Fukushima Accident : An overview, LL and implications

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Part I Overview of the Accident
Part II Offsite consequences
Part III Recovery actions
Part IV Key Lessons Learned
Part V Implications

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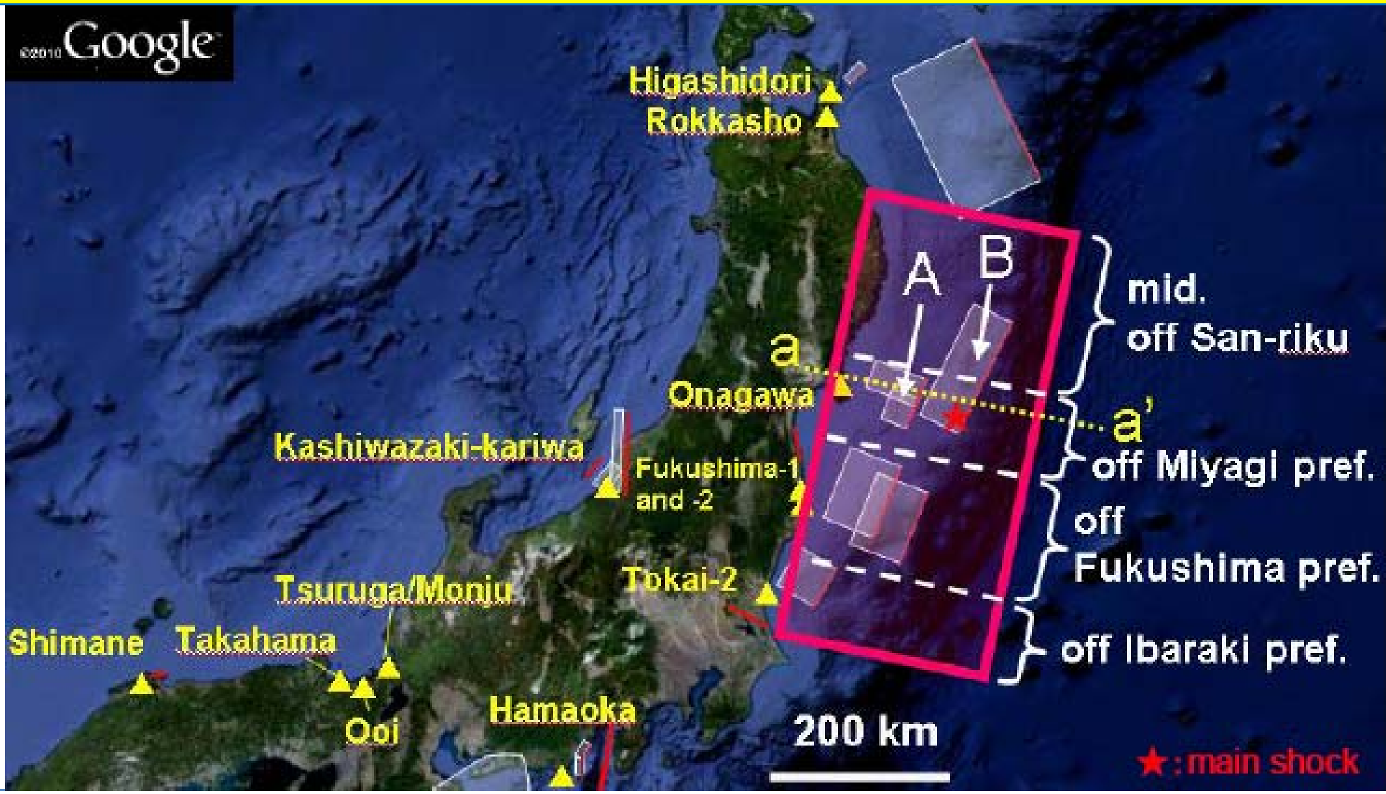
- *Part II Offsite consequences*
- *Part III Recovery actions*
- *Part IV Key Lessons Learned*
- *Part V Implications*

3.11 earthquake



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

Government Report to the IAEA, June2011: Initiation from B, then propagated westwards to area A, and further to the North and South. The Headquarter had alerted 99% probability of occurrence within 30 years for the Aregion with a magnitude of M7.5, but had not correctly estimated the <u>size of the source area</u> (400km x 200km) nor the <u>magnitude</u> (M9) nor the amount of <u>slip</u>*[SOURCE] Gov. Report to the IAEA, June2011*

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

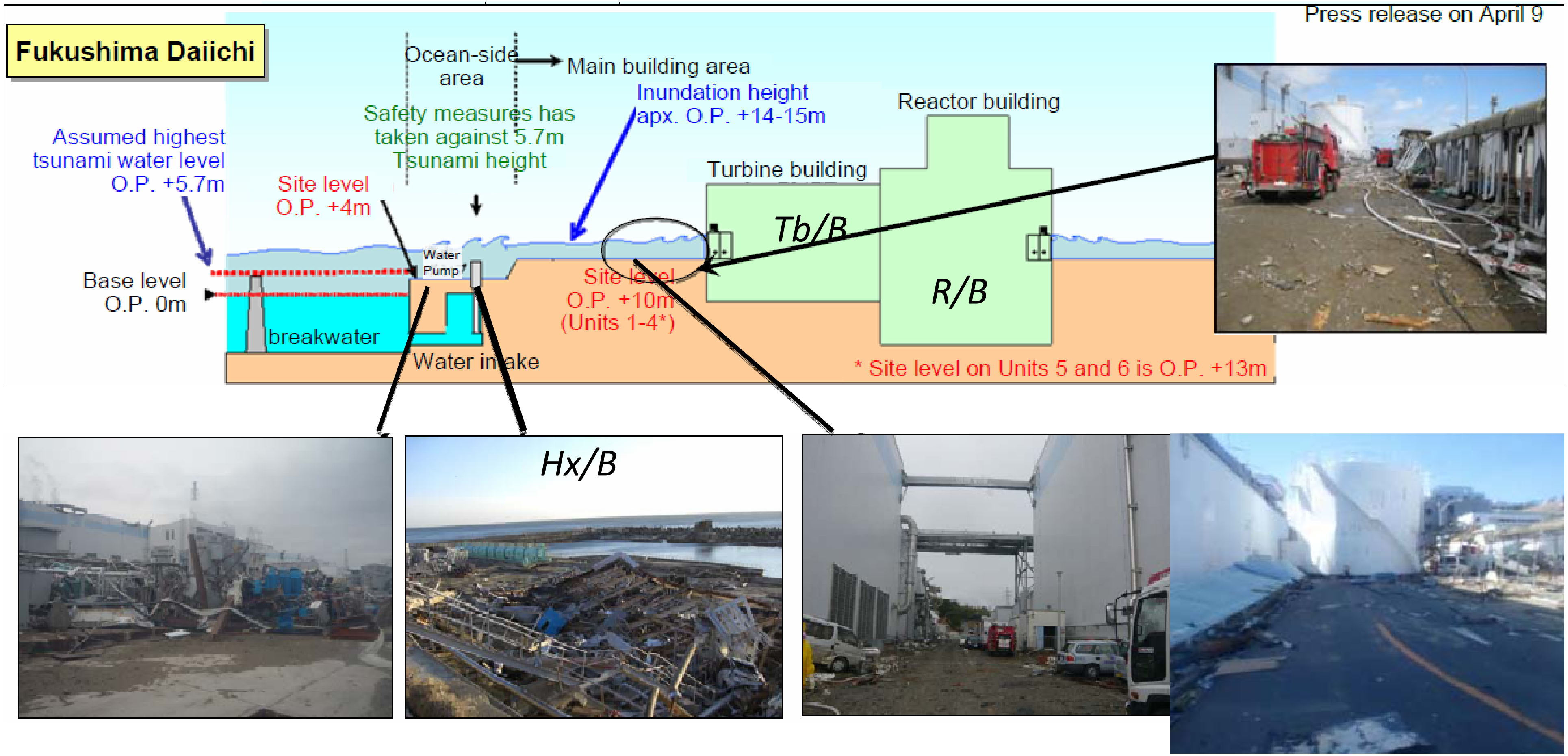
Note 1: **Damage by the earthquake**:

- ✓Not fully inspected but maybe not significant damage 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 6 offsite power lines to 1F were lost due to failure of breaker, 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 R/B basement: Horizontal=135 gal, Vertical=100 gal

