# A Probabilistic Risk Assessment Practioner looks at the Great East Japan Earthquake and Tsunami

## A Ninokata Laboratory White Paper

**Woody Epstein**

**Visiting Research Scientist**

**Ninokata Laboratory**

**Tokyo Institute of Technology**

**April 29th, 2011**

## INTRODUCTION

### Background

The Fukushima Daiichi Nuclear Power Plant accident is an ongoing sequence of equipment, planning, and institutional failures resulting in releases of radioactive materials following the 9.0$M_W$ Tōhoku earthquake and three tsunami, the largest of which was reported by TEPCO to be 14m tsunami, on March 11th, 2011, at 14:46 JST. The maximum PGA (peak ground acceleration) of the earthquake was measured at 2.99g in Miyagi prefecture at seismic site MYG004; the PGA in the vicinity of Fukushima Daiichi can be estimated as having been between 1.38g and 1.51g, the readings measured at FKS010 and FKS016, respectively, but perhaps greater.

Eleven reactors in Japan went into automatic shutdown.

The Fukushima Daiichi plant is connected to the rest of the power grid by three lines, the 500 kV Futaba Line and the two 275 kV Ookuma Lines to the Shin-Fukushima substation.

The Shin-Fukushima substation also connects to the Fukushima Daini plant by the Fukuoka Line. Its major connection to the north is the Iwaki Line, which is managed by another company. It has two connections to the south-west that connect it to the Shin-Iwaki substation.

At the time of the quake, reactor 4 had just been defueled while 5 and 6 were in cold shutdown for planned maintenance. The quake caused loss of offsite power, as the external power grid failed. The remaining reactors shut down automatically after the earthquake, with emergency diesel generators starting up to run the control electronics and water pumps needed to cool reactors.

The earthquake intensity has been estimated to be Shindo 6+ at the Fukushima sites. The Shindo scale is a measure of intensity, based to some extent on PGA (peak ground acceleration) and indicates a PGA of somewhere between 3.0m/s$^2$ to +4.0m/s$^2$.

At this time, there seems to have been no substantial seismic damage to the safety systems of any of the three NPP sites, Onagawa, Fukushima Daini, and Tokai. Seismic damage to Fukushima Daiichi has not yet been ascertained. Until a detailed seismic walkdown can be done at all four NPP affected, it is impossible to make an informed judgement.

The plant was protected by a tsunami wall designed to withstand a 5.7m tsunami, but was not high enough to withstand the three tsunami waves which arrived during a 41 to 60 minute interval after the earthquake.

The entire plant was flooded, including the low lying diesel generators and electrical switchgear in reactor basements and external pumps for supplying cooling seawater. The connection to the electrical grid was totally lost and all emergency power was lost. All power for cooling was lost and the reactors started to overheat, due to natural decay of the fission products created before shutdown. The flooding and earthquake damage hindered external assistance, and subsequent releases of radioactivity to the air, soil, and sea have resulted.

As of the writing of this report, April 29, 2011, this accident has not yet reached a conclusion. The on-going situation is still a clear and present danger.

## The Purpose of the Report

Why did this accident occur? Could it have been prevented or mitigated? What are the implications for the people of Japan? What are the implications for the nuclear industry?

From the Probabilistic Risk Assessment (PRA) point of view, the answers to these “whys” are the answers to the fundamental questions of risk assessment: What went wrong? How likely was it? What are the consequences?

It will be some time until definitive answers to these questions can be fully made. However, in an attempt to provide some guidance, even at this early stage, I will try to collect and analyze data and informed opinion concerning the Fukishima Daiichi accident as it was impacted by the earthquake and tsunami, focusing on the first two questions of PRA: What went wrong? How likely was it?

## Acknowledgements

The information in this report was gathered from three main sources: public media, private interviews, and discussions with nuclear professional colleagues.

In particular, I would like to thank the following people for their comments and ideas: Mr. Jerzy Grynblat and Frank Cronin of Lloyd's Register; Peter Yanev of Yanev Consulting; Kunso Cho of Tokyo Broadcasting System; Dr. Akira Yamaguchi of Osaka University; Takahiro Kuramoto of Nuclear Engineering, Ltd.; Dr. Dennis Bley of the Advisory Committee on Reactor Safety of the US NRC; Mark Reinhart, formerly of the US NRC and the IAEA; Dr. Tsunoyama of Aizu University; Dr. Robert Geller of the Seismology Department of Tokyo University; Dr. Hakata of THK Consulting; and Dr. Erik Hollnagel of the Paris École des Mines.

Heart-felt *domo arigato gozaimasu* to: Dr. David Johnson of ABS Consulting for the countless conversations he had with the author and the observations he made, not only about the accident at Fukushima Daiichi, but for his keen observations about the 2011 Major League Baseball season; Dr. Antoine Rauzy of the École Polytechnique for his review and suggestions for the mathematics and philosophy of risk employed; and especially Dr. Hisashi Ninokata, Professor of Nuclear Engineering at Tokyo Institute of Technology, and his students at the Ninokata Lab, who provided collegiality, comments, thoughts, advice, and guidance necessary for this research.

I would like to thank the individuals from the Japanese central government, the Fukushima Prefectural government, the Nuclear Safety Commission, the Japan Atomic Energy Agency, the Japan Nuclear Energy Safety Organization, the Atomic Energy Commission of Japan, and workers from TEPCO, Toshiba, and their subcontractors, whose requests for confidentiality will be respected.

The author personally would like to thank his wife, Kyoko Fukushima, for patiently translating news conferences, papers, articles, and interviews as well as accompanying him on two trips to Fukushima Prefecture.

# WHAT WENT WRONG? EARTHQUAKE, TSUNAMI, LOSS OF COOLING

"… an accident can seldom count higher than three ... which is a mystery of probability that my intuition tells me is rooted at the very base of physics." -- Field Marshall Strassnitzky of the First Hussars of the Belvedere during WW I

**From the PRA Point of View**

The tsunami generated by the Great East Japan Earthquake caused the sequence of events and cascading accidents resulting in total station blackout at Fukushima Daiichi, loss of cooling, hydrogen explosions, and eventually radioactive dispersion into the air, deposition onto the land, and flow into the ocean. From preliminary seismic walkdowns at the Onagawa, the Fukushima Daini, and Tokai NPPs we can perhaps infer that no seismically caused safety system damages occurred. The author wants to emphasize the word "perhaps".

The earthquake did cause the loss of offsite power initiating event as well as severely hampering recovery activities because of the damage to the local infrastructure. Seismic damage to the piping systems and concrete inside the Daiichi reactors may never be known, in some cases, because of the damage caused by the tsunami and hydrogen explosions. High radiation levels detected in Unit 1 on the evening of March11th could have been the result structural damage caused by the earthquake or the tsunami shock wave.

We know, from risk studies all over the world, that the most likely cause of nuclear accidents are from earthquakes (and now tsunami) causing diesel generator failure, leading to total station blackout, leading to failure of cooling systems iand release of radioactive material..

The events at Fukushima Daiichi also point to omissions in many risk assessments which led to less than optimal emergency planning. While not directly contributing to "what went wrong", they certainly contributed to an attitude of complacency and subsequent belief that the events which did occur on March 11$^{th}$ were ***sōtēgai***, "unforeseeable".

In this section, I answer the question of "what went wrong" by examining the earthquake, the tsunami, and the PRA omissions. Discussion of the adequacy of the frequency estimates for both an earthquake and tsunami of the size experienced is in the next section, "How likely was it?"

The following synopsis of the current situation at Daiichi, by Professor Ninokata from the Tokyo Institute of Technology, is presented here:

> As of today, in the No.1 to No. 3 BWR units of the Fukushima Daiichi NPP, it is still necessary to inject water into the reactor pressure vessel. The amount of water to inject is that of a make up for the evaporation plus leakage from the RPV. Then, far more than 100,000 tons of highly contaminated water is estimated to have leaked from the RPV/primary boundary and then out of the primary containment vessel of type Mark-I and now stays in their reactor buildings as well as into the turbine buildings. The contaminated water, also from the spent fuel pools, is flooding a large portion of the basement spaces. This is a consequence of the failure in removing the decay heat generated in all three units since the gigantic tsunami has washed away all the engineered safety systems in place and caused station blackout (SBO) around 15:40, one hour after the M9 quake. SBO has disabled every decay heat removal capability except for the Isolation Condensers installed in the old unit No. 1. However, the IC did not work long enough for some erratic reasons. With the PCV isolated and without any decay heat removals and transport capabilities to outside the PCV (Loss of Ultimate Heat Sink), the cores of the three units have started to melt and eventually melt down to the bottom of the RPV. The timing of the core melt has depended on the termination of IC for Unit 1 and of Reactor Core Isolation Cooling for Unit 2 and Unit 3. In alternative words, the timing was dictated by the amount of water available inside the PCV. The core melt has been a rapid process and taken place within a few days at the latest. The venting and following water injection (borated) were made too late and hydrogen explosions followed the ventilation. At that time I considered the PCV flooding was only way to save RPV but no action was taken possibly due to no electricity and/or mobile generators/pumps available in time.

## The Earthquake

The Great East Japan Earthquake occurred at 14:46 JST, March 11, 2011. Its epicentre was located at 38.3 °N, 142.4 °E, which is off the Sendai coast 130km ESE of Oshika Peninsula, with a focal depth of 24km.

Two days before the main shock, an earthquake of 7.3$M_W$ occurred off the Sendai coast at 11:45, March 9. It was accompanied by active aftershocks including a 6.8$M_W$ event the next day. These events were located just north of the March 11$^{th}$ epicentre, implying, but after the fact of the main shock, that it was indeed a foreshock. Interestingly, Yoshimitsu Okada, the President of NIED (National Research Institute for Earth Science and Disaster Prevention), later stated that "… since an earthquake of 7.3 $M_W$ is a sufficiently large one by itself, no one could ***imagine*** that this event could be linked to a coming huge earthquake" (the bold italics ours).

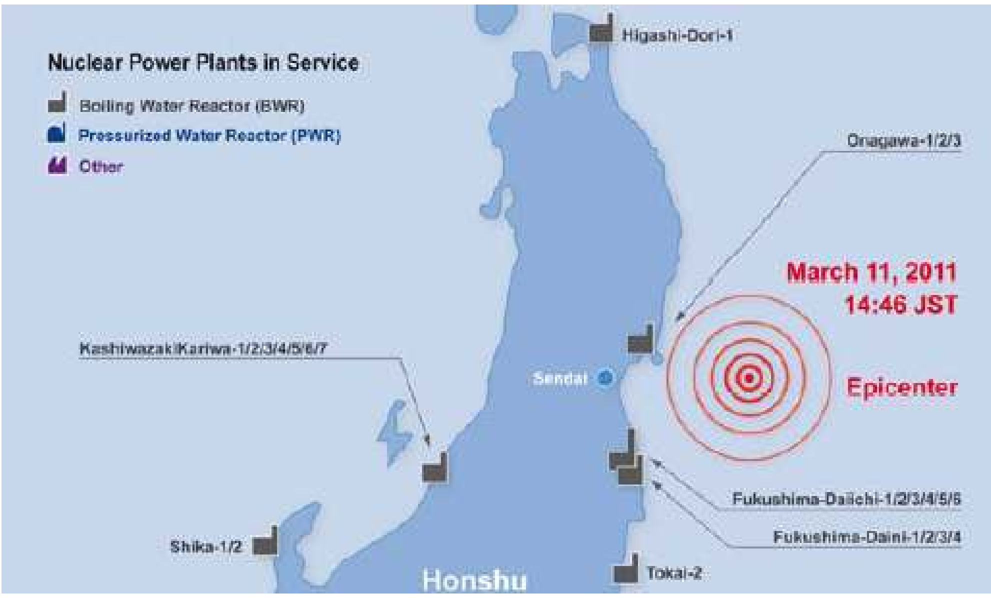
There was no need to ***imagine*** that it was a foreshock. Foreshocks should be analyzed with Bayes' Theorem. Historical studies should be done to understand the likelihood that given we have had a large earthquake, how often has it been preceded by a sizeable foreshock. Then it would be possible to know given a putative foreshock, what is the probability that it is a true foreshock.

A seismic intensity of 7 on the JMA (Japan Meteorological Agency) scale was recorded at Kurihara City, Miyagi Prefecture, and intensities of 6+ or 6- were observed in a wide area along the Pacific region, ranging from Iwate Prefecture to Ibaraki Prefecture.

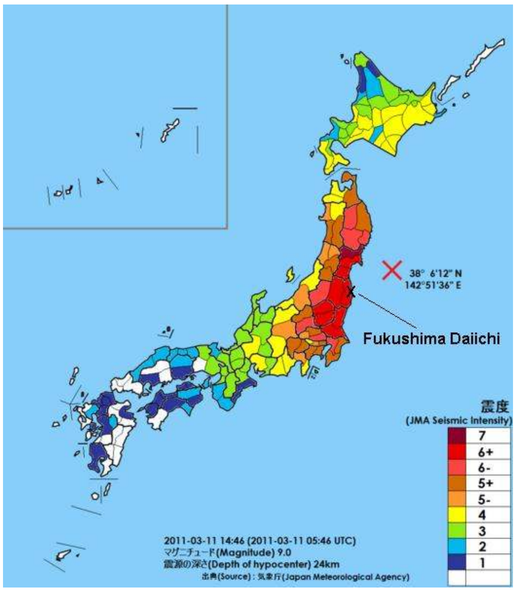
A PGA of 2,933gal (a composite of the three vector components) was observed at Tsukidate, Kurihara City, one of the NIED K-NET station.

It was the third time that an intensity of 7 was recorded in Japan following the 1995 Kobe Earthquake (7.3$M_W$) and 2004 mid-Niigata Earthquake (6.8$M_W$).

The magnitude of the earthquake was initially announced as 7.9$M_W$ by JMA and was then revised to 8.4$M_W$ at 16:00 and again revised to 8.8$M_W$ at 17:30. It was finally determined to be 9.0$M_W$ on March 13,




The measure of an earthquake in Japan is given by the JMA (Japan Meteorological Agency) Shindo scale of 1 to 7, which is an intensity scale. Many Sanriku and Sendai coast accelerations were estimated because some of the K-Net stations, K-Net is the electronic seismic network of NIED, were inoperable. The estimated intensity for Fukushima Daiichi was 6+.

