



Rijksinstituut voor Volksgezondheid
en Milieu

*Ministerie van Volksgezondheid,
Welzijn en Sport*

Unit 4 reactor building after the hydrogen explosion



Fukushima Daiichi nuclear accident: spotlight on Unit 4

Cristina P. Tanzi

den Haag

8 november 2019



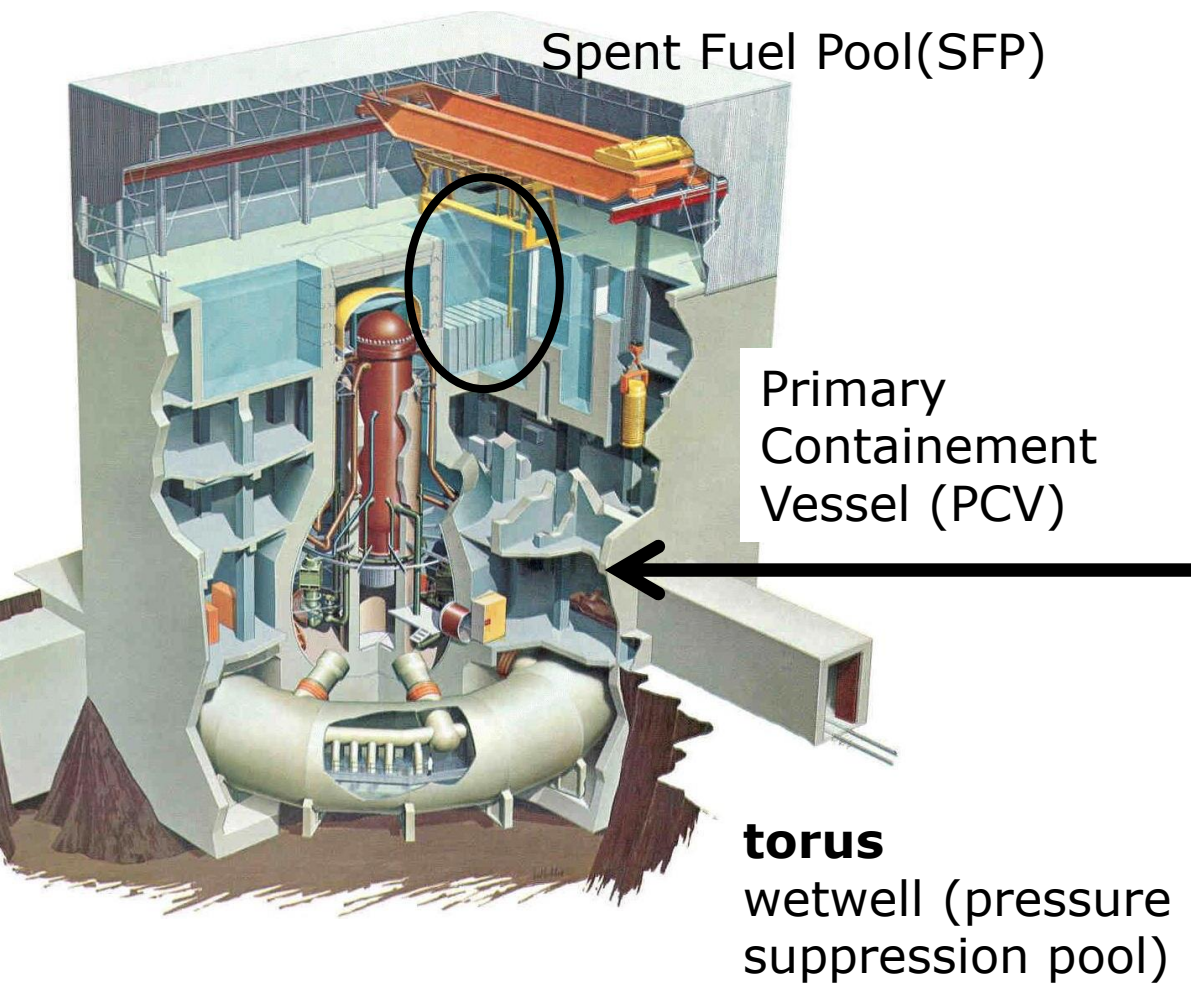
Summary before the accident

| | UNIT 1 | UNIT 2 | UNIT 3 | UNIT 4 |
|--------------------------|--------|--------|--------|----------------|
| in operation | ✓ | ✓ | ✓ | NO (-102 days) |
| SFP (MW) heat content | < 0.2 | < 1 | < 1 | 2.3 |

Summary AFTER the accident

| | UNIT 1 | UNIT 2 | UNIT 3 | UNIT 4 |
|--------------------------------------------|--------|--------|--------|--------|
| core melt | ✓ | ✓ | ✓ | NO |
| Reactor Building visibly damaged | ✓ | NO | ✓ | ✓ |
| largest release radioactivity to air | | ✓ | | |

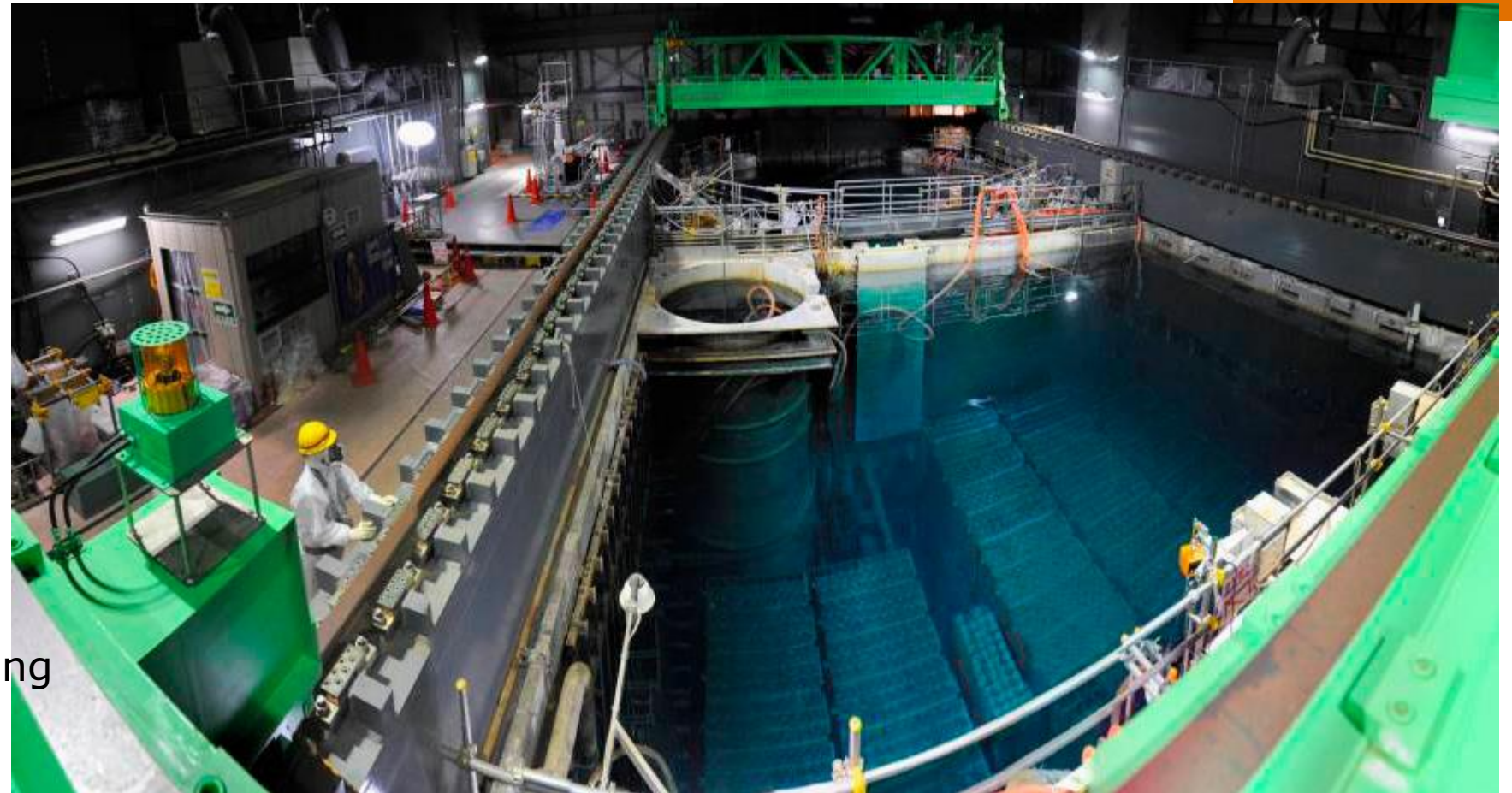
Fukushima 1 (Daiichi) – Boiling Water Reactor – GE BWR3/4 design ('60s)
in USA: 23 such reactors (retrofitted, unlike the ones in Japan)



Unit 4 refueling deck on November 7, 2013

- SFP in foreground: fuel racks visible at bottom

fuel handling machine



- reactor well (background) separated by the steel gate far wall
- green apparatus above reactor well lifts gates



Overview of Unit 4 events

1. Operational status at 11 March 2011 (earthquake and tsunami)

2. Major event at tsunami impact
loss of cooling function

3. Major unexpected event on March 15:
explosion in Unit 4 reactor building
06:14 JST on March 15, 2011



1. Operational status at 11 March 2011

- 102 days shutdown
- RPV empty
- all 548 core fuel assemblies in Spent Fuel Pool (SFP)
(+ 783 + 202 new = 1535 total)
- 95% occupancy
- decay heat 2,3 MW

Earthquake 14:46 11-3-2011 ($M_w=9$)

Ground acceleration at RB base: about 0.5 g

Water loss estimate due to sloshing of the pool on 4th floor:
0.5 m of about 7 m above top of fuel assemblies

Two Fukushima Daiichi workers drowned by tsunami had been ordered to inspect basement

The Mainichi Daily News reports that two Fukushima Daiichi nuclear power plant workers, whose drowned bodies were discovered on March 30th, nearly three weeks after the earthquake-triggered tsunami inundated the northeastern Japan atomic site, had been ordered by a Tokyo Electric Power Company (Tepco) supervisor down to the turbine building basement of Unit 4 to check for leaks from pipes, despite warnings that large tsunamis were inbound.