Fukushima Dai-ichi NPP



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

Relocated tank prevented recovery actions

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

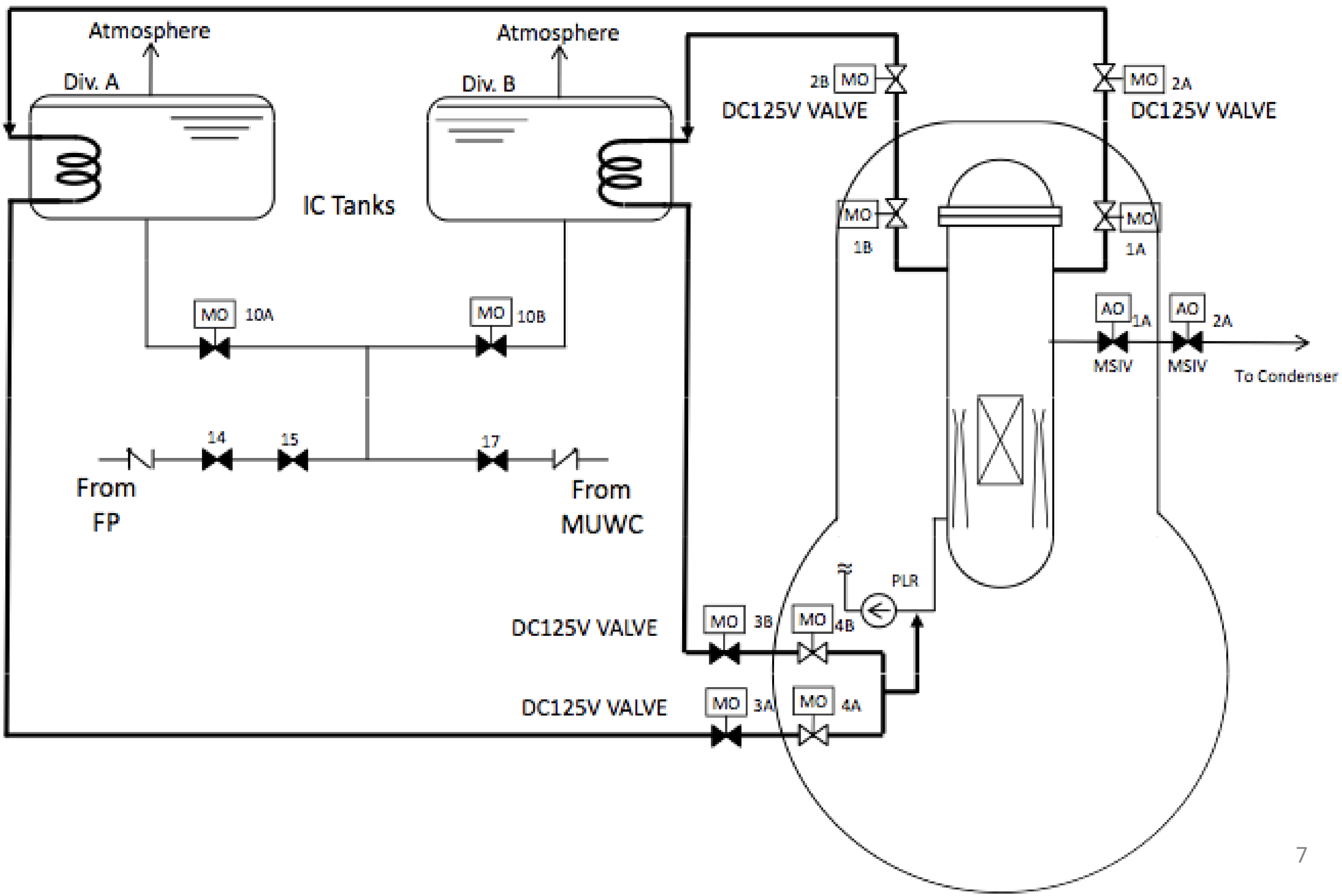
Then, while trying to restore AC/DC power and Heat Sink

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

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

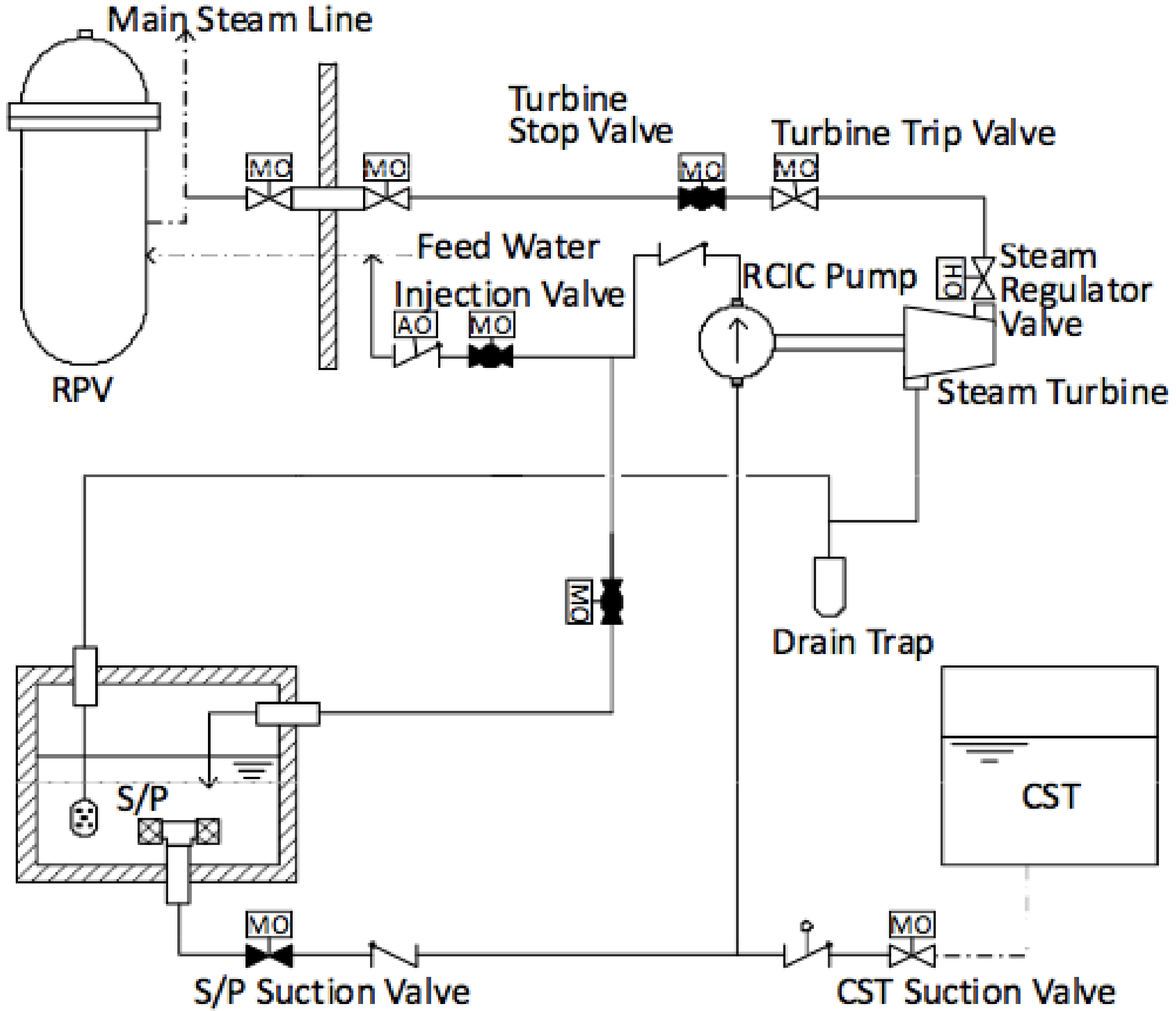
IC (Isolation Condenser)

Heat dissipation to the air



RCIC (Reactor Core Isolation Cooling)

Use of own steam to makeup water to the reactor core



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

TMI and Fukushima core uncover: estimation

	TMI		Fukushima
Day 1	00	Tb trip, Loss of FDW	00 Earthquake LOOP, EDGs start, IC/RCIC operation
	03 sec	SRV stuck open	
	3 min	HPI stop	1 hr Tsunami Blackout &loss of UHS
	100 min	Coolant circulation stop	(1F1)
	174 min	B pump start (fuel collapse)	(1F2)
	113-174 min	Core uncover	(1F3)
	200 min	HPI restart	
	224 min	Slumping to RPV bottom	