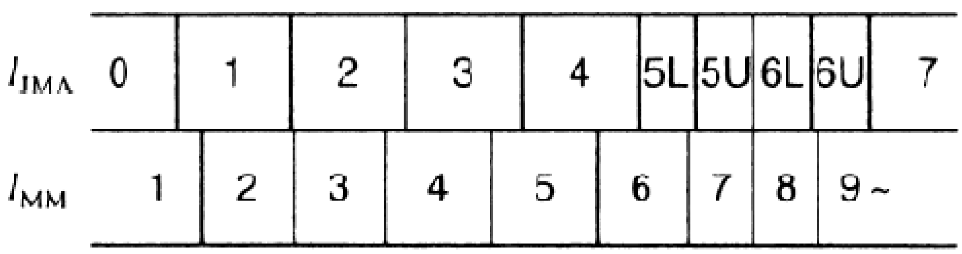

38° 6'12" N
142°51'36" E
Fukushima Daiichi
震度
(JMA Seismic Intensity)
7
6+
6-
5+
5-
4
3
2
1
2011-03-11 14:46 (2011-03-11 05:46 UTC)
マグニチュード(Magnitude) 9.0
震源の深さ(Depth of hypocenter) 24km
出典(Source) : 気象庁(Japan Meteorological Agency)

## Shindo Scale

| Number (Shindo Number in Japanese) / *Meter reading* | People | Indoor situations | Outdoor situations | Wooden houses | Reinforced-concrete buildings | Lifelines | Ground and slopes | PGA |
|---|---|---|---|---|---|---|---|---|
| 0 (0) / *0–0.4* | Imperceptible to people. | | | | | | | Less than 0.008 m/s² |
| 1 (1) / *0.5–1.4* | Felt by only some people indoors. | | | | | | | 0.008–0.025 m/s² |
| 2 (2) / *1.5–2.4* | Felt by most people indoors. Some people awake. | Hanging objects such as lamps swing slightly. | | | | | | 0.025–0.08 m/s² |
| 3 (3) / *2.5–3.4* | Felt by most people indoors. Some people are frightened. | Dishes in a cupboard rattle occasionally. | Electric wires swing slightly. | | | | | 0.08–0.25 m/s² |
| 4 (4) / *3.5-4.4* | Many people are frightened. Some people try to escape from danger. Most sleeping people awake. | Hanging objects swing considerably and dishes in a cupboard rattle. Unstable ornaments fall occasionally. | Electric wires swing considerably. People walking on a street and some people driving automobiles notice the tremor. | | | | | 0.25–0.80 m/s² |
| 5-lower (5弱) / *4.5-4.9* | Most people try to escape from a danger. Some people find it difficult to move. | Hanging objects swing violently. Most unstable ornaments fall. Occasionally, dishes in a cupboard and books on a bookshelf fall and furniture moves. | People notice electric-light poles swing. Occasionally, windowpanes are broken and fall, unreinforced concrete-block walls collapse, and roads suffer damage. | Occasionally, less earthquake-resistant houses suffer damage to walls and pillars. | Occasionally, cracks are formed in walls of less earthquake-resistant buildings. | A safety device cuts off the gas service at some houses. On rare occasions water pipes are damaged and water service is interrupted. (Electrical service is interrupted at some houses) | Occasionally, cracks appear in soft ground, and rockfalls and small slope failures take place in mountainous districts. | 0.80–1.40 m/s² |
| 5-upper (5強) / *5.0–5.4* | Many people are considerably frightened and find it difficult to move. | Most dishes in a cupboard and most books on a bookshelf fall. Occasionally, a TV set on a rack falls, heavy furniture such as a chest of drawers fall, sliding doors slip out of their groove and the deformation of door frames makes it impossible to open doors. | In many cases, unreinforced concrete-block walls collapse and tombstones overturn. Many automobiles stop because it becomes difficult to drive. Occasionally, poorly-installed vending machines fall. | Occasionally, less earthquake-resistant houses suffer heavy damage to walls and pillars and lean. | Occasionally, large cracks are formed in walls, crossbeams and pillars of less earthquake-resistant buildings and even highly earthquake-resistant buildings have cracks in walls. | Occasionally, gas pipes and / or water mains are damaged.(Occasionally, gas service and / or water service are interrupted in some regions) | Occasionally, cracks appear in soft ground. and rockfalls and small slope failures take place in mountainous districts. | 1.40–2.50 m/s² |

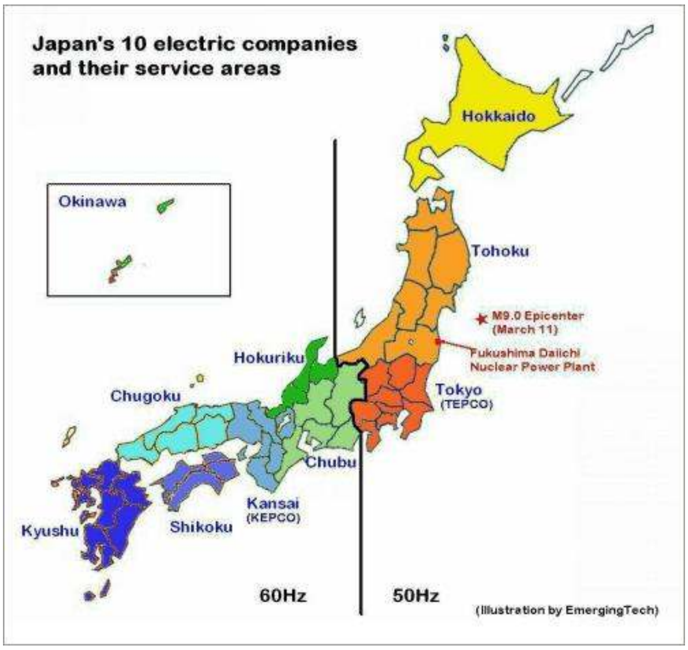
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6-lower (6 弱) / *5.5–5.9* | Difficult to keep standing. | A lot of heavy and unfixed furniture moves and falls. It is impossible to open the door in many cases. | In some buildings, wall tiles and windowpanes are damaged and fall. | Occasionally, less earthquake-resistant houses collapse and even walls and pillars of highly earthquake-resistant houses are damaged. | Occasionally, walls and pillars of less earthquake-resistant buildings are destroyed and even highly earthquake-resistant buildings have large cracks in walls, crossbeams and pillars. | Gas pipes and/or water mains are damaged. (In some regions, gas service and water service are interrupted and electrical service is interrupted occasionally.) | Occasionally, cracks appear in the ground, and landslides take place. | 2.50–3.15 m/s² |
| 6-upper (6 強) / *6.0–6.4* | Impossible to keep standing and to move without crawling. | Most heavy and unfixed furniture moves and falls. Occasionally, sliding doors are thrown from their groove. | In many buildings, wall tiles and windowpanes are damaged and fall. Most unreinforced concrete-block walls collapse. | Many, less earthquake-resistant houses collapse. In some cases, even walls and pillars of highly earthquake-resistant houses are heavily damaged. | Occasionally, less earthquake-resistant buildings collapse. In some cases, even highly earthquake-resistant buildings suffer damage to walls and pillars. | Occasionally, gas mains and / or water mains are damaged.(Electrical service is interrupted in some regions. Occasionally, gas service and / or water service are interrupted over a large area.) | Occasionally, cracks appear in the ground, and landslides take place. | 3.15–4.00 m/s² |
| 7 (7) / *6.5 and up* | Thrown by the shaking and impossible to move at will. | Most furniture moves to a large extent and some jumps up. | In most buildings, wall tiles and windowpanes are damaged and fall. In some cases, reinforced concrete-block walls collapse. | Occasionally, even highly earthquake-resistant buildings are severely damaged and lean. | Occasionally, even highly earthquake-resistant buildings are severely damaged and lean. | Electrical service gas service and water service are interrupted over a large area. | The ground is considerably distorted by large cracks and fissures, and slope failures and landslides take place, which occasionally change topographic features. | Greater than 4 m/s² |

The empirically obtained relationship between Shindo instrumental intensity, $I_{JMA}$, and instrumental modified Mercalli intensity, $I_{MM}$, is clearly given below:




The four nuclear power plants directly affected were Onagawa, Fukushima Daiichi, Fukushima Daini, and Tokai; they are approximately 90km, 160km, 170km, and 260km from the epicentre, respectively. The largest city in Tōhoku, Sendai, is approximately 150km from the epicentre.

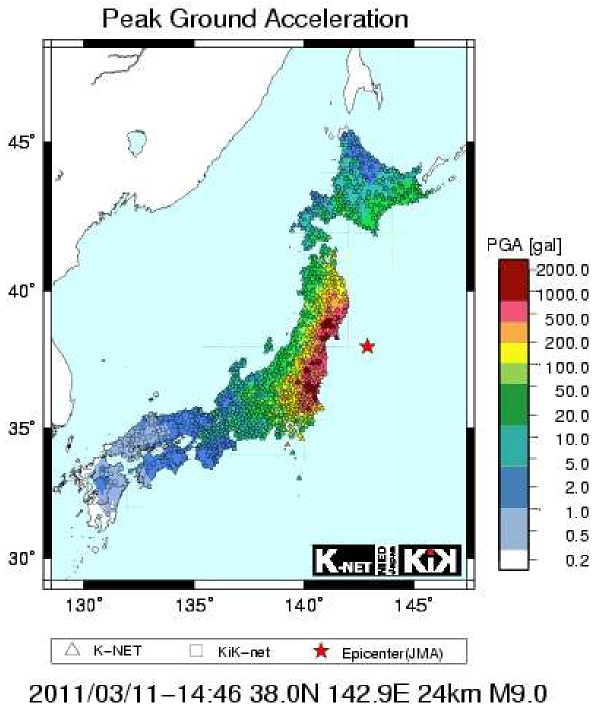
There were earthquake induced shutdowns of several conventional power plants and all nuclear power plants, 11 units, in Tōhoku.




Western and eastern Japan have different electrical frequencies, the western section at 60Hz and the eastern section at 50Hz. The reason for this difference is historical and although a unified electrical grid has been suggested many times since World War II, the high cost of the venture was always deferred since the investment of capital into actual power generation was deemed more important as post-war Japan recovered. As a result, there are only three frequency converters with a total capacity of approximately 1GW.

When the shutdown of 11 units caused a 10GW shortfall in electricity, rolling blackouts occurred all through eastern Japan for several weeks. While not usually thought of as a risk, the frequency incompatibility contributed to slow recovery during emergency operations, hospital service, and even some deaths of the elderly and infirm from failures of medical devices and heat. Moreover, this summer when electrical consumption reaches its peak, power shortages will affect an already fragile economy.

The PGA of the earthquake and the design basis of the Fukushima plants and units are shown in the shake map and table below.




| Fukushima | PGA in $cm^2$ | | |
|---|---|---|---|
| | Horizontal | | Vertical |
| | N-S | E-W | |
| Daiichi 1 | 460 | 447 | 258 |
| Daiichi 2 | 348 | 550 | 302 |
| Daiichi 3 | 322 | 507 | 231 |
| Daiichi 4 | 281 | 319 | 200 |
| Daiichi 5 | 311 | 548 | 256 |
| Daiichi 6 | 298 | 444 | 244 |
| Design Basis | 441 | 438 | 412 |
| Daini 1 | 254 | 230 | 305 |
| Daini 2 | 243 | 196 | 232 |
| Daini 3 | 277 | 216 | 208 |
| Daini 4 | 210 | 205 | 288 |
| Design Basis | 415 | 415 | 504 |
| SCRAM Limit | 135 - 150 | | 100 |

The values in red show that measured acceleration values in the east-west direction were on the average 10% greater and in one case 26% greater than the design basis for the Daiichi units.

In Japan, the regulatory earthquake design basis for NPP is measured in PGA, not magnitude. This is proper, since the fragility studies in a earthquake PRA always use the PGA ranges as the initiating events and for calculating the hazard curves and fragility curves for components to understand system failures given an earthquake with a given PGA.

The ground type can significantly influence ground acceleration, so PGA values can display extreme variability over distances of a few kilometres, particularly with moderate to large earthquakes. Due to the complex conditions affecting PGA, earthquakes of similar magnitude can offer disparate results, with many moderate magnitude earthquakes generating significantly larger PGA values than larger magnitude quakes.

A digression in the spirit of risk assessment: the Kashiwazaki NPP on the Japan Sea in Niigata Prefecture has more units than any other site in the Japan. There are five BWR based on GE-BWR-5, and two ABWR. In the Niigata earthquake of 2007, both the older and newer units suffered accelerations 200% to 300% greater than design basis. There was no major damage to safety systems; however TEPCO did release radioactive water into the Japan Sea and vented contamination into the air without informing the local or central governments. In fact, TEPCO initially covered up the incident and only received a light admonishment by the regulator.

Three important lessons can be learned from Kashiwazaki. First, safety cannot be measured by an absence of accidents, which is largely dependent on luck, but is the result of constant, active identification of hazards and their elimination. Near misses, such as no major damage to safety systems, are not testimonials to safe practices. Second, beliefs that near misses, or invocations of backup systems, prove a plant to be robust is the first step into safety complacency. Third, a cultural of misrepresentation will eventually earn the enmity of everyone.

Seconds after the initial earthquake, the 11 units at Fukushima Daiichi, Fukushima Daini, Onagawa, and Tokai went into automatic shutdown. There was a turbine room fire at Onagawa-1 which was extinguished in 3 to 4 hours. Fukushima Daiichi suffered loss of offsite power as a result of the earthquake. The emergency generators started as did emergency cooling.

In a private interview with a worker at Fukushima Daini I learned that 3 out of the four power lines from the offsite grid failed after the earthquake, taking offsite power away from one of the units. The on-duty manager quickly understood the situation and distributed the remaining power line to the unit without power. It is unknown to us if the diesel generators at Daini were operable after the tsunami.

Dr. Robert Geller, of the Tokyo University Earth Science department, has a unique view as to why TEPCO, the central Japanese government, and the regulators were unprepared for such a large earthquake and tsunami. Even though earthquake experts such as Dr. Katsuhiko Ishibashi, of Kobe University, and Dr. Ryohei Morimoto, retired professor of volcanology, repeatedly warned about the dangers of earthquakes and tsunami to NPP, their voices went unheeded. Dr. Morimoto said, “I’ve heard the government and TEPCO say they couldn’t predict the tsunami would reach that high, but that is ridiculous, as any history book would have set them straight … and even if they could not predict, they should have been prepared for waves similar to the past.”

Dr. Geller believes that the government focuses on “foreseeable” earthquakes based on questionable modelling. He says that this in turn takes focus and emergency preparations away from other possibilities, particularly the dangers to areas considered to be less at risk by the model predictions, but with high consequences. Here are two short excerpts from his April 27, 2011 article in Nature.:

> The modellers assume that ‘characteristic earthquakes’ exist for various zones, choose the fault parameters for each zone as the input to their model, and then produce probabilistic hazard maps.
>
> Although such maps may seem authoritative, a model is just a model until the methods used to produce it have been verified. The regions assessed as most dangerous are the zones of three hypothetical ‘scenario earthquakes’ (Tokai, Tonankai and Nankai). However, since 1979, earthquakes that caused 10 or more fatalities in Japan actually occurred in places assigned a relatively low

> probability. This discrepancy — the latest in a string of negative results for the characteristic earthquake model and its cousin, the seismic-gap model, strongly suggests that the hazard map and the methods used to produce it are flawed and should be discarded. [Nature, Vol. 472, pg. 408]

and he goes on:

> It is time to tell the public frankly that earthquakes cannot be predicted, to scrap the Tokai prediction system and to repeal the LECA [a law which mandates government earthquake prediction systems]. All of Japan is at risk from earthquakes, and the present state of seismological science does not allow us to reliably differentiate the risk level in particular geographic areas. We should instead tell the public and the government to 'prepare for the unexpected' and do our best to communicate both what we know and what we do not. And future basic research in seismology must be soundly based on physics, impartially reviewed, and be led by Japan's top scientists rather than by faceless bureaucrats. [ibid, pg. 409]

Dr. Geller correctly points out that one of the leading contributors to "what went wrong" at Fukushima Daiichi was an inability by anyone involved in decision making or regulation to "expect the unexpected".

Even as late as January 1, 2011, NIED was representing only the Hamaoka NPP as having a probability higher than 10% during the next 30 years. The table below presents the original document and a translation.

| Probability of an earthquake Greater than Shindo 6 During the Next 30 Years | | |
|---|---|---|
| **NPP** | **Prefecture** | **Probability in %** |
| Tomari | Hokkaido | 0.4 |
| Higashi Dori | Aomori | 2.2 |
| Onagawa | Miyagi | 8.3 |
| Kashiwazaki | Niigata | 2.3 |
| Fukushima Daiichi | Fukushima | 0.0 |
| Fukushima Daini | Fukushima | 0.6 |
| Tokai Daini | Ibaraki | 2.4 |
| Hamaoka | Shizuoka | 84.0 |
| Shika | Ishikawa | 0.0 |
| Tsuruga | Fukui | 1.0 |
| Mihama | Fukui | 0.6 |
| Ooi | Fukui | 0.0 |
| Takahama | Fukui | 0.4 |
| Shimane | Shimane | 0.0 |
| Ikata | Ehime | 0.0 |
| Genkai | Saga | 0.0 |
| Sendai | Kagoshima | 2.3 |
| Monju | Fukui | 0.5 |

30年以内に震度６強以上の地震が起きる確率

〔算定基準日は2011年１月１日〕

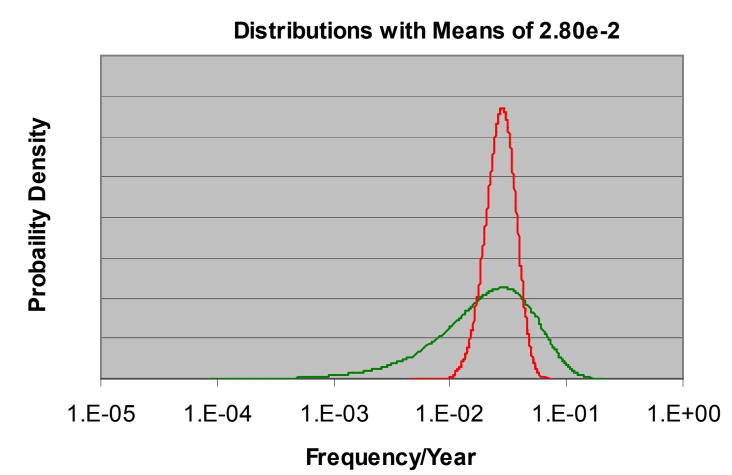
| 原　発 | 確率 |
|---|---|
| 泊　　（北海道） | 0.4% |
| 東　　通（青　森） | 2.2 |
| 女　　川（宮　城） | 8.3 |
| 柏崎刈羽（新　潟） | 2.3 |
| 福島第１（福　島） | 0.0 |
| 福島第２（福　島） | 0.6 |
| 東海第２（茨　城） | 2.4 |
| 浜　　岡（静　岡） | 84.0 |
| 志　　賀（石　川） | 0.0 |
| 敦　　賀（福　井） | 1.0 |
| 美　　浜（福　井） | 0.6 |
| 大　　飯（福　井） | 0.0 |
| 高　　浜（福　井） | 0.4 |
| 島　　根（島　根） | 0.0 |
| 伊　　方（愛　媛） | 0.0 |
| 玄　　海（佐　賀） | 0.0 |
| 川　　内（鹿児島） | 2.3 |
| もんじゅ（福　井） | 0.5 |

（注）原子炉の炉心での確率。カッコ内は所在地。福島原子力発電所事故対策統合本部の資料による

There are some disturbing aspects to this table.

