegetables: different modes of deposit

2.2.1 Transfer to plants and notably vegetables

After a nuclear accident has occurred, the radionuclides are deposited by gravity (dry fall-out) or attached to rain-drops or snow-flakes (wet fall-out). The



Source – the MEXT fallout map, August 26, 2011.

second mode of deposit is more consequent than the first and leads to very varied densities depending on the rainfall measures. The pattern of deposit is called a "spotted leopard skin".

Transfer of radionuclides to plants – in the year of contamination – is mainly on the leaf surfaces which are determining factors. In a second stage, after a slow migration to the soil, transfer affects the roots. Leaf deposit is higher than root deposit and it is for this reason that plant contamination is at its maximum during the year after the accident. Leaf deposit, thus, depends on the state of development of the contaminated plan. Migration of radionuclides depends mainly on the soil characteristic. It is very slow in open fields and underwoods; in contrast, contamination of forest produce (mushrooms and fruits will stay high for many years to come.

Following the fall-out from Fukushima, the highest levels of radioactivity were recorded for vegetables, notably those with extensive leaves such as spinach. The dairy products were also concerned, to a moderate degree and meat too, on a measured slow rate of contamination, and concerning mostly animals who had received fodder stored out of doors in the areas where there had been high level deposits of radionuclides.

Three categories of produce showed a significant level of contamination: bamboo shoots, tea-leaves (either new or seasoned) and Japanese apricots. The insert below is an excerpt from the IRSN status report, dated July 13 2011, describing contamination of the Japanese food-chains.

"The measured mass activities (^{134}Cs+^{137}Cs) may exceed the value of about 1 000 Bq/kg for newly picked tea leaves (1 330 Bq/kg for new tea-leaves at Kanagawa and 981 Bq/kg for new tea-leaves at Shizuoka measured on June 21, 2011) and for freshly cropped bamboo shoots (2 060 Bq/kg at Minamisoma and 1 070 Bq/kg at Souma on June 23). These levels of contamination correspond to relatively moderate deposits of caesium, estimated at several tens of thousands of Bq/m^2, up to several hundred kilometres distance from Fukushima Dai-ichi. It is therefore possible that much higher levels of contamination for the same produce may be observed in crops from the regions most affected by radioactive fallout. The measurements made on tea-leaves and bamboo shoots concern only the first crops … but in fact, tea-leaves in a second picking were less contaminated than the first crop leaves; the caesium levels measured in June varied from 29 to 306 Bq/kg for freshly cropped leaves. However, consumption of such foods-stuffs is not immediate and the packaged produce from the first crops may still be on the sales shelves for months to come.

Japanese apricots (*umé*) have a very early blossom, and they were probably blossoming in mid-March … the most recent measurements on these trees where the fruits had been gathered in the Fukushima prefecture ranged from 137 to 700 Bq/kg fresh fruits for caesium isotopes 134 and 137… This contamination resulted from the capture by the radioactive deposits on plant parts that existed at the time of the accident. It is quite probable that contamination of Japanese apricots will not be limited to last (2011) year's crop. Notwithstanding, the apricot production will be less sensitive in the future to this radioactive pollution than for tea-leaves or bamboo shoots."

The immediate consequences of the accident at Fukushima on Japanese food-chains must be analysed as a function of the date of deposit of the radionuclides which in fact turned out to be limited. Long-term consequences, however, must include the remnant level of contamination in the soils and the coefficients for transfer of the particles (principally caesium) to those parts of the plant that are consumed.

2.2.2 Contamination of aquatic fauna

The IRSN published on July 11 2011 (updated October 26 2011), an overview of contamination of marine life and milieus. A strong pollution of the East China Sea took place after the accident at Fukushima, the origin of which were the effluent waters that had been used to cool the damaged reactor installations and to a lesser degree the radioactive fallout in the ocean with some of the radionuclide matter released into the atmosphere during the first 10 days after the start of the accident, when the winds were facing out to sea.

In the case of iodine 131, which fixes itself on marine fauna and flora, the concentration level fell rapidly because of the short half-life [8 days], from maximum measures of several thousand of Bq/litre close to the canal where the radioactive cooling water was discharged.

The concentration of the two caesium isotopes reached levels of several hundreds of thousands of Bq/litre close to the coastline, gradually decreasing by end April to a level of approx.100 Bq/litre.

The soluble radioactive isotopes of caesium were transported by the marine currents throughout the oceanic masses. The decrease of caesium in the marine milieu close to the nuclear power plant has a half-life of 11 days.