Day 2

Day 3

Day 4

1F1: **4-15* hrs**

1F2: **75 -77* hrs**

1F3: **40 -43* hrs**

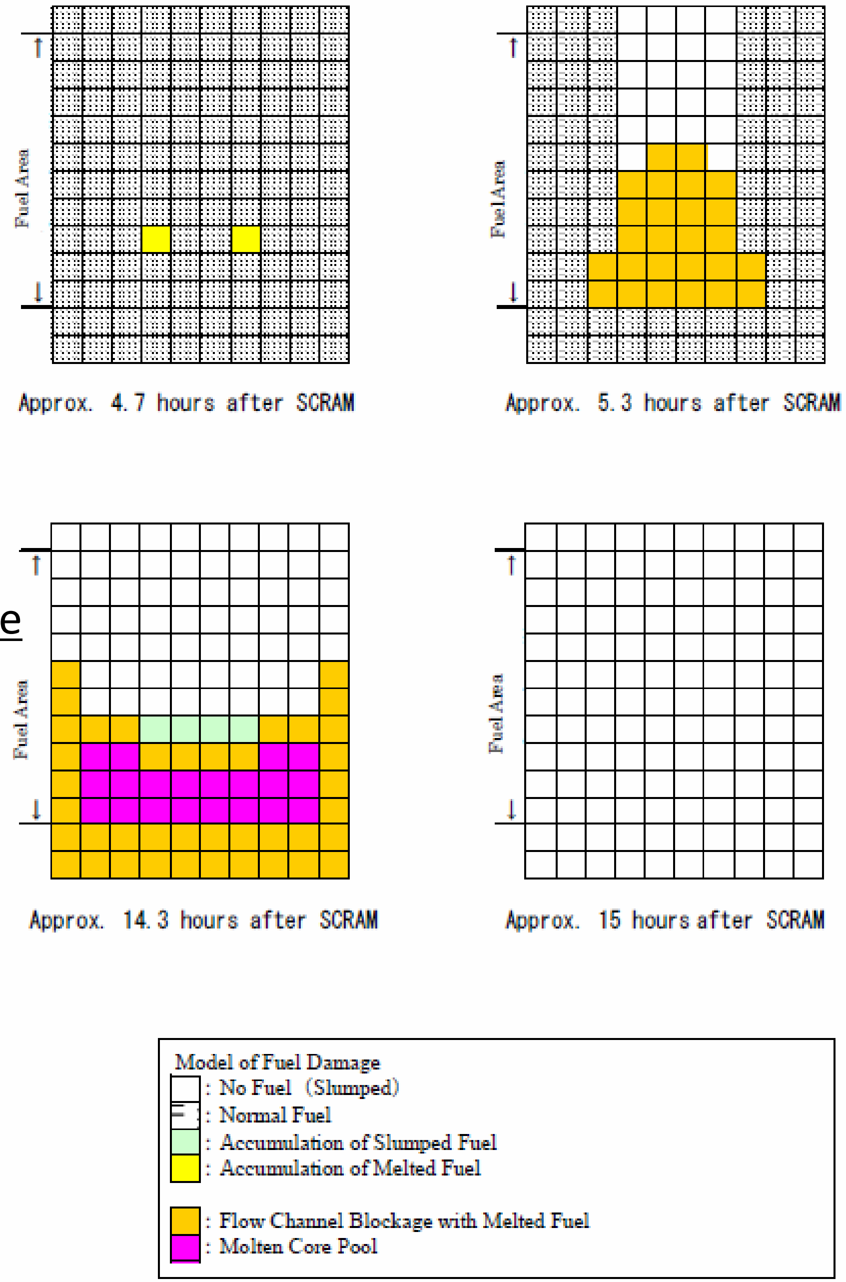
*Estimated time from start of core uncover to start of successful injection

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

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



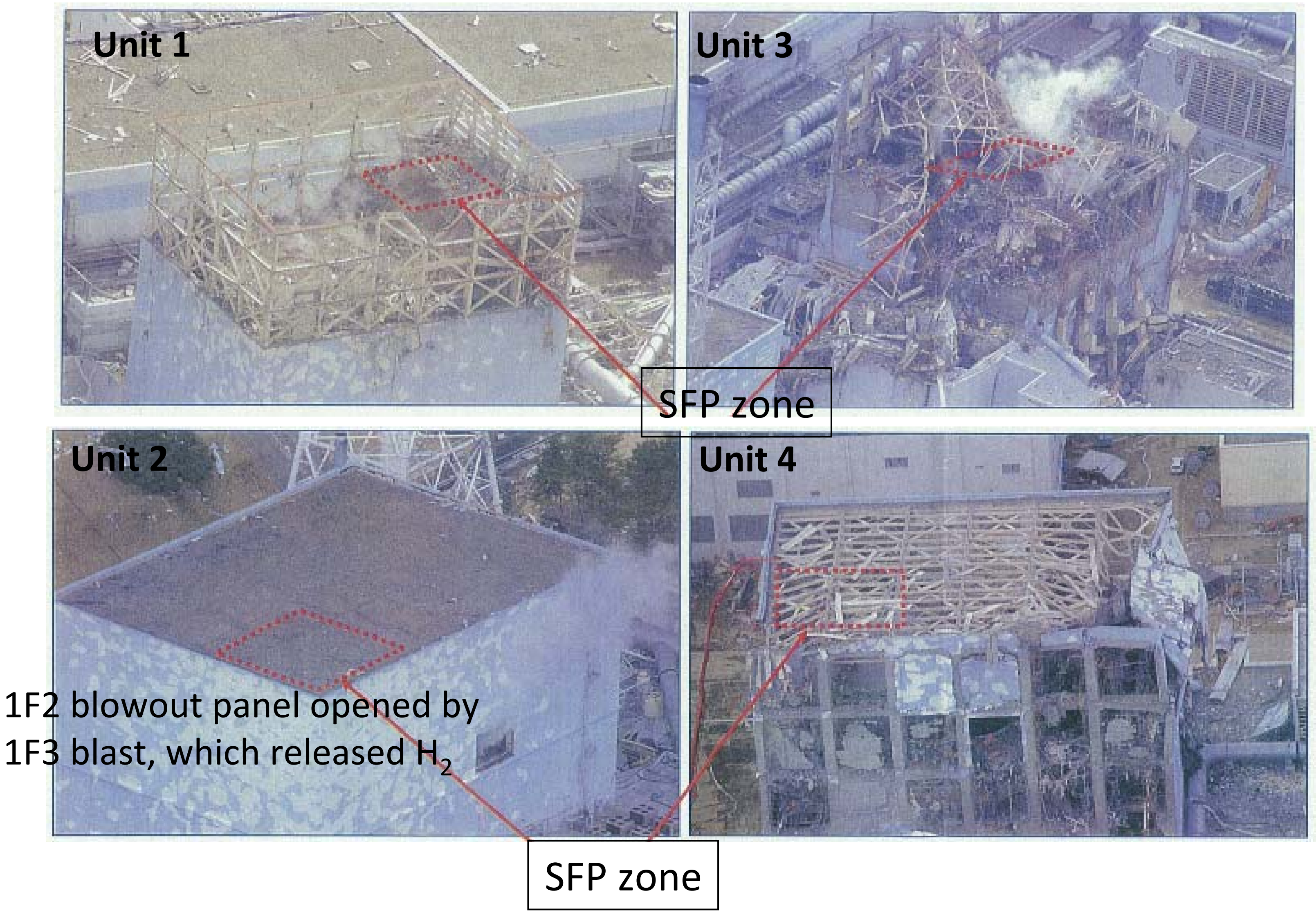
<u>Time of RPV melt-through (M/T) after the earthquake</u>

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



Hydrogen/Oxygen generation and combustion

- Flammable region : H_2>4% AND O_2>5%

- BWR containment
  - ✓Interted (Nitogen)
  - ✓ hydrogen recombiners, oxygen control
  - ✓ Steam inert condition in accident condition

- **Source of hydrogen caused 1F4 explosion**
  - ✓Water sample from SFP indicates SFs in 1F4 most probably remain intact (well-decayed Fission Products)
  - ✓Photo taken on March 17^{th} (before spray) indicateed SFs continued to be covered by water
  - ✓Unit 4 SGTS filter revealed higher contamination in downstream