The first is the notion of a “30 year event”, which originated in the insurance industry by actuaries to characterize payback periods. This is a misrepresentation, in the above case, of probability. For example, the Tomari NPP is given a 0.4% probability of a Shindo>=6 earthquake within the next 30 years. What this really means is that the probability of the event at Tomari is 1.33e-04/year. From a probabilistic standpoint, a Shindo>=6 earthquake could happen tomorrow, or perhaps never. Probability measures a state of knowledge or belief. Even from a statistical point of view we would say that as time approaches infinity, we could expect the yearly average of Shindo>=6 earthquakes to approach a rate of 1.33e-04/year.

The second aspect is that these percent per year values can only represent a mean value of some underlying probability distribution, which is not presented to us. The probability distribution represents our uncertainty, which is not some noisy variation around a mean value that represents the true situation. Variation itself is nature's only irreducible essence. Variation is the hard reality, not a set of imperfect measures for a central tendency. Means and medians are the abstractions. Moreover, it is possible to have many probability distributions with the same mean value, but represent entirely different ranges of uncertainty. Below, I present an example of two imagined distributions for the Hamaoka NPP, each with a mean value of 84% within 30 years, or 2.80e-2/year, as suggested by the NIED chart in 2.2.23.




| Name | Example 1 Value/Year | Example 2 Value/Year |
|---|---|---|
| Mean | 2.80e-2 | 2.80e-2 |
| 5th Percentile | 2.80e-2 | 1.57e-2 |
| 50th Percentile | 2.10e-2 | 2.69e-2 |
| 95th Percentile | 7.00e-2 | 4.19e-2 |
| Range Factor | 5.00 | 1.63 |

The two distributions represent entirely different states of knowledge. Example 1 has a long tail on the left and a broad uncertainty; example 2 is focused, with little variability and a smaller uncertainty than example 1. The decisions made for consequence preparation differs depending on which distribution actually represents our state of knowledge.

The third problem is the false sense of security that small numbers give to regulators, the government, and most importantly to the public. The small numbers produced by simulations, widely seen as involving complicated calculations, have the effect of what might be termed false or misplaced correctness, especially on policy makers and the general public. As a result, many people in evacuation centres told us that the government and TEPCO constantly assured them that the plant was 100% safe from natural hazards. TEPCO, the regulators, and the government considered the event as *sōtēgai,* out of imagination. Perhaps they knew better, or perhaps they believed, incorrectly, that since some of the plants would be decommissioned within 30 years there was no immediate threat. Ironically, Daiichi was scheduled for decommission, but was given a 10-year extension by the regulators and the government in February, 2011, one month before the earthquake and the tsunami. So much for 30 years.

And finally is the presentation of 6 plants as having a probability of 0.0% of a Shindo>=6 earthquake within the next 30 years. I assume that this means a probability of less than 0.05% (5.0e-4), since the other values all have one decimal place, with assumed round-up. Representations such as this only reinforce the belief that there is no danger; zero is a dangerous number to present, especially if the truth is greater than zero.

TEPCO and Toshiba have claimed that there was no damage to safety systems caused by the earthquake. Perhaps this is true. We may never know.

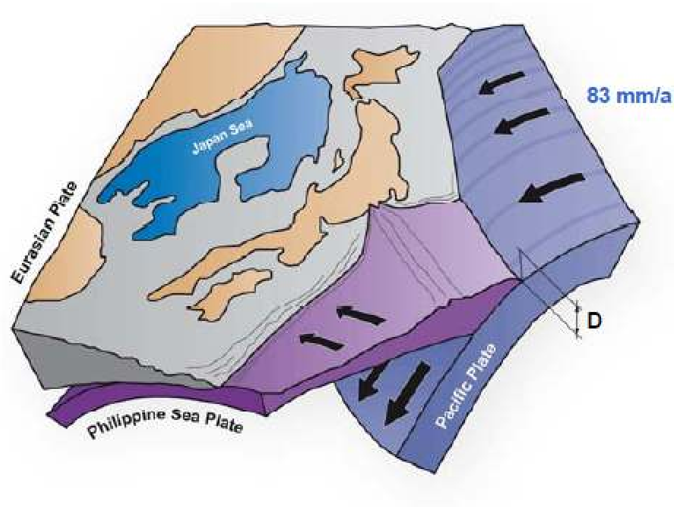
About 41 minutes after the earthquake the first of the tsunami arrived at Daiichi.

## The Tsunami

It is usual that an inter-plate earthquake occurring in a trench region can be accompanied by tsunami (called an *earthquake-induced tsunami*). Since the magnitude of this earthquake was so great, the scale of generated tsunami was also. In the case of the earthquakes that have occurred in recent years, a relationship between the Mw value determined by a earthquake wave analysis and the assumed Mw value of tsunami has been observed. In particular, the Pacific Ocean shows a trend in which the Mw value of the tsunami generally exceeds the Mw value of the earthquake

In Japan, large tsunami have occurred along the Pacific coast, from Hokkaido to Okinawa, and tsunami have also been observed along the coast of the Japan Sea, the Okhotsk Sea, and the East China Sea.

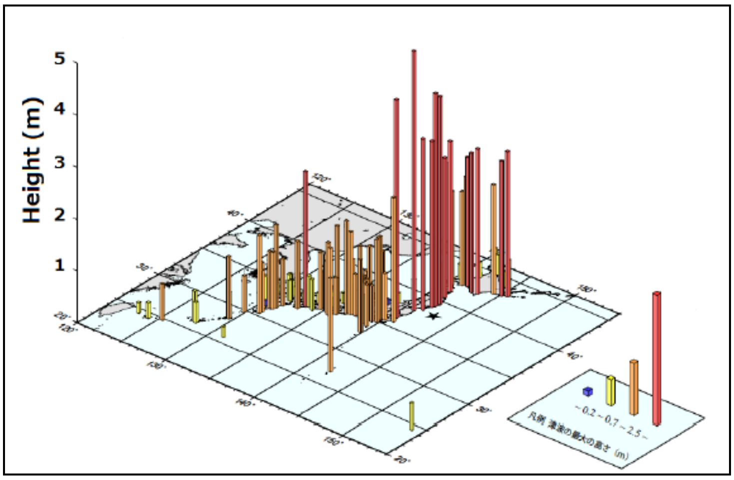
The Great East Japan Earthquake took place along the fault known as the Japan Trench Megathrust, in a subduction zone where the Pacific Plate, the Eurasian Plate, and the Philippine Sea Plate all meet.




| Measure Name | Amount (estimated) |
|---|---|
| Vertical Displacement (D) | 7m – 10m |
| Peak Displacement ($D_{max}$) | 17m – 25m |
| Rupture Zone (A) | 500km x 100km |
| Hypocenter Depth ($Z_H$) | 20km – 25km |
| Crack Velocity (v) | 2 km/s |
| Water Depth (Z) | 8km |

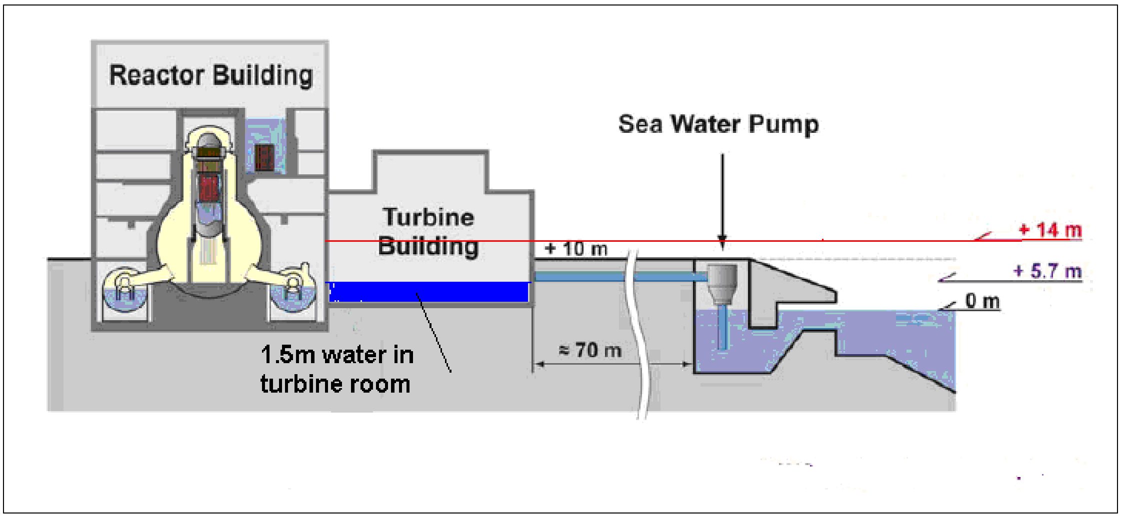
The volume of water displaced can be calculated as V = A x ¼D = 125km$^3$. This large, sudden displacement of water was the tsunami.

At the coastal cities of Kamaishi, Ishinomaki, and Ofunato, the first tsunami arrived at 14:46, simultaneously with the earthquake. The tsunami of maximum height reached these cities at approximately 15:20, 30 minutes after the earthquake. The maximum height of tsunami was recorded at more than 8.5m at Miyako, Iwate Prefecture, more than 8.0m at Ofunato, Iwate Prefecture, more than 7.3m at Soma, Fukushima Prefecture, and 4.2m at Oarai, Ibaraki Prefecture.

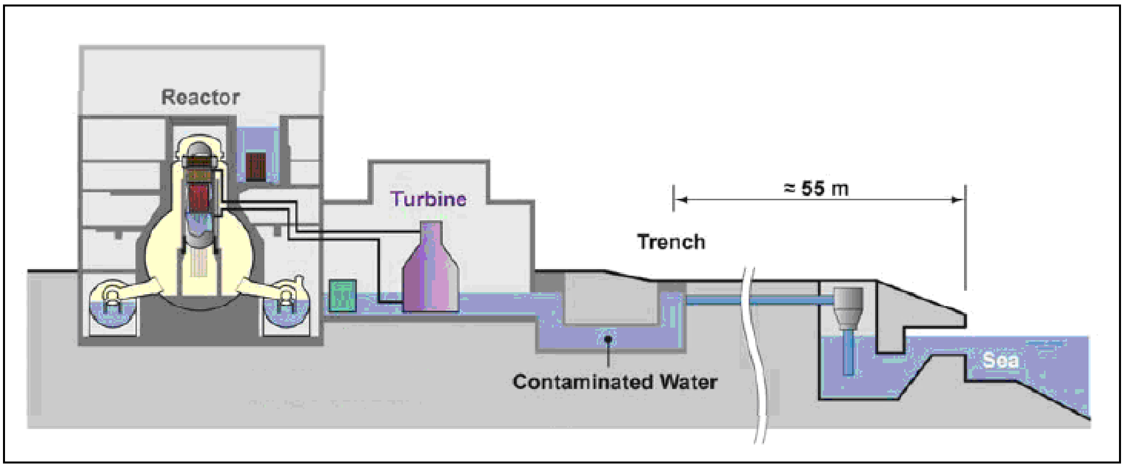


The JMA issued Major Tsunami Warnings at 14:49, 3 minutes after the earthquake, to Iwate, Miyagi, and Fukushima Prefectures. It was extended to Aomori, Ibaraki, and Chiba prefectures at 15:14, followed by warnings to the Japan Sea coast, the Bonin Islands, Sagami Bay, and to Shizuoka and Wakayama Prefectures. Subsequently they were downgraded to Tsunami Warnings, then to Tsunami Advisories for each region. All warnings and advisories were rescinded by 17:58, March 13th.

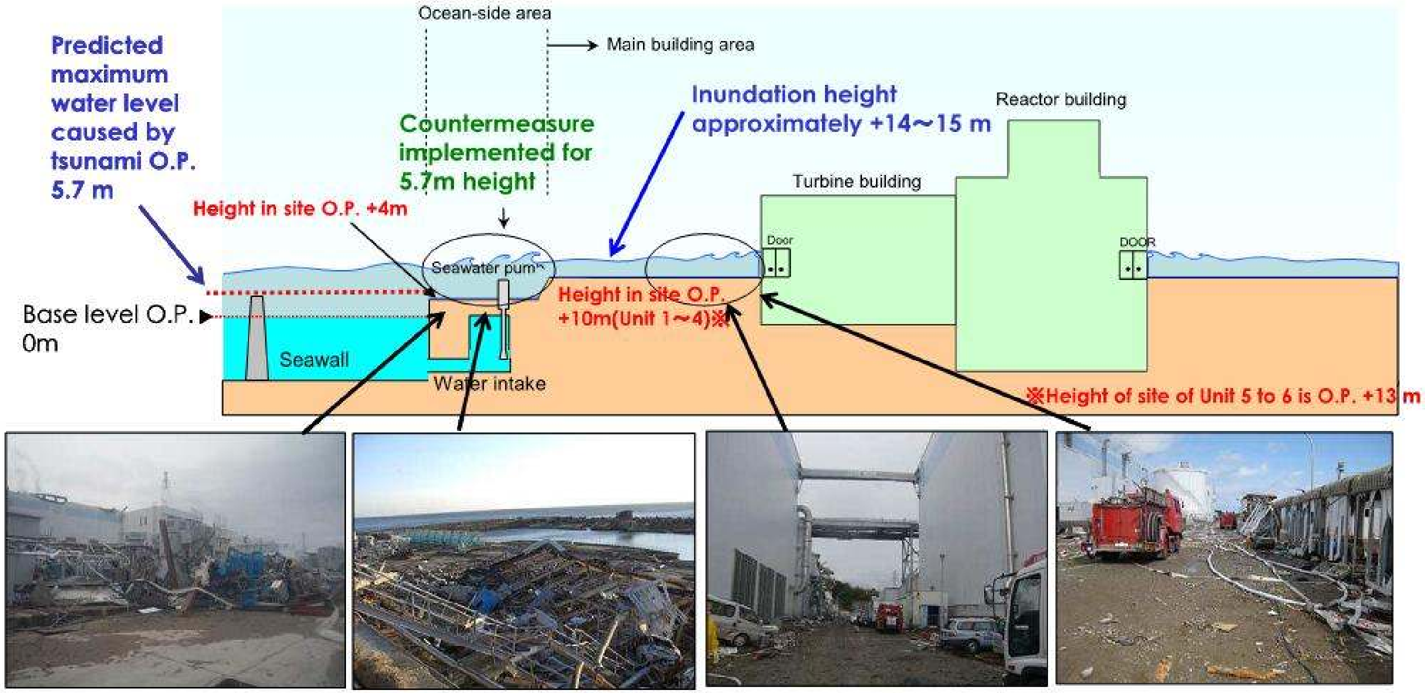
About 41 minutes after the active units at Fukushima Daiichi SCRAMed and emergency AC power generation began via the diesel generators, the first tsunami arrived. About 14 minutes later, a TEPCO estimated +14m tsunami overwhelmed the tsunami wall, which was 5.7m above the normal water level of Onahama Bay. The height of this wave has been estimated by water and debris marks on building walls. The diesel generators were completely taken out, as they were located in the basement of the turbine building, approximately 3m above sea level, as in the illustration below.




Each unit has an underground trench for piping and cabling which run from the basement of the turbine building. These trenches were found to be flooded, also, and the water contaminated, as shown below.




0.1.1 A more interesting illustration is from the TEPCO document, “Result of the Investigation on Tsunami at Fukushima Daiichi Nuclear Power Station” (sic), on the next page. Notice that the doors to both the reactor building and the turbine building are shown as inundated. The caption for the illustration is taken directly from the report.




