A PRA Practioner Looks at the Fukushima Daiichi Accident.

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What went wrong?
How likely was it?
What were the consequences?

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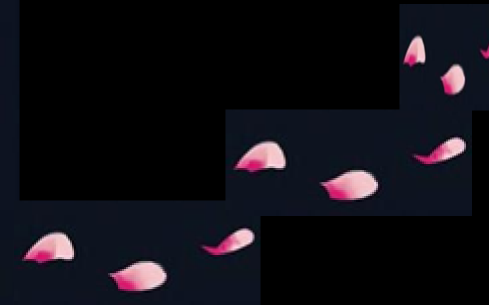
Lloyd's Register | 東京工業大学 Tokyo Institute of Technology | SCANDPOWER Risk Management — A member of the Lloyd's Register Group



March 11, 2011

“But one could hardly imagine that such an event would recur nor the greater event would happen in the land of the living.”

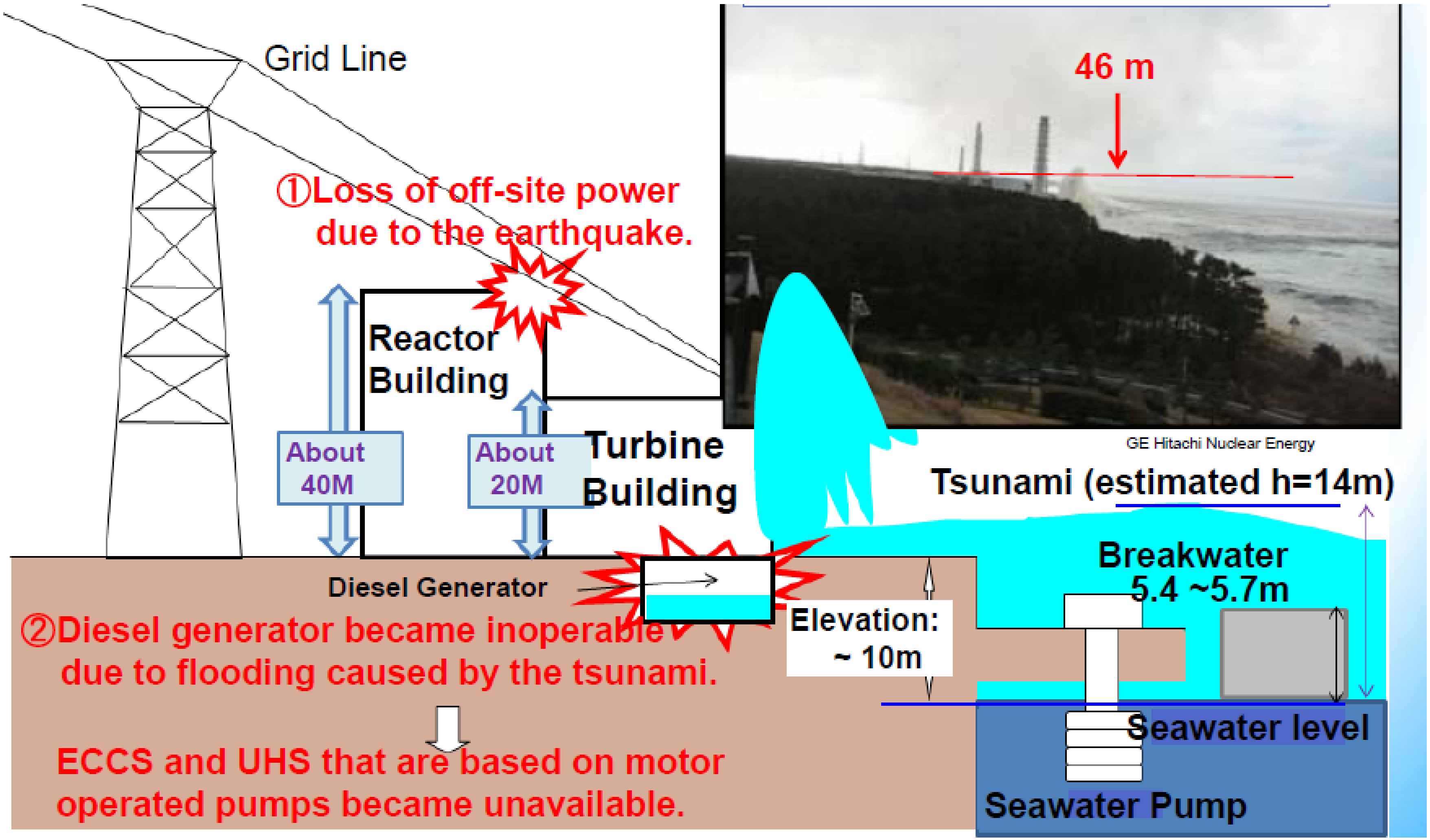
-- Yoshimitsu Okada, President, Japan National Research Institute for Earth Science and Disaster Prevention
March 25th, 2011