 August 2, 2011 |  [Print Article](#) |  [Share Article](#) |  [Email Article](#)



2. Major event at tsunami impact

- loss of SFP cooling function
- loss of measurements
 - NO water level
 - NO water temperature
 - NO radiation
 - NO cameras
- ANALYSIS: not enough decay heat for hydrogen production from Zr cladding until end of March



Hydrogen production from Zr cladding of fuel assemblies

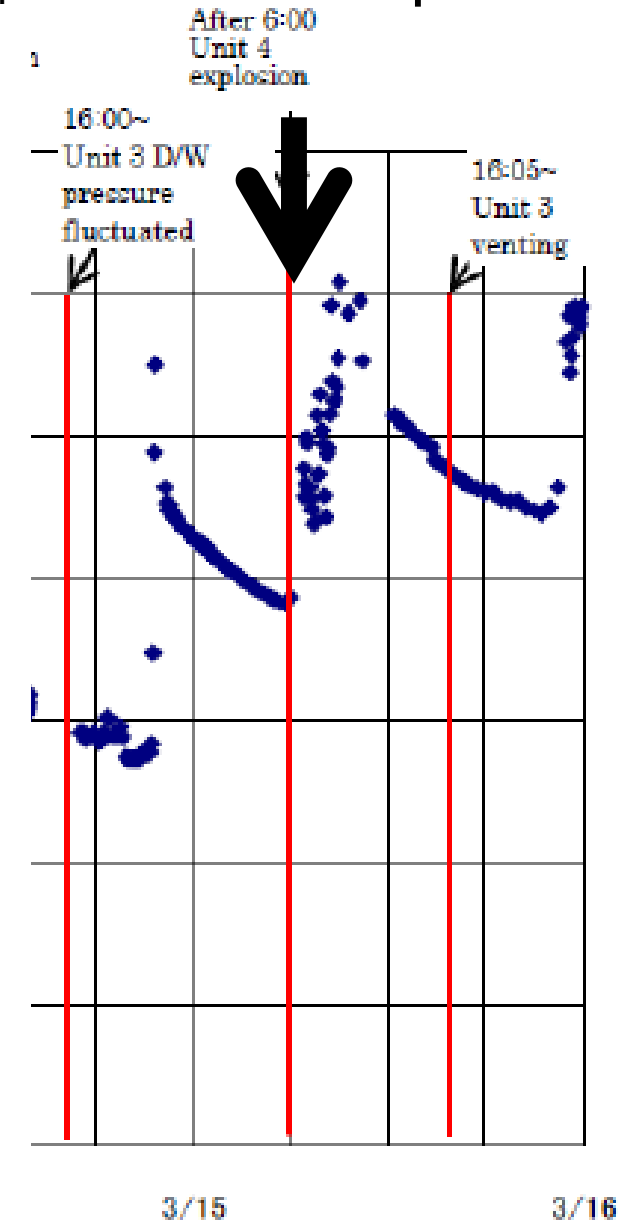
900°C - 1200°C

- $\text{Zr} + \text{O}_2 \rightarrow \text{ZrO}_2$ heat released = 1.2×10^7 J/kg
- $\text{Zr} + 2\text{H}_2\text{O}_{\text{steam}} \rightarrow \text{ZrO}_2 + 2\text{H}_2$ heat released = 5.8×10^6 J/kg

At about 1200°C the oxidation reaction will become self-sustaining:
zirconium cladding fire

Unit 4 reactor building after the hydrogen explosion of March 15 06:14

Unit 4 explosion



Dose rate in vicinity of Fukushima Daiichi NPS main gate



3. Major unexpected event on March 15

- **explosion in Unit 4 reactor building** at 06:14 JST
- destroys roof, most walls on the fourth and fifth (refueling deck) floors, damages third floor
- ALSO: an explosion noise heard at local HQ
- ALSO: white smoke/steam seen from Unit 2 at 08:25
- ALSO: radiation levels spike
(11.93 mSv/h at main gate 09:00, highest since start)
- ALSO: drop in pressure reading of Unit 2
(0! atm, possible PCV failure)



explosion of Unit 4 building observed by survey team, **reported 08:11**



?

- Statement from U.S. NRC Nuclear Regulatory Commission (Gregory Jaczko, Chairman)

“We believe at this point that Unit 4 may have lost a significant inventory, if not lost all, of its water”

evacuation 50 miles radius (Japanese authorities 20 km)

- helicopter overflight captured video of sunlight glinting off water in SFP



JAPAN MARCH 16, 2011 / 7:53 PM / 9 YEARS AGO

USNRC Chairman Gregory Jaczko provided an update at a congressional hearing

U.S. warns Japan spent fuel pool may have run dry

Tom Doggett

4 MIN READ



WASHINGTON (Reuters) - The top U.S. nuclear regulator warned on Wednesday that one pool holding spent fuel at Japan's stricken nuclear plant may have run dry and a second could be leaking, something experts say could accelerate the release of radiation.

“We believe at this point that Unit Four may have lost a significant inventory, if not lost all, of its water,” Gregory Jaczko, head of the U.S. Nuclear Regulatory Commission, told lawmakers at a House energy and commerce subcommittee hearing.

“We’ve been very careful only to provide information that we believe is very reliable,” he said.

Experts worry that this could expose the used nuclear fuel and start a fire that would release more radioactivity.

“There is no water in the spent fuel pool and we believe that radiation levels are extremely high, which could possibly impact the ability to take corrective measures,” said Jaczko, making his first appearance before Congress since the crisis began.

Jaczko also said that the 12-mile evacuation area around the Japanese reactors was smaller than the 50 miles the NRC would recommend. “For a comparable situation in the United States we would recommend an evacuation for a much larger radius than is currently being provided in Japan,” he said.

March 16th, 2011 – Unit 4 SFP walls have collapsed – Fuel may no longer be intact

From: Boska, John
To: Guzman, Richard

Sent: Wednesday, March 16, 2011 11:31 AM
Subject: Developments in Japan

In a briefing with Joe Giitter that just ended, we were informed that the situation is now much worse in Japan. **The walls of the Unit 4 spent fuel pool have collapsed, and there is no water in there. There were a large number of fuel assemblies in the pool, and the** fuel may no longer be intact. The radiation levels are increasing so much that it may prove difficult to work on the other 5 reactors at the site, which could lead to more fuel damage and releases.

The NRC plans to man the Operation Center (OC) 24/7 for a long period of time.

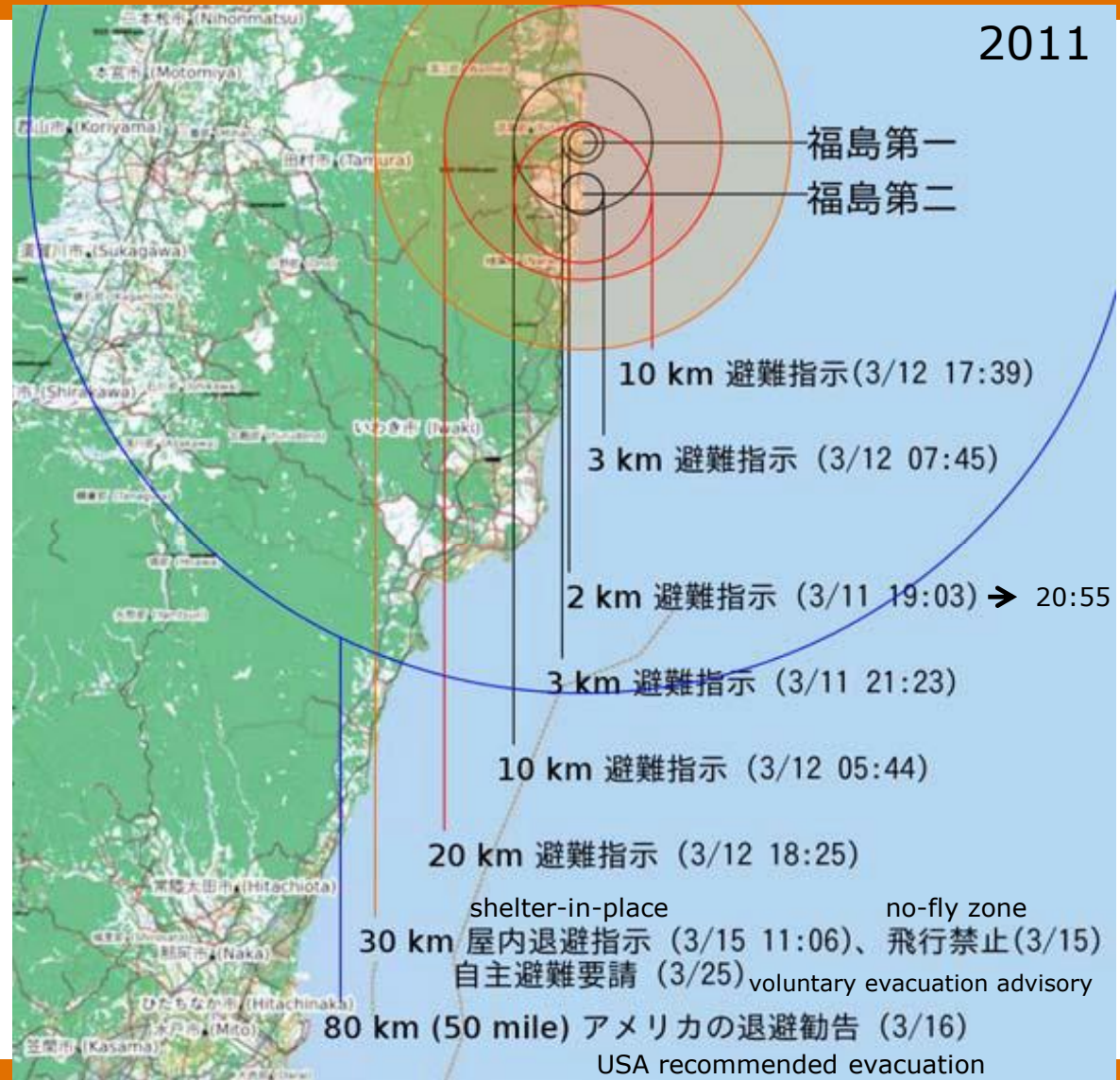
Fukushima's Spent Fuel Rods Pose Grave Danger

Even if reactor containment vessels hold, pools of spent fuel rods could combust and release clouds of radioactive cesium into the air—a calamity that could happen at US nuclear plants as well. The Nation, 15 March 2011



Evacuation order: progressive

- 2011/3/11 and 12: electricity black-out in evacuated areas and beyond
- 20-30 km sheltering in own home
- 50 mile: USA distance for evacuation
- Iodine prophylaxis order: issued **after** evacuation order







nuclear-
powered
supercarrier



Nimitz class



The Japanese government issued a measured public response to the U.S. government announcements about conditions in the Unit 4 SFP:

“Because we have been unable to go the scene, we cannot confirm whether there is water left or not in the spent fuel pool at Reactor No. 4.”
(Yoshitaka Nagayama, NISA)

“We can’t get inside to check, but we’ve been carefully watching the building’s environs, and there has not been any particular problem.”
(Hajime Motojuku, TEPCO)

March 16: helicopter overflight captured video of sunlight glinting off water in SFP

+ 3 weeks:

instruments lowered from a boom of concrete pump truck
yield first reliable measurement of water levels



Unit 4 refueling deck
(green equipment in center image is fuel handling machine)