"We have conducted the investigation on Tsunami arrived at Fukushima Daiichi Nuclear Power Station generated by the Tohoku-Chihou-Taiheiyo-Oki Earthquake on March 11th, 2011. Result of the investigation on height and area inundation and run-up height are as follows. We did not consider the effect of diastrophism [Author's note: deformation of the earth caused by a seismic event]. (1) Inundation height: Considering the vestiges on buildings and facilities, approximately O.P. +14 to 15m (inundation depth: approximately 4 to 5m) in most of the ocean-side of main building area. (2) Inundation area: Most of the ocean-side area (height of site: O.P. +4m) and the main building area. (3) Run-up height: Considering the vestiges in slope and surface of road, approximately O.P +14.5m." – Appendix A [in the TEPCO report]

The first question which comes to mind is why was the turbine building located near to the ocean and the floor of the building, where the diesel generators were located, below ground level? The diesel generators therefore were at risk from flood from any flooding source: tsunami, typhoon, or pipe breaks.

Fukushima Unit No.1 in at Daiichi was designed by GE and constructed by Ebasco in the 1960s. The placement of buildings, including the below ground level diesel generators, was done by Babcock & Wilcox. The tsunami wall was constructed in 1966. There remains no evidence as to whether historical tsunami data were referenced, or not. I believe that the current tsunami analysis was performed by a subsidiary company of TEPCO other than TEPSYS (TEPCO Systems), which has primary responsibility for TEPCO's PRA.

The second question is why did TEPCO choose a tsunami wall height of 5.7m? Was this wall high enough? On what evidence was this height chosen?

In 1990, the safety assessments for nuclear power plants were carried out based on NSC "Guideline about Safety Design for Light Water Nuclear Power Generating Facilities", and only considered regulations and authorized methods and codes for ground motion hazard calculations for NPPs. Never the less, no such guidelines were presented for tsunami hazards and the choice of method was left to the operators of each NPP, as the guideline states, "[the effect by] tsunami should be considered in design",

Beginning in 1999, the Tsunami Evaluation Subcommittee of the Nuclear Civil Engineering Committee of the JSCE began to create a unified methodology for the risk assessment of tsunami to NPPs. The subcommittee members were taken from academia, research institutions, and 11 nuclear power utilities. The report, "Tsunami Assessment Method for Nuclear Power Plants in Japan" (referred to hereafter as TAMNPP), was published in 2002. The method used was dubbed a deterministic method, as opposed to a probabilistic method, with the goal of presenting the minimum and maximum water levels, or run-ups, which an NPP could expect from tsunami by doing a parametric study of fault parameters by numerical simulation. The maximum and minimum run-ups refer to tidal or storm influences.

From 2003 to 2005, a probabilistic method was developed for run-ups which used numerical simulations of nonlinear dispersion wave theory with soliton fission, as well as simulations of split wave-breaking tsunami wave force on breakwaters and tsunami walls. The development of a methodology for probabilistic tsunami hazard analysis was undertaken from 2006 to 2008, and the revision of the TAMNPP was begun in 2009. Ironically it was to be published by the end of the 2011 fiscal year.

Because the tsunami defences at Fukushima Daiichi should not be judged by the availability of the yet to be published revised TAMNPP, I will limit our discussion here to the deterministic methodology and its results The paper, available on the internet, is called "Logic-tree

Approach for Probabilistic Tsunami Hazard Analysis and its Applications to the Japanese Coasts" and includes many details for the revised TAMNPP. Interestingly, two TEPCO staff members are co-authors.

The methodology for the deterministic TAMNPP was:

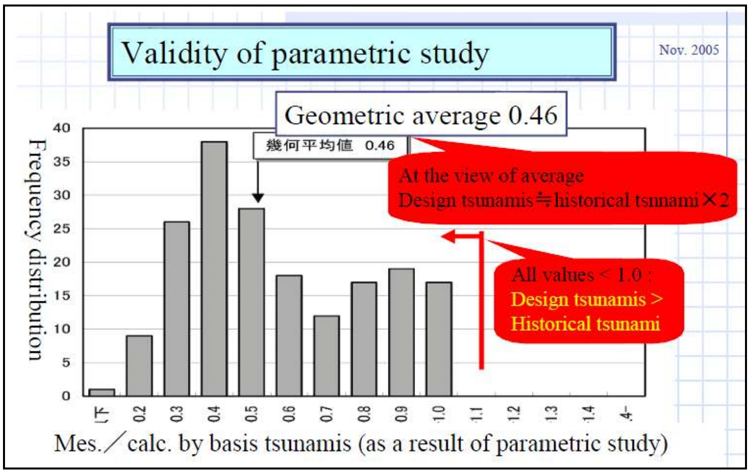
a) to create a database of historical tsunami and to choose, for each NPP site, a "scenario tsunami" by maximum run-up;

b) to validate the numerical simulations by comparing the actual run-up with the simulated run-up;

c) to create a design basis tsunami for each NPP with the simulation;

d) and finally to validate the results against the historical records.

The goal was to calculate a design basis tsunami height which exceeded all the recorded and calculated historical tsunami heights at the target site. .In the vicinity of the target site, the envelope of the scenario tsunami heights should exceed all the recorded calculated historical tsunami heights. The step 2 validation results are show in the graph below:




The x-axis of the graph represents the ratio of the scenario tsunami to the simulated design basis tsunami. In all cases, the simulations calculated ratios less than, or equal to, 1, with a median ratio of about 0.46, indicating that the proposed method can be considered conservative and purports to give design values 2 times the scenario basis.

What is not clear from the TAMNPP is how many NPPs were considered in the validation study. We only know that 185 scenario tsunami were validated. The NPP examples given in the report are from the northwest Japan Sea coastline in Niigata Prefecture, Aomori Prefecture, and Hokkaido. Each utility was required by NISA to do a study following the TAMNPP guidelines. It is not clear if each NPP wrote their own simulation software, or if the software written by JSCE was used by all NPPs. The simulation software was never verified by an independent group.

After the NSC revised the Seismic Design Guide in 2006, all operators of NPP in Japan were requested to conduct a earthquake PRA including tsunami risk according to the JSCE guidelines in TAMNPP, which will be finalized within a few years. I have included presentations of the preliminary results from 4 NPP sites: Fukushima Daiichi, Kashiwazaki, Onagawa, and Hamaoka.

From the author's conversations with Dr. Hakata, from THK Consulting and formerly of the NSC and a earthquake expert, I have the following information: TEPCO did follow the JSCE tsunami calculation method (TMANPP) for their NPP, but did not adopt probabilistic method (LTA) since it had not yet been accepted by JSCE, scheduled as previously mentioned for acceptance at the end of fiscal 2011.

I am also not sure how TEPCO applied the JSCE guidelines. The presentation made by TEPCO in 2008, after their preliminary tsunami risk assessment, only indicates that they used the Chilean Tsunami of 1960 as the scenario tsunami for the far field study; there is no mention of the scenario for the near field study which produced the results of a 5.7m design basis for Daiichi. Perhaps the correct application of the JSCE methods, both historical data collection and implementation of the mathematics, was beyond the scope of TEPCO PRA analysts.

A presentation made on June 27$^{th}$, 2011, by Dr. Akira Omoto, Vice Chairman of the AEC of Japan, stated that the design basis, or characteristic scenario, for near field tsunami at Daiichi was 3.1 meters; there is no reference or rational given for the choice of characteristic scenario.

It must be noted that the site location of Fukushima Daiichi originally was 35 meters above sea-level. The site was reduced by 25 meters before construction so that the buildings would be based upon bedrock, a standard and regulation to protect the facility against severe earthquake accelerations, as well as to make the cost of building construction and of the seawater pumps less expensive. The levelling of the site was prudent from an earthquake risk point of view. However, the levelling erased all geological evidence of former tsunami run-up heights and run-up distances inferred from geological excavations in the area were therefore invalid, if they were done at all.

In contrast, the Onagawa NPP tsunami risk assessment is quite clear about the choice of scenario tsunami. By making bore holes in the hills about 1km behind the NPP, it was estimated that the largest local tsunami run-up height was between 6m and 8m caused by the 1611 earthquake. They therefore constructed a tsunami wall of 10m. But from a reactor operator at Onagawa I have the following story:

> After the earthquake, we lost offsite power. The tsunami run-up height was 50cm below the ground level of the NPP, but the force of the wave hitting the wall made the water jump over the wall. The inundation took out the diesel

> generators, just as it had at Daiichi. But unlike Daiichi, the offsite power was quickly restored. Only by luck we did not have the same consequence as Daiichi.

If the TAMNPP methodology is correct, why did TEPCO's implementation of it indicate a tsunami wall of 5.7m was sufficient?

There are two possibilities. The first is that the implementation was correct, the second that it was wrong. If correct, then perhaps the tsunami of March 11th was absolutely unpredictable, and I will look at this possibility in Section 2; if the event was predictable, then we must consider TEPCO negligent in their stewardship of a nuclear power plant and the regulatory culture of Japan complicit in an enormous disaster by not improving defences. However, the TAMNPP provided an excuse for TEPCO by assuring the utilities that what they previously had done (prior to the new 2006 regulations) considered tsunami safety and the latest information:

> By referring to the guideline, the design tsunami has been determined site by site by a numerical simulation based on information regarding the maximum historical tsunami and the greatest influenced submarine active fault induced tsunami. Accordingly, the safety design has been implemented based on the tsunami thus determined. It is considered that the guideline by the Nuclear Safety Commission of Japan will not create problems in the near future for the following two reasons: various safety insurances have been considered in the process of tsunami evaluation, and the latest information has been taken into account for the assessment. (TAMNPP, Page 3);

Amazingly, the tsunami wall, built in 1966 with a height of 5.7m, was high enough to conform to the guidelines published in 2002. As presented in 2008, TEPCO said that "We have assessed and confirmed the safety of the nuclear plants [at Daiichi] based on the JSCE method published in 2002." ["Tsunami Study for Fukushima 1 and 2", pg. 14]. We hope that during final review the regulators review and confirm the calculations.

As for the second possibility, in what way could the implementation have been wrong? Let us quote some passages from the guidelines and a conference companion paper, "Tsunami Assessment for Risk Management at Nuclear Power Facilities in Japan" (referred to as TARM), from 2007. First, from the paper:

> In Japan, old tsunami records documented before the 1896 Meiji-Sanriku tsunami are less reliable because of misreading, misrecording (sic), and the low technology available for the measurement itself. The data can be compared with that from other documents and plotted on the map. Tsunami run-up records that appear unreliable should be excluded. TARM, (Page 568);

> As earthquakes and tsunamis are natural phenomena, their variable and uncertain aspects should be considered. In the process of tsunami assessment, uncertainties and errors in many important parameters are unavoidable, including the tsunami source, fault position, depth of the upper edge of the fault plane, strike direction, dip angle, dip direction, slip angle and combination of segments. In the numerical simulation, the governing equations, boundary conditions, initial conditions, grid division, modeling of

> bathymetry data and reliability of run-up heights may also involve uncertainties. However, it is rather difficult to estimate those uncertainties quantitatively and to deal with them one by one. **Consequently, only uncertainties concerning the tsunami source are dealt with in this study, because they can significantly influence tsunami assessment**. (TARM, Page 570) [bold underling by the author];

An earthquake engineer from NIED remarked that the slip angle of the Pacific plate during the March 11th event was much more acute than had been predicated along the fault line and this was the major cause of such a large tsunami. The uncertainties in the model which were not addressed caused the failure of the simulation to perform accurately as a prediction tool.

More on uncertainty from the TAMNPP:

> The run-up heights of tsunamis older than the 1896 Meiji-Sanriku earthquake tsunami have been assumed by researchers on the basis of old records, documents etc.; the reliability of the data must be closely examined. In the case of the run-up heights of comparatively recent tsunamis that occurred after 1896, the investigation method should focus on the heights mentioned in individual documents and their reliability. If the reliability of any run-up height is doubtful, the accuracy of the data must be re-examined based on the original document. Further, if the reliability is too low, they can be eliminated when the goodness of fit is evaluated. (TAMNPP, Page 28)

These excerpts focus on two uncertainties: the uncertainty of historical records and oral histories; and the uncertainties inherent in the parameters used in mathematical modelling. Interestingly, software and mathematical errors are not addressed, but must be considered.

The historical records and oral history accounts before 1896 may be considered unreliable by laboratory bound researchers. However for those of us who have been to Tōhoku, especially to the Sanriku countryside, there are tsunami stones (*tsunami-seki*), some more than 400 years old, placed in the ground to mark tsunami inundation points, such as the photograph below, and to serve as reminders to villagers.

During volunteer work at an evacuation centre in Watari, Miyagi Prefecture, the author made a special visit to one such stone in Aneyoshi, a village halfway between Sendai and Aomori in Iwate Prefecture on coastal Route 45. In the recent tsunami, inundation at Aneyoshi was more than 1.8km and stopped about 100m short of the stone. Was this type of evidence considered reliable by the authors of the TAMNPP report?

Another source of historical data that was probably ignored is the rich Japanese oral tradition and village historians. Miyamoto Tsuneichi, a leading Japanese folklorist of the mid-twentieth century, travelled all through the villages of Japan conducting interviews and capturing a vanishing way of life. During his travels he met many older Japanese villagers who passed down written ledgers and accounts about tsunami, because, as one village historian said, "… as time passes, people inevitably forget, until another tsunami comes that kills 10,000 more people;" (The Forgotten Japanese: Encounters with Rural Life and Folklore, 1960).

More disturbing is the statement in the TAMNPP that only tsunami run-ups near the actual sites of the NPP were considered, instead of looking at historical run-up affects a hundred kilometres north or south of the site for evidence. As a probabilistic risk analyst, I strongly take issue with the TAMNPP and I believe that this was a source of error. The large amount of model uncertainty requires the analyst to consider large tsunami even if that tsunami had little effect on the exact location of the target NPP.

In principle, the design tsunami should satisfy the following two points in order to confirm its adequacy.

a. At the target site, the height of the design tsunami should exceed all the calculated historical tsunami heights.
b. In the vicinity of the target site, the envelope of the scenario tsunami heights should exceed all the recorded historical tsunami heights (see Figure3-2). "The vicinity of the target site" should be appropriately set taking into account the following three points: the number of run-up heights by the dominant historical tsunami, the distribution of run-up heights by the dominant historical tsunami, and the similarities between submarine topography and coastal landform. Here, the historical tsunamis that have no recorded tsunami run-up heights in the vicinity of the target site can be excluded from consideration. However, if the following three points are satisfied, the abovementioned criteria need not be met: existence of a tsunami run-up trace by the dominant historical tsunami at the target site, slight variation between submarine topography and coastal landform, and the design tsunami exceeding the historical tsunami run-up height at the target site. (TAMNPP, Page 10);

   As shown in Figure3-2, it is necessary that all the scenario tsunami heights exceed all the recorded historical tsunami heights. Since the tsunami sources of the historical tsunamis may differ from that of the design tsunami, it is not necessary to compare the design tsunami with the neighbouring recorded historical tsunami heights. (TAMNPP, Page 12)

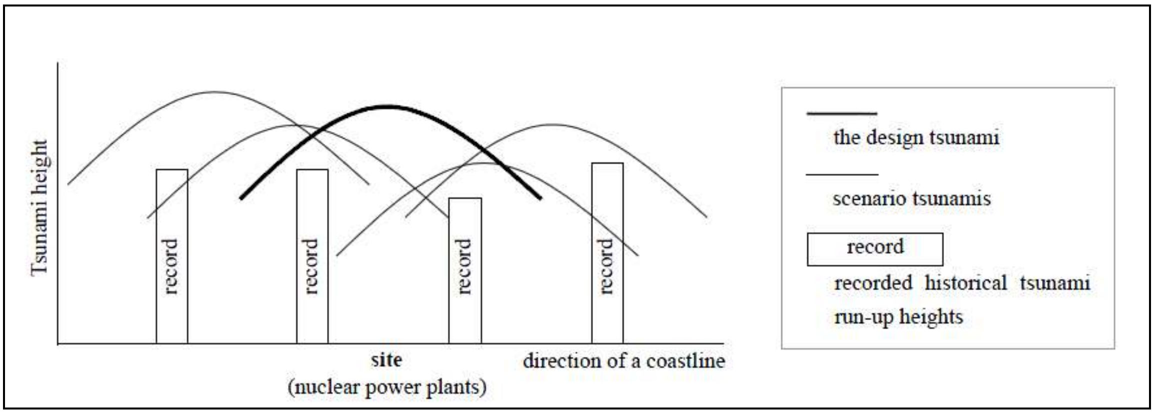



**Figure3-2 Relationship between scenario tsunamis and recorded historical tsunami-run up heights**

Perhaps, also, there is misunderstanding of mathematical uncertainty, as exemplified by the claims that the average ratio of scenario tsunami to design basis tsunami is 2 to 1:

> In this framework, in which the design tsunami is compared with the historical tsunamis, it might appear as though their heights are identical. However, it is confirmed the height of the design tsunami that is obtained in this paper is twice that of historical tsunamis on an average.
>
> …… even if a calculation reproduces the recorded historical tsunami heights well on average, which implies K = 1.0, there is a 50% possibility that the true historical tsunami heights are not exceeded. That is because uncertainties and errors exist. In other words, it is possible that the calculated heights do not exceed the recorded historical tsunami heights. (TAMNPP, Page 10);

It is not clear what this observation means. It could mean either:

a) There is a 50% possibility that the true historical tsunami heights are not exceed by the calculation of the design basis because of errors and uncertainties in the method and/or parameters, or
b) There is a 50% probability that the chosen scenario tsunami are actually lower than the true historical tsunami;

In either case, to our way of thinking, this means that the methods, parameters, and data are not of much use; a 50% probability represents a prediction which is no better than a coin toss. It means we may be right, but we may be wrong.