For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.

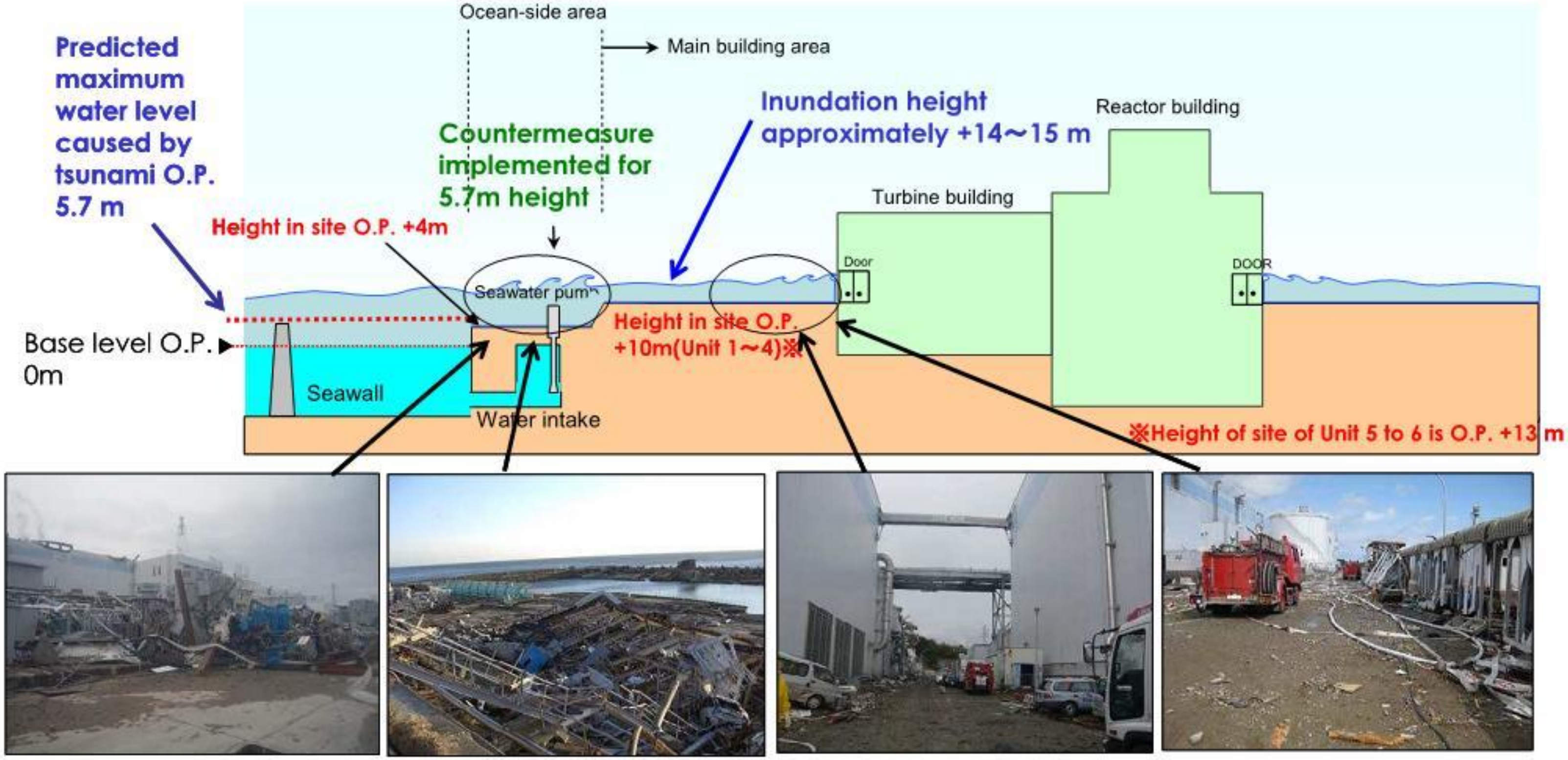
--- Richard P. Feynman, after the NASA Challenger accident, 1988

