Fukushima Accident : An overview

5 July 2011, Akira OMOTO, Commissioner of AECJ

OUTLINE

Part I 3.11 Earthquake and Tsunami
Part II Response of the nuclear reactors
Part III Recovery actions
Part IV Offsite consequences
Part V Key Lessons Learned

2

✓*Part I 3.11 Earthquake and Tsunami*

Part II Response of the nuclear reactors

Part III Recovery actions

Part IV Offsite consequences

Part V Key Lessons Learned

3

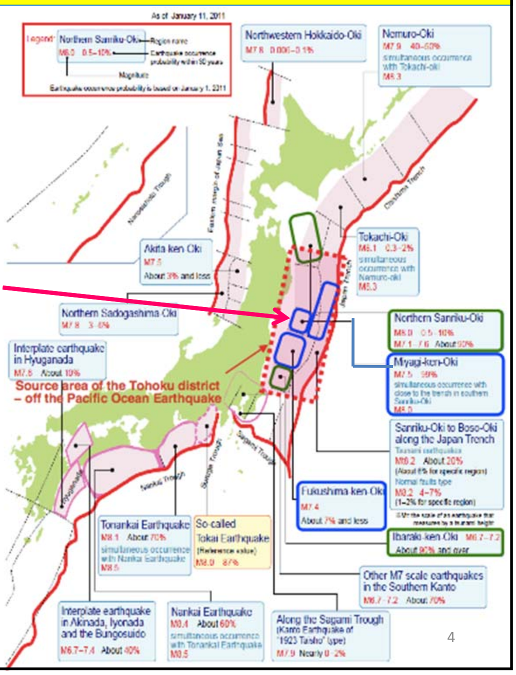
How the occurrence of this earthquake was estimated?

Estimated probability of occurrence by the Headquarter of Earthquake Research (2011 January 1st)

The Headquarter;

a) Had alerted 99% probability of occurrence within 30 years for the Miyagi-oki region with a magnitude of M7.5

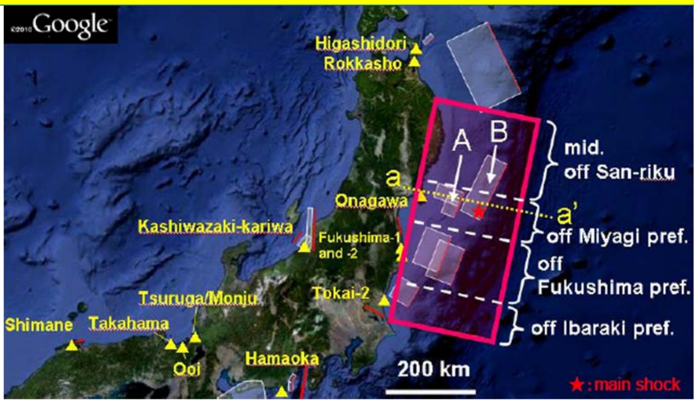
b) Had not correctly estimated the size of the source area (400km x 200km) nor the magnitude (M9) nor the amount of slip



[SOURCE] Gov. Report to the IAEA, June2011

4

Source area of the 3.11 earthquake (multi-segment rupture)



Government Report to the IAEA, June2011
Initiation from B, then propagated westwards to area A, and further to the North and South down to Ibaraki
[SOURCE] Gov. Report to the IAEA, June2011

Statement by the Headquarter for Earthquake Research, 11March2011
The Committee evaluated earthquake motion and tsunami for the individual region off-shore …..but occurrence of the earthquake that is linked to all of these regions is "out of hypothesis".
[SOURCE] http://www.jishin.go.jp/main/index-e.html The 2011 off the Pacific Coast of Tohoku Earthquake

3.11 Earthquake

At the Basement of Reactor Building

Nr.	MWe	3.11 Observed (max. gal)			Design (Ss) (max. gal)		
		N-S	E-W	Vertical	N-S	E-W	Vertical
1Fuku1	460	460	447	258	487	489	412
1Fuku2	784	348	550	302	441	438	420
1Fuku3	784	322	507	231	449	441	429
1Fuku4	784	281	319	200	447	445	422
1Fuku5	784	311	548	256	452	452	427
1Fuku6	1100	298	444	244	445	448	415

Note 1: **Damage by the earthquake**: Not fully inspected but maybe not significant to safety systems, considering the KK earthquake (2007) where no damage to safety functions even though the observed acceleration exceeded design basis by factor 2-3. However, all the 7 offsite power lines to 1F were lost due to failure of breaker, cable damage and collapse of transmission line tower. (In KK earthquake (2007), 3 out of the 4 offsite power lines remained intact.)

Note 2: **Reactor Scram by the earthquake**
Set points by acceleration at the basement of Reactor Building
Horizontal=135 gal, Vertical=100 gal

6

Earthquake: Renewed evaluation basis (2009)

◆ **Renewed seismic design standard (2006)**

◆ **"Chuetsu-oki" earthquake hit KK NPS (2007)**

◆ **Design review of existing NPSs in the light of the above two**

- ✓ Fukushima seismicity review by NISA/Advisers/TEPCO (2009)
- ✓ TEPCO document shows "Probability of exceedence" (10(-4)-10(-6)/year)
- ✓ Tsunami review to come later after studies of year-869 Tsunan

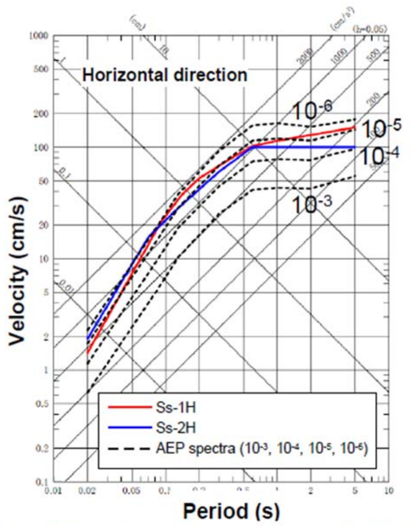


Fig. III-2-3 Annual exceedence probability (AEP) of DBGM Ss for Fukushima Dai-ichi NPS.

[SOURCE] Gov. Report to the IAEA, June2011

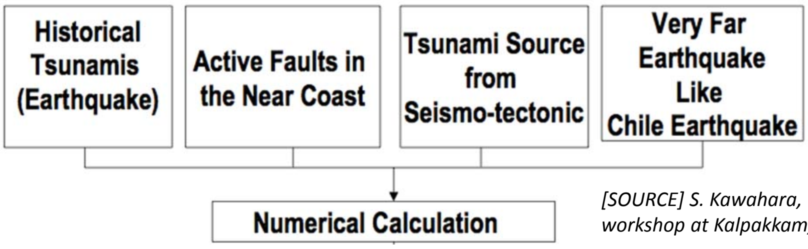
Tsunami design basis

◆ **Safety Design Guide (NSC) Nr. 2 [footnote]**

- ➢ "….Anticipated natural hazard includes flood, Tsunami …."

