INSTITUT DE FRANCE
Académie des sciences

INTERIM REPORT BY AND *AD HOC* WORKING PARTY OF THE

ACADÉMIE DES SCIENCES

Solidarity

Japan

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Introduction

Prof. Alain CARPENTIER,

President of the Académie des sciences – Institut de France

> *"Although it is Japan government 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, 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 leading through the return on experience to 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 24 page 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, attached hereto, 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 comprises 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 co-operation. 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, if the section produced by the medical sub-group is still being finalised, given the sheer avalanche of new information arriving each week and enriching the dossier, the reports of the seismic and nuclear sub-groups 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.

Académie des sciences – Institut-de-France

REPORT

“*Megaseisms and megatsunamis*” *

by the Academy’s *ad hoc*

‘SEISMIC’ Working Party

Working Party, Chair and Members

Jacques FRIEDEL, Chair, former President of the Académie des sciences – Institut de France (hereinafter referred to as the Academy)

Pierre-Yves BARD, Observatoire de sciences de l’Univers, University of Grenobles

Pascal BERNARD, Institut de physique du globe de Paris

Michel CARA, School and Observatoire des sciences de la Terre, University of Strasbourg

Vincent COURTILLOT, Member of the Académie des sciences - Institut de France

Jean DERCOURT, Honorary Perpetual Secretary of the Académie des sciences – Institut de France

Claude JAUPART, Member of the Académie des sciences – Institut de France

Xavier LE PICHON, Member of the Académie des sciences – Institut de France

Raùl MADARIAGA, École normale supérieure.

Jean-Paul MONTAGNER, Institut de physique du globe de Paris

Alain PECKER, Fellow of the National Academy of Technologies of France (NATF)

Jean-Paul POIRIER, Member of the Académie des sciences, Institut-de-France

Jean SALENÇON, Past President of the Académie des sciences – Institut de France

François SCHINDELÉ, French Commissariat for Atomic Energy (CEA)

Paul TAPPONNIER, Member of the Académie des sciences – Institut de France

Personalities invited for a hearing by the Working Party

Rolando ARMIJO, Institut de physique du globe de Paris

Robert DAUTRAY, Member of the Académie des sciences, Institut-de-France

John DOUGLAS, BRGM

Nikolaï SHAPIRO, Institut de physique du globe de Paris

Steve TAIT, Institut de physique du globe de Paris

Critical review of the Report assured by:

Alain CARPENTIER, President of the Académie des sciences, Institut-de-France

Philippe TAQUET, Vice-President of the Académie des sciences, Institut-de-France

René BLANCHET, Member of the Académie des sciences, Institut-de-France

Jean-Louis LEMOUËL, Member of the Académie des sciences, Institut-de-France

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* Translated from the original in French.

Contents

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.* Fig. 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 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 5.7m 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 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 7 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; fortunately 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 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 co-operation 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 (‘métropolitan’) 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 1-3m 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 2m 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 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 *co-ordinate* 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 tsunamic 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.