What Went Wrong?

The big wave as it hit the turbine building at Fukushima Daiichi



Thank you to Professor Kondo, JAEC, and Kunso Cho, TBS Television



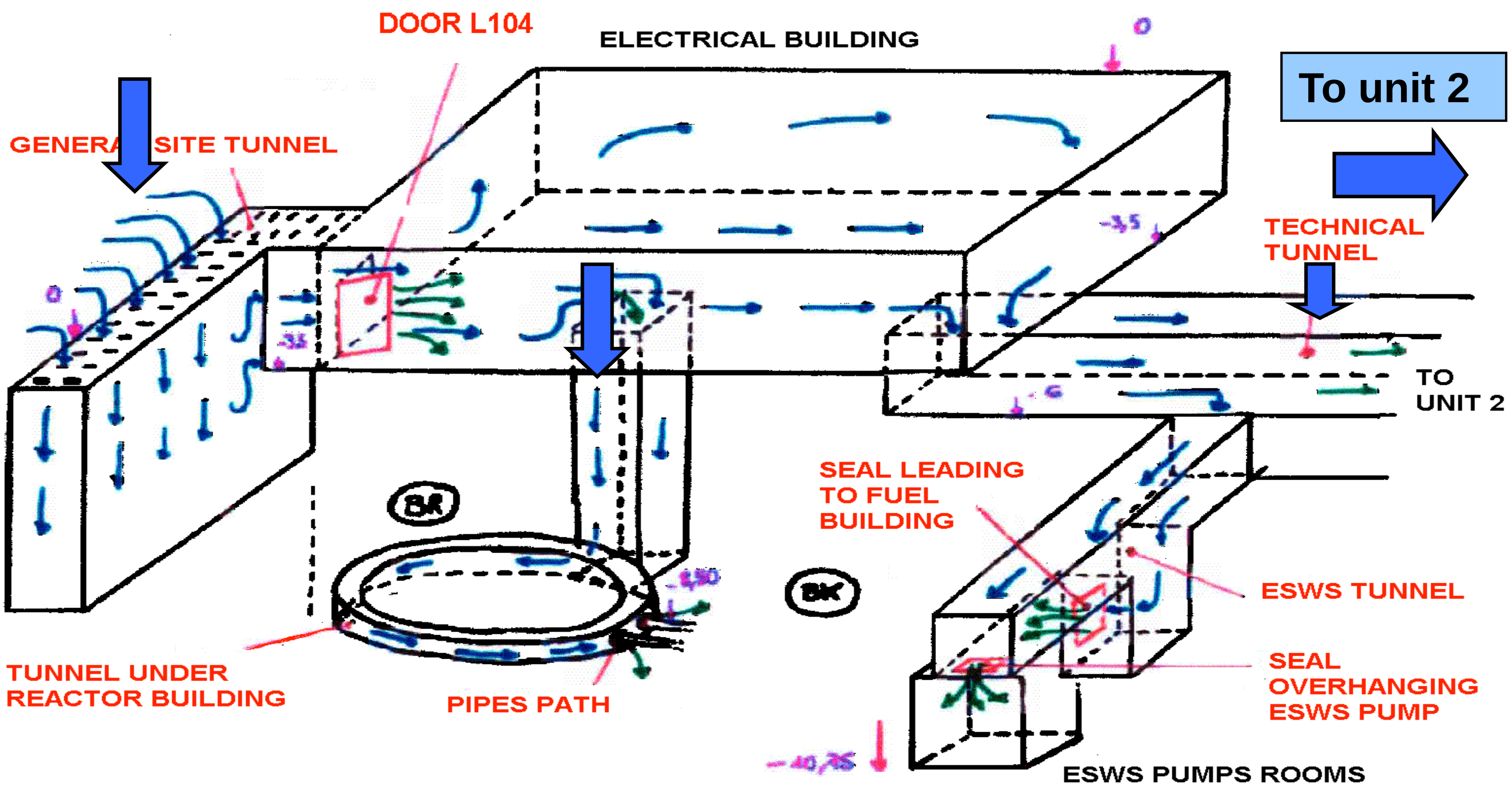
From TEPCO: “Result of the Investigation on Tsunami at Fukushima Daiichi Nuclear Power Station”