◆ **JSCE (Japan Society of Civil Engineers) guideline on Tsunami (2002)**

- ➢ From JSCE Nuclear Civil Engineering Committee http://committees.jsce.or.jp/ceofnp/system/files/JSCE_Tsunami_060519.pdf



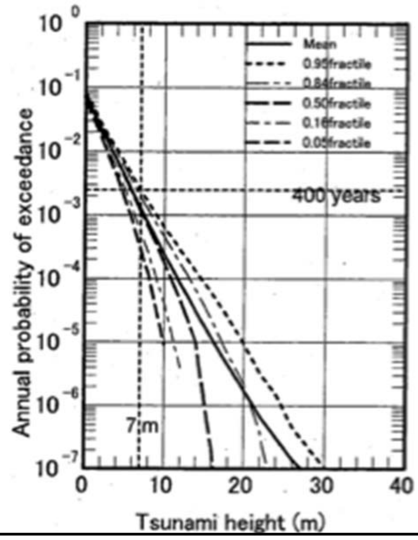
[SOURCE] S. Kawahara, IAEA workshop at Kalpakkam, 2005

- ➢ Deterministic approach
- ➢ Need to exceed historical highest
- ➢ Probability of "combination of Tsunami source" not considered, if no historical evidence
- ➢ NPP modifications based on this guideline

8

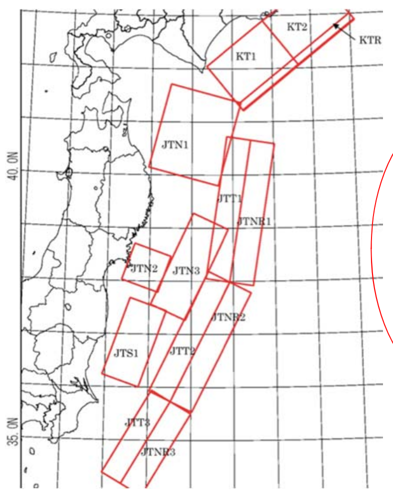
Tsunami design guideline based on probabilistic study

- **Tsunami Probabilistic Hazard study**
  - Probabilistic Tsunami hazard analysis (TEPCo, ICONE-14, 2006)
  - Methodology guide from **JSCE** Nuclear Civil Engineering Com. (2009)
- **IAEA DS417 (draft)**
  - Includes guide on Tsunami analysis



9

Tsunami design guideline based on probabilistic study



Logic tree to represent epistemic uncertainty

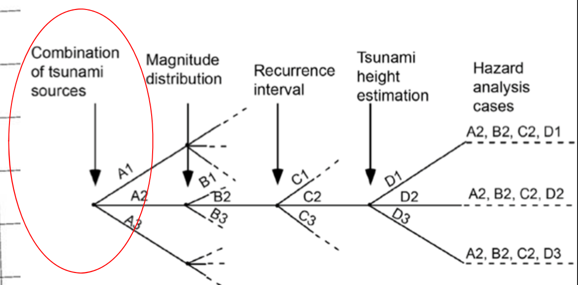


Fig. 1 Logic-tree representation of uncertain parameters

[SOURCE] T. Annaka, "A method of Probabilistic Tsunami Hazard analysis, 12th Civil Engineering Society, 2006

10

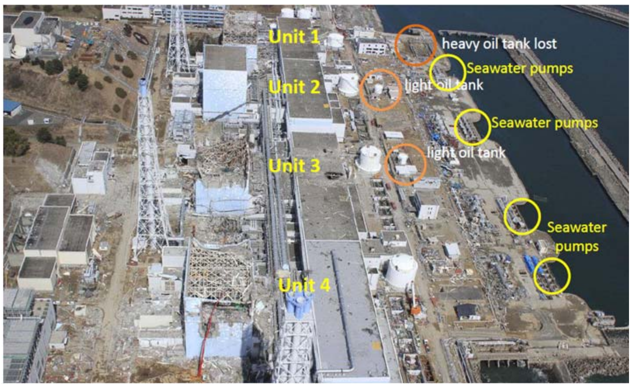
Part I 3.11 Earthquake and Tsunami

✓ Part II Response of the nuclear reactors

Part III Recovery actions

Part IV Offsite consequences

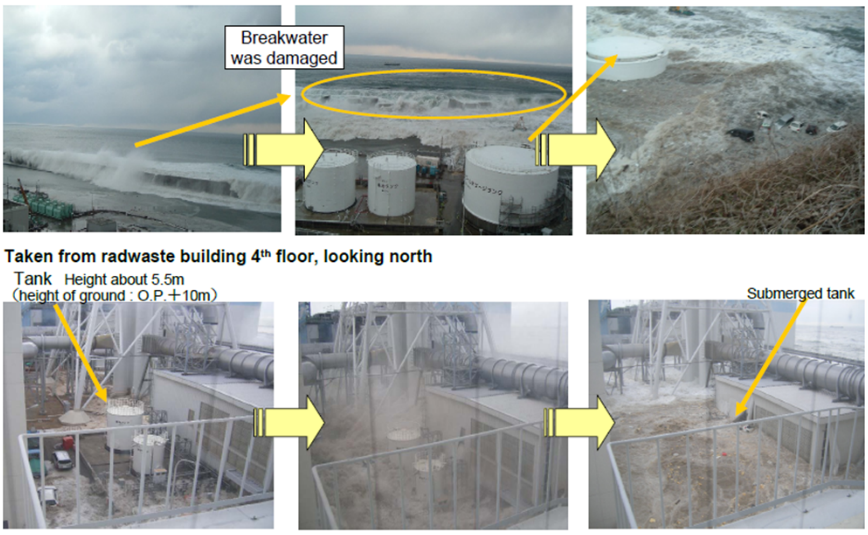
Part V Key Lessons Learned



Fukushima Daiichi being struck by the tsunami

Taken from near the south side of Unit 5, looking east

Taken from radwaste building 4th floor, looking north

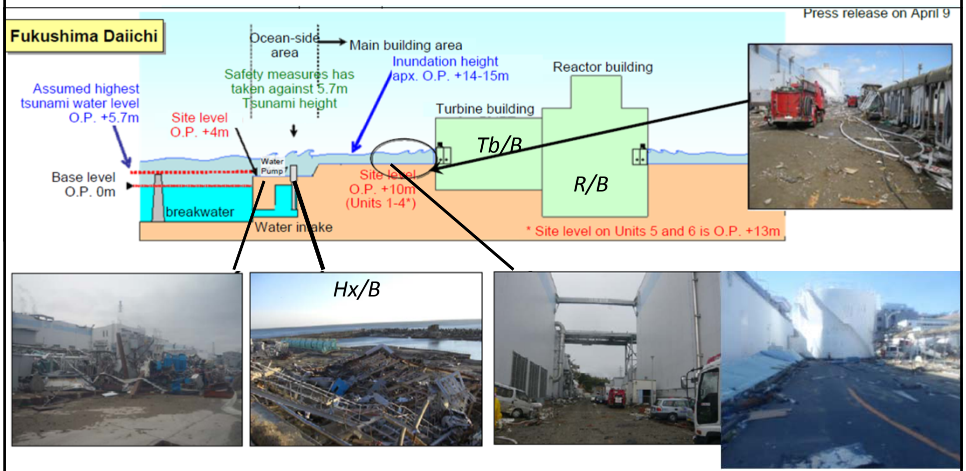


O.P. : Onahama bay construction base level

東京電力

12 5

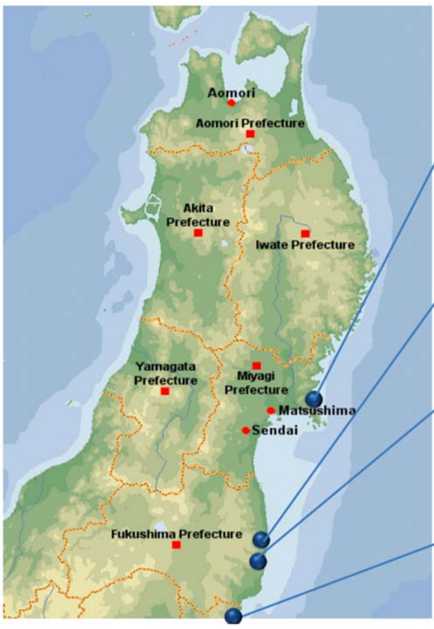
Fukushima Dai-ichi Unit 1-4



Relocated tank prevented recovery actions

[SOURCE] http://www.tepco.co.jp/cc/press/betu11_j/images/110618l.pdf and TEPCO May 23 report