In August 2011, the IAAE published an overview of the consequences on coastal fishing. The only species where an excess was noted for sand-eels, with values exceeding 10 000 Bq/kg of iodine 131 in a fishing zone situated some 40-60 km South of Fukushima. All fishing was suspended in the waters off the Fukushima prefecture and particularly to the South the fishing grounds of Ibaraki.

2.3 Land decontamination

2.3.1 Reducing contamination in built-up areas

The main aim of actions taken to reduce contamination after a nuclear accident is to tm prove the radiological situation of the environment and to reduce the exposure of populations who for some reason or another remain in the contaminated area or who move back to the area after temporary evacuation. However, such actions will not allow a return to the initial state, *viz.*, one of total decontamination. Taking account of this dimension requires that the population itself trusts the measures taken by the public authorities.

2.3.2 Major exposure in built-up areas and actions to reduce contamination

It is mainly through contaminated roofs, road, pavements and "urban" vegetation that populations are radiated externally, and the respective scale of each of these exposure sources varies according to the life style of the populations involved (individual, separate houses or social, collective housing) and on the type of deposit (dry or wet). Concentration due to collectors for rainwater carrying particles from roofs (*via* guttering, sewers for large-scale urban surfaces) must likewise be taken into account. The accident at Chernobyl shows that you also have to be vigilant with ventilation (air-condition) ducting in houses and buildings.

Possible actions to reduce contamination carry with them specific implementation constraints that depend on the operational availability of the equipment needed and on the time elapsed since the accident occurred. These actions, that can production a reduction of a factor 2 or 3 are set out in detail in Appendix 14, in French « Réduction de la contamination en milieu bâti » [reducing contamination in built-up areas].

2.3.3 Steps to restore quality for contaminated soils

The return on experience from Chernobyl tells us that one cannot completely restore quality to soils: the important point is to require an economic value for the contaminated soils. It is a highly complex programme with several identified stages, likewise described in Appendix 15. In short, the actions undertaken presuppose that we have an excellent knowledge of the ground areas that were contaminated, that we develop mechanical procedures and physicochemical decontaminants, that we choose relevant crops that either offer an excellent coverage, or are "immune", so to speak, to caesium (concentrating it or being oblivious to it), or gain can leads to a delayed industrial utilisation, or finally as a biomass to produce energy in special infrastructures specific to this task.

2.4 Contaminated wastes

Treatment of wastes is a major political issue in Japan; on one hand, the challenge is to clean-up the debris resulting from the tsunami and the nuclear site liquids that have been stored 'temporarily' on a site created near the nuclear power plant. On the other, dealing with all the wastes that result from surface treatment of the zones undergoing rehabilitation.

The Japanese have set a target consisting of treating those zones where the residual radioactivity can be reduced to doses of 5 mSv/yr (which corresponds to 1 μSv/yr). For those areas where exposure is already less than 5 mSv/yr, the Japanese Government has judged that this activity will decrease fairly quickly to fall below the threshold value for resident populations (1 mSv/yr with prevailing meteorological conditions of wind and rainfall).

Concerning the evacuated zones and again with the objective to recovery use of the contaminated soils, important surface scraping operations will be needed, down to a depth of 5cm, to capture the caesium particles. The calculations show that this amounts to some 400 tonnes/hectare, in order to achieve a division of a factor 4 to 5 of the remnant dose potential. These scraping operations, for the moment, do not concern forest land (covering 70% of the contaminated area). Collecting the leaves as they fall and pruning the trees could suffice. Moreover, the volume of contaminated wastes could also be reduced by incineration, but would lead inevitably to a concentration of the contaminants.

In the zones that were not subject to evacuation orders, a precise diagnosis will be undertaken for the state of the surface soils and the more contaminated levels will be removed and stored, following the doctrine we already use to store very low radioactivity wastes. Ploughing, to a greater or lesser ploughshare depth, using fertilizers, etc., which were processes tested at Chernobyl (cf. 2011 UNSCEAR report[16]) will also be implemented.

[16] UNSCEAR Report 2008: Sources and effects of ionizing radiation. Vol II Appendix E: *Effects of ionizing radiation on non human biota*, United Nations, New-York 2011.

The Japanese ministry for the Environment has evaluated the surface around Fukushima to be treated at 2 400 km^2 and the volumes contaminated and that will require long-term storage at 29 Mm^3.