March 16, 2011, helicopter overflight

SOURCE: TEPCO

Fukushima 1 (Daiichi) – decay heat, hydrogen production, explosions



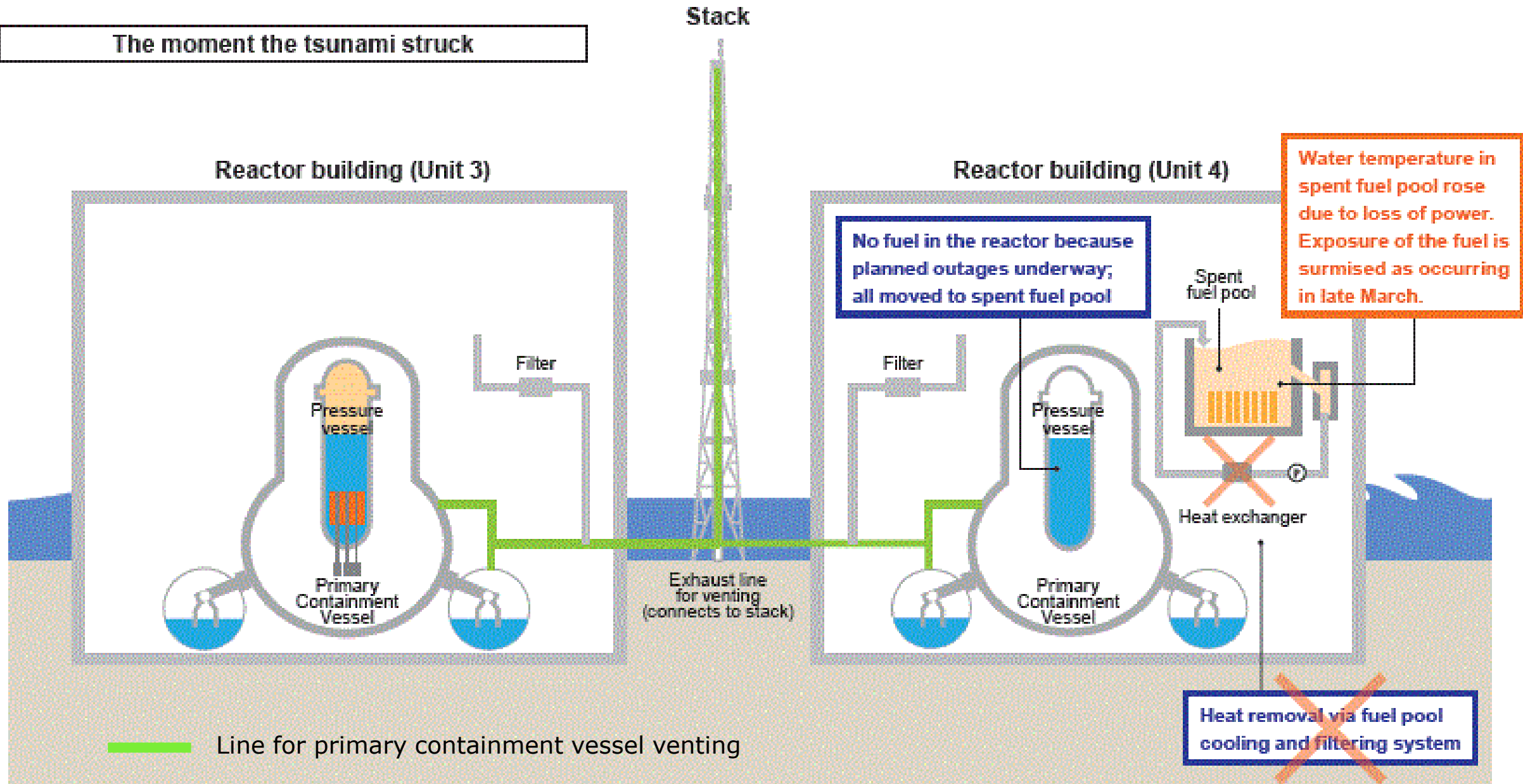
16 March 2011 - Unit 4, 3, 2, 1



?

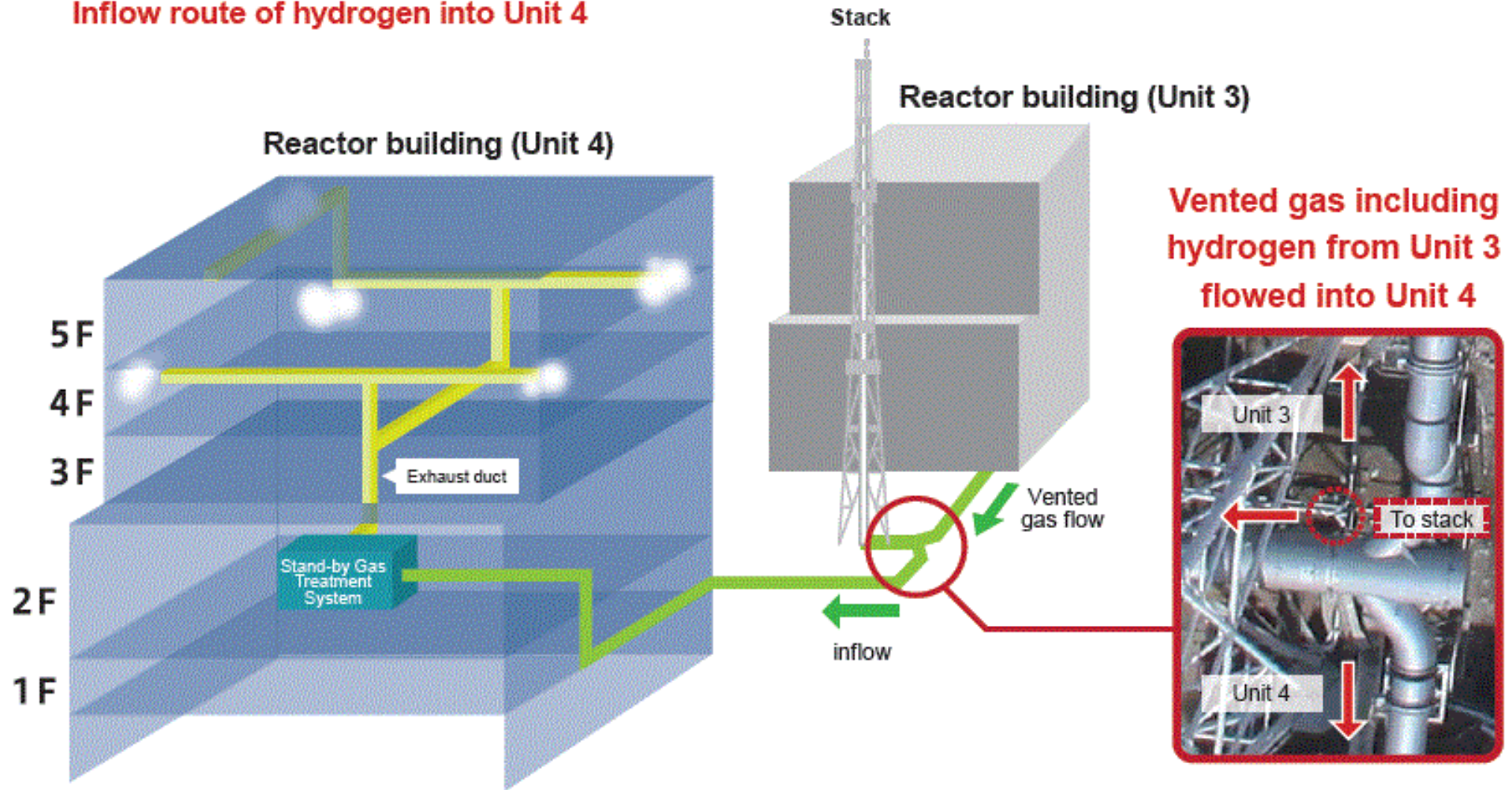
Changes at Unit 4 when the tsunami struck

The moment the tsunami struck





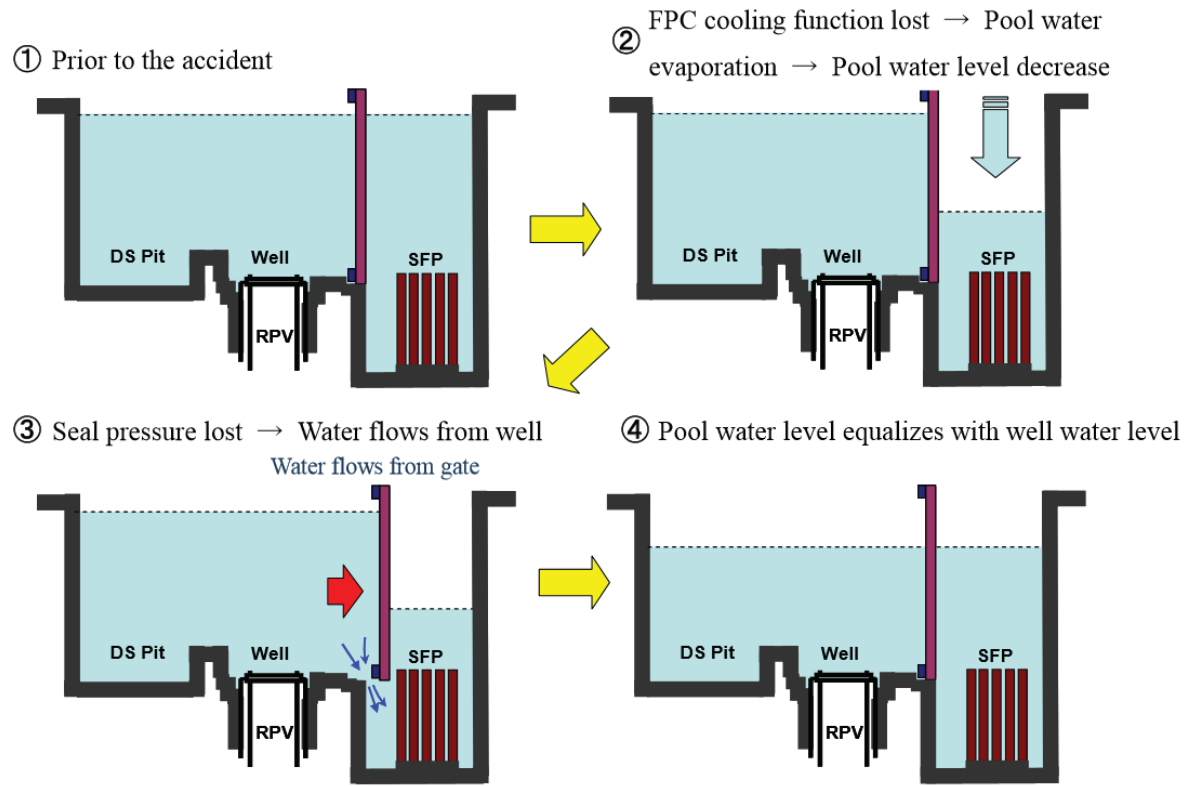
Inflow route of hydrogen into Unit 4



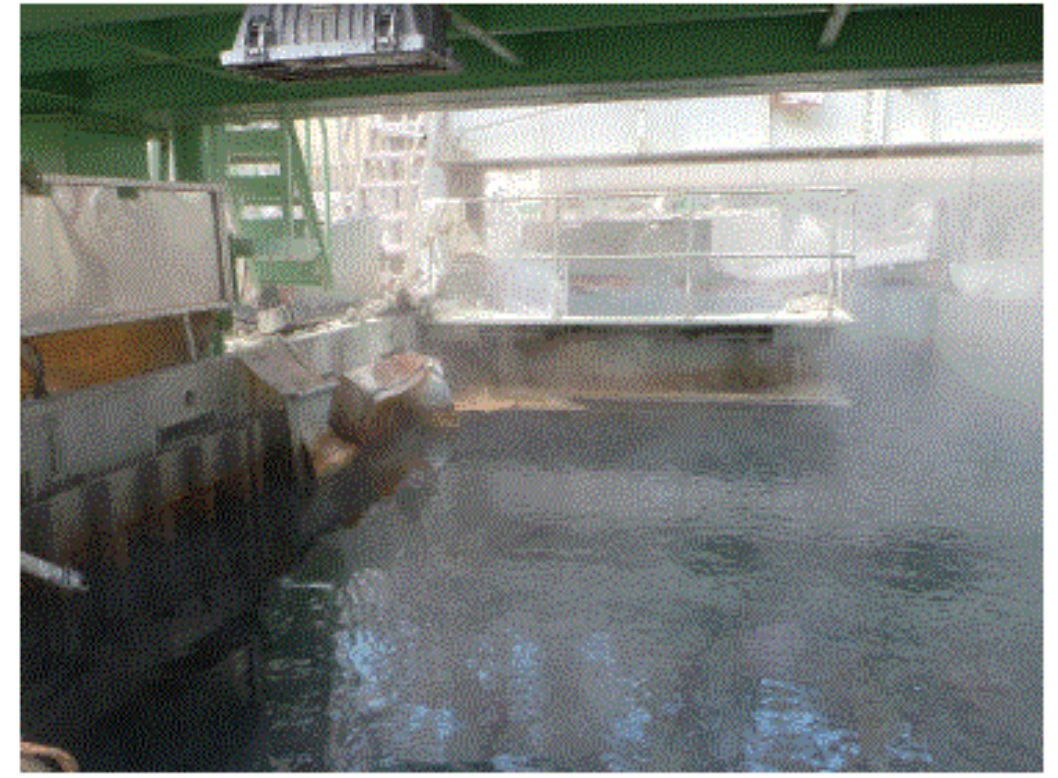


Fortunately:

- Unit 4 reactor well was flooded during maintenance
- between reactor well SFP: gate for fuel transfer
- water leaked from well to SFP partially refilling it



Conditions at the Unit 4 spent fuel pool, photographed June 29, 2011



Debris on top of fuel racks in Unit 4 pool





Cooling function stably restored on July 31

- Water dumped from helicopters (largely unsuccessful)
- March 20, water-spraying truck of Self-Defense Force sprayed freshwater;
- by March 21, ~250 tons water sprayed from the ground
- March 22, concrete pump truck with boom sprayed **seawater**
- June 16, water injection by a temporary injection facility
- July 31, SFP (78 C) water cooling by alternative cooling system started
- August 4, steady condition (water temperature stabilized at 40 C)





Recurring reports of danger from SFP Unit 4

2012, December 11 :

- magnitude 7.3 earthquake off the coast of Japan
- Murata Mitsuhei, Japan's former Ambassador to Switzerland, sent an e-mail to chief editors of newspaper and tv etc.
warning that the unit 4 fuel pool is in danger of either draining or collapsing



Epilogue

- **What must have happened**
- May 2011: TEPCO says that the explosion was due to the combustion of hydrogen that was generated in Unit 3 and flowed into Unit 4 through the ventilation system.
- WAS TOP OF FUEL EVER UNCOVERED? Unlikely; if so, no damage

- **What happened next?**
- clearing tonnes of radioactive debris from the top of building
- construction of a a cantilevered structure and airtight cover
- removal of 2 assemblies for inspection in 2012
- **Nov 2013 – Dec 2014: All assemblies removed:
(71 casks): moved to common storage pool (202 unirradiated to SFP Unit 6)**



~~2. Major event at tsunami impact~~

Lessons learned

Resilience and restoration

- ~~loss~~ of SFP cooling function
- ~~loss~~ of measurements
 - ~~NO~~ water level
 - ~~NO~~ water temperature
 - ~~NO~~ radiation
 - ~~NO~~ cameras



Questions ...





Some reference material

- Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants: Phase 2 (2016)
Chapter: 2 Fukushima Daiichi Nuclear Accident: Lessons Learned for Spent Fuel Storage (National Academy of Sciences)
- The Development of and Lessons from the Fukushima Daiichi Nuclear Accident, TEPCO March 2013
- http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120620e0104.pdf
- Wang, D. et al., Study of Fukushima Dai-ichi Nuclear Power Station Unit 4 Spent Fuel Pool, Nuclear technology, Nov 2012, DOI: 10.13182/NT12-A14634
- IAEA, THE FUKUSHIMA DAIICHI ACCIDENT, TECHNICAL VOLUME 1, DESCRIPTION AND CONTEXT OF THE ACCIDENT
- MOVIE <https://www.youtube.com/watch?v=QVqfPCsl2AA> (debris top assemblies)
- MOVIE <https://www.youtube.com/watch?v=-pZVPux-bzs> (completion removal)



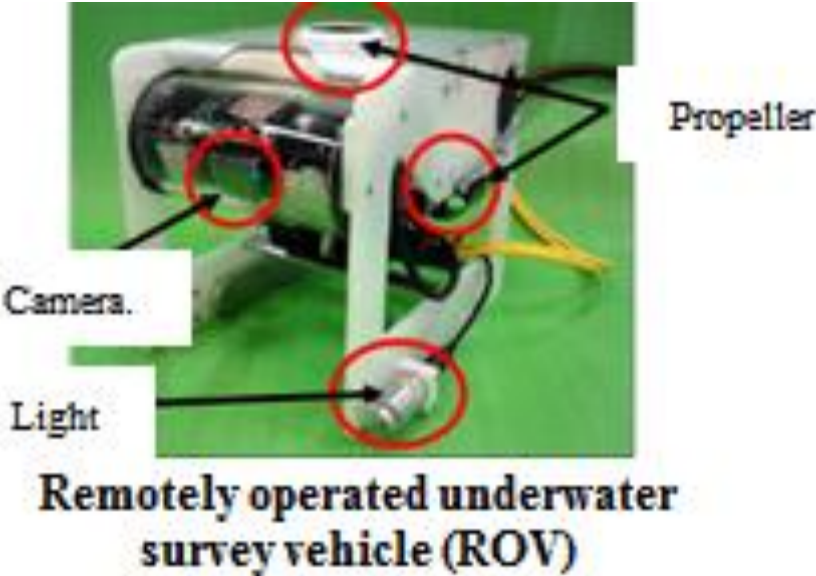
Extra slides

Unit 4 reactor building after the hydrogen explosion

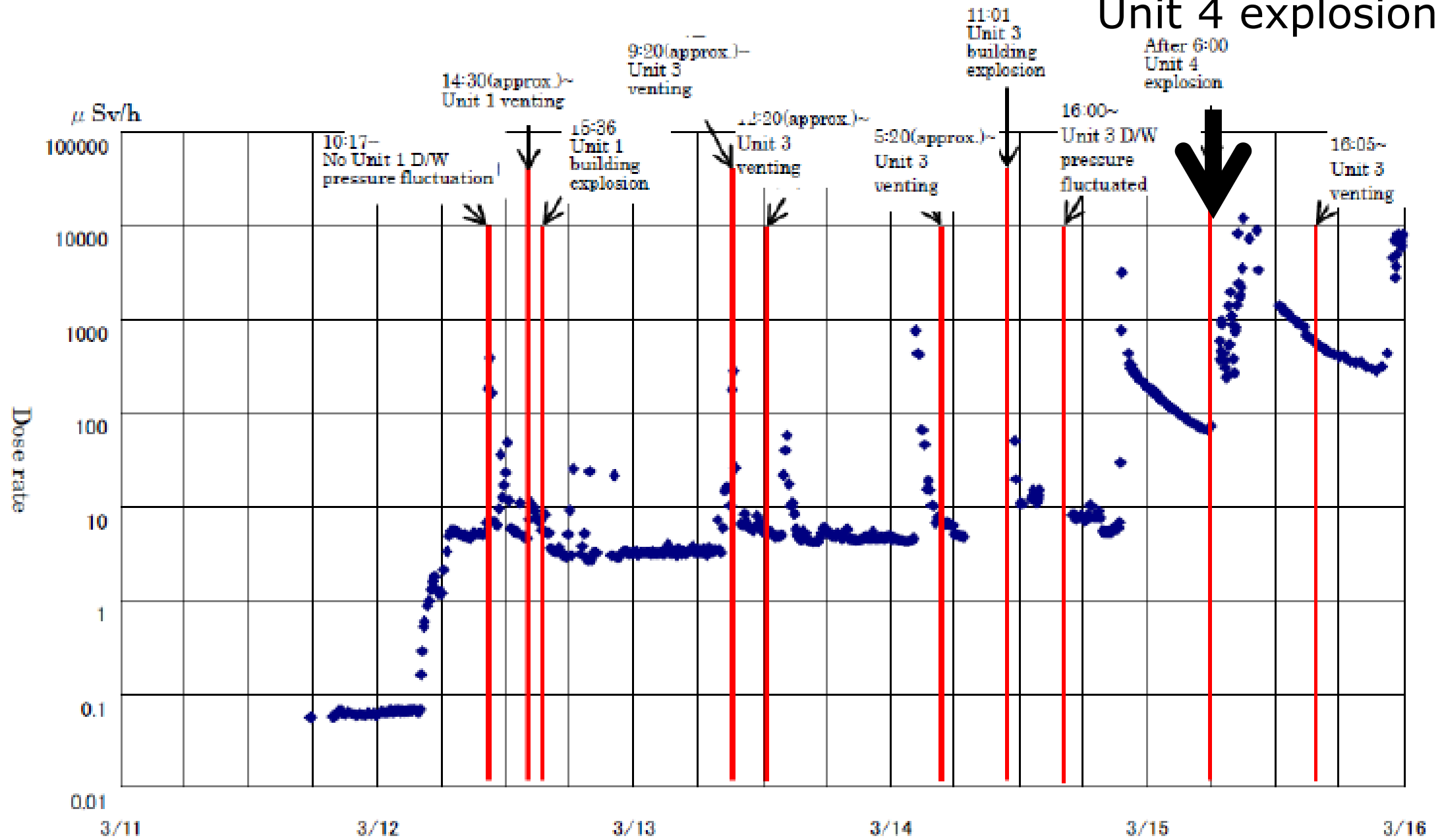




Unit 4 SFP debris dispersion survey



Unit 4 explosion



Dose rate in vicinity of Fukushima Daiichi NPS main gate



Fukushima Dai-ichi Measuring Post MP7, left-to-right, top-to-bottom:
before (3/17/2004) - after the earthquake/tsunami (4/24/2011)
temporary (8/26/2011) - newly built (7/24/2012)



Retrieval fuel assemblies from Unit 4 SPF

- **2013 November 18 started**
- **2014 December 22 completed**
- all 1,331 assemblies (spent fuel + non-irradiated)