14 NPPs along the coastal line affected by Tsunami



Onagawa
- Unit1: 524 MW, 1984-
- Unit2: 825 MW, 1995-
- Unit3: 825 MW, 2002-

Fukushima Ⅰ
- Unit1: 460 MW, 1971-
- Unit2: 784 MW, 1974-
- Unit3: 784 MW, 1976-
- Unit4: 784 MW, 1978-
- Unit5: 784 MW, 1978-
- Unit6: 1,100 MW, 1979-

Fukushima Ⅱ
- Unit1: 1,100 MW, 1982-
- Unit2: 1,100 MW, 1984-
- Unit3: 1,100 MW, 1985-
- Unit4: 1,100 MW, 1987-

Tokai Ⅱ (1,100 MW, 1978-)

All except for O-2, 1F-4,5,6 were in operation when hit by the 3.11 earthquake

3.11 Tsunami

Unit	Ground Level R/B, Tb/B [m]	Ground Level Intake str. [m]	Tsunami height [m] DB	Tsunami height [m] Mod (2002)	Tsunami height [m] 3.11	Location of Electric Equipment Room (M/C, P/C, Battery)	Type & location of Emergency Diesel Generator SC: Seawater-cooled AC: Air-cooler
1Fuku1,2,3,& 4	10.2	4	3.1	5.7	14-15		1F1.3: 2 SC-EDGs (design) 1F2,4: 1 SC-EDG (design) + 1 AC-EDG (SAM)
1Fuku5	13.2	4	3.1				2 SC- EDGs
1Fuku6							2 SC-EDGs (design) **1 AC-EDG (SAM)**
2Fuku1,2,3 & 4	12	7	3.7	5.2			3 SC-EDGs
Onagawa1,2 & 3	14.8		9.1	-	13		3 SC-EDGs
Tokai 2	8.0	3	1.5	4.86	5.1-5.4		3 SC-EDGs

Location info not listed here.

2F

- **Different Tsunami inundation path from 1F**
- **One of the offsite power lines stayed alive during & after the Earthquake/Tsunami**

Fuel damage or not ---- What made the difference?

Simply said,

(1) Elevation vs. Tsunami height

- Site ground level→ saved Onagawa and Tokai
- Location of EDG/EE room/battery

(2) Availability of power

- Offsite power (together with SAM under loss of UHS) → saved 2F
- Air-cooled EDG coupled with the above location and SAM under loss of UHS) → saved 1F6
  - Air-cooled EDG was added for 1F2,4,6 respectively in the 1990's as a part of SAM modifications.

(3) Implementation of AMG by using then-available resources

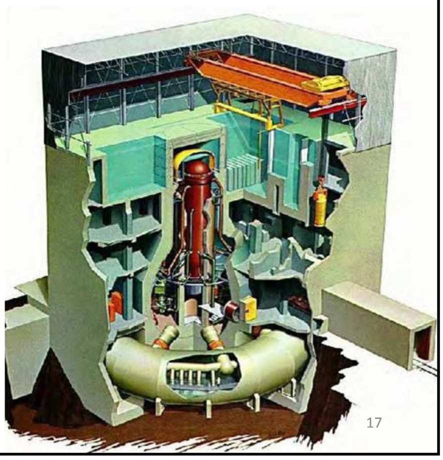
→ saved 1F5 (power supply from adjacent 1F6)
saved SFPs (makeup water)

16

BWR/3,4 generation plant

BWR/3 (460MWe, 1Fuku1)
- Mark I Containment (Drywell + Suppression Pool, Pd=62psig)
- IC (Isolation condenser)
  - high pressure core makeup
  - No need for AC power
- Battery : 10 hrs

BWR/4 (784MWe, 1Fuku 2,3,4 &5)
- Mark I Containment (Drywell + Suppression Pool, Pd=45psig)
- RCIC (Reactor Core Isolation Cooling) & HPCI (High Pressure Core Injection)
  - high pressure core makeup
  - No need for AC power
- Battery : 8 hrs

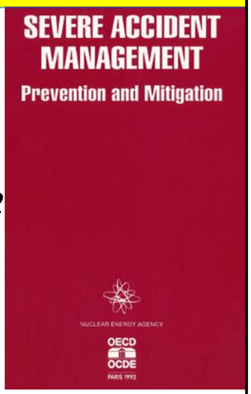


17

What SAM (Severe Accident Management) was in place?

(OECD/NEA)
In the aftermath of Chernobyl, OECD/NEA organized a series of meetings by SESAM (Senior Expert for Severe Accident Management)

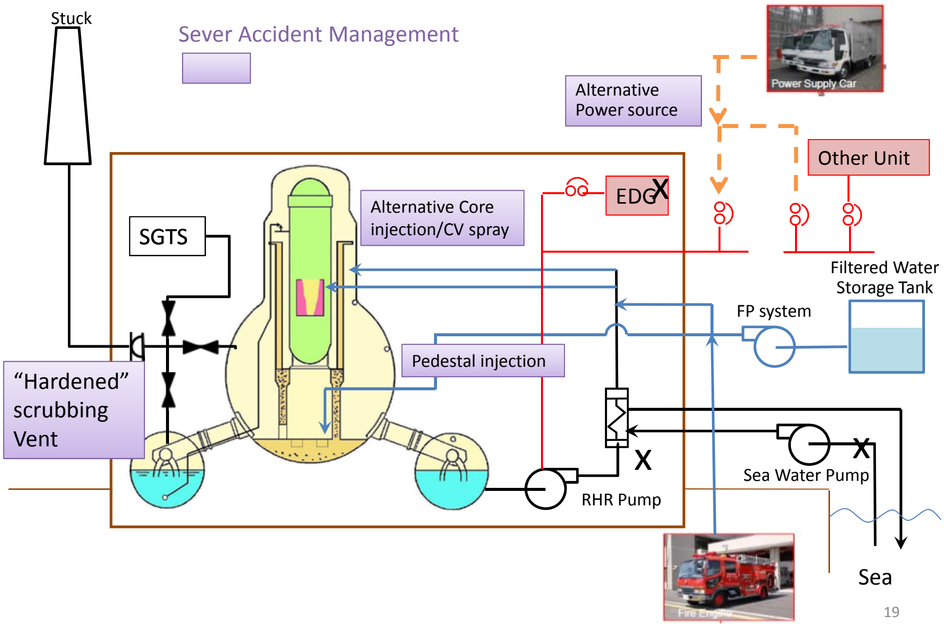
"Severe Accident Management": published in 1992
"Implementing Severe Accident Management in Nuclear Power Plants", published in 1996



(Japan)
- NSC recommendation for SAM preparation (1992)
- SAM study followed by SAMG and modifications (hardened vent, injection to RPV and RPV-pedestal region etc)
- Technical basis for SAM by Utility/Industry/Academia (NSRI guideline, 1999, http://www.nsra.or.jp/safe/cv/index.html)
- Submittal of Utility report to NISA, followed by evaluation by NISA

18

What SAM (Severe Accident Management) was in place?