Possible Flooding Paths

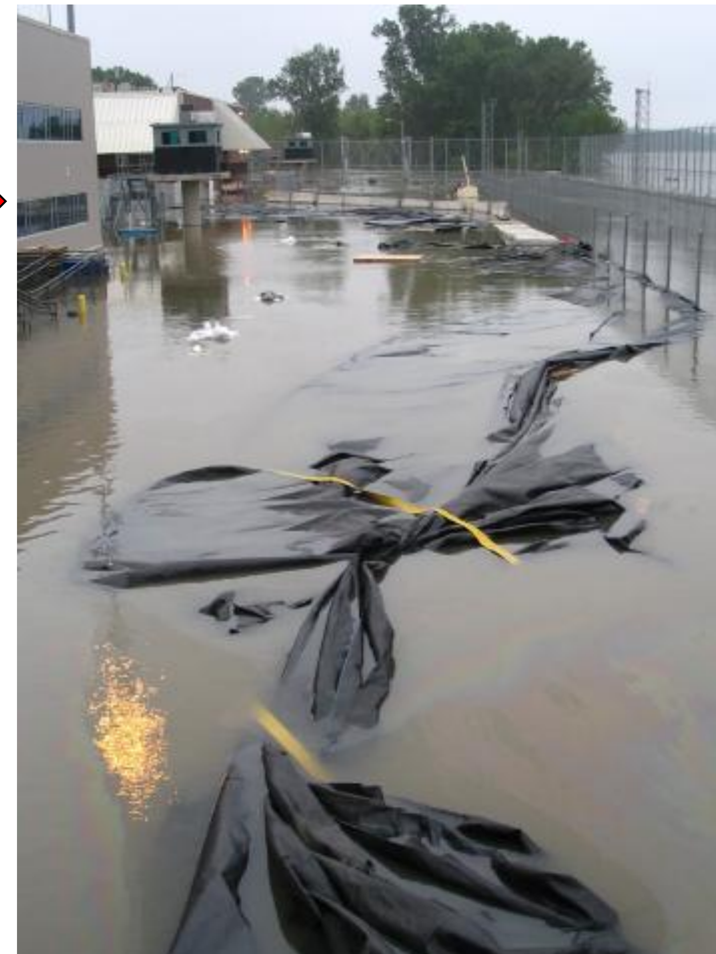
1. DG Louvres
2. Doors
3. Hatch
4. Trenches
5. Ducts

le Blayais Flooding in 1999

1. The fire doors burst open;
2. Water entered through the pipes and penetrated the fuel building basement;
3. Rooms flooded into the pumping station building;
4. Galleries flooded.



Defense in depth must move from strong to stronger.



- On June 25, 2011, the river level at Fort Calhoun peaked at 1006 feet and 10 inches;
- On June 26, 2011, a small front-end loader ran into the aquadam puncturing it;
- Failure threatened the normal transformers and caused plant operators to disconnect from offsite power.~

Two Points to consider:

Fukushima Daiichi design, siting, and construction decisions which left it vulnerable to tsunami.