TIME

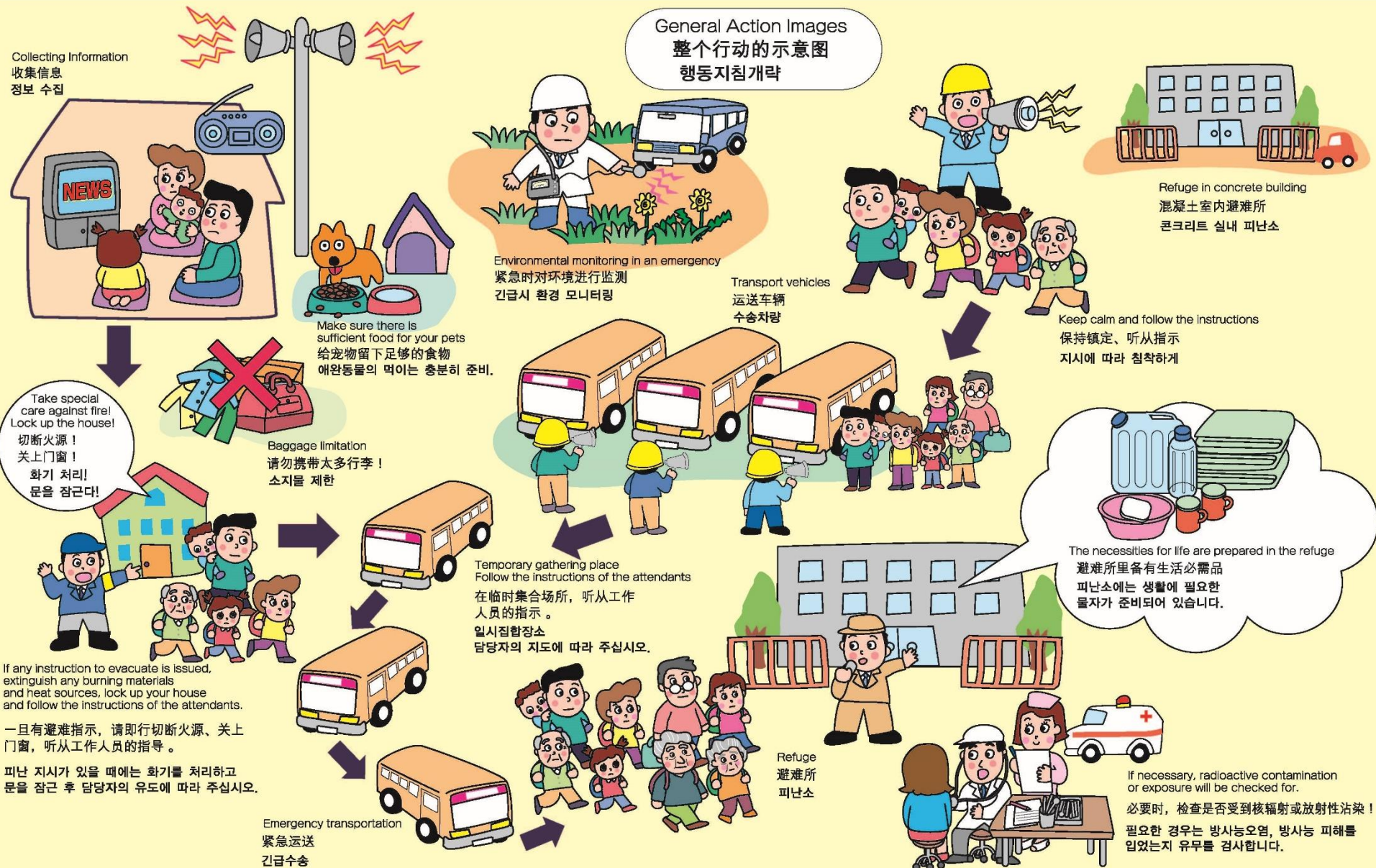
JAPAN'S NUCLEAR NIGHTMARE



Tokaimura criticality accident
1999, September 30 (Thursday)

What to do in a Nuclear Emergency

核紧急事故的应急措施 원자력 재해 발생시의 대처 방법

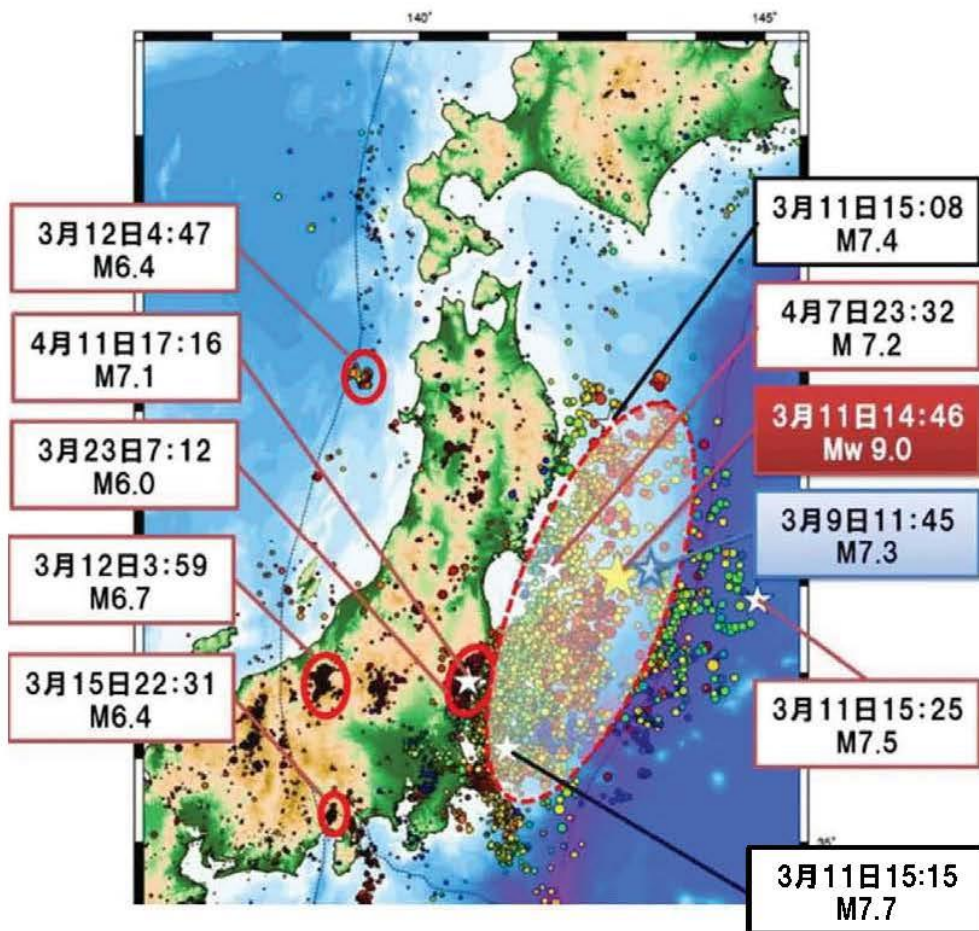


2011

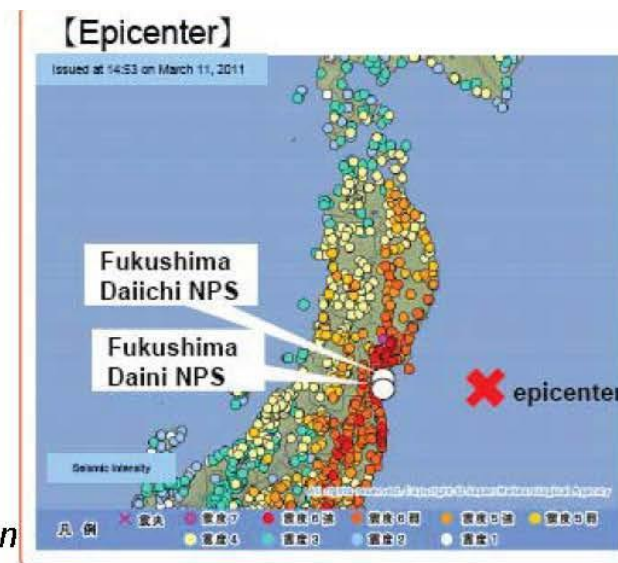
3.11 Earthquake and aftershock

3月11日

The triple disaster



- Earthquake
- Tsunami
- Nuclear
- 18,564 killed and missing



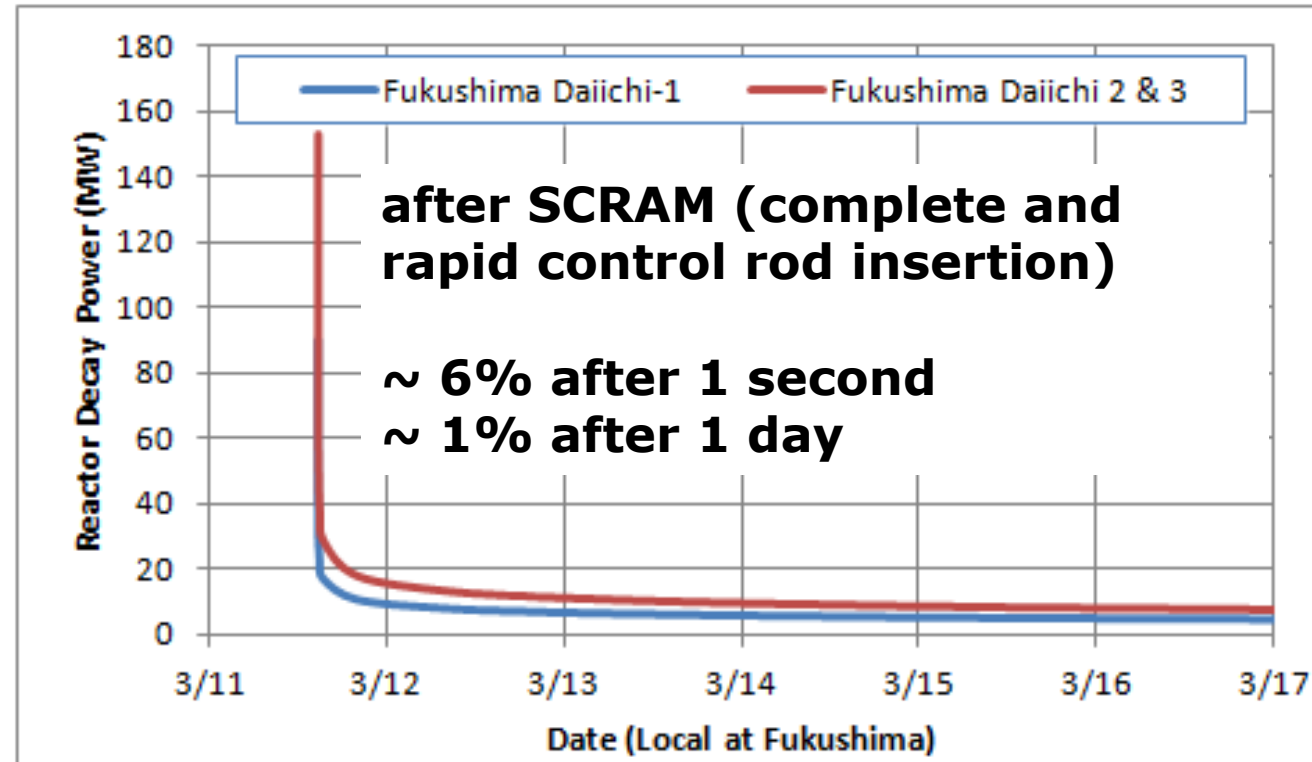
[SOURCE]

Fukushima Accident : An overview

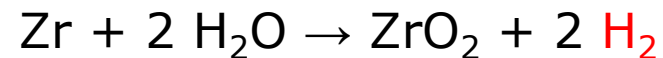
ICAPP 2011, 3 May 2011 Akira OMOTO, University of Tokyo, Japan



Fukushima 1 (Daiichi) – decay heat, hydrogen production, explosions



Zirconium cladding of the uranium fuel rods reacts with water steam at high temperatures:



Hydrogen Explosion at Unit 1

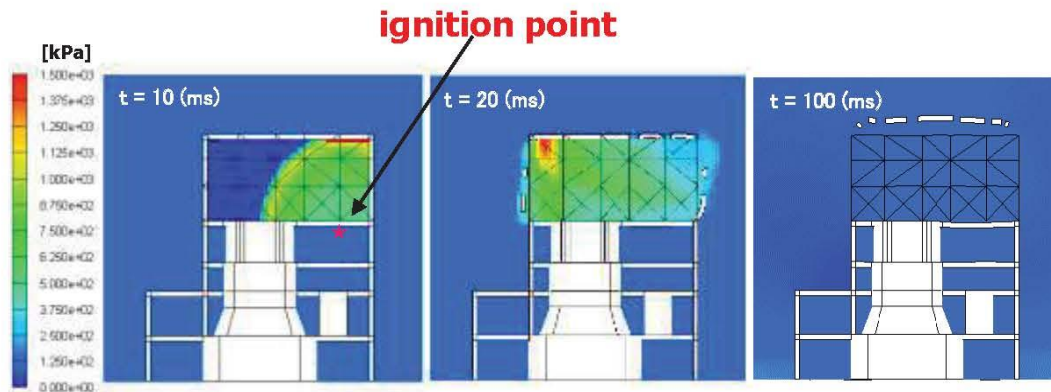
2011-03-12 15:36
Saturday

Analysis well reproduced the observed explosion:

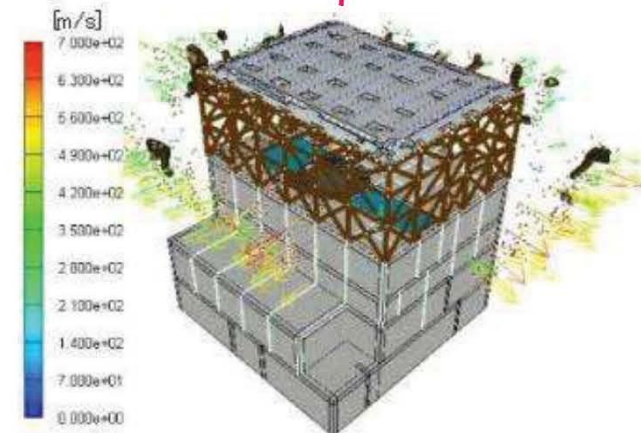
- Explosion developed horizontally.
- Walls and roofs of top floor (5F) were largely damaged and debris scattered around R/B.