19

Continuous improvement of SAM through drill and information from other countries？

1. Not effective enough, give 3.11 situation

- Location of CV vent valve
- Sharing of vent line with adjacent units and connection with SGTS
- No reactor building venting provision
- No provisions for battery recharger etc
- SAM assuming working environment after Tsunami and Hydrogen explosion

2. Not learning SAM from outside of Japan

Small diesel-powered generators or small power-packs to SRV
Air-cooled "blackout diesel generator"

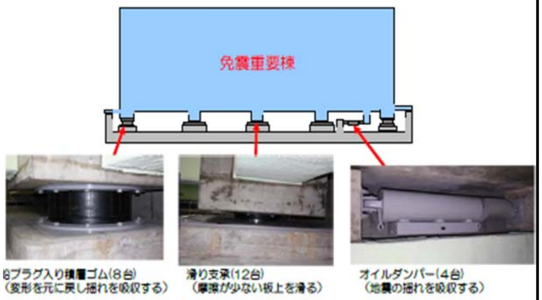
3. Some improvements after KK earthquake (2007 July)

a) Emergency response center (ERC) : seismic isolation, shielding, communication etc
If not for this ERC, on-site actions would have been severely hampered

b) Underground water tank (16 units/site x 40m3 /unit) and
Fire Engines (3/site) ([source] http://www.tepco.co.jp/cc/press/betu11_j/images/110618l.pdf)
Nevertheless,
- Prior RCS depressurization
- Limited amount of water for multiple units
- Mobility in post-Tsunami environment and post-HE environment

20

Onsite ERC



21

Actions to avoid core damage

14.46 Earthquake, Loss of offsite power, Start of EDG, IC/RCIC
15.38-41 Tsunami followed by Loss of AC/DC, Isolation from UHS

Given this situation, operation to avoid core damage

Short term

- Reactor water makeup by AC-independent IC/RCIC/HPCI
- Containment vent to avoid over-pressure failure

Then, while trying to restore AC/DC power and Heat Sink

- Depressurize RCS by Safety/Relief Valves (Need DC and gas pressure to cylinder and reduced back-pressure from the containment, If CV pressure is high)
- Activate LP injection systems (FP, MUWC etc)

Failure of RCIC/HPCI on the 3rd and 4th day
Delayed de-pressurization and LP injection

22

Actions for core injection(1F2 as an example)

3.11.17:12 Initiated actions for alternative core injection by FP system, Fire Engine etc.
3.12. 2:55 Confirmed RCIC operation
3.13.8:10 Opening containment vent valve
Given high temperature in the suppression chamber (S/C), difficulty of steam condensation expected even though SRV send steam to S/C

3.14.13:25 Suspected RCIC trip → Core uncovered
16:30 Activate Fire Engine to inject water to RPV
18:00 Reactor pressure started decrease because SRV was opened by utilizing temporary batteries
19.54 Start water injection to reactor

Unavailability of power (AC/DC power and air) to vent and RCS depressurization

[SOURCE] http://www.tepco.co.jp/cc/press/betu11_j/images/110618l.pdf

23

Actions for AC/DC power

AC
LOOP(6+1)
EDG: only 1 air-cooled EDG functioned properly
(13 EDG on site, 3 air-cooled, except for 1F6 location problem)
Delayed arrival of mobile power units
Problems such as submerged M/C,P/C and cable connection after hydrogen explosion

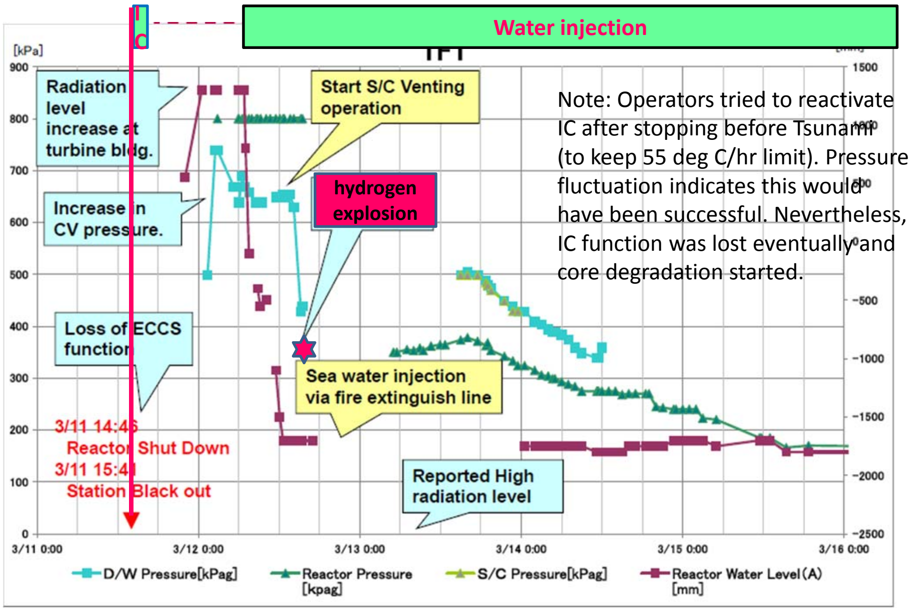
DC
Loss of instrument reading & power to operate some valves→ Serial connection of batteries from automobile etc. to power essential instrumentations and valves

[SOURCE] http://www.tepco.co.jp/cc/press/betu11_j/images/110618l.pdf

24

1Fuku1

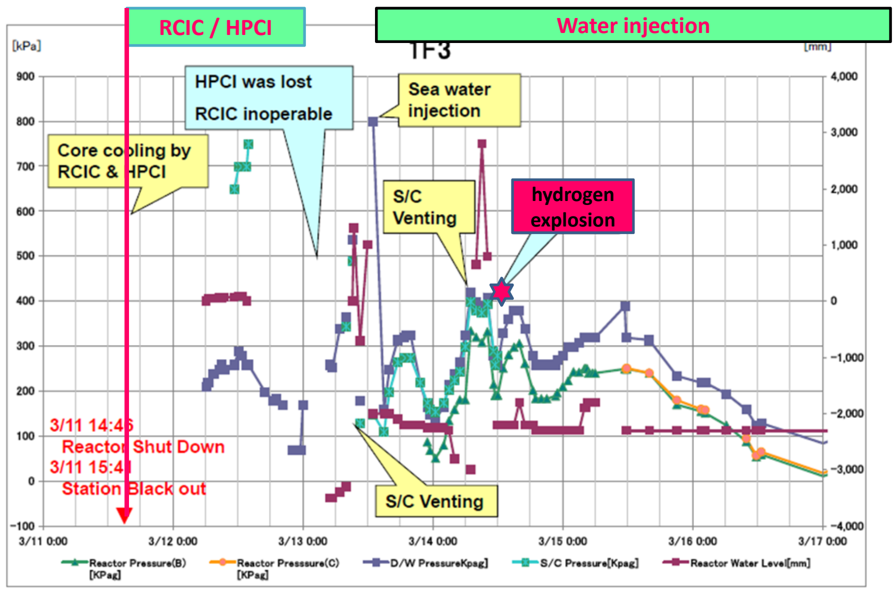
IC trip (March 11.15.37) Start of injection via FP line (March 12. 05.6)



[Based on NISA slide, IAEA Safety Convention Meeting, 2011April4 and Gov report to IAEA, TEPCO report June18] 25

1Fuku3

RCIC/HPCI trip (March 12.02.42) Start of injection via FP line (March 12.09.25)

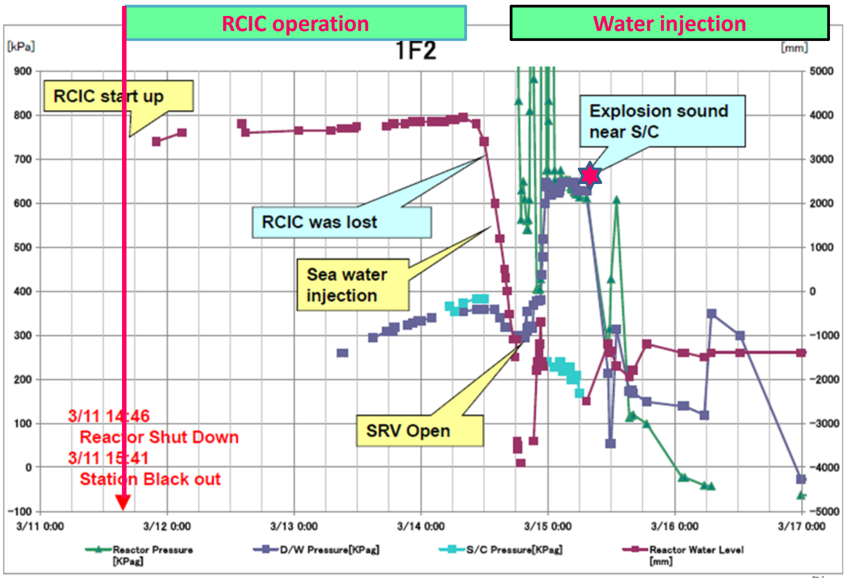


[Based on NISA slide, IAEA Safety Convention Meeting, 2011April4 and Gov report to IAEA]