There is one more source of historical tsunami that I believe was not used to create the historical database, and therefore caused the Jōgan tsunami, in 869, to be ignored: geological inference. Three studies which I have read, “The 869 Jōgan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan” [2001], “Unusually large earthquakes inferred from tsunami deposits along the Kuril trench” [2003], and “Tsunami Inundation History in Sendai Plain, Inferred from Tsunami Deposits” [2007], all seem to be of good scholarly pedigree, and seem to indicate that the recurrence probability of large tsunami in the Sendai region is between 1.25e-03 and 9.09e-04 per year.

And finally, the Fukushima accident could perhaps have been mitigated to some extent if the backup diesel generators had not been located in the basement of the turbine building. TEPCO had been warned against this, and were aware of countermeasures. In Switzerland an independent emergency shutdown system building at the Beznau NPP has been constructed. Mr. Martin Richner of the Beznau NPP risk assessment group has sent to us this simplified explanation:

> The Notstand (independent emergency shutdown system) building represents a bunkered (1 m of concrete wall) safety facility with double water-tight entrances that provides the following major features:
>
> - an independent Notstand feed water system;
> - an independent RCP seal injection system;
> - an external recirculation system;
> - one of the three safety injection pumps replaced by a new pump in the bunker;
> - two ECCS accumulators;
> - a separate offsite grid supply and an independent diesel generator (with a crosstie to the other unit);
> - a separate cooling water supply by a independent well water system (with a crosstie to the other unit);
> - an independent instrumentation and control system;
> - a separate control room to actuate and control the Notstand equipment.
>
> These Notstand systems are designed as a single-train redundant backup to the other plant systems. However, at any single failure of an active component, the operators can align another component to enable core cooling (for example by alignment of a crosstie to the other unit).
>
> The first and automatic train of the Notstand systems is designed to start and run automatically for at least 10 hours. All equipment and structures are designed to meet the current licensing requirements for external events (seismic, fire separation, flooding). The Notstand systems of Unit 2 went into operation in 1992, those of Unit 1 in 1993.

TEPCO seems to have ignored the need for a structure and facility like this. In fact, TEPCO over the last 2 years has repeatedly delayed performing a Level 2 flood PRA on the grounds that it was too expensive and of low priority. It seems, in retrospect, to be less expensive than the current situation.

Japan has implemented an extensive program of building tsunami walls in front of populated coastal areas. Some localities have also built floodgates and channels to redirect the water from incoming tsunamis. However, their effectiveness has been questioned, as tsunamis are often higher than the barriers. For instance, the tsunami which hit the island of Hokkaido on July 12, 1993 created waves as much as 30 m (100 ft) tall - as high as a 10-story building. The port town of Aonae was completely surrounded by a tsunami wall, but the waves washed right over the wall and destroyed all the wood-framed structures in the area. The wall may have succeeded in slowing down and moderating the height of the tsunami, but it did not prevent major destruction and loss of life.


Peter Yanev, an earthquake expert and former president of Earthquake Engineering International (EQE), in a private conversation recounted to the author that in 1993, when he went to see the damage in Okushiri Island after the Hokkaido Nansei Oki M7.8 earthquake, he observed a 5 meter tsunami wall but the resulting tsunami was 5-10 meters. In 1983 when he toured Shizuoka, in the predicted Tokai earthquake zone, he observed 5-7 meters tsunami walls at the Hamaoka NPP. On May 7th, Chubu Electric, the operator of Hamaoka, announced plans to build a 15m tsunami wall in back of 10m sand dunes.

While a tsunami wall is not a total solution, it could moderate the tsunami; but if it traps the water between itself and the land, and there are more tsunami waves, the wall could exacerbate the situation. Imagine a bath tub half-full of water, and one throws a bucket of water into the tub, sloshing the water in a to and fro motion. Now imagine the same tub completely full and one throws a bucket of water into the tub; in this situation, the water will overflow the tub's rails. Entrapment of water by the tsunami wall can have the same effect. Even though there is an open gap between the tsunami walls (see the illustration on page 13) the strong on-shore flow can trap the water on the land-side of the tsunami wall.

There is also a large enough probability that a tsunami wall would fail in places from the force of the tsunami (at Sendai the force was estimated at 40 tons/$m^2$ and at Daiichi 100 tons/$m^2$) and from the lateral and vertical motion from the earthquake acceleration. As estimated in 2007 by the Ministry of Land, Infrastructure, Transport, and Tourism, 63% of the tsunami walls on the Japan coast could not withstand a Shindo +6 earthquake. Since all near field tsunami are caused by an earthquake, the Japan coast is at severe risk. In large land structures, there are many built-in safety factors for earthquakes. But with tsunami walls, there are no such known factors. The size and strength of tsunami depends on the distance from subduction zone and is difficult to predict.


How did tsunami walls fare in Tōhoku after the earthquake? The 2.4km long tsunami wall in Miyako, Iwate Prefecture was destroyed. The 6m, 2km long wall in Kamaishi, Iwate Prefecture was overwhelmed, but delayed the tsunami inundation by 5 minutes. The 15.5m tsunami wall in Fundai, Iwate Prefecture, provided the best protection, but it is good to note that the original design was only 10m. The village mayor fought to make it higher from information in the village historical records. The biggest problem is that tsunami walls give a false sense of security and other preparedness measures may not be undertaken.

The author believes that tsunami walls cannot be the total solution to, or the last defence against, tsunami inundation of a nuclear power plant. As implemented today in Japan, there are no defence in depth countermeasures against tsunami at nuclear power plants.

But most importantly, there is growing evidence that height of the largest tsunami wave was not 14 to 15 meters, as reported by TEPCO, but a maximum of 10 meters. There is no evidence of a wave of 14m making landfall to the south or north of Daiichi. There is evidence of a run-up height of 14m at the plant itself, but that does not necessarily translate into a wave height of 14m. Also there are no known differences in the topography of the sea bottom at Daiichi which would amplify the height in comparison with points south or north.

In a recently published interview with Dr. Fumihiko Imamura, who is a professor at Tohoku University and an advisor at the Willis Research Network, a non-profit research group sponsored by Willis, an insurance broker, Dr. Imamura said that his examinations of the photographs released by TEPCO show the tsunami as only slightly higher than a 10m levee. The height of the wave might have been amplified by the previously entrapped water behind the tsunami wall, as well the funnelling of the water between buildings as shown below:

Dr. Imamura said that proper countermeasures must distinguish between tsunami wave height and tsunami run-up height; he continued that it is quite normal that run-up can become higher than the wave itself after it comes in contact with the land and buildings.

Since many tidal gauges near the coastline have not provided consistent or accurate data, and the coastline at Daiichi is off limits for investigations because of high radiation levels, we will have to wait some time before we can get accurate measurements.

One only hopes that TEPCO is not exaggerating the tsunami height so as to avoid paying compensation to Fukushima residents by claiming that the accident at Fukushima was an unforeseen Act of God. TEPCO is now arguing that according to the law on nuclear accident compensation it has immunity from compensation liability in such a situation.

## Physician, Heal Thyself: The Adequacy of PRA Considerations

Nuclear PRA, as currently done, has as its goal the knowledge of the probability of damage to the reactor core and the release of radioactive materials. There are 5 main activities to achieve this goal: (1) data analysis of component failure rates; (2) system and initiating event analysis, usually done with fault trees; (3) accident scenario analysis, usually done with event trees; (4) release of radioactive materials and dispersion/deposition analysis; and (5) the probable maximum likelihood calculations (PML) in terms of cost to life, property and the environment.

The author has been advising the Technical Analysis Subcommittee Committee for Investigation of Nuclear Safety of the Atomic Energy Society of Japan (AESJ) since March 11, 2011 on matters related to PRA. The AESJ comprehensive recommendations and lessons learned from the Daiichi accident were finalized on May 9$^{th}$, 2011. Professor Ninokata, from Tokyo Institute of Technology, a member and former president of AESJ, and the author have just finished the translation into English. The translation has is entitled, “AESJ Lessons learned from the accident at the Fukushima Daiichi Nuclear Power Plant”. <u>I urge readers to closely attend to the AESJ report.</u>

One of the early lessons we should learn from the Fukushima Daiichi accident is the events, considerations, and scenarios which we PRA analysts omitted from our studies in general.

I contacted several PRA professionals to ask them this question, "How could we make PRA better considering the accident at Fukushima Daiichi?" I asked them to provide us with short responses. I hope at a later time to go into depth with several of the responders and perhaps suggest changes to PRA methodologies to the PRA community. Several responders, of course, focused on the same issues. I present them below in no special order, in this, the concluding section, "What went wrong?"

***Did we consider large tsunami and tsunami wall breach impacts?***

This question was asked by several responders. Are tsunamis, as a joint initiating event with earthquake, a stand-alone initiating event, or the failure of defences as a top event explicitly considered in the PRA? In the USA, the Diablo Canyon NPP PRA and San Onofre NGS PRA that tsunami is considered in plant design. In both cases a deterministic analysis was performed.

> The Diablo Canyon tsunami evaluation and design evolved as a result of a number of studies and analyses during the original plant design period, during the operating license review period, and following breakwater damage in a 1981 storm. The plant's design assumes that the worst tsunami ever documented on the California coast occurs during the worst tide and storm induced wave conditions, resulting in a combined wave run-up of 34.6 feet. The site has been designed to sustain this wave run up without damage to the plant. [AB 1632 Assessment of California's Operating Nuclear Plants, page 64];
>
> The tsunami design basis for SONGS appears to be based on the original engineering studies from 1972. This hypothetical tsunami is the result of an earthquake with a 7.07-foot vertical displacement of the sea floor five miles offshore from the plant. SCE estimated that a tsunami generated from this earthquake that occurred during high tide and storm-induced wave conditions could increase water levels to elevation 27 feet above Mean Lower Low Water. SCE constructed a reinforced concrete seawall to elevation 30 feet above Mean Lower Low Water to protect SONGS from such a tsunami. SCE officials maintain that this seawall is sufficient. They are not planning a reassessment of the tsunami risks. [ibid, page 65]. [*Author's note: the California Coastal commission has instructed SCE to reassess given that the safety margin is only 3 feet*]

However, there is no consideration in either PRA for failure of these assumptions. In other words, there is no explicit top event in the event trees for the probability of tsunami exceeding the defences in place and the cascading consequences, such as flood contamination of the diesel generator fuel supplies, tsunami impacts to offsite power, or destruction of all access roads to the NPP.

***Did we consider multi-unit impact?***

Dr. Hakata strongly remarks that we do not consider multi-unit site impacts by external events in PRA, nor do we consider the mathematical correlation of the effects on multi-units. He points out that external events, such as earthquakes, floods, and tsunami, may cause simultaneous multiple nuclear reactor damages on a site. He suggests that site integrated CSD / LERF/ CCF per site-year are necessary in addition to per reactor-year to understand the true risks for nuclear sites. Dr. Hakata has researched methods for earthquake PRA of multi-unit sites. He says that there still remains need of further work in collecting correlation data, researching tsunami correlations and impacts, and for Level 3 PRA correlations.

Another open question is the extent of analysis for several seriously damaged units at the same site. This is not covered normally in current safety analysis. What about accessibility of different installations given radioactive releases from one or more reactors at the same site? What about accessibility of the site itself and possibility of supplying material/components etc. when having serious damage in the surrounding areas? Multi-unit failures should be considered in common cause analysis.

***Did we consider the double impact of earthquake and tsunami?***

PRA which include earthquake initiating events as part of the Level 2 analysis, usually do not include tsunami initiating events, nor do they include earthquake induced tsunami initiating events. From the Fukushima Daiichi accident, we can see that the double event caused loss of offsite power (conditional probability: 1), loss of all backup systems (conditional probability: 1), loss of HPCI (conditional probability: 1), finally leading to core damage and release. This could reduce the probability of all dependent accident scenarios to the initiating event probability. If the double initiating event experienced at Daiichi had a probability of 9.0e-4/year, as some analysts contend, then the lower bound for CDF at just one reactor would be 9.0e-4/reactor_year, above the NRC and NSC limit of 1.0e-4/reactor_year.

***Did we consider partial core exposure or hydrogen generation?***

Only calculating CDF seems not to go far enough after Daiichi. Partial core exposure (PCE) has its own unique accident progression and recovery questions which should be included in the event trees. Moreover, both CDF and PCE can generate hydrogen which caused explosions, releases, and weakened structures. Many of the responders now believe that we must include these types of events and consequences as top events and end states.

***Did we consider impacts of ground separation or displacement?***

An interesting question posed by Steve Eder, an earthquake expert from Facility Risks, Inc. In fragility analysis we consider the impact of ground acceleration on diesel generators, offsite power, steam generators, backup cooling pumps, etc. But do we consider ground separation or displacement on these systems and how that will affect operability? Also, ground displacement can lower and weaken tsunami walls, making them ineffective against run-up heights lower than the walls' design.

***Did we analyze accidents with durations greater than 24 hours or have procedures for events lasting longer than 24 hours?***

Generally we assume a time frame of 24 hours for PRA Level 1, with additional 24 hours for subsequent PRA Level 2 in some countries.  After those time limits, it was generally assumed that we have different options available to cope with the occurred situation so the residual risk could be neglected. Similar assumptions apply for the emergency planning, it is based on long time lasting events.

***Did we consider severe aftershocks and their impact on weakened facilities or equipment?***

Aftershocks, even in the first 24 hours after the initial earthquake, are rarely included in the PRA.  As in the question about consideration of ground displacement, how will strong aftershocks affect the operability of key systems whose structure may already be compromised?

***Did we consider systems to mitigate station blackout?***

In some PRA, it is assumed that station blackout will be mitigated before the batteries become ineffective.  Given that the local infrastructure was badly damaged, it was impossible to reach Daiichi with mobile power units and extra batteries until 1 hour before the batteries died.  When electrical connections proved impossible and extra power cables were needed, the batteries lost power and the second stage of the accident had begun.  There should be mobile power units available at a distance where their arrival to the NPP will be assured long before the battery lifetime under normal conditions, and a bunkered facility, such as the Beznau Notstand facility, available for situations where the local roads make it impossible for mobile systems to arrive quickly.

***Did we consider extended fuel storage or fires impacting the storage?***

The onsite fuel storage, and events which could cause a release, are not completely considered in the PRA, and certainly not external event impacts.  We do analyze loss of cooling for spent fuel pools during the annual outage. However this analysis is limited with respect to some chosen time frame, assuming that a transient will be limited in time and that after the limit of 24 hours there, will be a many mitigating options available.  Not only must we consider fuel storage, but we must consider impacts on all non-reactor facilities where impacts to these facilities could compromise the safety of the reactor or cause a release.

***How can we defend the current PRA technology statistically when in fact we have just had 2 or more severe accidents in the LWR at Daiichi?***

This is a thorny issue, indeed.  If we also consider the radiation deaths from the Tokai Mura accident and the release at Kashiwazaki Kariwa after the 2007 Chuetsu earthquake when some radioactive materials escaped into the sea when ground subsidence pulled underground electric cables downward and created an opening in the reactor's basement wall (TEPCO remarked, "It was beyond our imagination that a space could be made in the hole on the outer wall for the electric cables."), it seems that the claim in Japan that the possibility of nuclear accidents is small has been statistically invalidated.  How can we explain to the regulators, let alone the public, that probability is not statistics? Do we sufficiently include uncertainty in our calculations and in our explanations to aid both in understanding the risk levels in nuclear power? Too often the “P” in PRA is entirely forgotten and we focus on means and medians. As was said before, uncertainty, the measure of which is probability, is not some noisy variation around a mean value that represents the true situation. All decisions, all risk assessments are made under uncertainty. How do we explain this to decision makers and the public?