Potential location of leakage: top head flange of PCV



Propagation of detonation pressure in Unit 1



Detonation analysis with AUTODYN

Hydrogen Explosion at Unit 3

2011-03-14 11:15
Monday

Web site: TEPCO

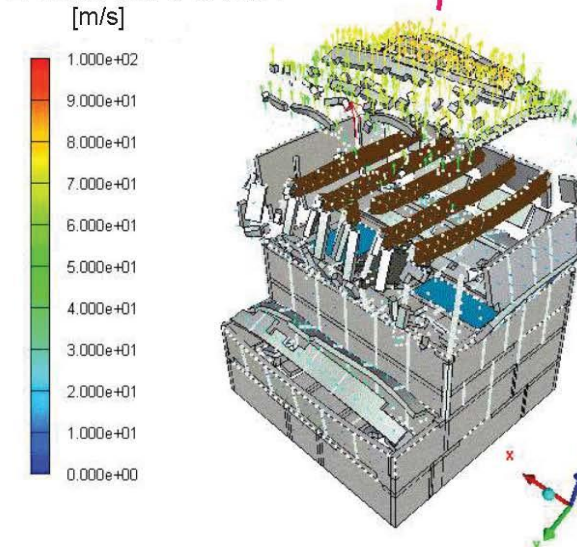
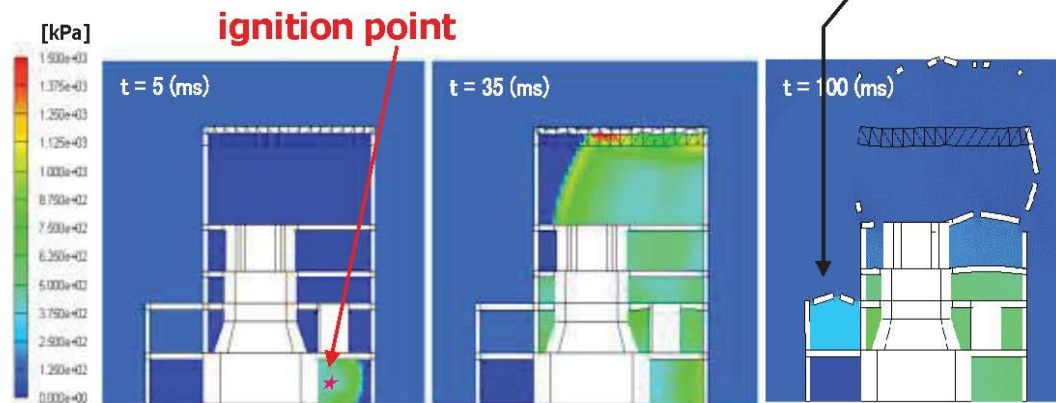
Analysis well reproduced the observed explosion:

- Explosion developed vertically.
- Walls and roofs of top floor (5F) were largely damaged.
- Adjacent low building was also damaged.
- Locally high dose rate was detected at 1st floor.



The top of a two-story building next to the R/B has also been damaged.

Potential location of leakage: device hatch



Propagation of detonation pressure in Unit 3

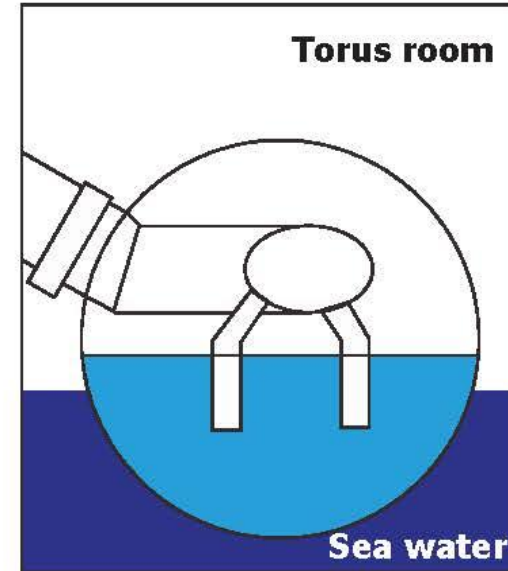
Detonation analysis with AUTODYN

3.2. Accident Progression at Unit 2

2011-03-15 06:12
Tuesday

Unit 4

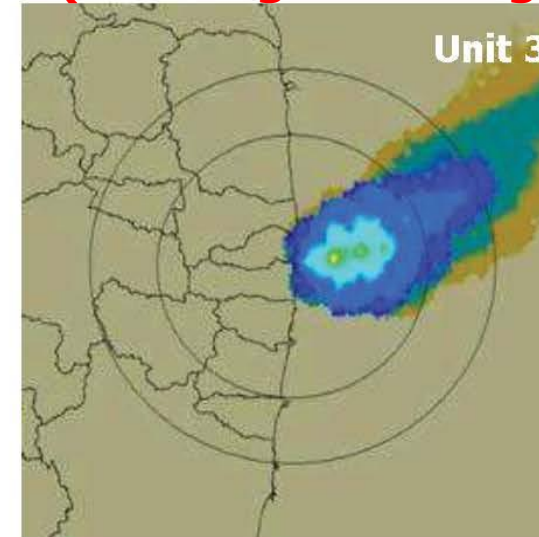
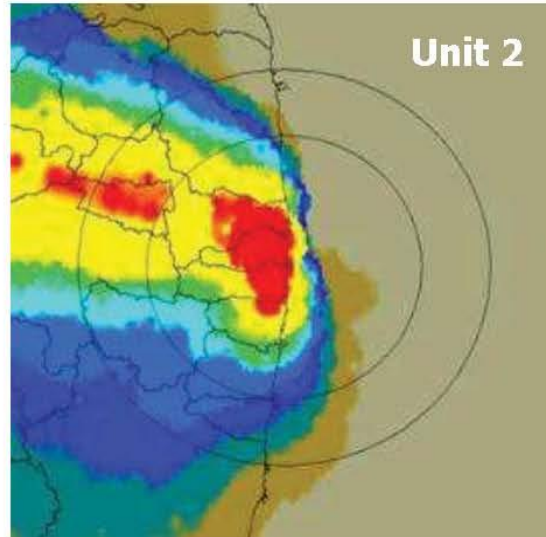
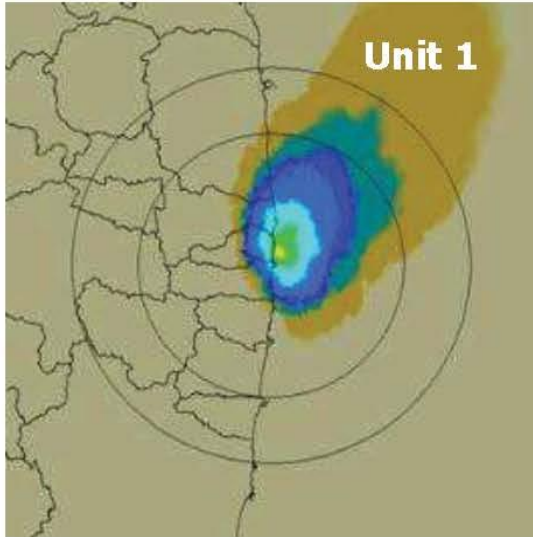
- RCIC operation without DC power.
 - Two phase fluid flew into RCIC turbine that reduced the RCIC flow rate.
- Slow pressurization rate of PCV
 - Possibility of heat removal from S/P by seawater flooded in the torus room.
- A large PCV leakage is assumed to occur in the morning on March 15
 - Based on observed D/W pressure
 - Explosion sound was not from unit 2 but from unit 4, which was confirmed through the analysis of vibration using seismometers by TEPCO*



Pressure indicator Unit 2 S/C 0MPA[abs]

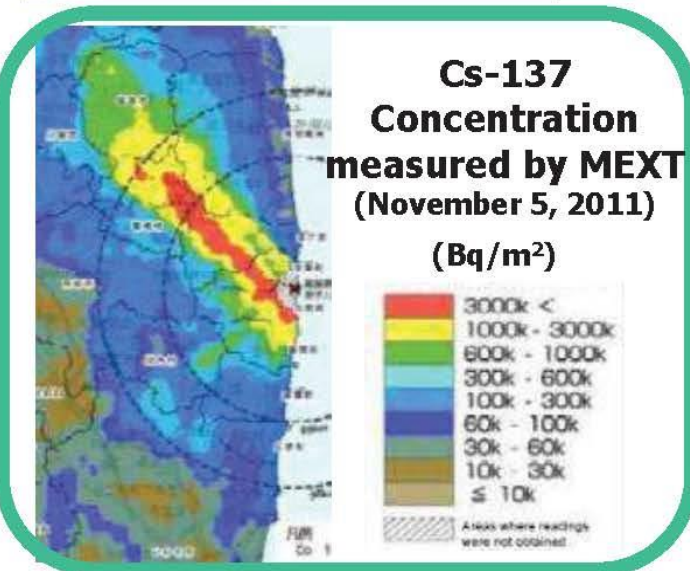
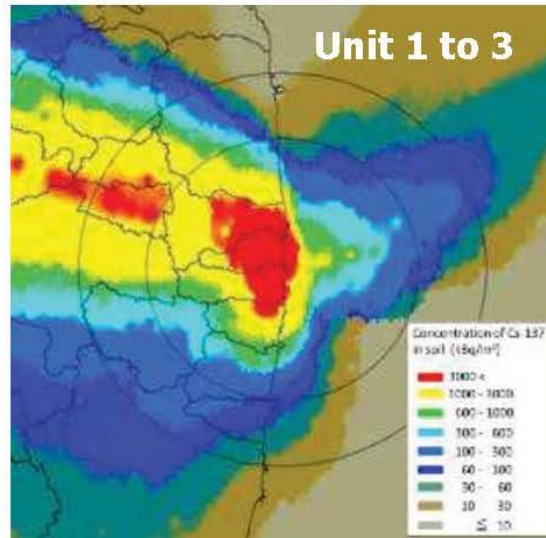
Environmental Consequence Analysis