- the placement of the turbine building;
- the height of the tsunami wall;
- the site was originally 35m above sea level, but was brought down to 10m for construction ease and for bedrock foundations;

No defense in depth systems existed.

How Likely Was It?

Were the earthquake and tsunami truly unforeseeable events?

Japan Meteorological Agency, January 2011
Earthquake predictions within 30 years

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

Dr. Robert Geller of Tokyo University in Nature, Vol. 472, pg. 408, 13 April 2011

- 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.
- It is time to tell the public frankly that earthquakes cannot be predicted, to scrap the Tokai prediction system. **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.

Was there a tsunami PRA? How were the design heights determined?

"Tsunami Assessment Method for Nuclear Power Plants in Japan (2002) "

published by

Tsunami Evaluation Subcommittee,
Nuclear Civil Engineering Committee,
JSCE (Japan Society of Civil Engineers)

English version
http://www.jsce.or.jp/committee/ceofnp/Tsunami/eng/tsunami_eng.html

TEPCO, from a 2008 presentation about Fukushima Daiichi tsunami defenses :

Summary

- ✓ We assessed and confirmed the safety of the nuclear power plants based on the JSCE method which was published in 2002.
- ✓ On Feb. 28, in response to the “Tsunami warning” issued by the Japan Meteorological Agency, appropriate measures in accordance with "Accident Operating Procedures (AOP) " were executed.
- ✓ Daily operations were NOT impacted.

東京電力

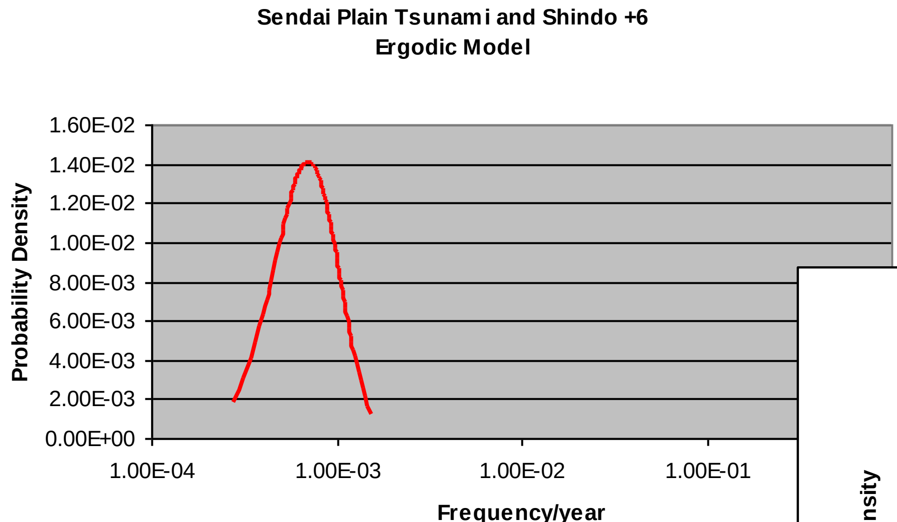
The tsunami wall, built in 1966 with a height of 5.7m, was high enough to conform to the JSCE guidelines published in 2002.

To complement the JSCE methods, I made a simple Bayesian Study of the historical data.