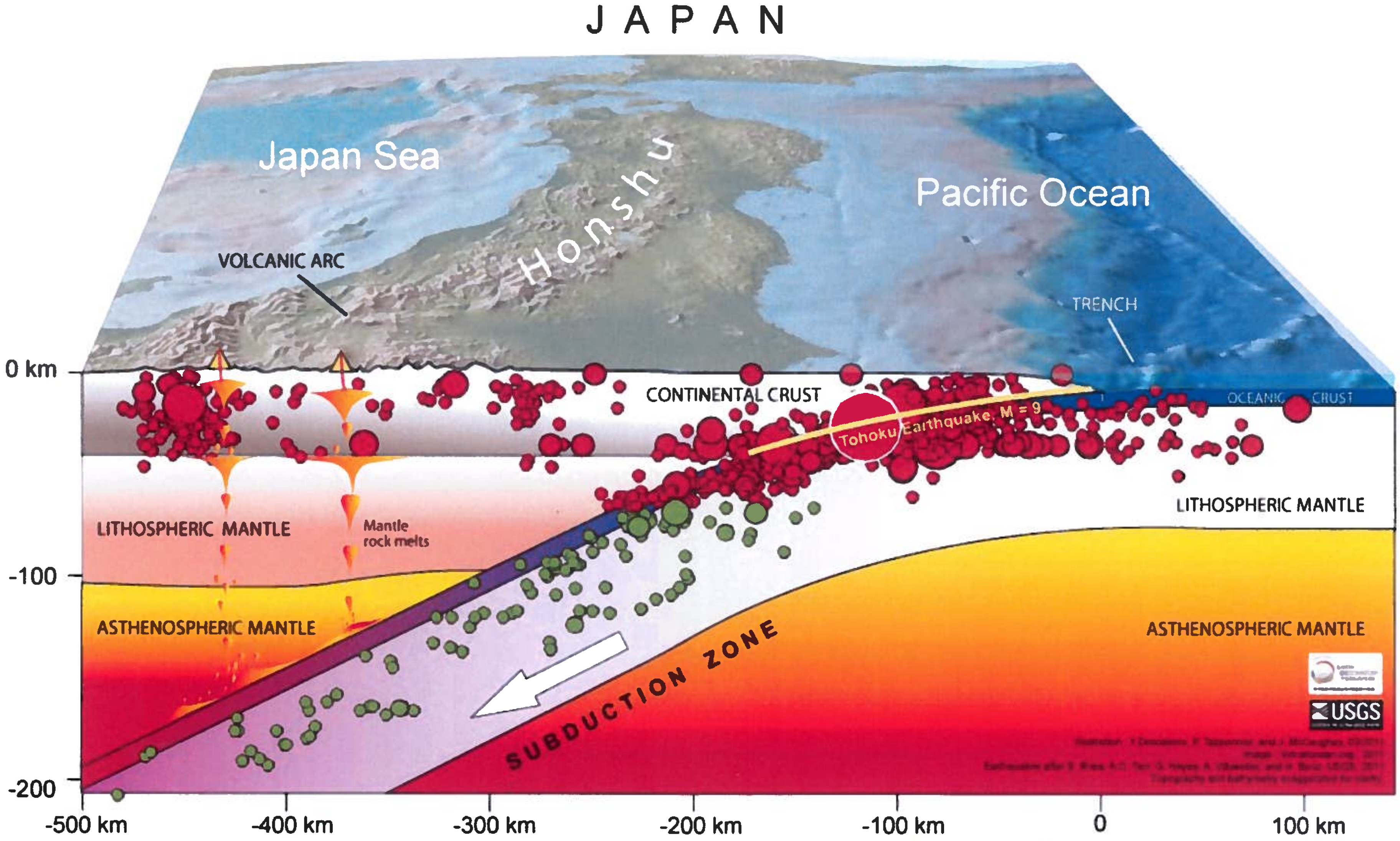
Neither was the megatsunami predicted by the Japanese Authorities and this was both the cause of tremendous physical damage, notably to the nuclear reactors built near the coast-line and of considerable loss of lives. The Japanese example also throws light on certain questions and issues that should 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 this 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 State guaranteed, regular financing, both for medium-term and long-term investments. 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 '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.

Megathrust Earthquake
of 11/03/2011
Mw 9.0

Total Rupture
of subduction interface



rupture length 500 km; width 200 km
whole crust, from 40 km depth up to ocean floor

Académie des sciences – Institut-de-France

REPORT

*“The major accident at Fukushima Dai-ichi”**

by the Academy’s *ad hoc*
‘NUCLEAR’
Working Party

Working Party, Chair and Members

Edouard BRÉZIN, Chair, Former President of Académie des sciences – Institut de France

Sébastien BALIBAR, Member of the Académie des sciences – Institut de France

Yves BAMBERGER, EDF, Fellow of the National Academy of Technologies of France (NATF)

Bertrand BARRÉ, Areva

Sébastien CANDEL, Member of the Académie des sciences – Institut de France

Catherine CÉSARSKY, Member of the Académie des sciences – Institut de France

Marie-Pierre COMETS, French authority for Nuclear Safety [Autorité de sûreté nucléaire]