1Fuku2

RCIC trip (March 14.13.25)

Start of injection via FP line
(March 14.19.54)



[Based on NISA slide, IAEA Safety Convention Meeting, 2011April4 and Gov report to IAEA]

TMI and Fukushima core uncover: estimation

TMI

Day 1

00	Tb trip, Loss of FDW
03 sec	SRV stuck open
3 min	HPI stop
100 min	Coolant circulation stop
174 min	B pump start (fuel collapse)
113-174 min	Core uncover
200 min	HPI restart
224 min	Slumping to RPV bottom

Fukushima

00 Earthquake LOOP, EDGs start, IC/RCIC operation

1 hr Tsunami Blackout &loss of UHS

(1F1)	(1F2)	(1F3)
4-15* hrs (Day 1 – Day 2)	75 -77* hrs (Day 4)	40 -43* hrs (Day 3)

Day 2

*Estimated time from start of core uncover to start of successful injection

Day 3

Day 4

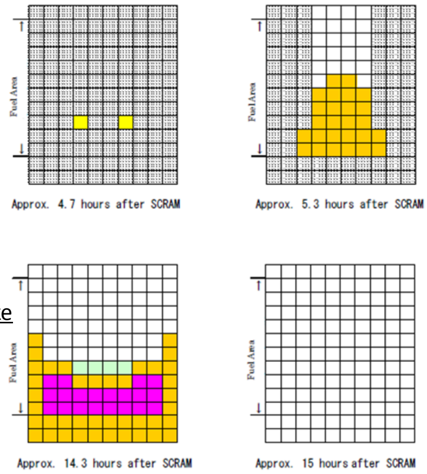
[SOURCE] Based on Gov. report to the IAEA and TEPCO May 23 report

28

What are the results of code assessment?

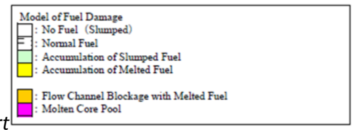
MAAP (TEPCO), MELCOR (JNES), SAMPSON (IAE/NUPEC)

- MAAP calculation by TEPCO in the Gov. report to the IAEA (Ex.)1F1→
- MELCOR calculation by JNES



Time of RPV melt-through (M/T) after the earthquake

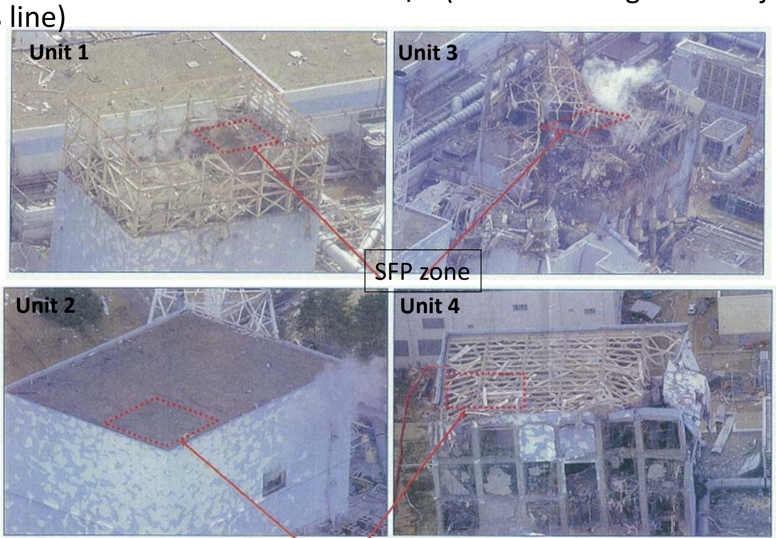
	MAAP(TEPCO)	MELCOR (JNES)
1F1	5-12 hrs	15 hrs
1F2	109 hrs or no M/T	80 hrs or no M/T
1F3	66 hrs or no M/T	79 hrs or no M/T



[SOURCE] Based on Gov. report to the IAEA and TEPCO May 23 report

Hydrogen explosion

Possible Path 1 : Excessive leakage by over-pressure at CV flange/airlocks
Possible Path 2: Vent line→ SGTS→R/B (vent line merge with adjacent unit's line)



1F2 blowout panel opened by 1F3 blast, which released H_2

SFP zone

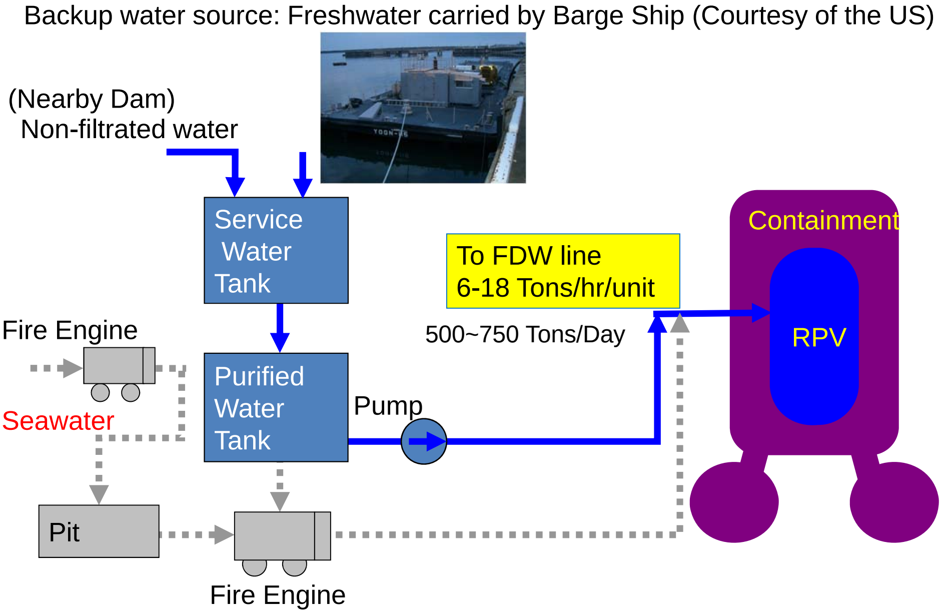
Water sample from SFP and photo indicate SFs in 1F4 most probably remain intact

30

31

Water Injection to the reactor core

Backup water source: Freshwater carried by Barge Ship (Courtesy of the US)