***Do we model accident management and emergency recovery human factors in our PRA?***

In short, no, we do not. At the moment, accident management and recovery actions are taking place, with no risk assessment oversight. Will the actions have a high probability of exacerbating the situation instead of mitigating it? Will a strong aftershock damage the temporary tsunami wall under construction leading to no protection if a tsunami ensues? Are the new external cooling units seismically safety rated? What is the probability that overtired, underfed, undertrained sub-contractors, who have no stake in the recovery actions, will make a disastrous error? The recovery situation must be modelled to be understood. The local governments must be made aware of the ongoing danger in a rational way.

***Do the regulators have an interim stress test available?***

In response to the tsunami and insufficient emergency response, NISA has proposed to all NPPs a flowchart outlining new accident countermeasures to ensure safety, to be able to mitigate “what went wrong”. Dr. David Johnson, of ABS Consulting, made these extremely germane and focused comments.

a) The countermeasure directive seems to be based completely on getting alternative power, ventilation and depressurization modes in place before the loss of decay cooling starts to materially impact on the RPV integrity.

b) All of the recovery and countermeasures must be analyzed by PRA. There are many alternative countermeasures depending on initiating events. We suggest most strongly that these measures all are analyzed with respect to the Level 1 and Level 2 PRA in place at each plant to insure that there will be a high probability of success.

c) The Level 2 initiating events must take into account all possible external events which can impact each individual plant, especially fire after earthquake, flooding from typhoon, internal flooding, as well as tsunami and earthquakes.

d) Now is the time to consider many things which have not been considered before. If the countermeasures are only directed at past events, then we will have a new event which will create the same situation as we now have at Daiichi.

e) The actions mentioned would fall under 'severe accident guidelines ' or 'emergency procedure guides'. However, more must be said so that they are complete. For example, to prevent the exhaustion of the battery, one could include DC load management to stretch out the life of the battery as much as possible; for support of RCIC, this might mean preventing unnecessary cycling of the pump; perhaps the operators could split the flow between the vessel and the water source (condensate storage tank or torus so that it does not reach a high level trip. Are there ways to cross connect other DC sources of power? Do these units have HPCI? HPCI has a much larger pumping ability and would be more difficult to control level long term since makeup requirements are quite modest. Can they cross connect to the HPCI battery? In any event, if there are any indications that RCIC failure is anticipated (low steam pressure or erratic running) they should attempt to fill the vessel. Many hours into the event, a full vessel would take maybe an hour to steam off, giving additional recovery time. The idea of using a portable engine to charge the batteries is a good. Note also that they will need to keep critical instrumentation functioning.

f) The directive does not look in depth at the means of providing alternatives or if roads and the national infrastructure allows alternatives to be brought to the site, or if the site staff are competent, capable, or have sufficient morale.

g) Unit 1 had isolation condensers, not RCIC. The long term requirement for these condensers should be included, as appropriate. (it should focus on keeping the shell side of the condenser full of water). These ICs are typically initiated by opening two 'return' valves. If these valves fail to open, priority should be given to having the ability to manually open them.

h) These plans should not focus on specific causes like 'tsunami'. There are other ways to get large quantities of water into the reactor building. (I have assumed the placement of critical electrical equipment low in the building was a contributing factor). For example, if a large raw cooling water pipe were to break, a significant amount of water could be introduced into the building, potentially having similar failure impacts. The spatial interaction analysis or internal flooding analysis MUST be done to confirm. The point is that there may be other specific initiators that could benefit from this planning.

i) It is a good idea to have dedicated on-site emergency power and pumping equipment. The scheme should also make sure there is sufficient equipment to address the needs of multiple units. The USA has designed a 'mobile recovery vehicle' for a plant many years, but it was never built. That truck would have the ability to deliver AC, DC, compressed air, and water (with flexible hoses to reach a source). The key to success will be preplanning how these necessities would be coupled to the plant.

j) The idea to have the on-site emergency power and pumping vehicles must take into account the ability of this equipment to reach the NPPs. If the cause of station blackout is a natural disaster such as an earthquake or tsunami, roads might be destroyed or difficult to navigate.

k) A major observation is that there should be a countermeasure to put into place an electrical infrastructure to replace the assumed unavailable existing plant infrastructure. It would be useless to have alternative power source available at point A on the site and be unable to transfer the power to where it was needed at Point B. I think this was partially addressed at Fukushima when we heard there were cables being installed to deliver power to the RPV circ pumps. A Plant should be able to have such a scheme and the hardware assembled at a distance from the site and capable of being lifted into place within half a day of the event and installed (cables/switchgear etc) within another day.

### *Questions to the ANS Fukushima Daiichi Investigation Committee*

Many nuclear professionals in the USA have asked questions to the ANS Investigating Committee. We present some of the more interesting questions and the answers as of the writing of this report. The words below have not been edited by the author of this report.

**Question:** Why weren't they able to refill the tank of the Isolation Condenser at Unit 1? The IC is a 100% decay heat removal system, which operates passively and requires only water refilling in a tank which sits outside the containment. The tank can be refilled with saltwater without contaminating the reactor water. All it takes is a fire truck with a hose, which apparently they had at the station all along.

**Answer:** There are several conflicting stories on this. The most believable is ICs were terminated because according to procedure they were trying to avoid a cooldown rate in excess of tech spec limits. With 2/2 ICs working that would have happened for the first couple 100F until the delta-T went down. If this is true, once isolation valves were closed, tsunami came and wiped out AC power so valves could not be reopened (some MOVs are inside containment). There should have been plenty of water (several hours worth – I have been told 8 to 10), and as you say refilling the IC shell is relatively easy to do, if you have access to the refueling floor. Since core melt happened at this plant first, I have to believe the IC function was lost early. As for HPCI at unit 1, there is a NISA presentation that says the batteries that support HPCI were flooded, which goes a long way towards explaining why this unit reached core melt first.

**Question:** Why did the RCIC fail? The RCIC is a 100% decay heat removal system operating on steam-turbine-driven pumps, which require only DC power for their control. My understanding is that new batteries were brought to the site within a few hours after accident initiation. So, what happened? Did the steam-turbine-driven pumps cavitate because the wet-well water (from which they draw) reached 100 C? But the RCIC can also draw water from the Condensate Storage tank, which sits outside in plain air... so again, all is needed is a fire hose.

**Answer:** Good question. The best info I have is they did run for several hours until batteries were exhausted, well before there was an NPSH problem. Don't know if the new batteries brought had enough capacity to handle RCIC as well as other division loads, as I don't know what kind of load shedding could have been done in that division. Remember, plant is black, so getting to the RCIC room or any other room to do load shedding would be quite an adventure. As for the condensate storage tank, it too was wiped out by the tsunami. There are some straightforward design changes that could greatly prolong RCIC, but they would also have to be implemented together with early containment venting to limit the suppression pool temperature; otherwise you can't get RCIC to go longer than 8 hours anyway. (Early containment venting via the existing hardened vent can't be done unless the configuration is changed to allow bypass of the rupture disk.) If RCIC quits within the first 12 hours and you have no other injection the core will start melting in an additional 3 to 4 hours. As decay heat goes down the time between RCIC failure and core melt, of course, lengthens.

**Question:** Did $H^2$ leak into the buildings through a gap in the containment vessel head (due to high containment pressure) or through weak vent ductwork?

**Answer:** The hard vent P&ID that I have seen shows at least one closed MOV and one AOV normally closed in series with a rupture disk that cannot be bypassed. (See TEPCo 5/24 presentation you discovered.) Since the containment wasn't vented until the pressure was well in excess of rupture disk setpoint, it indicates a problem with the configuration that I think will be the subject of regulatory scrutiny, both in Japan and here, as I have seen a few US P&IDs that also show no (easy) ability to open the vent if AC power is lost. ABWR has AOVs only (plus a rupture disk), normally open. Sawyer speculation: Something wrong with command and control if you have to wait until after core melt and significant pressurization from hydrogen before you decide to vent. Not enough local decision making allowed in Japan. I believe there was direct leakage to the reactor building probably through the drywell head cover with the containment at high pressure, which means that for venting trying to manually manipulate valves in a high radiation environment. It probably took couple of hours to manually open the large isolation valves.

**Question:** We believe that the earthquake did not cause major damage to the plant structures, but little cracks here and there may have had major safety consequences. For example, were the containment vent pipes damaged by the earthquake? Were the RCIC steam-turbine-driven pumps and pump supports damaged by the earthquake?

**Answer:** We don't know, but it seems that at least one unit (unit 2) leaks appeared in the torus region, which may be the reason for hydrogen explosion in that area. Current speculation in Japan is that due to high pressure before venting, leaks appeared (maybe drywell head cover) that allowed hydrogen to accumulate in the refueling floor area. Currently, TEPCo is having trouble flooding containment in at least one other unit, an indication that there is a significant leak in the lower drywell.

**Question:** Is there any evidence of water leaks at the spent fuel pools? The latest info from TEPCO (along with the videos I have seen online) suggest that the fuel in the spent fuel pools at Units 1-4 actually did not overheat. The fuel in the Unit 3 spent fuel pool was damaged by the hydrogen explosion, but seem to have been always under water. As was the fuel at Unit 4.

**Answer:** The latest info I have says the hydrogen explosion at unit 4 reactor building was actually caused by gas coming from unit 3 via common ductwork, not due to spent fuel being uncovered and heating up.

**Question:** What was the "explosion" in or near the containment in Unit 2 due to? If it was within the containment, it cannot be due to hydrogen since the containment was filled with steam and nitrogen at that time. Was it a steam explosion due to corium contact with water under the RPV?

**Answer:** Sounds like hydrogen explosion happened in a lower floor of the RB due to leaks that may have been either caused by the earthquake, or weakened enough that when high containment pressures occurred leaks started.

**Question:** Why did the $H^2$ venting not go to the stack, but rather into the reactor building?

**Answer:** On one reactor you could understand that earthquake damage might have severed the duct, but not on the others.

**Question:** What caused the batteries to die. Why was there no means to charge them via the steam driven turbines?

**Answer:** RCIC and HCPI turbines do not have generators/alternators on turbine shaft. This has been proposed many times in the past going back to TMI, but it was never implemented, primarily because in the US, no one believed that station blackout could possibly last longer than 4 to 8 hours. The only turbine that is coupled to a generator is the main turbine. It takes DC power to run the RCIC and HPCI turbine speed control system and the injection valves, and unfortunately the flow is not controlled to match decay heat, meaning the systems run full out until high water level trip followed by cyclic action to start and stop these systems as the water level cycles between high and low water levels. Every time the valves are opened and closed, it is a drain on the batteries.

**Question:** How much diesel fuel was at the site. Was it really stored only in the two tanks swept away by the tsunami? Why were the tanks not protected better?

**Answer:** I believe that is correct for units 1-4. The only tank saved was at the unit 5/6 area which was at a higher elevation. The same is true of the condensate storage tank, the only simple source of fresh water. If you believe that the highest tsunami would be 5 meters, you see no problem with the location of the tanks.

**Question:** What means of on-site, off-site communication were available during the first 24 hours? How did they make decisions, and coordinate with the authorities? What did the staff know of the whole site status?

**Answer:** We don't know, but believe that Japanese process requires local and national government approval to take critical actions, such as pump sea water or vent the containment. It should have been known from lots of PRA studies that in a SBO there are only a few hours available to make critical decisions. TEPCO continues to "no answer" why it took so long to decide to add sea water, or to vent the containment, but I think it's only a matter of time before IAEA forces the issue. Sawyer speculation: Japan will have to change their command and control process, not easy in a society based on consensus decision making. In the US, the control room operator is empowered to take unilateral action if there is no TSC available to give guidance    God help us if you need a bureaucrat far removed from the scene to give permissions.

**Question:** Where did coupling of services (ventilation, power, etc.) between plants help or hurt accident response? (I suspect that some of the hydrogen damage was a consequence of a common off-gas system where without power the filtration and stack offered higher resistance to gas flow when pressurized hydrogen entered by one of many intakes and then flowed out of other intakes)

**Answer:** I believe you are right in the case of the hydrogen explosion at unit 4, but it was by a shared Standby Gas Treatment System (SGTS), not a shared off-gas system. Regarding other services, such as common diesel fuel tanks and condensate storage tank, having separate tanks for each unit would not have made any difference, assuming they were all at the same elevation.

**Question:** Do we need passive containment cooling to assure containment integrity?

**Answer:** The containment structure is passive but if it requires active cooling systems it has the same risk profile as the ECCS with a different time line. Ignoring the emergency going on inside the RPV for the moment, the solution to the containment problem (and the one called for in BWR EPGs and SAGs) is to vent the containment. There are a couple of days of boil away water in the suppression pool (that is also easily replaced). It's been well-known going back to WASH-1400 days that pressure suppression containments barely make it to a day in SBO core melt scenarios (Mark I's are even less) if their job is to not let any radiation out. Wetwell venting is preferable in my opinion to an uncontrolled containment failure, and as I noted above, an improved RCIC, together with early venting could allow indefinite core and containment integrity during an extended SBO. By the way, the same can be said for current PWR containments – they just last a little longer with no operator action.

Retrofit of a PCCS to existing plants is a prohibitively expensive proposition for BWRs and PWRs, and would only work once the core is ex-vessel. I hate solutions that require the core to melt before they work. The reason it works without requiring the core to relocate in ESBWR and AP-1000 is that there is also a gravity ECCS that the PCCS condensate can connect to, to close the loop.

**Question:** When was the information available to operators about the pressure and temperature lost (due to lack of electricity) and when was it restored?

**Answer:** We don't know for sure, but we think the plant operators at least knew RPV water level, RPV pressure and Containment pressure from the beginning

**Question:** Did TEPCO have training of operators on severe accidents? And did that include loss of power type events?

**Answer:** I only know what is in the media. TEPCo supposedly implemented the BWROG EPGs, but I do not know whether they implemented the SAGs. These procedures are symptom-based and don't care what the event was. Having said that, there should have been no need to enter the SAGs at all if any water - sea water, fire trucks, etc. – were added to the RPV before the water level dropped below the jet pumps. The 8 hour makeup rate in any of the damaged Fukushima units is less than 100 gpm. I hope we will eventually find out why it took core melting to get around to sea water injection.

***In Conclusion***

We are only in the first 4 weeks of this disaster. Over the next year there will be several commissions of inquiry, both inside and outside of Japan, who will investigate this accident and try to uncover the root causes to better prepare the international nuclear community for the possibility of severe accident initiation and propagation, as well timely and effective mitigation. I hope that my early contribution to this discussion is informative and germane.

# How likely was it?

# Understanding uncertainty

"But one could hardly imagine that such an event would recur nor the greater event would happen in the land of the living." -- Yoshimitsu Okada, President, Japan National Research Institute for Earth Science and Disaster Prevention, March 25th, 2011

## Preliminary Considerations

We have established that the Fukushima Daiichi core damage and radioactive release had three main causes: loss of offsite power from the earthquake; station blackout from the tsunami; and an underlying organizational culture which could not react quickly to rare events and could not tell the truth, even to themselves.

In this section I will ask the question, "how likely was it?" by examining two categories of unconsidered actions which may have prevented or mitigated the accident:

a. an alternative way to understand the probable frequency of an earthquake and tsunami of the magnitude experienced;
b. impediments to possible mitigation and recovery.

## Bayes' Theorem

Bayes' Theorem provides a mathematically rigorous method, called Bayesian updating, for increasing our state of knowledge about the probability of an uncertain event based on new evidence. The theorem is named for Thomas Bayes and often called Bayes' law or Bayes' rule. Bayes' theorem expresses the conditional probability, or "posterior probability", of an event A, given evidence B is observed, Pr(A|B), in terms of the "prior probability" of A, Pr(A), the prior probability of B, Pr(B), and the conditional probability of B given A, called the "likelihood", Pr(B|A):

$$Pr(A, B) = Pr(A) \bullet Pr(B|A) = Pr(B) \bullet Pr(A|B)$$

$$Pr(A)\, Pr(B|A) = Pr(B) \bullet Pr(A|B)$$

$$Pr(A|B) = \frac{Pr(B|A)\, Pr(A)}{Pr(B)}$$

| | | |
|---|---|---|
| A | → | The frequency of some event takes on a specific value. |
| B | → | The accumulation of evidence about the frequency of the event. |
| Pr(A) | → | Probability of "A" prior to, or without knowledge of, the evidence of event B ("The Prior"). |
| Pr(A\|B) | → | Probability of "A" after, or given knowledge of, the evidence of event B ("The Posterior"). |
| Pr(B\|A) | → | Probability of observing evidence B given A; i.e., given the event frequency takes on a specific value (The Likelihood"). |
| Pr(B) | → | Probability of observing evidence B. |

For example, imagine an elementary school student. The student comes into the medical office with red spots on his belly. One possible childhood illness is Chicken Pox. So the school nurse reasons from symptoms and an etiology to a diagnosis thusly: the chance that in the general population an elementary student will get Chicken Pox during childhood is n%, the **prior**. That there are red spots on the belly, GIVEN that Chicken Pox is the illness is m%, is the **likelihood**. So the chances that the illness is Chicken Pox, GIVEN that red spots are observed is n% * m%, the **posterior** (with a "correction" factor left out).