It will be recalled that for Chernobyl, in the most contaminated areas, close to the damaged reactors, the wastes were evacuated and buried in the "Red Forest" area. In fact, this operation had another aim, to make the access to the nuclear installations easier and not to rehabilitate the scraped zone.

RECOMMENDATIONS

1 | Education, information and communication

When a catastrophe occurs, whatever its form, information and communication play a key role to circulate the instructions issued by the competent authorities, aimed at protecting the populations and avoiding panic phenomena that can prove particularly disastrous (we remind readers that the only victims of Three Mile Island in the USA were deaths by accident on the road among people who were fleeing the fallout (which turned out to be extremely low)). Compared with Chernobyl, Fukushima served to demonstrate that in France there is a significant advance in terms of information circulation in Japan and transparency and transparency in France – guaranteed by the French High Committee for Transparency and Information in Nuclear Safety (HCTISN). This advance is illustrated by:

- daily efforts in terms of institutional information, for example the communiqués issued by the French Nuclear Safety Authority (ASN);
- availability of experts and scientists to serve media demand;
- constant on-line drafting of information on Web-sites such as that of the IRSN which serve to supply numerous answers to questions as they arise.

Nevertheless, the difficulty lies in the media treatment of the information, often included in an unending stream of other headline news, often of a worrisome nature, sometimes self-contradictory, this requires verification. In this respect, the recently founded social networks constitute a new information vector that must be taken into account.

<u>The Academy recommends the following measures</u>:

1. That health sector professionals and the public at large be able to rapidly access synthetic information on Internet sites guaranteed "reliable" by HCTISN.
2. That school and HE programmes be modified to include technical and sanitary information that are validated on a regular basis, in various energy related areas[17] This requires that experts in the field be associated with the drafting of the school-books and university documents.

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[17] The Baccalaureate programme in France has a section on *Nuclear transformations* in the science stream S and *Global energy issues in the economic and literary streams* ES et L.

3. That communication on nuclear risks should include the possibility of accidents and that crisis management be organised so as to better anticipate these risks.
4. That, in the event of a serious accident at a nuclear power plant, multi-disciplinary expert groups with scientists and representatives of the population be appointed, for the purpose of making fully available the information, as and when acquired and validated, about the state of the environment and provide a constantly updated estimation of risk levels.
5. That social network specialists be integrated to the crisis unit teams.

2 | Future organisation of the nuclear power production industrial sector

1. That the local authorities appoint rapid task-forces capable of intervening in less than 24h after a major accident to mitigate and control immediate consequences, up to an including a possible reactor core melt-down. Creation of such forces will also generate a strong accident ready culture and help prepare for intervention among and alongside the nuclear power plant operational staff.
2. That the INERS scale be revised, in the case of such accidents, by separating issues of safety of the nuclear infrastructures from sanitary and environmental consequences.
3. That ongoing studies by the Comité directeur de gestion des phases post-accidentelles (CODIRPA)[18] [French executive committee for post-accident phased management] be completed.

3 | National and international research programmes

The nuclear accident at Fukushima, notwithstanding the fact that the sanitary and environmental consequences were limited to Japan, led to world-wide expressions of emotion, reminding us that nuclear accidents have no frontiers.

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[18] The CODIRPA standing committee was set up by the ASN in 2005. It has the special remit to manage the transition phase between the response plans to handle a radiological emergency, on one hand, and that with longer terms consequences in respect to management of contaminated territories (sanitary management of the populations at risk, economic consequences, rehabilitation of "normal" lifestyles in the zones affected).

This point alone calls for mobilisation on a world-scale as to the lessons that ought to be drawn and lead on to recommendations to pursue, finance and extend research thematics and appoint specific organisations to do[19].

The Academy recommends that collaboration of the nature outlined above should be prioritised, in: studies related to:

1. The consequences of long exposures to low-level ionising radiation, the results of which will help set the limit values making evaluation necessary to protect the populations without leading to ill-advised population displacements, where the net impact in terms of public health would be negative.
2. Internal decontamination studies and results that should be better taken into account[20].
3. Research to be conducted into identifying markers specific to radioactive-induced cancers.
4. Development of industrial decontamination equipment and soil rehabilitation based on validated methods (on demonstration sites and sites contaminated by previous accidents. Inventories using these results should be assembled for plant resources as a function of their capacity to concentrate or not radionuclides.
5. Stocks of plant genetic resources that should be constituted, specifically selected as a function of their capacity to concentrate radionuclide particles, in order to be able to intervene rapidly on contaminated soils.
6. Increased studies and development of robots adapted to degraded, radioactive situations.