Robert DAUTRAY, Member of the Académie des sciences – Institut de France

Denis GRATIAS, Member of the Académie des sciences – Institut de France

Robert GUILLAUMONT, Member of the Académie des sciences – Institut de France

Guy LAVAL, Member of the Académie des sciences – Institut de France

Yves QUÉRÉ, Member of the Académie des sciences – Institut de France

Michel SCHWARZ, Institut de radioprotection et de sûreté nucléaire (IRSN)

Bernard TISSOT, Member of the Académie des sciences – Institut de France

André ZAOUI, Member of the Académie des sciences – Institut de France

with the collaboration of Yves BRÉCHET, Member of the Académie des sciences – Institut de France.

Personalities invited for a hearing:

David BAUMONT, IRSN

Philippe BILLIOT, CEA

Bernard BOULLIS, CEA

François GAUCHÉ, CEA

Gilbert GUILHEM, IRSN

Philippe JAMET, French Authority for Nuclear Safety [Autorité de sûreté nucléaire]

Xavier POUGET-ABADIE, EDF

Jacques REPUSSARD, Director General for the French Institute for Nuclear Satefy [IRSN]

Alan ZAETTA, CEA

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* Translated from the original in French.

Critical review of the Report assured by:

Alain CARPENTIER, President of the Académie des sciences, Institut-de-France

Jean-Claude DUPLESSY, Member of the Académie des sciences, Institut-de-France

Denis JÉROME, Member of the Académie des sciences, Institut-de-France

* * *

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 Dai-ichi ?
  [referred to hereinafter as Fukushima]
- 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 a hearing.

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Appendices on line at: (http://www.academie-sciences.fr/activite/rapport/rads0611.htm)
(Texts in French)

1. The Fukushima accident - L'accident de la centrale nucléaire de Fukushima Dai-ichi ; texte ASN et IRSN ; plus a complementary text on treatment of contaminated matter - Plus : traitement des aux contaminées ; author B. Barré
2. Glossary - Glossaire nucléaire
3. PWRs and BWRs so-called light water (or common) reactors. Les réacteurs à eau légère (ou ordinaire) – Réacteurs à eau pressurisée (REP) et réacteurs à eau bouillante (REB) ; author B. Barré

Description of water moderated reactors, either boiling water (BWRs) as at Fukushima or pressurised water (PWRs) as used in France.

4. Serious accidents occurring with BWRs

   A specific description of how a serious accident at a BWR site evolved

5. Improvements of safety factors in French nuclear power generation stations as introduced by the operator EDF – an account of incidents and accidents.

6. The hydrogen risk in French reactor vessels – ISRN text

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7. Assessment of French nuclear stations' capacity to resist earthquakes; text by IRSN

8. Return on experience at Fukushima, research on nuclear fuel questions; author R. Guillaumont

9. L'apport des recherches de l'IRSN, concernant les accidents avec fusion de cœur, à la compréhension de l'accident de Fukushima et des ses conséquences ; texte IRSN

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18 Onboard nuclear power units (for ship propulsion systems); author B. Barré

19 ASN document: Presentation of complementary information about safety factors for French nuclear sites after Fukushima.

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.

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 time.

The para-seismic devices did come on line and reactors 1,2 and 3 were automatically shut down (reactors 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

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[1] Several web sites allow Internauts to follow the evolution in time of the 6 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.

[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.

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 minute after the earthquake, submerging the emergency electric generators of reactors 1, 2, 3 and 4[4], damaging the sea water intake devices as it travelled inland,

For each reactor, there still remained the emergency turbine generators that can operate the valves using steam pressure from the reactor vessel (one for reactor N°1, two for reactors 2 and 3). These turbo-pumps will remain active for as long as the electric batteries that feed the control circuits for the steam flow regulation valves are charged. This device ensures an internal cooling process but is essentially temporary[5], since there is no external electric source or external water supply. These turbo-pumps stopped on March 11 – at 16h36 for reactor N°1 and on March 13 for reactor N°3 and on March 14, the pump for reactor N°2 likewise ceases to function. To date, we simply do not know if the loss of these cooling systems was due to possible human error or were a direct consequence of the tsunami.