Bayesian methodology has three import characteristics: all types of information are used, the use of judgment is visible and explicit, and it handles the case of no events being experienced. The important properties of Bayesian Updating are: with weak evidence, the prior probability dominates results; with strong evidence, the results are insensitive to prior, they are dominated by the evidence; and successive updating gives the same result as one-step updating with consistent evidence.

In what follows, please consider the Bayesian analyses to be rough, first cuts. Perhaps incorporating expert opinion and data from geographical areas outside of the Sanriku and Sendai regions with a Bayesian 2-stage analysis would give more accurate estimates.

The following calculations are meant to be bounding calculations, not final words, to complement the simulations and theoretical considerations used by the JSCE and NIED. However, I believe that analyses such as I have done were not considered at all, and that the simulations and attendant theories were believed prima facia. Our analyses give an entirely different picture.

## Bayesian Analysis of Earthquake Recurrence Frequency at Daiichi

In section 1, I presented a table from NIED which depicted the recurrence frequency mean value for a Shindo>=6 earthquake at Daiichi as being less than 0.05% within 30 years. This value was arrived at by numerical simulations using such models as the characteristic earthquake model and its cousin, the seismic-gap model.

Our historical research shows that there have been six earthquakes greater than, or equal to 8 $M_{w,}$ along the Sanriku and Sendai coasts, excluding the event of March 11:

| Year | Magnitude | Interval in Years |
|---|---|---|
| 869 | 8.6 | |
| 1611 | 8.1 | 742 |
| 1793 | 8.2 | 182 |
| 1896 | 8.5 | 103 |
| 1933 | 8.1 | 37 |
| 1960 | 8.5 | 27 |

Dr. Jens Jens-Uwe Klügel, Manager of PSA at KKG in Switzerland and leader of the European Project PEGASOS to understand probabilistic approaches to earthquake risk assessment, has commented to the author:

> … earthquake recurrence may be a non-ergodic stochastic process (instationary), therefore the use of Bayes theorem is to some extent misleading - stationary data distributions may not be applicable … [but] a ‘temporary stable state’ of the stochastic non-ergodic process of earthquake occurrence in Japan may be applicable for about 400 years - but this is only temporary.

I will estimate the probability before March 11th, using Bayesian Analysis. I will make five reasonable assumptions:

a) Historical data is consistently given in $M_w$ values. We will assume that all earthquakes greater than 8.0$M_w$ have a Shindo of greater than 6;

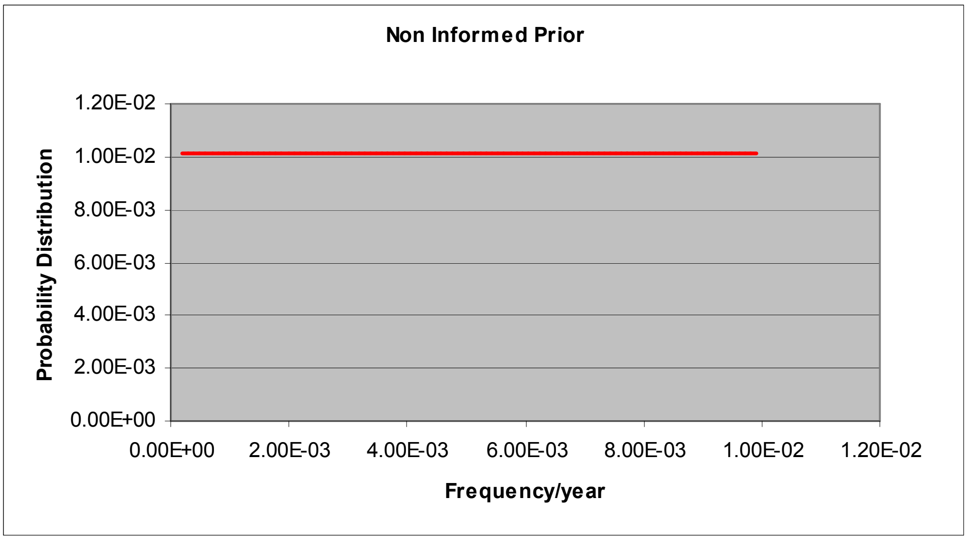
b) We will only look at earthquakes which affected the Sendai coast;

c) We will begin with the prior probability distribution known as the non-informed prior, which means that we have no prior knowledge as to the actual recurrence probability;

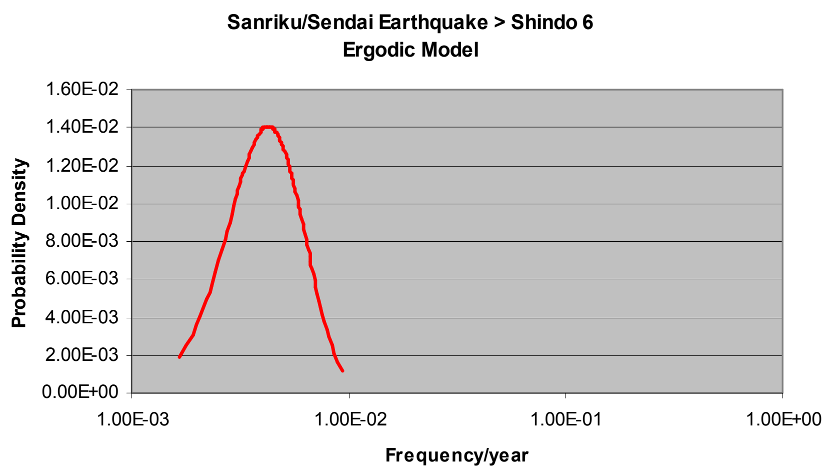
d) To be conservative, since we do not have evidence of an earthquake with Shindo 6 or greater before 869, we will start the analysis with the Jōgan earthquake and we will do a 1-step update with 6 events in 1141 years (869-2010), then employ the non-ergodic thesis and make a 1-step update with 5 events in 399 years (1611-2010). One step updates take into account long time intervals with no events.

e) We will assume that the range of the probability can be between 1/10,000 years and 1/100 years for the non-informed prior.

The prior can be seen below:

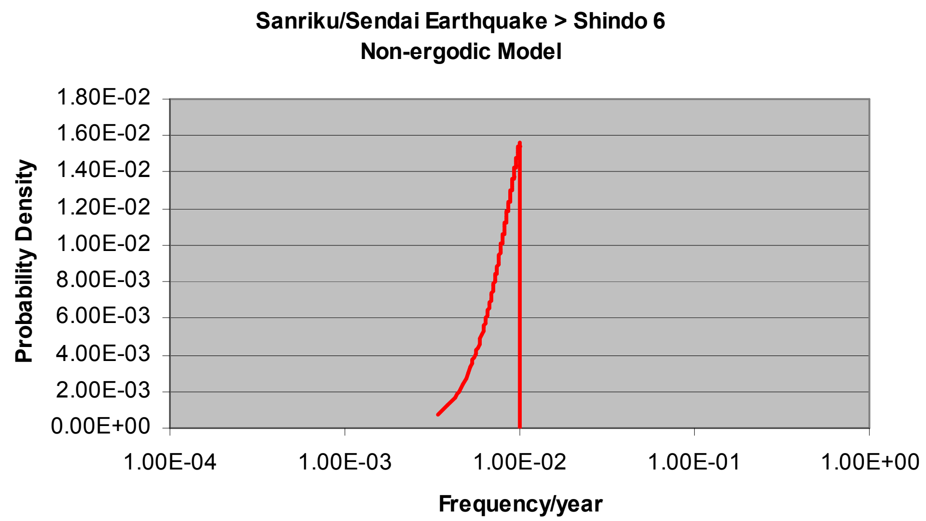



and after the Bayesian update of 6 events in 1141 years:




| Name | Value/Year | Recurrence/yr | % Recurrence/30 yr |
|---|---|---|---|
| Mean | 4.88e-3 | 1/205 | 14.64% |
| 5th Percentile | 2.32e-3 | 1/431 | 6.97% |
| 50th Percentile | 4.70e-3 | 1/213 | 14.10% |
| 95th Percentile | 8.10e-3 | 1/123 | 24.31% |
| Range Factor | 1.87 | | |

and after the Bayesian update of 5 events in 399 years:




| Name | Value/Year | Recurrence/yr | % Recurrence/30 yr |
|---|---|---|---|
| Mean | 7.73e-3 | 1/129 | 23.19% |
| 5th Percentile | 4.54e-3 | 1/220 | 13.62% |
| 50th Percentile | 8.05e-3 | 1/124 | 24.14% |
| 95th Percentile | 9.83e-3 | 1/102 | 29.48% |
| Range Factor | 1.50 | | |

Mean values of 4.88e-3/year to 7.73e-3/year gives us mean recurrence fractions of approximately 1/129 to 1/205 years, but we do not know when, if ever, such an event will occur. Bayesian analysis is not a prediction method such as that used by NIED, presented in section 1, where NIED predicts an earthquake at Daiichi of less than 0.05% within the next 30 years. The method presented here is simply a probability distribution based on historical data: a Shindo 6+ earthquake in Sanriku or Sendai could happen again tomorrow, or perhaps never again.

It must be strongly pointed out that the Bayesian analysis only reflects assumptions and our state of knowledge from historical events, just as the NIED values only reflect assumptions and a state of knowledge given by the numerical simulation and the modelling methods. All sets of values need to be considered when making a judgement under uncertainty. However, NIED, NSC, and information released to the public ignored presentation of the historical evidence and presented the results from the simulation as fact.

The mean value of an uncertainty distribution should never be taken as the final word in risk assessment; doing so is to miss the point of PRA. In PRA quantification, or measuring, the risk/safety of a situation is to explicitly make clear our state of knowledge. The act of trying to measure the risk involved, and learning about the facility being investigated, is the goal. The acts of trying to assign values, combining them, questioning their validity, building the model, and understanding our own uncertainty are the great treasure of probabilistic risk assessment and the source of knowledge. To be prepared for the unforeseen event, a good analyst must constantly change the model, question assumptions, run scenarios, examine results, and understand the uncertainty.

It is our opinion that TEPCO, and probably all NPP operators in Japan, paid little attention to the NIED methods. Each of the major nuclear facility construction companies in Japan (Kajima, Obayashi, Taisei, and Shimizu) has their own earthquake research centres and proprietary simulation software. All NPPs in Japan do extensive fragility analysis probabilistically, based on the seminal work done by PLG, Inc in 1981. The article, "A Methodology for Seismic Risk Analysis of Nuclear Power Plants", can be found on the internet. The author spent many years working with all three authors of the article in creating earthquake risk assessment software methodologies. These methods are the most pervasive in Japan.

The design basis for Daiichi was a Shindo 6. The PGA experienced was, for the most part, designed for; a 23% exceedence of the design basis PGA seems to have done no damage to the important structures, but the jury is still out. There seems to be radioactive water leaking from the reactor buildings which may have been caused by the earthquake; we know nothing with respect to the spent fuel pools.

However, even after the earthquake at Kashiwazaki in 2008, where the PGA of the earthquake exceeded the design basis by almost 300%, the NPP was able to go to cold shutdown with no problems with minimal damage to safety systems.

## Bayesian Analysis of Tsunami Recurrence Frequency at Daiichi

In Section 1, I presented the guidelines published by the Japanese Society of Civil Engineers to be used in the tsunami risk assessment of NPPs. By application of these guidelines, TEPCO believed that the 5.7m tsunami wall built in 1966, during the construction of the Daiichi NPP, was sufficient to withstand any reasonable tsunami which could arrive at the plant. In particular, the historical scenario tsunami which they chose for the design basis (which is not given in their presentation) was expected to be below 5.7m.

Since no defence in depth existed for tsunami at Daiichi, particularly the undefended location of the backup diesel generators in front of the reactor building, I hope that TEPCO's choice of the height of the scenario tsunami was well below 5.7m. I have been told that around 2003, NISA recommended to TEPCO that the existing tsunami wall was not high enough; TEPCO rejected this suggestion, and the regulator did not press the point, as there was no official regulation about tsunami risk in effect at that time.

Our analysis will neither depend upon, nor comment on, the models used and simulations performed by TEPCO. However, the deterministic approach to tsunami was questionable and the proposed probabilistic logic tree method is very questionable because it can lead to ignorance of extreme events.

Instead, I will look at historical evidence; I will look not only at modern, recorded history, but on well founded geological inference of tsunami run-up distance and height on the Sanriku and Sendai coasts from the aforementioned articles, mentioned on page 50. I will also focus on the Hama-dori coastline where Daiichi and Daini are located.

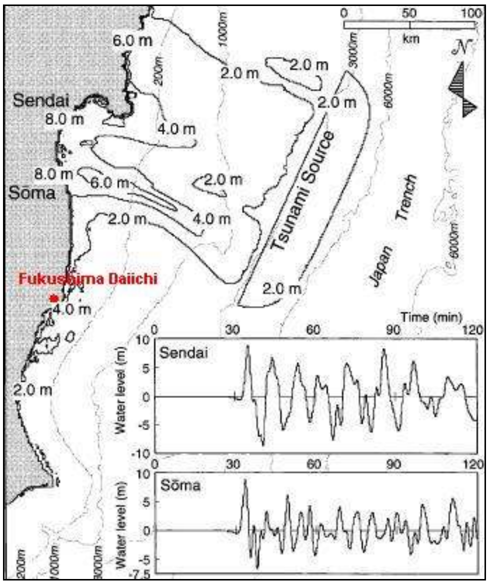
The lower bond for the study assumes a non-ergodic model, which shows that we have had no tsunami greater than 8m on the Sendai coast in the last 400 years, and no graph will be presented. The upper bound will be the ergodic model which assumes 3 tsunami in 2800 years.

The investigation of the Jōgan tsunami of 869 employed sediment analysis and numerical hydrodynamic models, the results of which indicate that the tsunami was approximately 8m in height with a run-up of 4 to 5 kilometres. Further analysis based on sediment depositions and $^{14}C$ dating suggests that there were two other gigantic tsunami of the same height and extent: the first between 910 BCE and 670 BCE, the second between 140 BCE and 150 CE, with a standard deviation of 1σ (the underlying probability distribution is not available).

As in the Bayesian study of earthquake recurrence, I present the following table, using the midpoints of the estimated occurrences of the two pre-historical tsunami. I will use information from the Sendai plain and Hama-dori regions only, since the coastal topography of the Hama-dori coast, at Daiichi, is more similar to the Sendai region than it is to Sanriku, although the Sanriku coast is only 260km further north. If I had included run-up heights from Sanriku, the 1896 and 1933 tsunami had run-up heights of 38m and 29m, respectively:

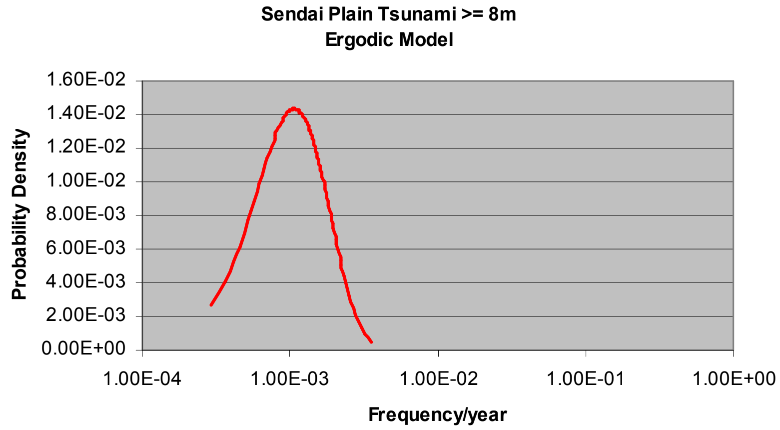
| Year | Estimated Maximum Run-up Height | Interval in Years |
|---|---|---|
| 790 BCE | 8m | |
| 5 CE | 8m | 795 |
| 869 | 8m | 864 |

The inferred run-up heights for the Jōgan tsunami at different locations on the Sendai coast are depicted below. Please note the location of Fukushima Daiichi indicates the inferred run-up height was about 4m. Our analysis, however, does not assume that the run-up height was actually the maximum, 8m; it is simply an analysis of the recurrence frequency of very large tsunami on the Sendai coastal plain. I will discuss the run-up height assumptions after the analysis. As an aside, one of the articles predicts, “Our numerical findings indicate that a tsunami similar to the Jōgan one would inundate the present [Sendai] coastal plain for about 2.5 to 3 km inland.” It was uncannily accurate.