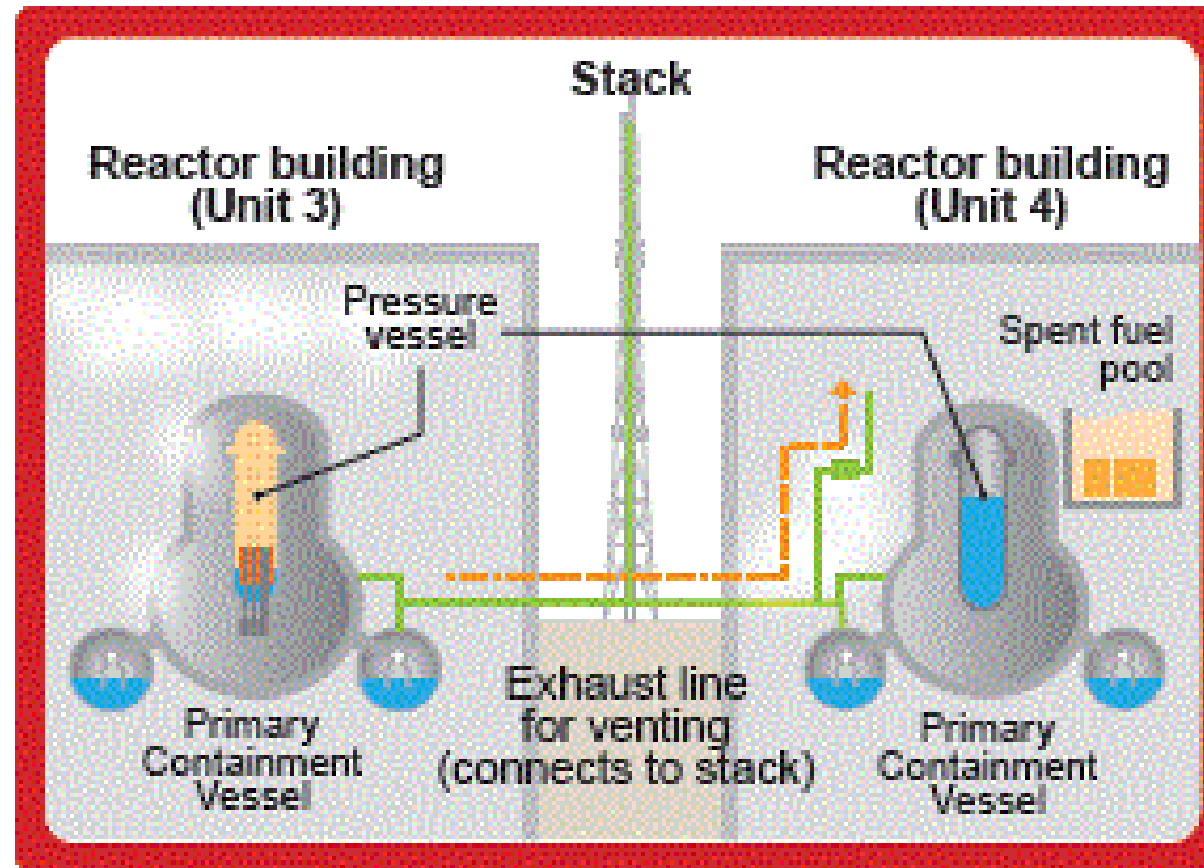
by JAEA/JNES **largest release from Unit 2 (building undamaged)**

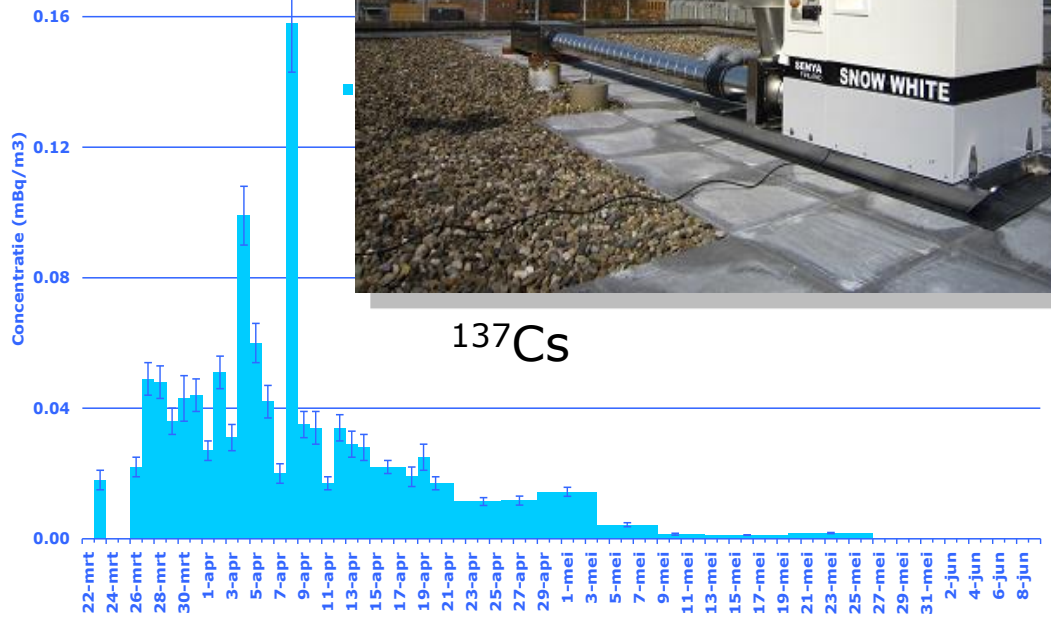
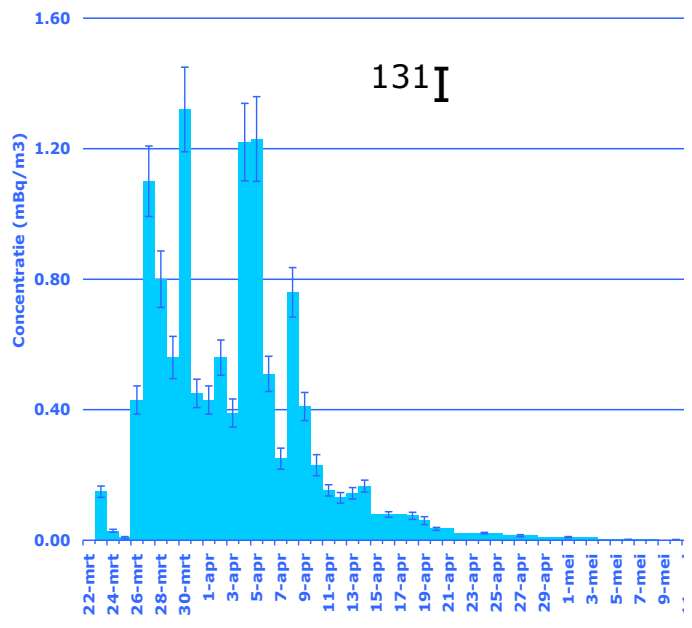


Concentration of Cs-137 in soil

Environmental consequence analysis by JAEA (OSCAAR) using the source terms by JNES (MELCOR)







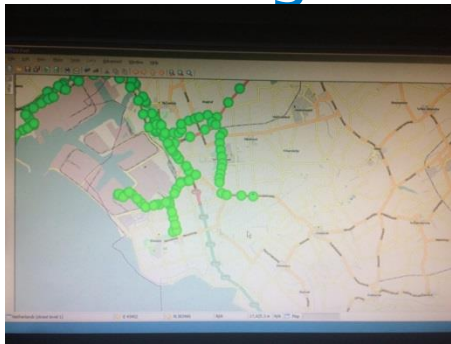
Japanse straling in Bilthoven gevonden

vrijdag 25 maart 2011

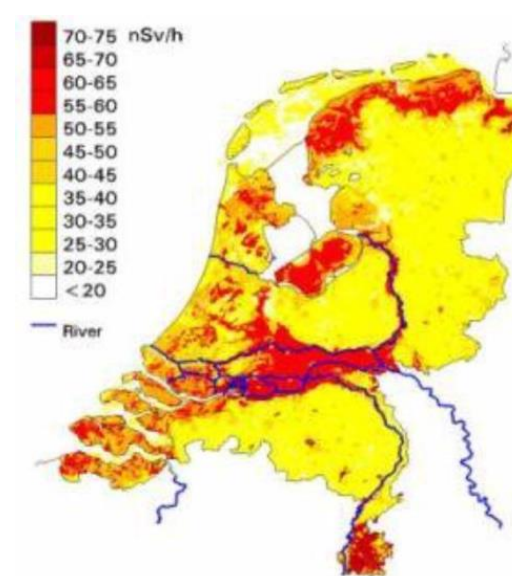
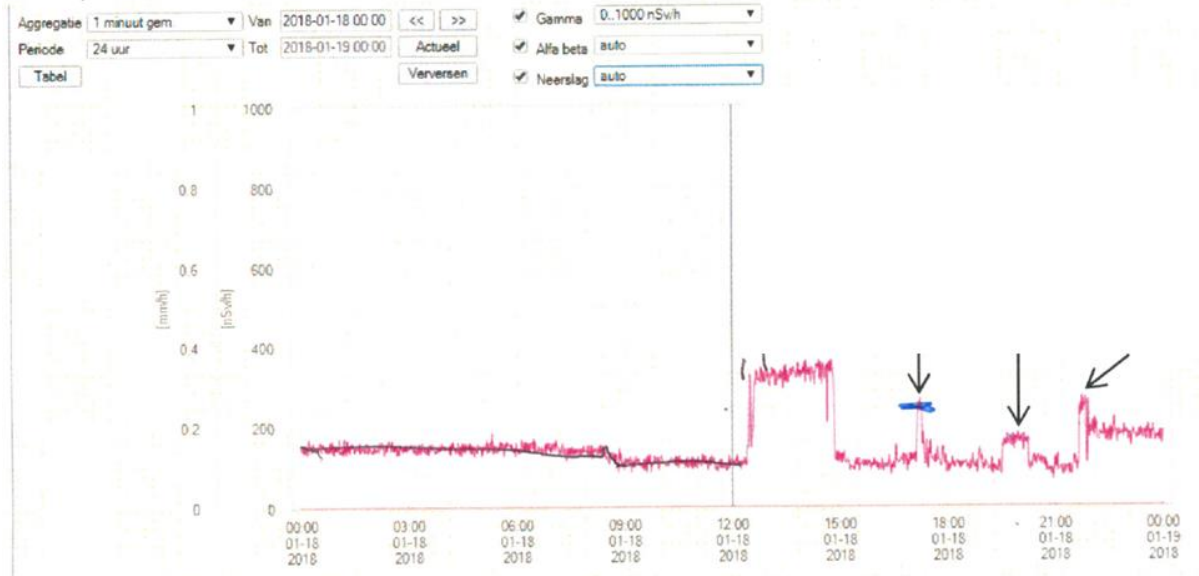
BILTHOVEN - In Nederland zijn radioactieve deeltjes gevonden van de nucleaire ramp in Japan. Dat meldt het Rijksinstituut voor Volksgezondheid en Milieu (RIVM) in Bilthoven. Het instituut voerde de meting uit tussen woensdag- en donderdagochtend. De radioactieve deeltjes zijn afkomstig van de beschadigde kernreactoren in het Japanse Fukushima. De concentratie in de lucht boven Bilthoven is ruim een factor 10.000 lager dan na de ramp in Tsjernobyl. Omdat het om zo'n kleine hoeveelheid radioactiviteit gaat, zijn gras, gewassen en drinkwater niet besmet, volgens het RIVM.