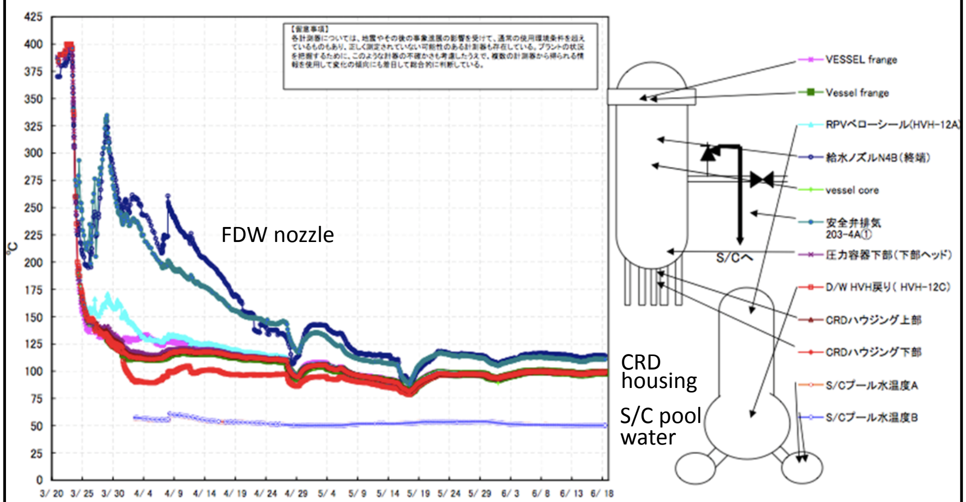


[SOURCE] Modified based on NISA, IAEA Safety Convention Meeting, 2011April4

32

Recent trend of 1F1 temperature

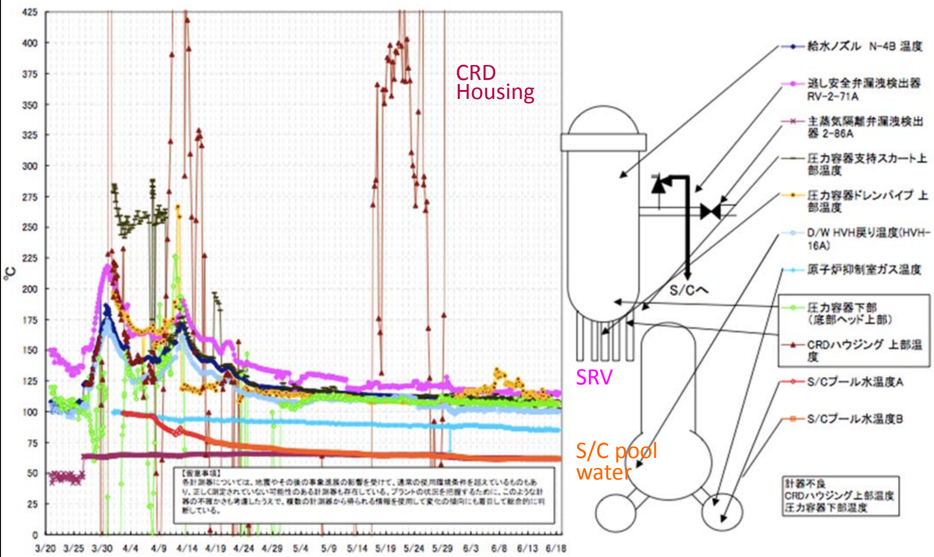
CAUTION: include questionable data



[SOURCE] http://www.tepco.co.jp/nu/fukushima-np/f1/images/11061812_temp_data_1u-j.pdf 33

Recent trend of 1F2 temperature

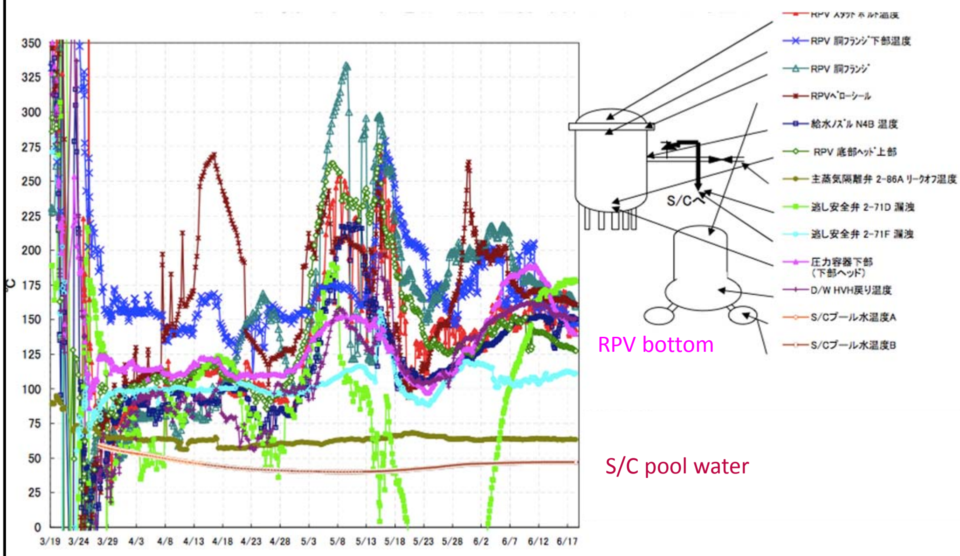
CAUTION: include questionable data



34
[SOURCE] http://www.tepco.co.jp/nu/fukushima-np/f1/images/11061812_temp_data_2u-j.pdf

Recent trend of 1F3 temperature

CAUTION: include questionable data

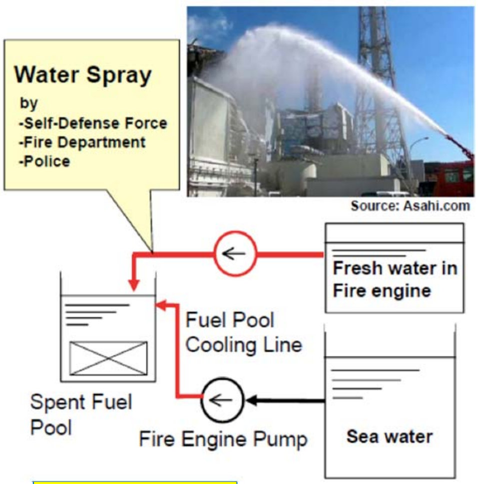


[SOURCE] http://www.tepco.co.jp/nu/fukushima-np/f1/images/11061812_temp_data_3u-j.pdf

35

Water Injection to Spent Fuel Pool

Used to be



2-5Tons/hr/unit

Current

1F1-3 : Fuel pool makeup using FPC system
- **Use of plant system**
- **No spray**

1F4 : Still spray from outside due to damaged FPC line

36

Key near-term recovery actions

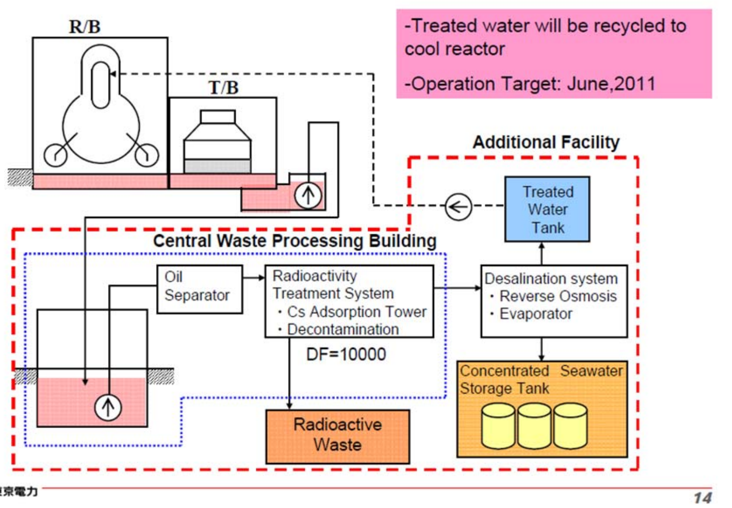
1. COOLING
   - Flooding the containment to a certain level & installation of heat exchanger to remove heat, *[challenge] working environment & leakage of water from the containment*
   - SFP cooling system (rather than spray and evaporation)