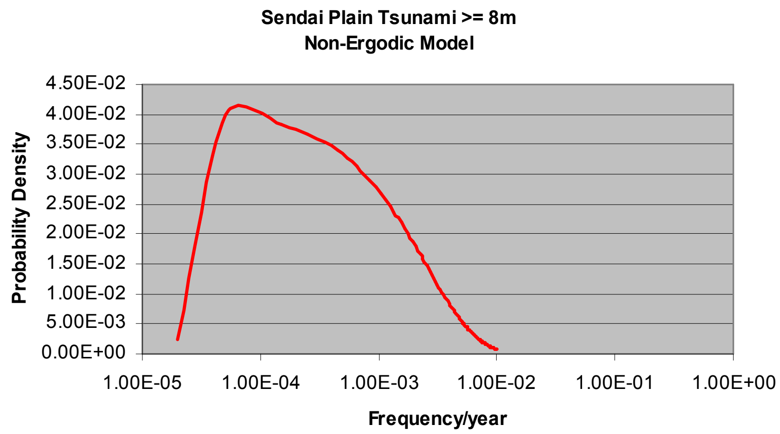


I will start with the same non-informed prior as I did with the earthquake study. To be conservative, I have done a 1-step update of three events in 2800 years (790BCE to 2010). The results are depicted below:




| Name | Value/Year | Recurrence/yr | % Recurrence/30 yr |
|---|---|---|---|
| Mean | 1.43e-3 | 1/730 | 4.29% |
| 5th Percentile | 4.89e-4 | 1/2045 | 1.47% |
| 50th Percentile | 1.31e-3 | 1/763 | 3.94% |
| 95th Percentile | 2.77e-3 | 1/361 | 8.31% |
| Range Factor | 1.58 | | |

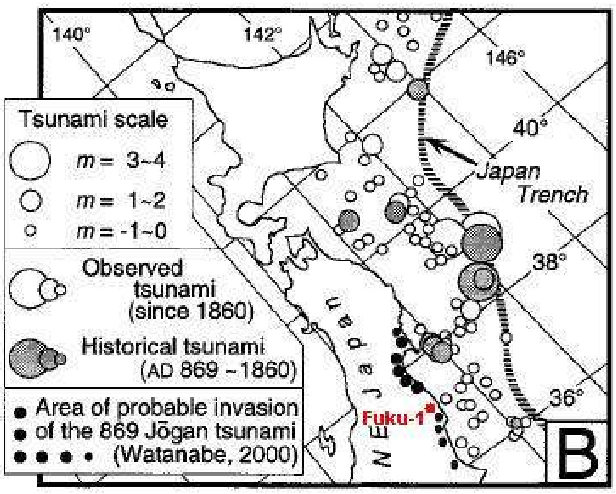
The non-ergodic thesis would give us the probability of an 8m tsunami in the last 400 years as equal to zero. But by using Bayesian analysis, which takes into account NO events in 399 years, we can estimate a distribution. We start with a non-informed prior with a lower limit of 1e-5 and an upper limit of 1e-2. We then do a Bayesian update of no events in 399 years (0 out of 399). The results are:



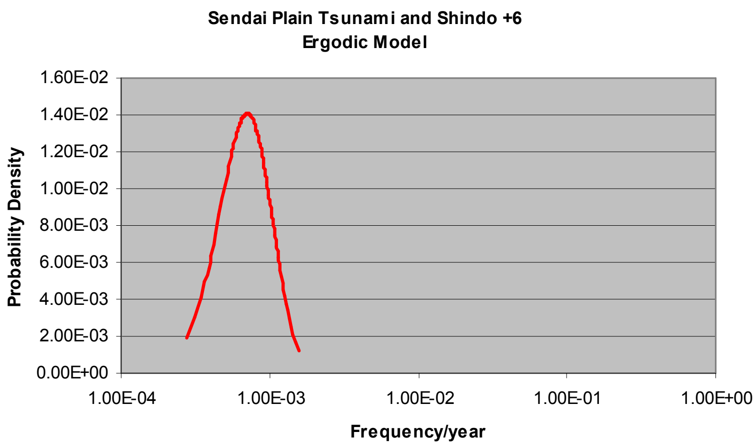

| Name | Value/Year | Recurrence/yr | % Recurrence/30 yr |
|---|---|---|---|
| Mean | 2.32e-3 | 1/431 | 6.96% |
| 5th Percentile | 2.75e-5 | 1/36364 | 0.08% |
| 50th Percentile | 1.59e-3 | 1/629 | 4.77% |
| 95th Percentile | 6.65e-3 | 1/150 | 19.95% |
| Range Factor | 29.03 | | |

More importantly, it is necessary to calculate the joint probability of an earthquake greater than Shindo 6 and a tsunami with a run-up of 3 to 4 kilometres and maximum run-up height greater than 5.7m. This probability will let us understand if the tsunami wall at Daiichi was large enough.

Let us use the distribution calculated for the probability of an earthquake with a Shindo greater than 6 in the previous section, Pr(Shindo>=6); then by looking at the 6 earthquakes with a Shindo greater than six, we can see that only one of them was accompanied by a tsunami with a height greater than 5.7m, the Jōgan earthquake of 869, and it had an estimated height of 8m. We verified this historically from the geological papers already sited. An illustration of the history of such tsunami is shown below; note the location of Daiichi in red:



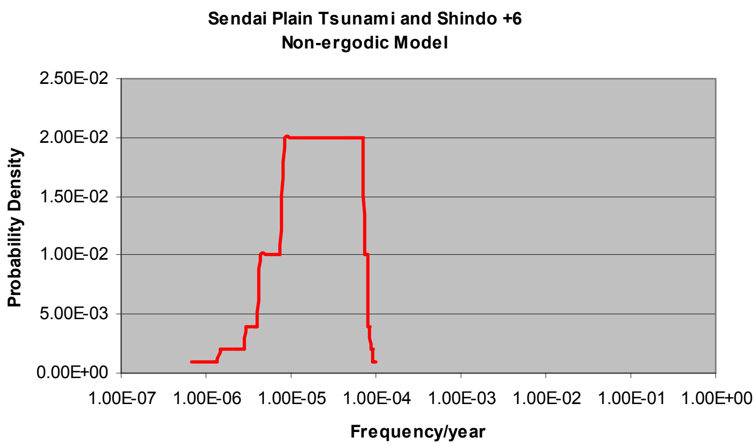

For the ergodic model, we assume one such tsunami out of six Shindo 6 events gives us a mean occurrence probability of 1.67e-01, which is the conditional probability that given a Shindo 6 event, the probability of a tsunami height of approximately 8m: Pr(Tsunami≈8m | Shindo>=6) = 1.67e-01. We then multiply the two probabilities and obtain get the joint probability of both the earthquake and the tsunami: Pr(Shindo>=6) * Pr(Tsunami≈8m | Shindo>=6) = Pr(Shindo>=6 , Tsunami≈8m). The results are depicted below:




| Name | Value/Year | Recurrence/yr | % Recurrence/30 yr |
|---|---|---|---|
| Mean | 8.14e-4 | 1/1229 | 2.44% |
| 5th Percentile | 3.87e-4 | 1/2584 | 1.16% |
| 50th Percentile | 7.83e-4 | 1/1277 | 2.35% |
| 95th Percentile | 1.35e-3 | 1/741 | 4.05% |
| Range Factor | 2.01 | | |

These statistics agree well with the estimated range in the sited articles: 1.25e-3/year to 9.09e-4/year.

For the non-ergodic model, we start with the non-ergodic earthquake Bayesian analysis and combine with a Bayesian analysis of no tsunami events with a run-up of greater than 8m in the last 400 years, using a Monte Carlo discrete distribution calculation, which gives us the lower bound:




| Name | Value/Year | Recurrence/yr | % Recurrence/30 yr |
|---|---|---|---|
| Mean | 3.92e-5 | 1/25,510 | 0.12% |
| 5th Percentile | 3.96e-6 | 1/252,525 | 0.01% |
| 50th Percentile | 3.59e-5 | 1/25,316 | 0.11% |
| 95th Percentile | 7.97e-5 | 1/12,547 | 0.241% |
| Range Factor | 4.48 | | |

What do mean values between 3.92e-5 and 8.14e-4 indicate in terms of CDF? For the upper bound, if we consider this as the mean value of the initiating event, then a tsunami height of approximately 8m and run-up of 4km would surely overrun the tsunami wall at Daiichi, inundate the turbine room, destroy the diesel generators, make the batteries inoperable, cause loss of offsite power, and therefore cause total station blackout for a period of more than 8 hours. Given the devastation to the equipment on site and total loss of offsite power from such an event, we can estimate that this one sequence would have a probability in the range of 5.00e-4/year and lead to core damage; this one sequence alone would be 5 times greater than the regulation for CDF of 1.00e-4/year.

However, we must also consider LERF (large early release factor) which is a regulatory limit for unplanned for release of radiation. Mr. Jerzy Grynblat, Director of Nuclear Consulting at Lloyd's Register, comments:

> "What I want to stress is that it is not the probability of CDF only, to be compared with regulation value of 1e-4/y, it is the probability of uncontrolled releases, i.e. PSA Level 2 and not only Level 1, since given the analyzed scenario there was no defence against radioactive releases. Given core melt there will be penetration of the primary loop and also damage to the reactor containment, both due to the forces of tsunami but also as a consequence of hydrogen explosions that will follow melting of the fuel. What I am trying to say is that the calculated value of 1e-3/y should be compared with a regulation value of uncontrolled releases to the environment, or with LERF, in the range of 1e-5/y - 1e-6/y (I'm not sure what value is stipulated in Japan) and not 1e-4/y".

The regulation for LERF in Japan is 1e-6/year per unit, and is smaller than both the upper and lower Bayesian analysis bounds.

The maximum tsunami run-up heights in the data used for the analysis was 8m, while the one inferred data point estimates the Jōgan run-up near the Daiichi site was about 4m. What should we infer for the purpose of insuring safe operations of the NPP?

Conservatism is an earmark of good risk assessment, especially with large uncertainties with respect to the model, the simulation, and the data. Indeed, as I mentioned before, both the numerical simulations by JSCE and the Bayesian analyses done by the author should be used as bounding studies to inform risk management. As researchers such as Dr. Robert Geller have pointed out, we cannot predict where on a fault a rupture will occur, nor can we predict all of a rupture's actual attributes; in the March 11$^{th}$ earthquake, most experts had not predicted that the angle of subduction would be so acute, the effect of which was the large tsunami.

Japanese NPP operators constantly say that they build structures which are able to withstand 2 times the anticipated $M_W$. The JSCE wrote that their methodology in the TAMNPP consistently showed that that their design tsunami exceeded the scenario tsunami by a 2 times height, on average. [TAMNPP pg.10]. Surely, therefore, TEPCO should have built a tsunami wall capable of withstanding an 8m run-up (2 times 4m), given that 8m was historically encountered from reliable sources.

Should TEPCO have anticipated a tsunami run-up of 14m? The consequences of a tsunami which could breach the tsunami 5.7m wall were especially high, given that there was no tsunami defence in depth and the turbine building was especially vulnerable because of its location. Even if the initiating event mean value of an 14m tsunami run-up height at Daiichi was 10 times smaller than 5.0e-4/year, in other words 5.0e-5/year, the dominant accident sequence would have a value uncomfortably close to the total CDF/year of 1.0e-4 and greater than uncontrolled release regulations of 1.0e-5/year. I therefore believe that NPP operators in Japan should prepare for the maximum tsunami run-up height which could happen within a large radius, make extensive changes in plant layout, and create defence in depth capabilities, such as the Notstand system at the Beznau NPP mentioned earlier.

As an aside, when the author asked a TEPCO analyst why TEPCO did not do bounding analyses, the answer he received was that bounding analyses were not included in the guidelines, therefore TEPCO felt comfortable only doing what was asked by the regulators, nothing more.

One final observation: TEPCO’s and the regulators’ complacency that a 5.7m tsunami wall was adequate, given that it was constructed more than 35 years before the 2002 study by JSCE and given that building new defences was extremely expensive, is highly suspect. TEPCO will book a group net loss of JPY 1.2 trillion (GBP 9 billion) from the Fukushima Daiichi accident. The lessoned learned is that the accident always costs more than the defence.

## Unconsidered (But Likely) Impediments to Recovery at Daiichi

**Radioactive releases hampering activities were not considered.** During the first few hours after the tsunami, high levels of radiation made manual operation of the isolation condenser valve almost impossible, as well has restricting access to control rooms and turbine buildings. Radiation levels continue to make the execution of TEPCO’s roadmap to cold shutdown extraordinarily difficult; it has been revised twice as of the writing of this report. In Fukushima Prefecture, 70% of the local hospitals equipped for radiation exposure victims have been closed because they are within the 20km exclusion zone

**Effects of hydrogen explosions were not considered.** The effects of the three hydrogen explosions not only released radioactivity, but also stopped the possibilities of putting the Units 1 through 3 into cold shutdown quickly. The site area was a mess. The spent fuel pools were filled with debris. Shock waves from the explosion may have further damaged reactors and piping and further weakened structures vulnerable to aftershocks.

**The difficulty recovering from damage to many units at the same site was not considered.** Emergency recovery actions were necessary at four units at the simultaneously by stressed workers and managers who were not prepared for the workload. It seems that the common cause impact by earthquake and tsunami to all operating units was never considered. There was only one fire truck on site even though fire caused by earthquake is a dominant sequence leading towards CDF. Emergency plans did consider cross tying cooling and power systems from an undamaged reactor to a damaged reactor, but in this case it was impossible since all systems were damaged. No remote power sources were available.

**The difficulty removing heat after the loss of RCIC or HPIC.** The following is a comment from Gene Hughes, President of ETRANCO, a nuclear risk consulting firm:

> For the BWR/4 the thing that matters is getting the heat out by venting and getting water to the core sufficient to keep it covered. Now at this time there is a trick to this. We do not have RCIC or HPCI so we have some kind of emergency injection. We also may have condensate booster pumps but they are big. Now here is the trick. To vent we have to have steam going to the suppression pool which we also replenish, assuming it is intact, of course. But when we get steam to the suppression pool we have the SR valves open and should fire water be off in the injection rate we risk flooding the steam line if we overfill the vessel and starving the core if we under fill it. So far so good, just tricky. But we are not continuing to vent so where is the heat going? There is only one place without a heat exchanger. We are not venting so we are flushing. That is we keep the core cool by injecting and draining the hot water to cooler areas like the turbine building. This can occur by overfilling the vessel and draining to the suppression pool which may overfill and spill through open valves or lines to the basement and crap up everything. If the steam lines are open or the feedwater lines we cause large problems in the turbine building directly.

**Severe damage to the surrounding local infrastructure was not considered.** Station blackout times were considerably longer than planned for by the loss of the entire local power grid. Emergency supplies and personnel could not arrive in a timely manner due to severe damage to roads. Ambulances and fire trucks were not available, if they had been necessary. Dosimeters were not available for all personnel. The well-being of the families of plant workers could not be confirmed. The only communication link available with TEPCO headquarters was satellite telephony. While good civil emergency procedures were in place for a radiation accident, none considered simultaneous destruction of infrastructure by earthquake and tsunami, even though the dominant accident scenario for release is an earthquake and the dominant cause of tsunami is an earthquake.

**Uncertainty was not considered.** Time and time again in this report the author has pointed out the difficulty that TEPCO, the regulators, the government, and Japanese people have in expecting the unexpected. Nothing exemplifies this more than the TEPCO recovery roadmap, first proposed on April 17$^{th}$. The roadmap is written as a flowchart, with no consideration for encountering difficulties or unanticipated damages. Despite substantive changes to the plan, TEPCO is still claiming they will meet their goal of achieving cold shutdown within 7 months; no consideration is being given to make a decision-tree type of the plan or to try to anticipate coming difficulties and alternative countermeasures. The roadmap was created using data available from water gauges and other data gathering instruments with no consideration that they may have been damaged by the earthquake, tsunami, or hydrogen explosion.

**Seismic, Seismic, Seismic**. In a meeting in April, 2009, with a top official from the Atomic Energy Commission of Japan, we asked what the most important risk problem was for Japanese NPPs. He said, "There are three problems: (1) Seismic, (2) Seismic, and (3) Seismic. Now we can add tsunami.