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[19] It is likewise necessary to pursue INEX exercises as planned by the AEN after Chernobyl, similar to the ECURIE system decided by the European Union, and which considerably improved State to State transmission of information and for definition of counter-measures to mitigate consequences.

[20] After Chernobyl, various medical and paramedical initiatives were taken on a local scale to attempt to decrease personal exposure to radionuclides deposited in the environment. It is considered that this attitude can be justified in the case of radioactive iodine contamination – given that distribution of stable iodine when prescribed by sanitary authorities proves efficient to avoid exposure of healthy thyroid glands to ionising radiation - but for other radionuclides and in particular the caesium radio-isotopes, the benefits of such policies are uncertain to say the least. The protocols proposed have not yet been subjected to analysis as to their efficiency, our reference here being the requirements of EBM (evidence-based medicine) and leaves open the possibility for dishonest commercial acts.

4 | Management of sanitary conditions

1. Implement simple evaluation tools to measure internal contamination in degraded situations.
2. Supervise rapid distribution of stable iodine for the entire French population.
3. Relevant information should be given as to how stable iodine is prescribed, based on dose levels that can lead to a measurable risk for the thyroid gland.
4. Training for medical family practitioners must be improved on the basis of the principles that underscore radioprotection of populations.
5. Various scenarios and protocols for management of intervening emergency teams and the populations subject to exposure must be improved.
6. Appropriate reorganisation for hospitals, clinics, is needed.

In the case of a major nuclear accident, indeed for any environmental catastrophe, hospital organisation to produce a correct emergency response must be rethought, both for emergency care and for impacts on current care and programmed hospitalisation of patients other than those affected directly by the emergency events.

- *In the case of emergency care stemming directly from the accident*:

  – The so-called NRBC units (nuclear, radiological, bacteriological and chemical) must be set up at a constantly operational level.

  – Medical staff and nurses must be trained in reception and handling of contamination victims.

- *In the case of current care and programmed hospitalisation of patients other than those related to the emergency events*, authorities must anticipate on a break-down of continuous service as soon as the energy event occurs in order to re-establish a balance between demand and supply for care:

  – By preventively transferring, before any aggravation of their case, those hospitalised patients or out-house patients whose state may get worse in the hours or days following the event.

  – By setting up structures near the positions where victims are grouped together, to offer ambulatory out-house treatment and continued care for patients with chronic disorders.

– The above recommendation implies that medical sorting criteria are there to prioritise the patients who must benefit from such ambulatory care measures.

Consequently, it seems necessary in the view of the Academy, at the level of French Regional Health Agencies (ARS) or Defence zone ARSs:

– To list all evacuation means (medical or otherwise) available for the handling of ambulatory patients whose clinical status might worsen and to identify the modes to make these means rapidly operational.

– To identify those medical teams able to ensure continuity of service in the emergency zone and also in regions not affected by the catastrophe, plus the hospitals, clinics, etc., capable of admitting these patients until such time as the local situations returns to a condition that is compatible with their case and current status.

- *Finally and on a more prospective note*:

– Research into improved models of emergency response scenarios for the entire care system for accidents or environmental catastrophes, notably of a nuclear origin, must be encouraged.

7. Rapid organisation of technical and manpower epidemiological resources must be set in motion as soon as a major nuclear accident occurs; a real-time epidemiological monitoring process must be launched to provide regular data on physical health anomalies, on psychosocial consequences, on risk perception and determining factors, relying notably on aid from the multi-disciplinary teams proposed above in recommendation I.4. This system must include a critical assessment of the operations actually used.

8. Planning should be implemented, as needed, of technical and manpower resources ready to organise mid-term and long-term epidemiological surveys for populations exposed to radioactive contamination, including those who feel (perceive) they have been exposed. Medical monitoring must cover not only cancer prognosis and cases and reproduction anomalies considered to be *a priori* related to radiation doses received but should be extended to cases of mental health and other pathologies non-specifically related to radiation exposure. Regular assessment of distant evolution of risk perception of the event by the populations could rely on methodology developed by IRSN for its standing, permanent enquiry procedure.

9. University level training in public health should be organised, in particular for specialists called to handle the sanitary consequences of catastrophes and environmental accidents and research integrating media expertise that would allow for an assessment of their role in the event and context of environmental accidents should be encouraged.