With the absence 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°, the oxidation reaction metallic sheathes made of zirconium alloy, Zircaloy, that encapsulate the nuclear fuel[6] tends to accelerate strongly thereby freeing enormous quantities of gaseous hydrogen and associate energy inasmuch as this particular reaction is highly exothermic[7]. All this sequence probably took place in less than one hour.

When a system such as this type of reactor sees its coolant 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.

To decrease the internal reactor vessel pressure[8], 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

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[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.

[5] The turbo pumps draw their water from the torus pool. If the water is not cooled, the pumps stop as soon as the water boiling point is reached.

[6] 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.

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

[8] 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.

fact) with MOX fuel[9] 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[10] without any confinement for the fission products released, since the pool designers had not included such protection barriers for these storage and cooling pools[11]. 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[12] and reconnaissance sorties carried out by mobile robots. On April 23, the operator TEPCO announced that the pool temperature for the 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 time the Working Party drafted this paper, it would appear that the situation is coming under control (provide 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.

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[14] 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

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[9] 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..

[10] 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.

[11] With the exception 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.

[12] 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.

[13] International Nuclear Event Scale.

[14] *Cf.* in appendix, the comparative table between the Chernobyl and Fukushima events, on the basis of a scenario for the latter that remains to be consolidated

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 20km 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 piece of nonsense – an apocalyptic scenario such 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 ^{239}Plutonium produced in the reactor, simply do not allow you to trigger a nuclear explosion, whatever the sequence of events[15].

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 40m 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 10m higher than the others[16]..
- 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 turbine in the reactor failed (they are capable when required of keeping 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 just after 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 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°s 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

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

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

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[17] 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[18]. 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 shows 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.

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), 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[19] 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

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

[18] 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.

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

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* [20] for fuel loads and in the case of over 20 of the 58 reactors, a Mixed OXide, so-called *MOX* fuel (*cf.* appendix 14).

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), Londonderry, 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[21]. Bring the reactor back on line can only be done with approval from the French Nuclear Safety Authority (ASN). The oldest 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 outage for 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.

The accident at Fukushima does not constitute a reason for stopping France’s older nuclear power stations[22]. On the other hand, 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

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[20] *Cf.* Appendix 1: glossary.

[21] 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 1O year full; inspection. In addition, there are continuous spot checks and routine inspections

[22] 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.

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 Bessel 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[23] and ionising radiation. ASN is headed by a group of 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[24] 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 20 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 11 different sites, often in partnership agreements with the CEA[25], the CNRS and numerous international laboratories[26]. 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.

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[23] 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.

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

[25] CEA=Commissariat à l'énergie atomique et aux énergies alternatives [Commissariat for Atomic Energy and Alternate energy sources]

[26] Numerous references to IRSN programmes are found at the site www.irsn.fr. The document authored by M 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.]

Readers will find an appendix attached that describes the contribution of IRSN to accidents involving a core melt-down.

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 ad development teams.

Additional reinforced 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. situation For example, after the accident at TMI N°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 physico-chemical 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 release process. The arrangements needed to avoid this happening consist of adding a high relative concentration of water vapour to the vented H_2 - which in essence inerts the resulting H_20- H_2 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 volumes.

3. Nuclear fuel cycle and future possibilities

3.1. A comparison of safety equipment: EPR (Generation III)and Generation II reactors

Readers will find in appendix a detailed description of improvements incorporated in the EPR design[27] 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;
- A new fuel mixture, named MOX, is made incorporating the plutonium;
- The highly radioactive ultimate wastes are vitrified;
- A study has been 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[28] 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

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[27] European Pressurized Reactor.

[28] It should be noted that spent MOX fuel assemblies are not retreated

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[29] 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[30] 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.

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.

Closing remarks

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

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[29] 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.

[30] FSN – Fast Neutron Reactor aka breeder reactors; in French RNR for Réacteur à neutrons rapides.

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.

Provisional conclusions

- **about the major accident at Fukushima**

1 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.

2 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.

3 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

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

5 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.