Meetwagens RIVM

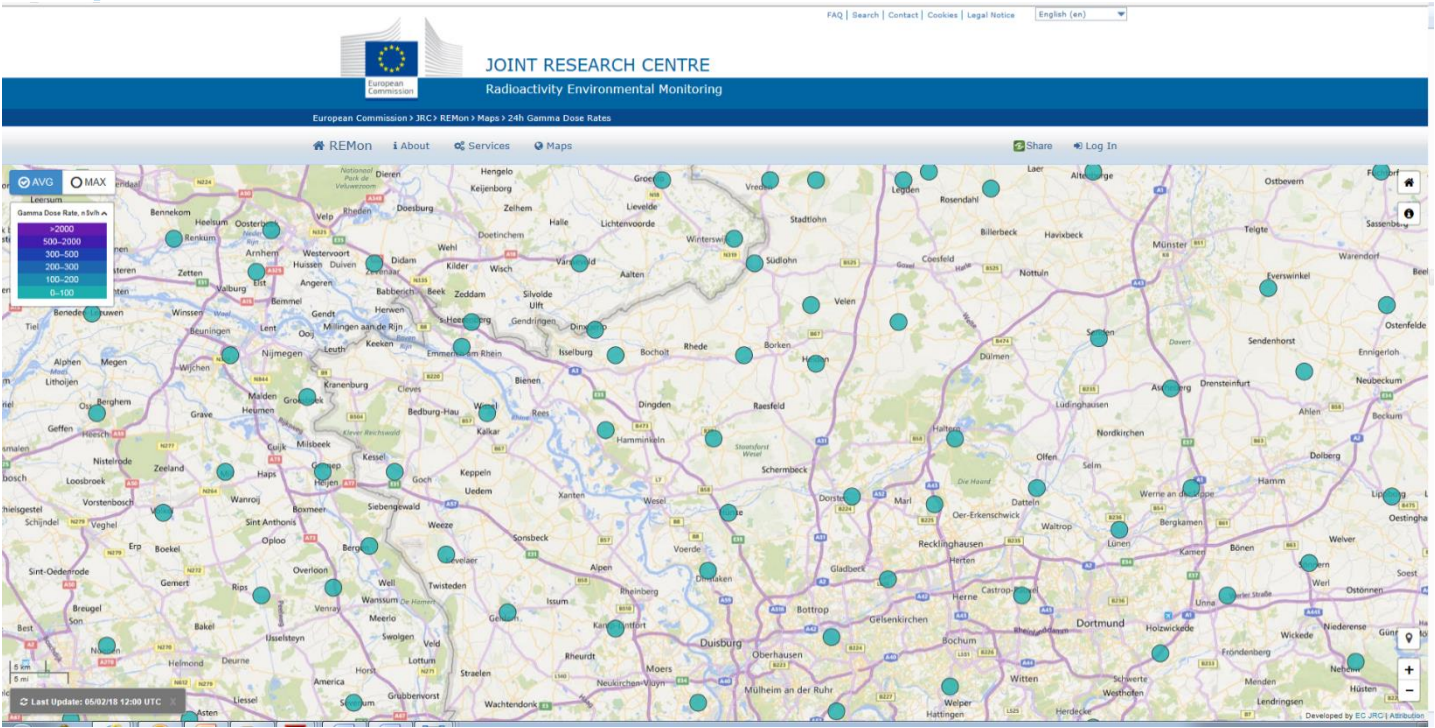


Meetpost 2016 : 1 minuutwaarden 18 januari 2018 van 00:00 tot 24:00





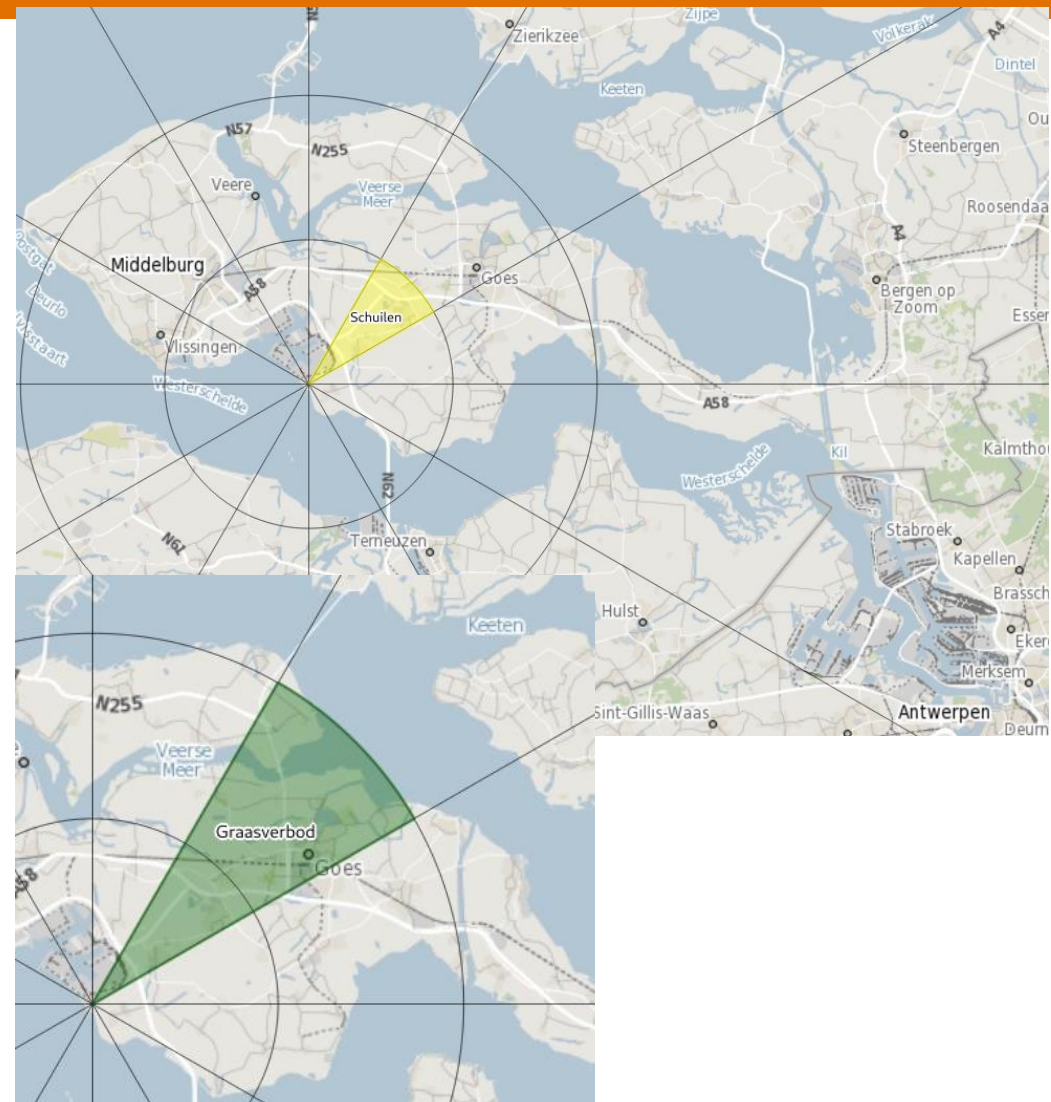
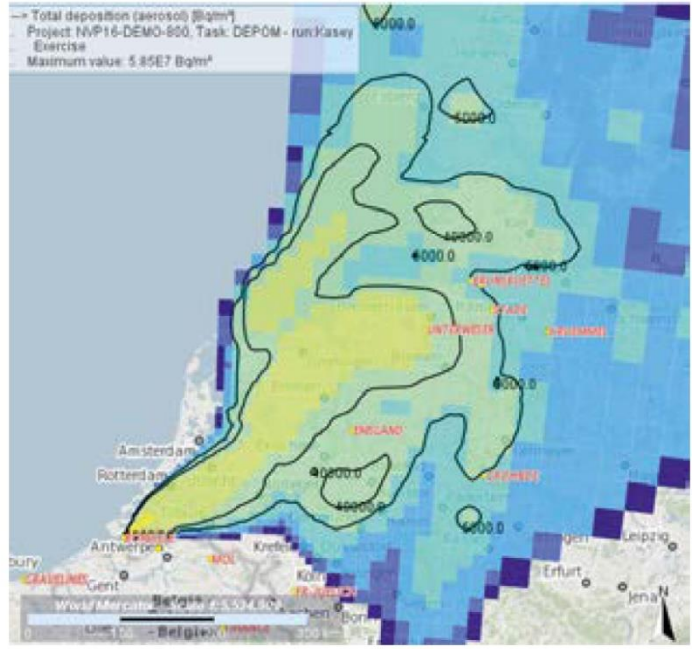
Internationale uitwisseling van meetgegevens: EURdep



<https://remap.jrc.ec.europa.eu/GammaDoseRates.aspx>

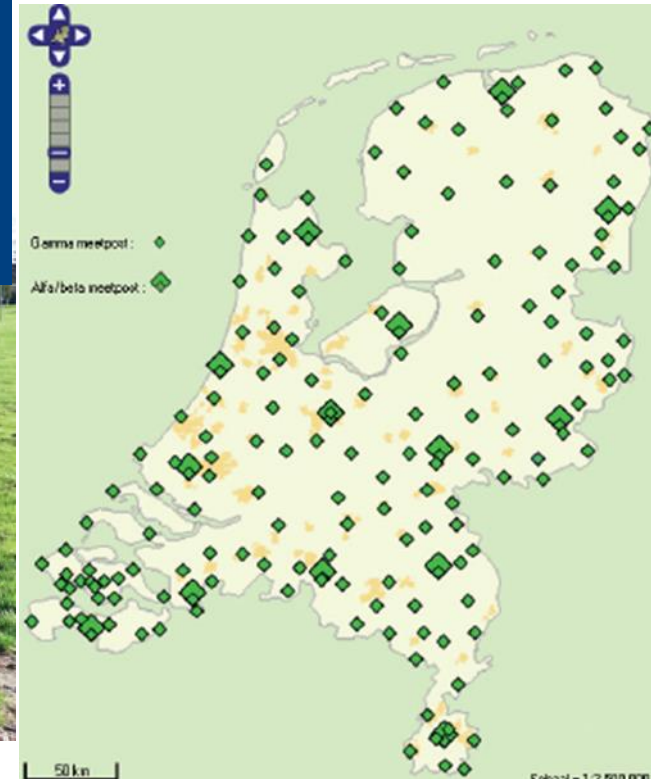


RIVM air dispersion modelling



RIVM meten

- Gammametingen
 - ruim 165 GM-detectoren
 - Alarmgrens 200 nSv/h
- Tijdig signaleren
- Inzicht krijgen
 - ondersteunen bij het treffen van maatregelen
 - natuurlijke stralingsachtergrond in Nederland



[http://www.rivm.nl/Onderwerpen/N/Nationaal Meetnet Radioactiviteit/Resultaten](http://www.rivm.nl/Onderwerpen/N/Nationaal_Meetnet_Radioactiviteit/Resultaten)



Lessons learned

~~Operational status at 11 March 2011 (earthquake and tsunami)~~

- ~~• 102 days shutdown; RPV empty; all 548 core fuel assemblies in Spent Fuel Pool (SFP) (+ 783 + 202 new = 1535 total); decay heat 2.3 MW; 95% occupancy~~

Resilient system AND speedy recovery of

SFP cooling function + measurements

(cameras, radiation, water temperature, water level)

~~———— ANALYSIS: not enough decay heat for hydrogen production from Zr cladding~~

~~Major unexpected event on March 15~~

- ~~• **explosion in Unit 4** reactor building at **06:14 JST** on March 15, 2011, destroys roof, most walls on the fourth and fifth (refueling deck) floors, damages third floor~~
- ~~• ALSO: noise heard at local HQ, white smoke/steam Unit 2 at 08:25, radiation levels spike (11.93 mSv/h at main gate at 09:00 on 15 March, highest measurement since beginning)~~
- ~~• ACTUAL EVENT: explosion heard in local headquarters, drop in pressure reading of Unit 2 (0! atm, possible PCV failure), explosion Unit 4 building observed, reported 08:11 to local HQ~~