→Hydrogen most probably came from path 2

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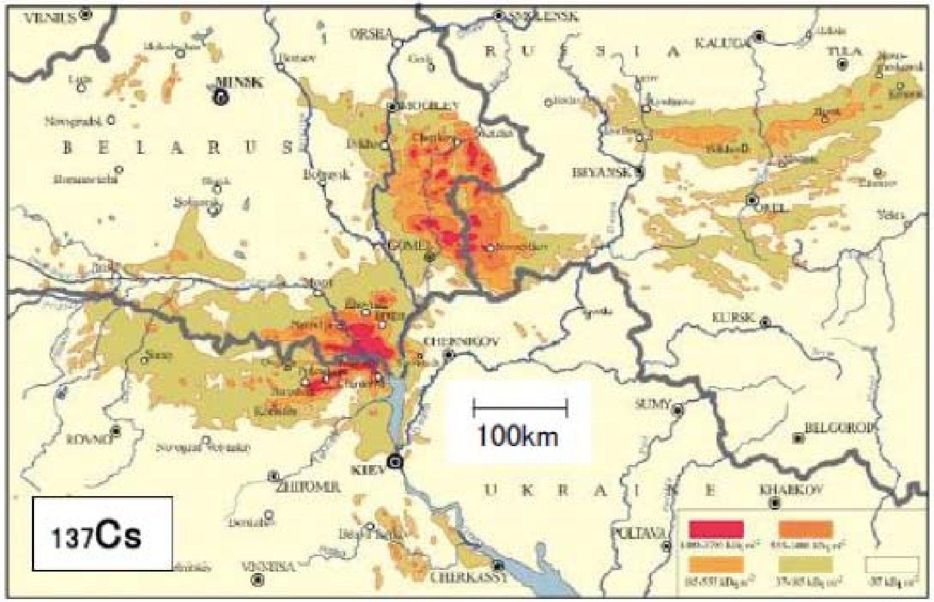
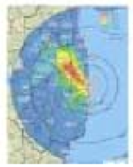


汚染レベル毎の面積	
37−185kBq/m2	: 162,160km2
185−555kBq/m2	: 19,100km2



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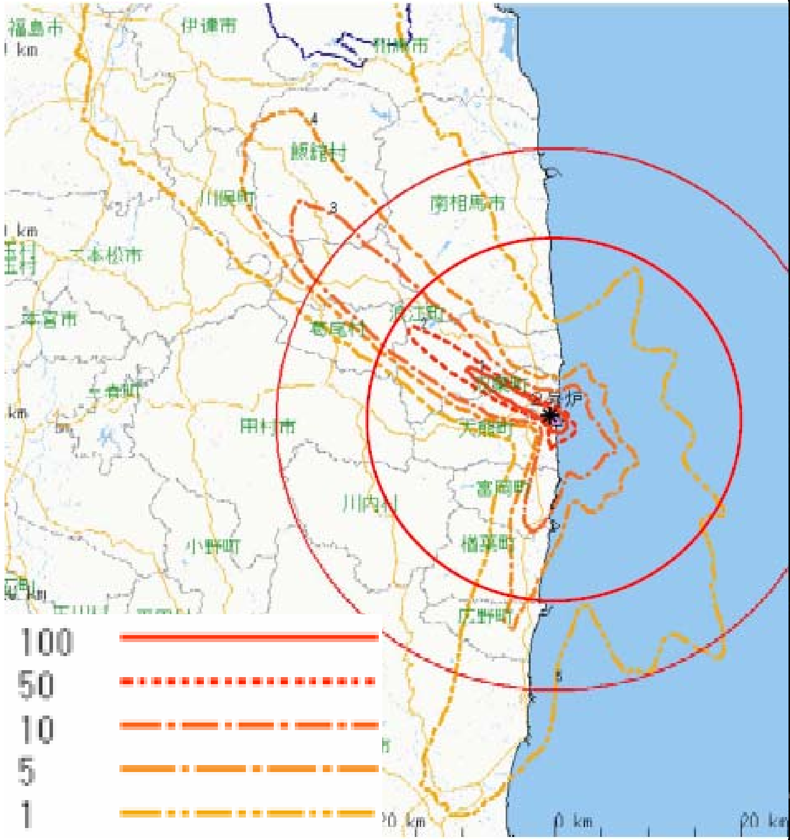
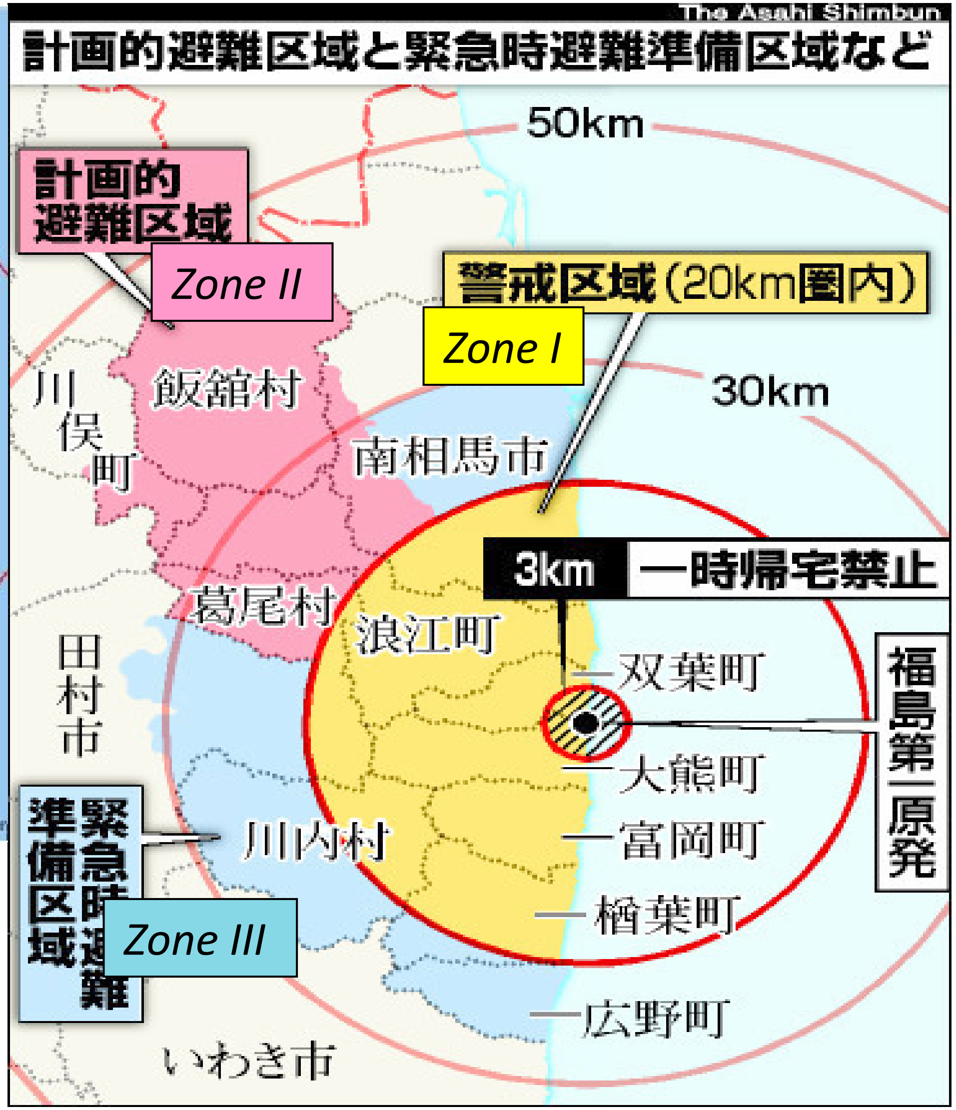
[Source] sunoyama, AEC hearing, 2011June14

What offsite emergency plan was enacted?