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

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

8 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

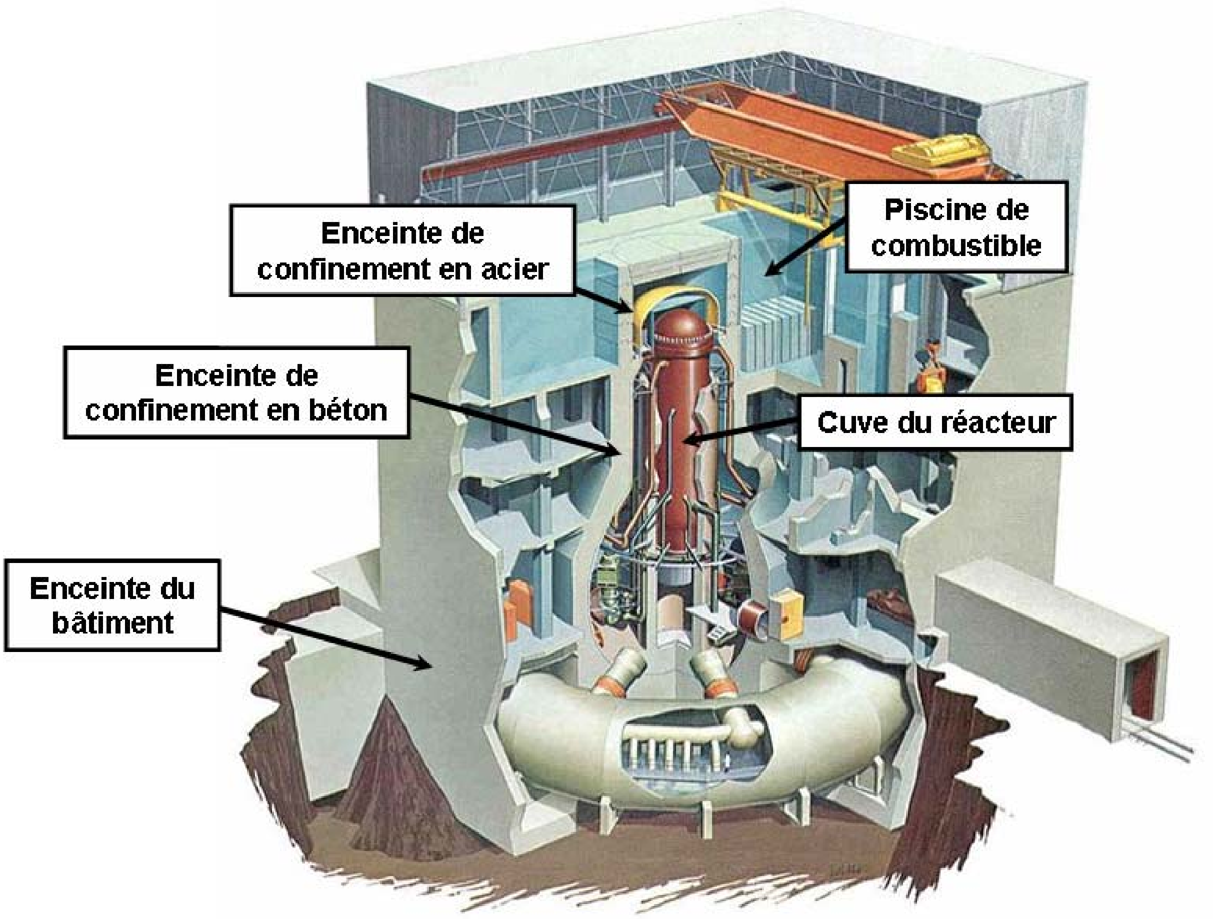
9 These events at Fukushima have shed new light on risk factors for reactors and spent fuel storage. We must not lose sight of the fact that the safety requirements outlined here concern all nuclear activities up to and including the definitive disposal of the ultimate radioactive waste matter.

10 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.

11 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.

12 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.

13 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 fro other sectors, and not forgetting the general context of global warming in which this debate will necessarily be conducted.



Nuclear power plant of Fukushima Daï-Ichi.