2. MINIMIZING AIRBORNE/LIQUID EFFLUENT
   - Recycling of water recovered from Tb/B through removal of radioactivity (France/US/Japan) and RO (Japan)
     ~1200 Tons/Day treatment
     500~750 Tons/Day treated water return to the reactors
   - Storage of contaminated water
   - Installation of R/B cover
   - Corrosion control (Deaeration of supply water, hydrazine)

3. MINIMIZING RESIDUAL RISKS
   - Aftershocks (Structural integrity of damaged R/B, Reliability of power/water supply)
   - Hydrogen

37

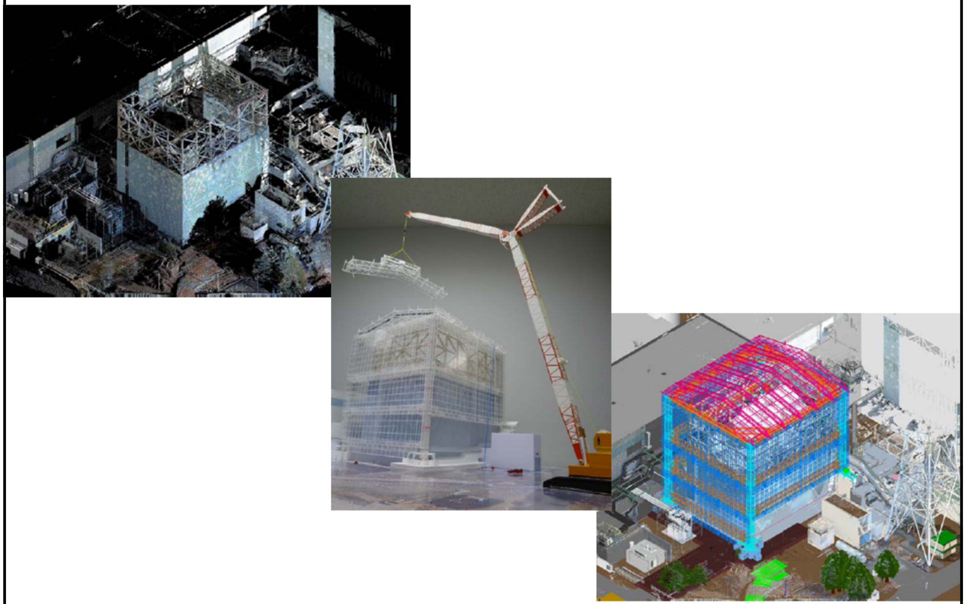
Installation of Water Treatment Facility



Water in the Tb/B is treated and recycled to the reactor for feed. Will balance by 2011/E.
✓Capacity of Treatment facility : 1200 Ton/Day x 6month (7-12) =216,000 Ton
✓Water to be treated : 1-4 Tb/B 87,500 Ton + (500-750) Ton/Daily feed x6month =177,500~22,250 Ton

38

Reactor building cover

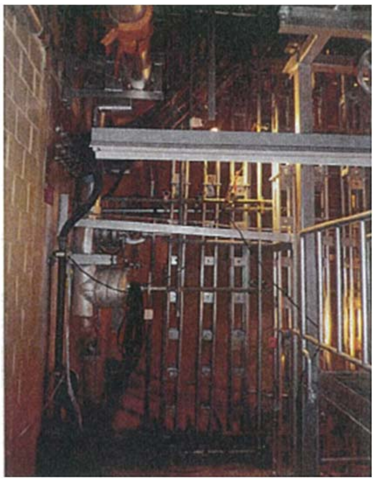


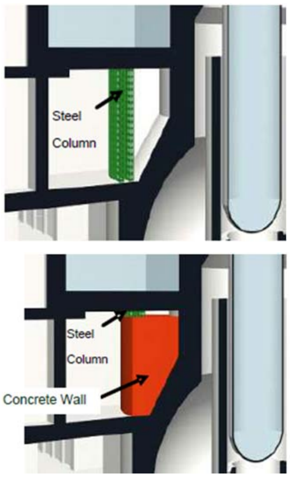
[SOURCE] http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110614e17.pdf

39

Support 1F4 SFP from bottom

- ◆Steel structure and concrete
- ◆Steel structure: completed by June 18th
- ◆Concrete filling : Ongoing to further take loads





40

Machines/Robotics in harsh radiation environment

Removal of debris
Taking samples
Remote camera
Remote radiation monitoring

41

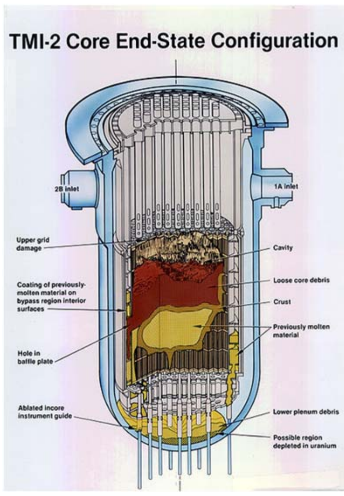
Beyond stabilization phase (ends early 2012)

１. **Defueling**
- Removal of intact SF in the SFPs
- Removal of debris
  - ✓ TMI-2 experience

2. **Continued waste management**
- contaminated water : 10-20 x TMI-2

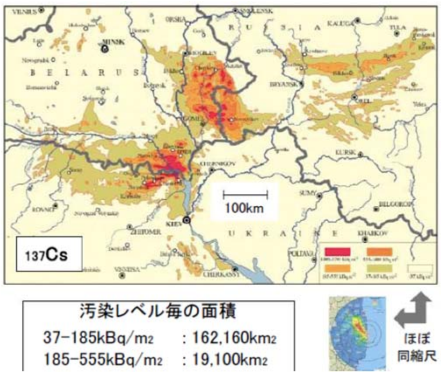
３. **Sarcophagus, Isolation of surrounding area by walls and dismantling**
- No experience of dismantling seriously damaged reactor
  - ✓ A-1 (Slovakia, 1977)
  - ✓ TMI-2(USA, 1979)
  - ✓ Chernobyl (Ukr, 1986)

４. **Final disposal of wastes**



42

Part I 3.11 Earthquake and Tsunami
Part II Response of the nuclear reactors
Part III Recovery actions
✓ ***Part IV Offsite consequences***
Part V Key Lessons Learned



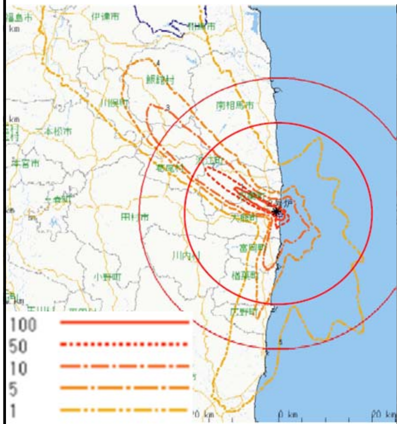
[Source] sunoyama, AEC hearing, 2011June14

Emergency Response Center

- Established on Mar.15 (4 days after quake) to facilitate crisis management
- Located at TEPCO corporate office
- Chief: Prime Minister of Japan
  Deputy Chief: Minister of Trade, Economy and Industry (METI)
  Chairman of TEPCO
- Other member includes liaisons from related ministries and organization:
  Nuclear and Industrial Safety Agency (NISA), Ministry of Foreign Affairs (MOFA), Ministry of Defense, Prime Minister Office, Self Defense Force (SDF), Tokyo Fire Dept. etc

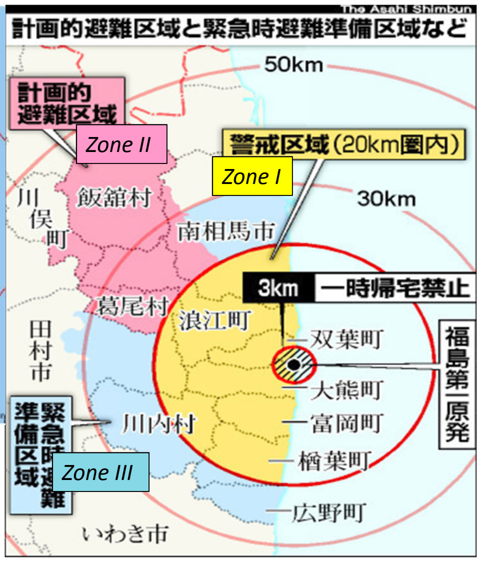
44

What offsite emergency plan was enacted?