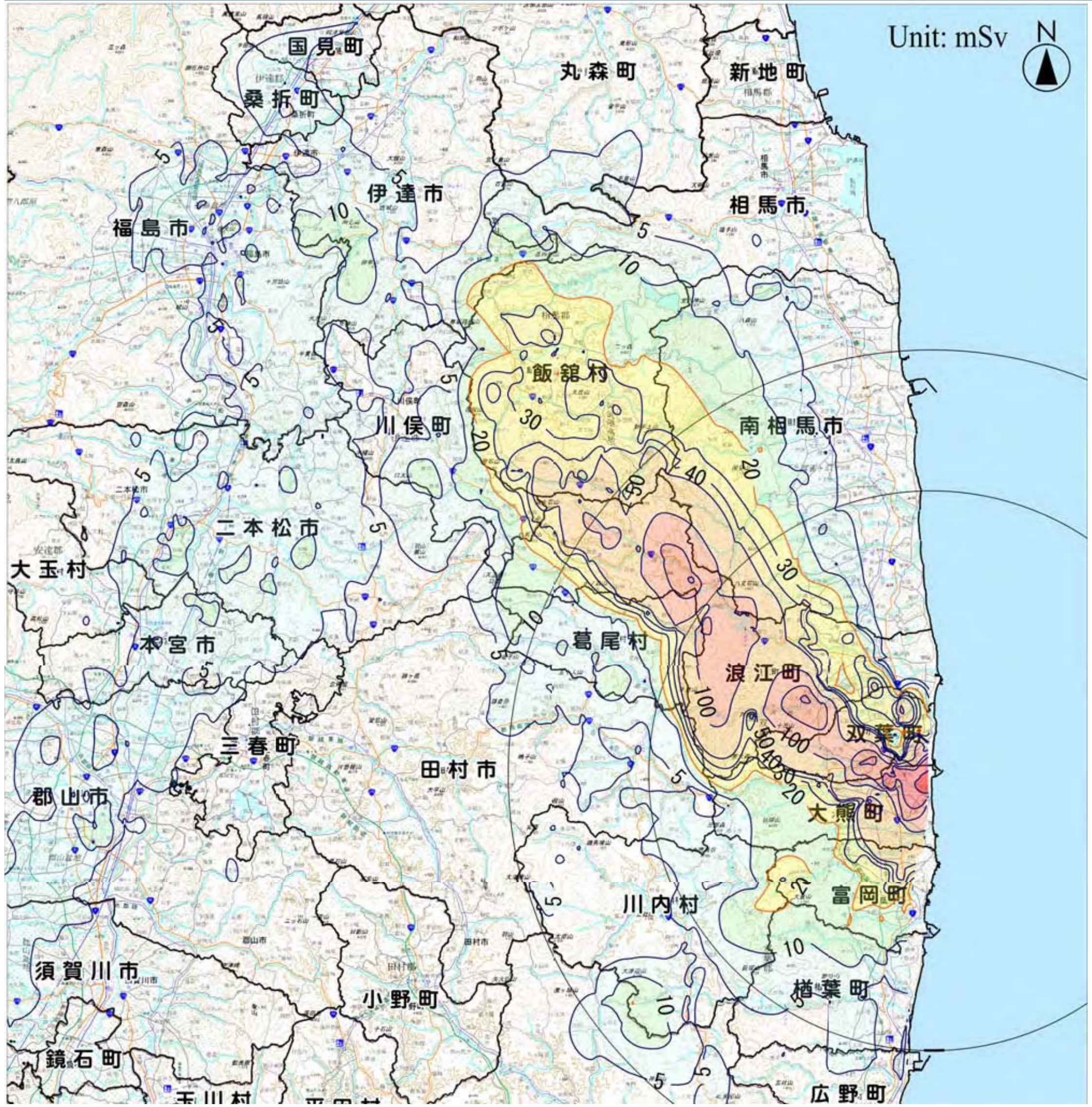
(mSv)

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"

Predicted accumulated dose (By 2012August 11)

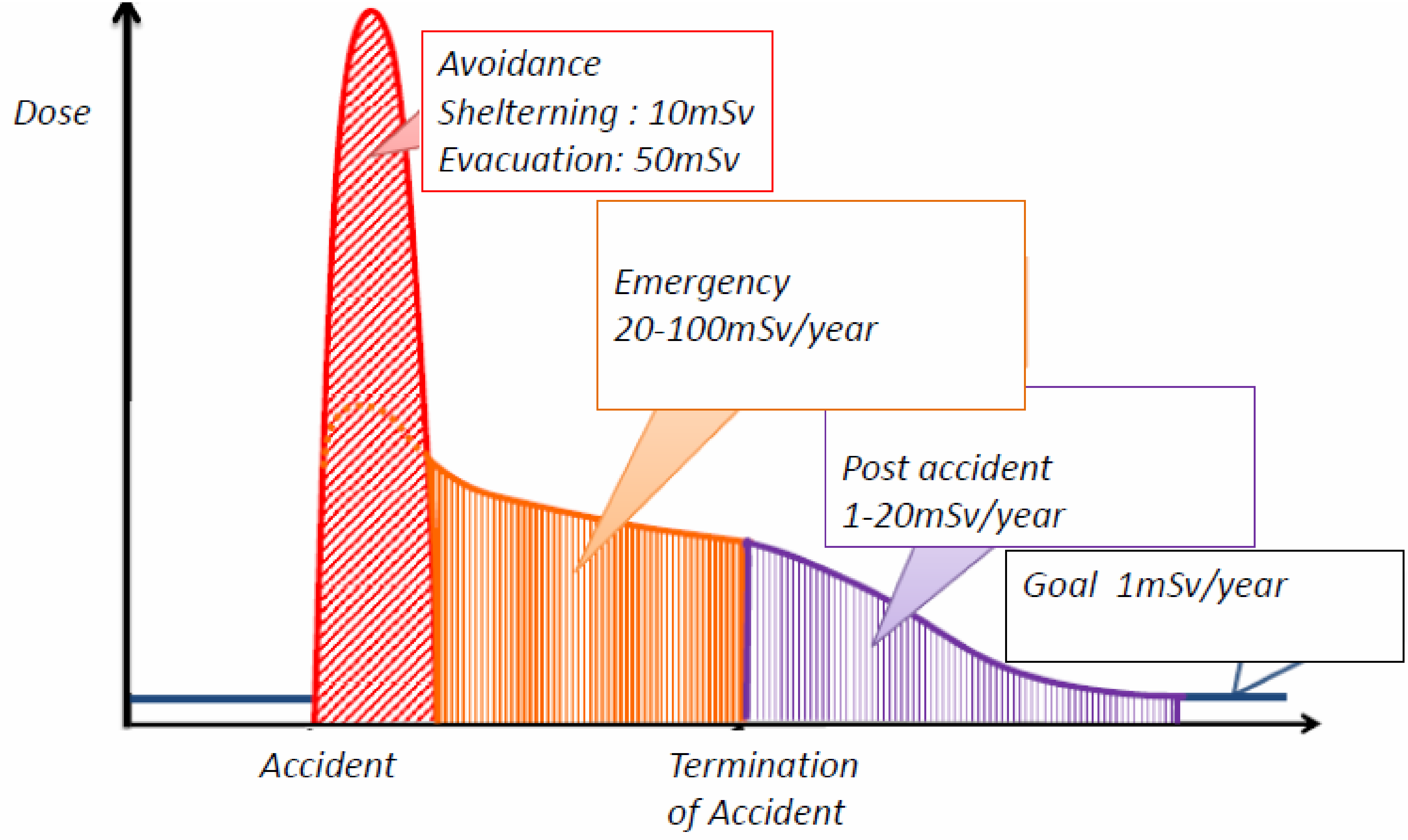


30km radius

20km radius

Based on environmental exposure measurement, Not including internal dose
[SOURCE] http://radioactivity.mext.go.jp/ja/1750/2011/08/1750_081914.pdf

By the Nuclear Safety Commission



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

Offsite decontamination

1. Specific purpose law to be enacted, followed by particulars on technical standards, classification of areas

2. Government announced "Basic Principles on Emergency Decontamination Works " (August 26th Nuclear Emergency Response Headquarters)
   a) Zone I & II: Government to reduce areas of dose higher than 20 mSv/yr
   b) Zone < 20mSv/yr: government to work with municipalities and local residents for effective decontamination, target to 1mSv/yr
   c) Target: 50% reduction (including weathering effect) in contamination level in 2 years
   d) High priority to schools
   e) Temporary storage of removed soil etc for later disposal

3. Decontamination team of Nuclear Emergency Response Headquarters located in Fukushima for one-stop service
   - ✓ In cooperation with JAEA and other research institute, AESJ, NPOs
   - ✓ Verification tests