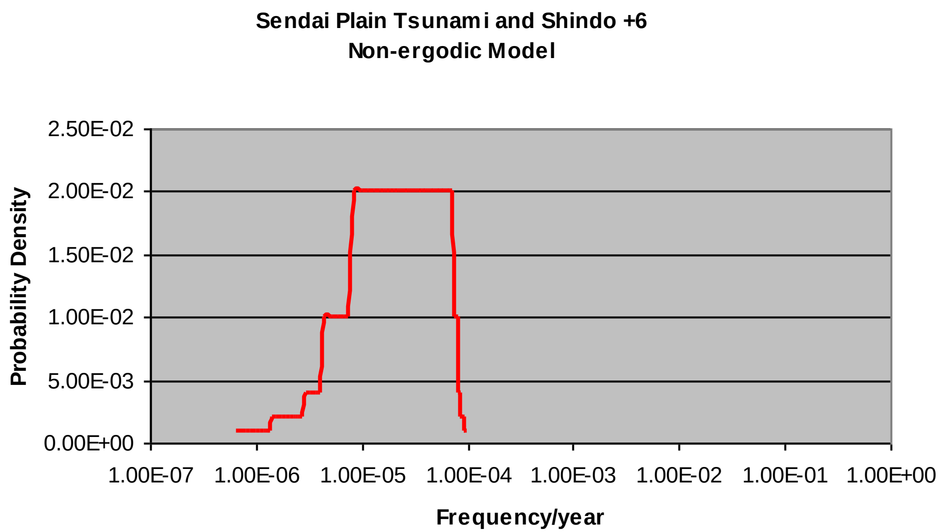
- Bayesian analyses reflect assumptions and states of knowledge derived from **historical events**;
- JSCE values reflect assumptions and states of knowledge derived from **numerical simulation and tsunami modeling methods**;
- We should use both methods as **points of light from under the veil of uncertainty**;
- **All information needs to be considered when making judgments under uncertainty;**

Bayesian Analyses of Tsunami >=8m, Earthquake > Shindo 6

We need to consider the dual event of large earthquake AND tsunami to account for the destruction of the local infrastructure.



Name	Value/Year	Recurrence/yr	% Recurrence/30 y
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		



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		

The analysis bounds show that the mean value of such an event is between 3.92e-5/yr. and 8.14e-4/yr.

The Big Lesson Learned:

all values per year

1.0e-5 (LERF) < 3.92e-5 < 1.0e-4 (CDF) < 8.14e-4

The lower and higher mean values of the Bayesian analyses show that accident scenarios initiated by a tsunami > 8m and an earthquake > Shindo 6 may be equal to, or greater than, regulatory limits for CDF and LERF… especially when some support and backup systems are guaranteed to fail after such events.

What were the Consequences?

Physician, Heal Thyself: The Inadequacy of PRA Considerations, things we have left out:

- **Tsunami initiating events**;
- Multi unit impacts (common cause?);
- The double initiator: earthquake and tsunami;
- Partial core exposure or hydrogen explosions;
- Spent fuel pools/storage;
- Ground separation or subsidence by earthquakes;
- Accidents with durations greater than 24 hours or procedures for events lasting longer than 24 hours;
- Severe aftershocks and their impact on weakened facilities or equipment;
- Extended fuel storage or fires impacting the storage;
- **Accident management and emergency recovery human factors.**

Unconsidered (But Likely) Impediments to Recovery at Daiichi

- **Radioactive releases hampering activities;**
- Effects of hydrogen explosions;
- The difficulty recovering from simultaneous damage to multi-unit sites;
- **Severe damage to the surrounding local infrastructure;**
- Uncertainty in the recovery roadmap.

Consequences to People, Plant & Performance

- **We had multi-unit, continual high radiation;**
- We have contaminated water and sludge to dispose of from the emergency cooling measures;
- The infrastructure and management are still unprepared for accidents during recovery;
- There is no defense in depth for the economy of Japan;
- There is increased seismic vulnerability of recovery equipment and structures;
- **There are +100,000 people evacuated from radiation zones when the surrounding area is overloaded with tsunami evacuees;**
- There are no level 2 or level 3 analyses available on site;
- Sub-contractors and TEPCO staff are stressed, underfed, overworked, sleep deprived doing dangerous work;
- We have inadequate risk communication to the public and other countries;
- **This accident has caused fear and mistrust in Japanese society and the world community, and continues daily.**

Expect the Unexpected

Tsunami Lessons

- Marine geologists had not considered phenomena which made the tsunami large:
  1. The angle of subduction was steep;
  2. the fault rupture length was 500km;
  3. shoreline amplification by resonance phenomenon;
  4. the earthquake caused an undersea landslide.