(mSv)

SPEEDI calculation March 11-April24
Cumulative exposure to adult
http://www.nsc.go.jp/info/110425_top_siryo.pdf



Zone I (20km); "evacuation"
Zone II (North-west): "evacuation plan (in a month)"
Zone III (20-30km); "preparedness for evacuation"

45

What offsite Emergency Actions?

March 11
16-18: Notification of no confirmation of water injection & increase of CV pressure (TEPCO)
19:03: Government declared nuclear emergency. (Setup of Government Nuclear Emergency Response Headquarter and Local Emergency Response Center)
21.23: PM directed <u>evacuation (3km radius) and sheltering (10km radius) of 1F site</u>

March 12
5.44 : PM directed <u>evacuation (10km radius) of 1F site</u>
7.45: PM directed evacuation (3km radius) and sheltering (10km radius) of 2F site
17.39: PM directed evacuation (10km radius) of 2F site
18.25: PM directed <u>evacuation (20km radius) of 1F site</u>

March 15
11.00: PM directed sheltering (20-30km radius) of 1F site
Local Emergency Response Headquarter issued "direction to administer the stable Iodine during evacuation from the evacuation area (20 km radius)" to the Prefecture Governors and the heads of cities, towns and villages.

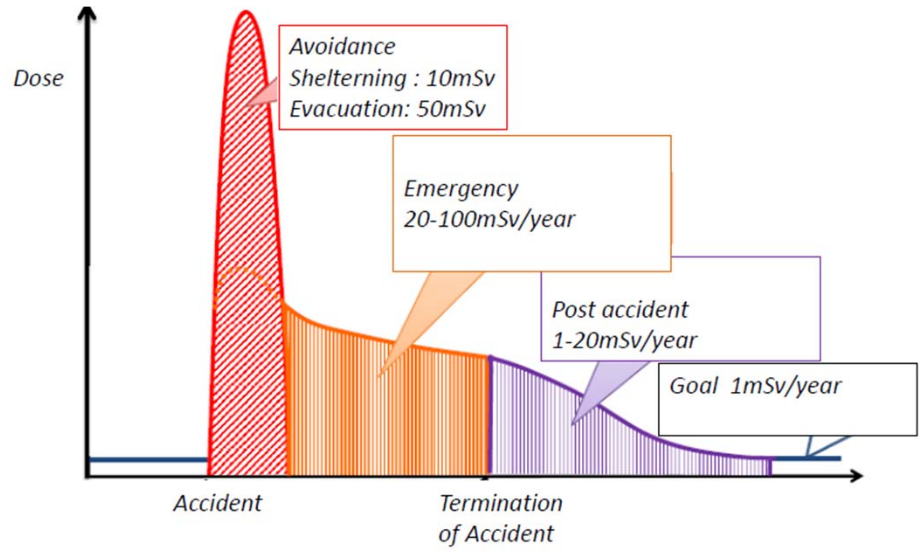
March 25
Chief Cabinet Secretary prompted <u>voluntary evacuation (20-30km radius) of 1F site</u>

April 11
Chief Cabinet Secretary set up an area of planned evacuation within 1 month to avoid exposure beyond 20mSv/yr and prompted preparation for evacuation (20-30km) of 1F site (reason: just in case of large release)

April 20
Chief Cabinet Secretary set-up of de-fact <u>exclusion zone for 20km radius of 1F</u>
(Nr. of residents: 7,8000) and reduction of EPZ to 8km around 2F

46

By the Nuclear Safety Commission



[SOURCE] NSC, http://www.nsc.go.jp/info/20110411_2.pdf

47

Part I 3.11 Earthquake and Tsunami
Part II Response of the nuclear reactors
Part III Recovery actions
Part IV Offsite consequences
✓ ***Part V Key Lessons Learned***

48

Key Lessons Learned

1. Design considerations against natural hazards
- CCF (such as of onsite/offsite power) by natural and man-made hazard
- Probabilistic approach suing logic tree to represent epistemic uncertainty

2. Design considerations against TOTAL loss of power and Isolation from UHS
- Diversified power & water supply: Air-cooled DG, Water from dam
- Diversified Ultimate Heat Sink (UHS) of Residual Heat Removal and Emergency Equipment Cooling Systems

3. Multi-unit installation

4. Passive safety
- Heat removal from reactor core/containment/SFP by Isolation Condenser, PCCS, external CV cooling, wall cooling etc
- Preparations for "what if onsite recovery actions were disabled"

5. SFP design
- Location
- Early transfer to storage facilities

49

Key Lessons Learned

6. Accident Management

a) Review and drill for the "use of all available resources (Apollo 13)"
- Provisions of Onsite or National/Regional Nuclear Crisis Management Center (or WANO), under appropriate delineation of responsibility, transportation systems and storage of mobile equipments such as Fire Engines, portable sweater pumps, batteries, remote sensing devices, remote spray system, robotics etc & drill for use

b) Implementation of recovery actions in harsh radiation environment

c) Potential of detonation/deflagration of leaked hydrogen outside of the CV
- Vent line pipe and SGTS line pipe
- "hydrogen deflagration/detonation in a BWR R/B" (NE&D 211,27-50)

d) Structure of Emergency Management organization

6. SAM Operational aids

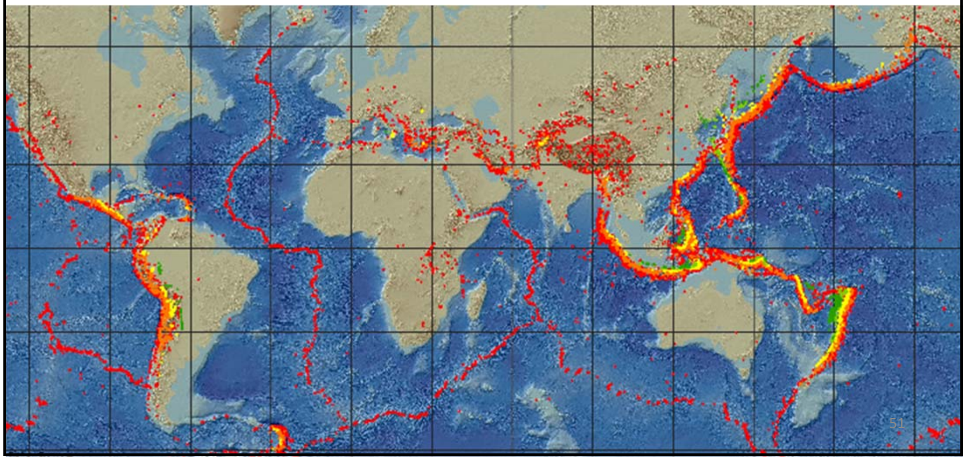
Real-time simulation of plant behaviour as an aid to decision-making from options and assess the current/future risks potentials, backed by precise accident data tracking system by recoding every plant behaviour and remedial actions

7. Accident instrumentation

8. Management (Who is in charge?, Operation and Tech Support, SPEEDI etc)

Key Lessons Learned

9. Regulatory system
10. International aspect
Peer review of design and SAM, CSC etc



Never, Ever Again
anywhere in the world