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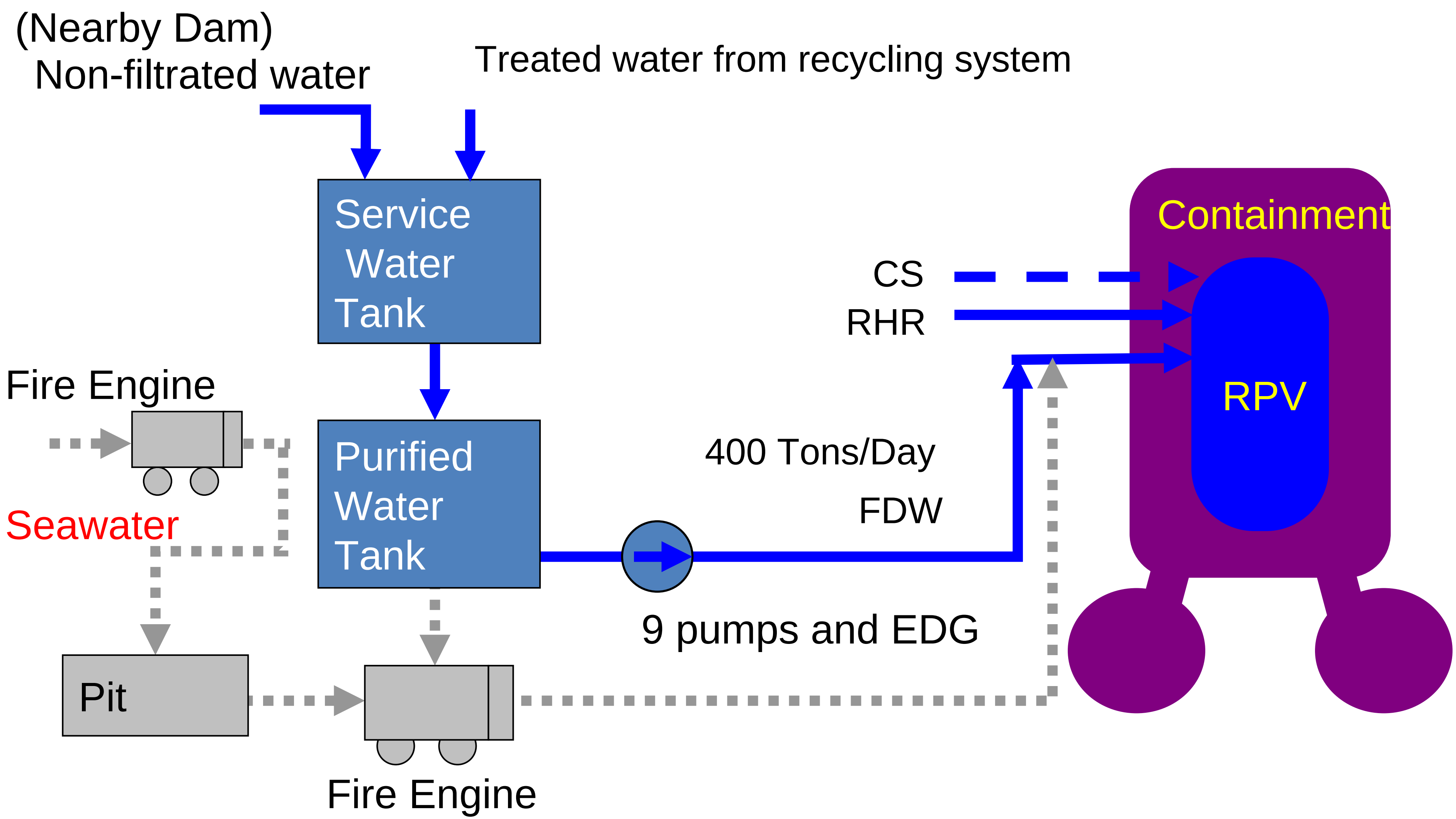
Key onsite recovery actions

1. COOLING
   - ✓ Stable cooling to low reactor temperature and subsequent flooding of the containment *[challenge] working environment & leakage of water from the containment*
2. MINIMIZING AIRBORNE/LIQUID EFFLUENT
   - ✓ Recycling of water recovered from Tb/B through removal of radioactivity and RO
     ~1200 Tons/Day treatment
     ~400 Tons/Day treated water return to the reactors
   - ✓ Storage of contaminated water
   - ✓ Installation of R/B cover
   - ✓ Corrosion control
3. MINIMIZING RESIDUAL RISKS
   - ✓ Aftershocks (Structural integrity of damaged R/B, Reliability of power/water supply)
   - ✓ Hydrogen

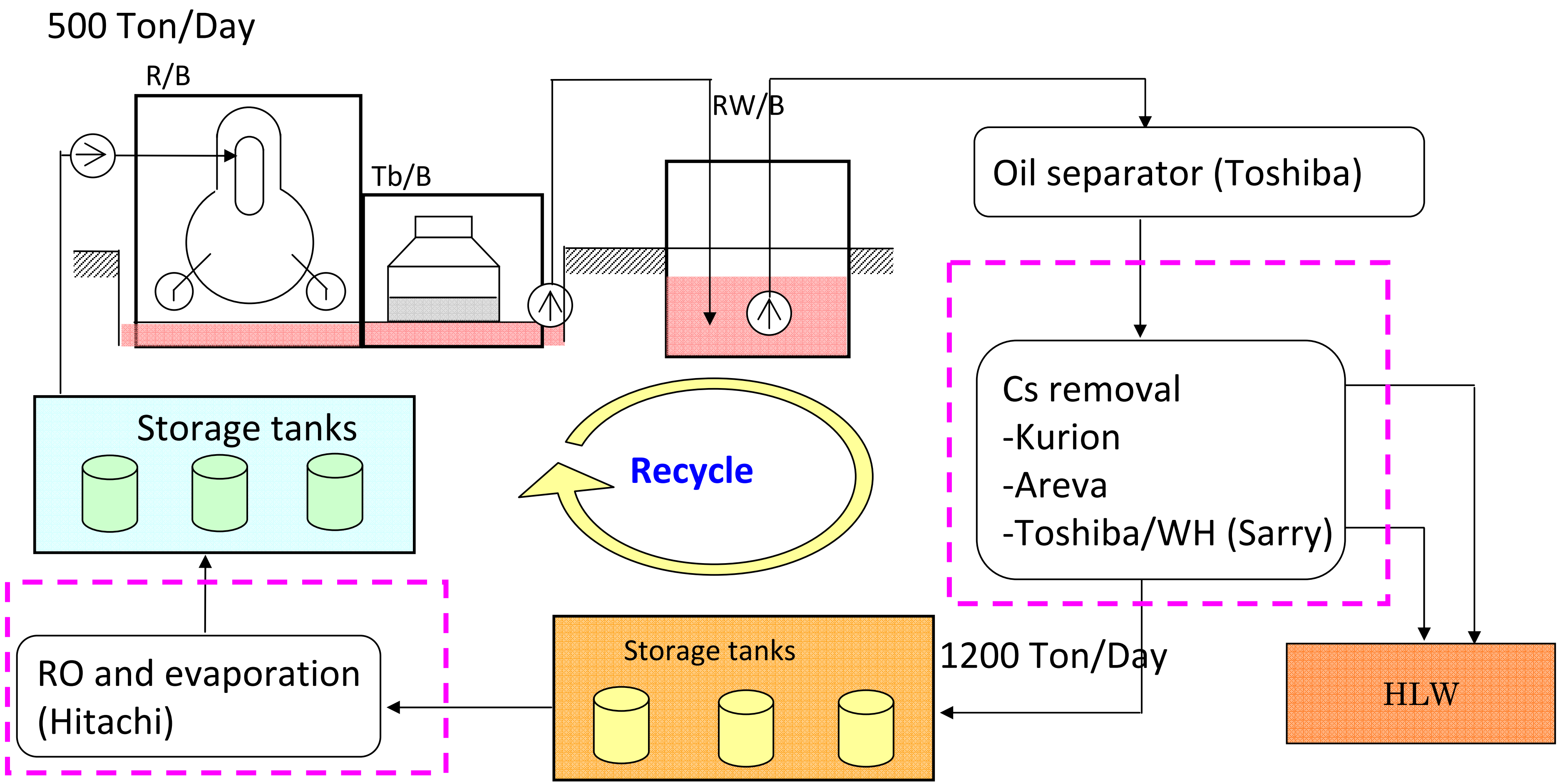
Water Injection to the reactor core

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



Recycling of water

Inventory control to avoid spill-over to the environment, Removal of Cs, Removal of Cloride