- The turbine building was extremely vulnerable because of its location between the reactor and the sea.

- Prepare for tsunami run-up heights which historically can happen within a large costal area of the plant;

Defense in depth: the Castle Defense:
each ring of a defense in depth system, must be stronger than the one before.

Station Blackout (SBO) and PRA

- Earthquake and flooding scenarios are the largest contributors to SBO;

- SBO should be a design basis event;

- SBO should be an initiating event with mitigation event trees.

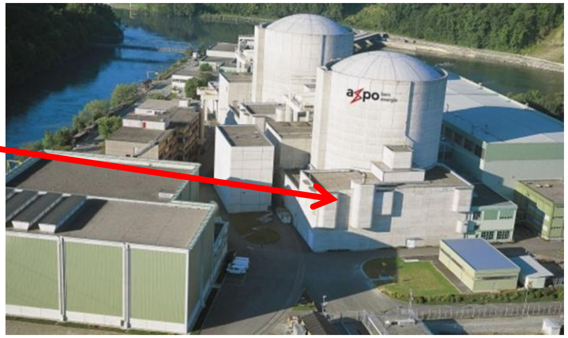
Specialists trained in accident management

From Electricité de France:

- Nuclear rapid response force (FARN)
- a national response system
  - specialist crews and equipment
  - take over site affected by an accident
  - deploy resources in less than 24 hours.
- fully operational by the end of 2014

Defense in Depth

Beznau NPP Notstand Building



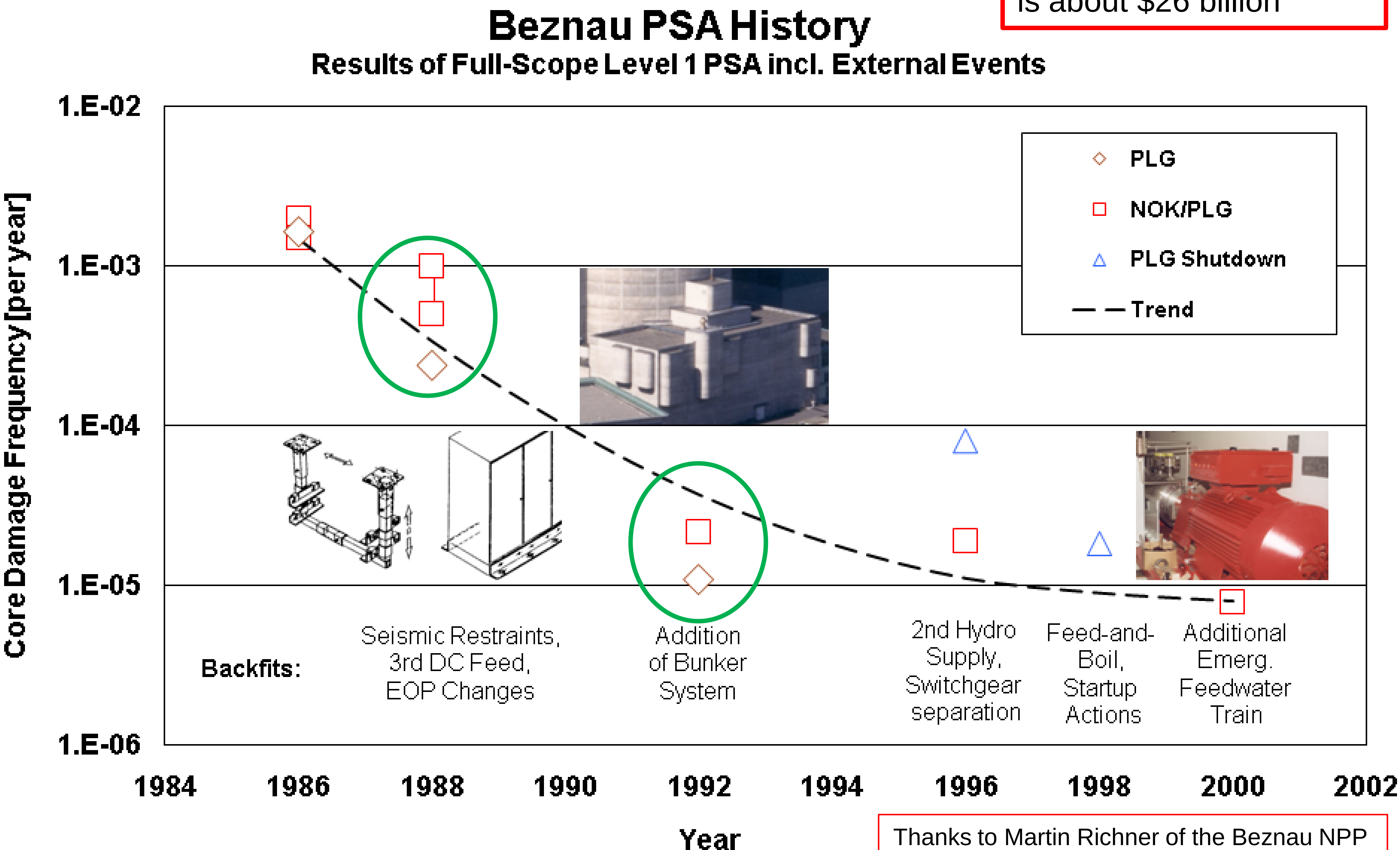
a bunkered (1 m of concrete wall and waterproof doors) safety facility that provides the following major features:

- an independent Notstand feedwater 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, etc.). The Notstand systems of Unit 2 went into operation in 1992, those of Unit 1 in 1993.

Thanks to Martin Richner of the Beznau NPP

A reduction in CDF of almost 2-orders of magnitude.

The cost of a bunkered building is about $500 million; the cost to TEPCO for the accident is about $26 billion



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Nuclear Power PRA

- **PRA has difficulties with rare events (very large models, calculation cutoffs, screening-out);**
- **PRA models must present uncertainty (the "P" in PRA) to decision makers;**
- **PRA must be used as a "living tool" not only for showing regulators that safety goals have been attained;**
- **PRA professionals must be willing to ask and to begin to answer the difficult questions to themselves, the regulators, and the public.**

Nuclear Power Core Damage Goals
(CDF <= 1.0e-4 events per reactor-year)

- Worldwide, there have been 593 nuclear power reactors that have operated approximately 14,400 reactor-years;
- the historical frequency of core damage in commercial reactors is 23/14,400 = **1.60e-3/yr. > 1.0e-4**;
- excluding the nine least severe fuel damage events, the CDF is 14/14,400 = **9.72e-4/yr. > 1.0e-4.**

1. Experimental Breeder Reactor-I (EBR-I)
2. Sodium Reactor Experiment (SRE)
3. Stationary Low-Power Reactor No. 1 (SL-1)
4. Enrico Fermi Reactor-1
5. Ågesta
6. Chapelcross-2
7. St. Laurent A-1
8. Lucens Experimental Power Reactor
9. St. Laurent A-2
10. Dresden-3
11. Three Mile Island-2
12. Hatch-1
13. Surry-1
14. Arkansas Nuclear One-1
15. Oyster Creek (two core damage events)
16. Atucha-1
17. Chernobyl-4
18. Limerick-1
19. Pickering A-1
20. Hadden Neck (Connecticut Yankee)
21. Greifswald-5
22. Fukushima Daiichi-1
23. Fukushima Daiichi-2
24. Fukushima Daiichi-3

Nuclear Power Safety Goals

- Immediate deaths and latent cancer risk are only one measure of safety goals.
- Regulatory values for CDF and LERF are another measure of safety goals.
- **But they are not enough.**
- We must review our risk models and safety goals.
- We must include evacuations, decontamination, and damage to local infrastructure.
- We must consider the health and societal effects of displacing people and their families from homes, schools, livelihoods, and their land.
- **Most importantly, risk communication: risk is perception, risk is a feeling, and risk communication means listening to the people.**

For more information:

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“Such an event is probable because many things should happen contrary to probability.”

-- Agathon as quoted in Aristotle’s Poetics