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 : 177,500~222,500 Ton

Storage of contaminated water

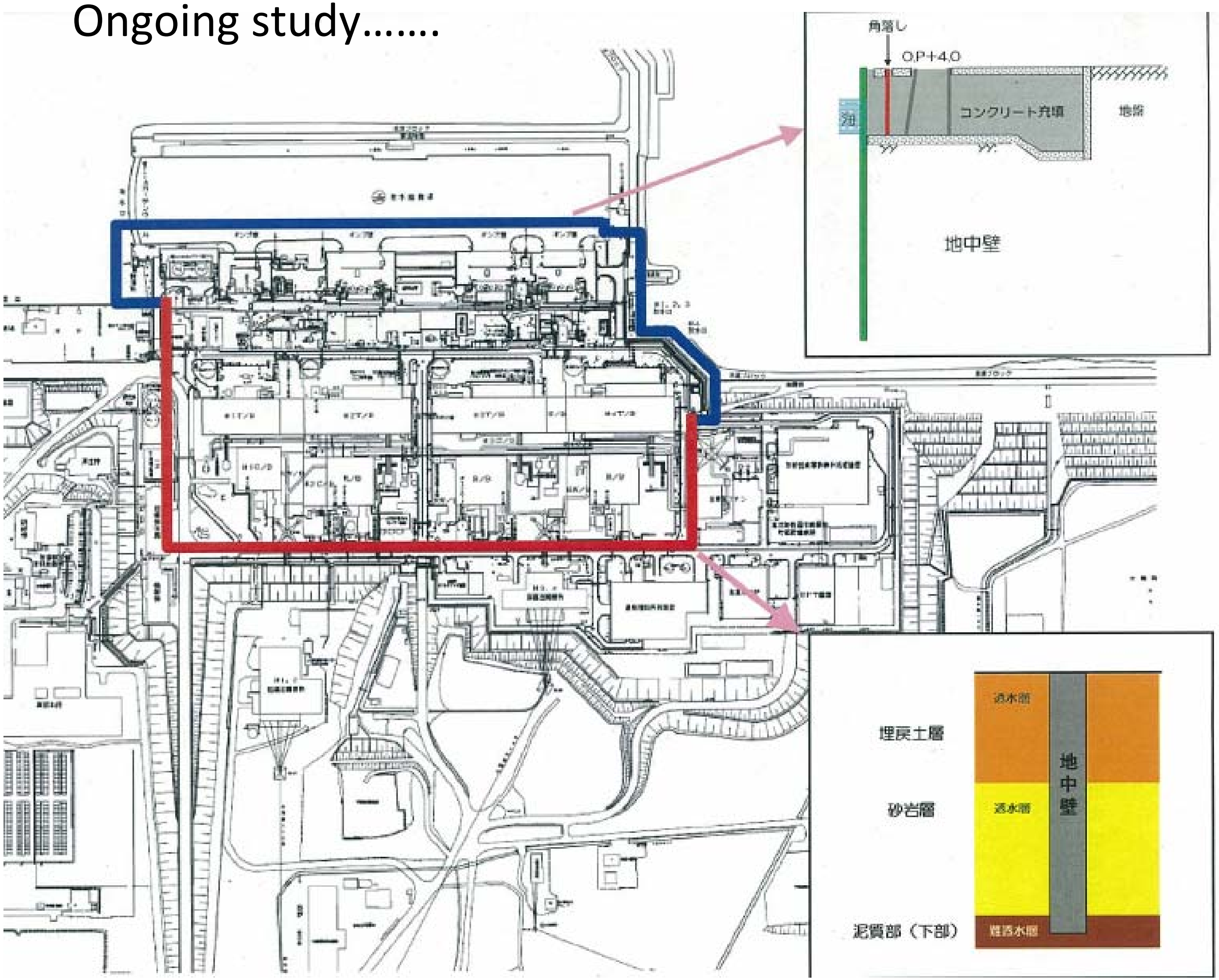
Area	Contents	ton	Note
B,F	Low level	18,400	
D,E,H	Condensed brine by RO	33,000	Addition of 20,000ton/month
G	High level	10,000	

Reactor building cover

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

Isolation of surrounding area by walls

Ongoing study.......



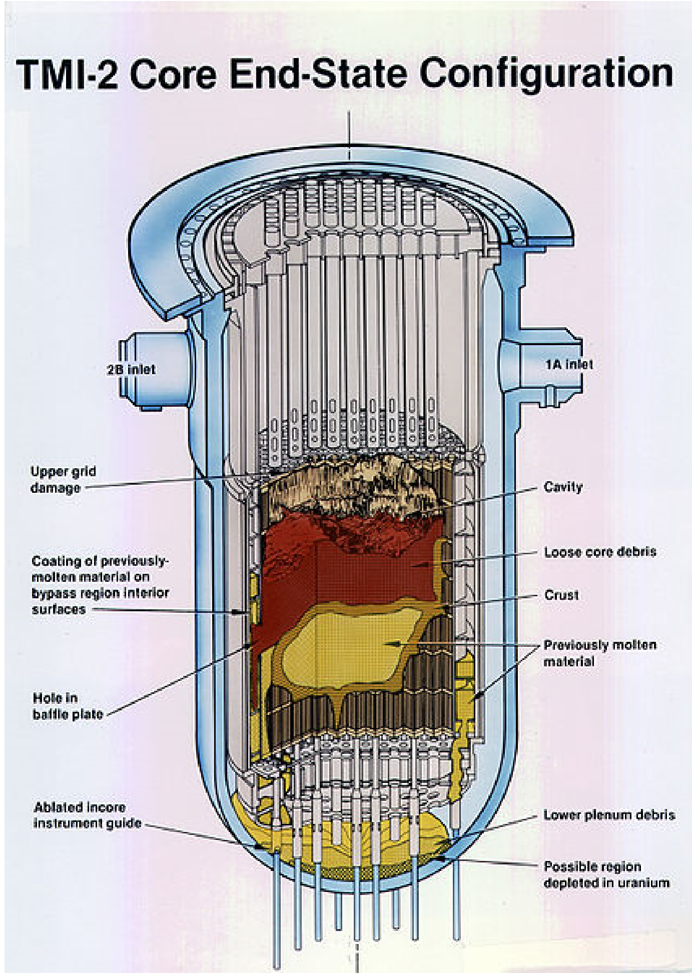
Beyond stabilization phase

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

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
     - ✓ Windscale (UK, 1957)
     - ✓ A-1 (Slovakia, 1977)
     - ✓ TMI-2(USA, 1979)
     - ✓ Chernobyl (Ukr, 1986)

4. **Final disposal of wastes**



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Key Lessons Learned (1)

- **Government report to the IAEA (2011 June) : 26 Lessons in 5 specific areas (Prevention of SA, SAM, Emergency response, Safety infrastructure, culture)**
  http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html
- **Below goes a bit further beyond Government report through deliberation**

1. Design considerations against natural hazards

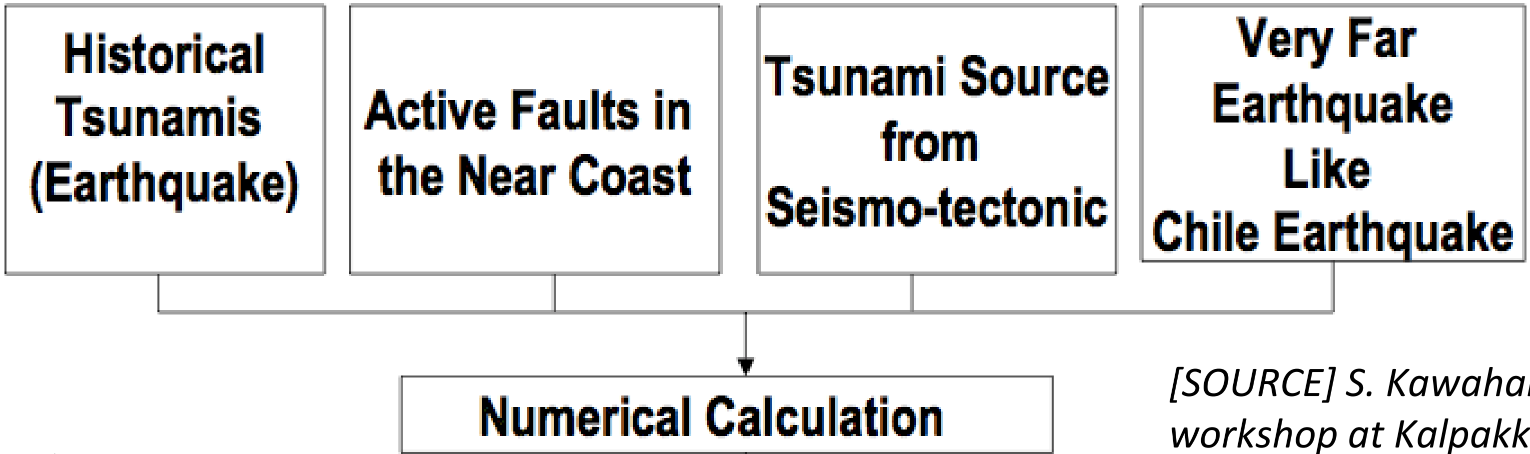
- *CCF (such as of onsite/offsite power) by natural and man-made hazard*
- *Treatment of uncertainties*

2. Design considerations against TOTAL loss of power and Isolation from UHS

- *Diversified power & water supply & heat sink: Air-cooled DG, Water from dam etc.*
- *Extensive use of passive safety features (use of stored energy, without power, reduced system inter-dependency)*

Tsunami design basis

- **Safety Design Guide (NSC) Nr. 2**
  - "….Anticipated natural hazard includes flood, Tsunami …."
  - "The severest conditions" refer to the conditions <u>not less severe than the past records</u> of the natural phenomena in question that are considered to be reliable and statistically reasonable. [footnote]
- **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 (2002)

Tsunami design guideline based on probabilistic study

- ◆ **Tsunami Probabilistic Hazard study**
  - ✓ Probabilistic Tsunami hazard analysis (TEPCo, ICONE-14, 2006)
  - ✓ Methodology guide from **JSCE** (2009)

- ◆ **IAEA DS417 (draft)**
  - ➢ Includes guide on Tsunami analysis

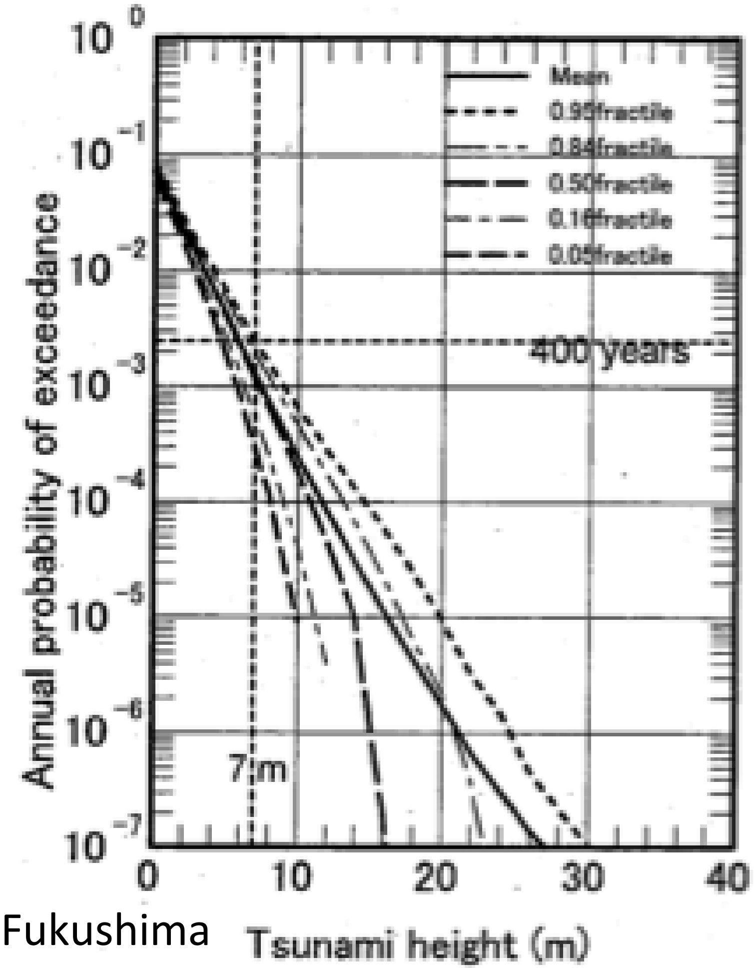


Fig: Not for Fukushima

Treatment of uncertainties

Logic tree to represent epistemic uncertainty

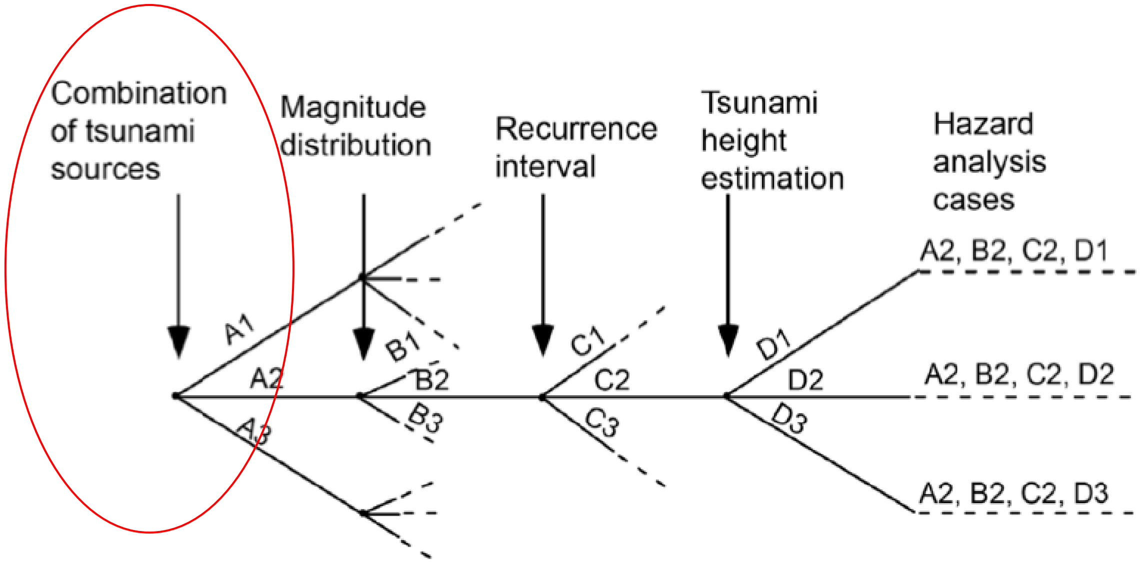
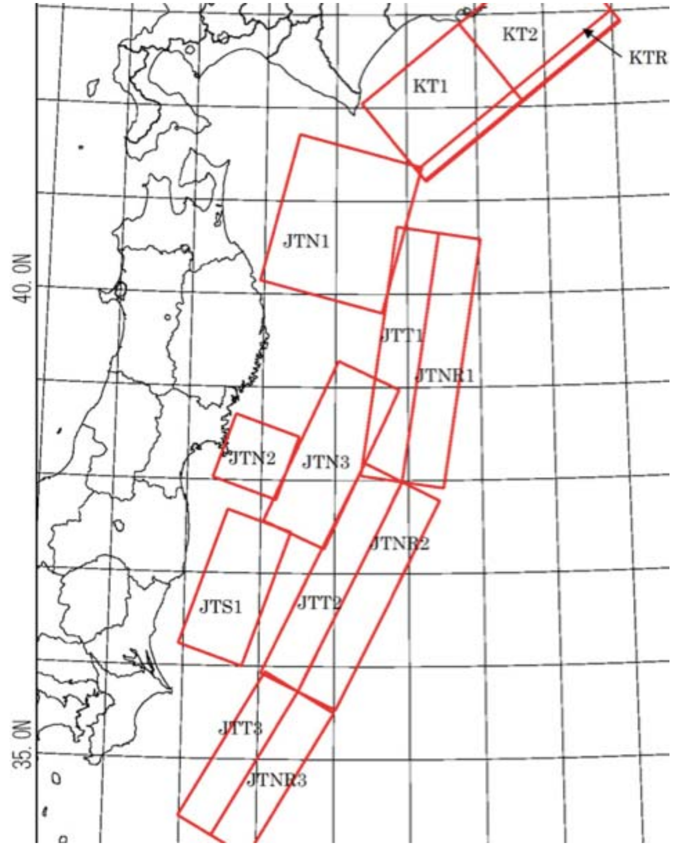


Fig. 1 Logic-tree representation of uncertain parameters

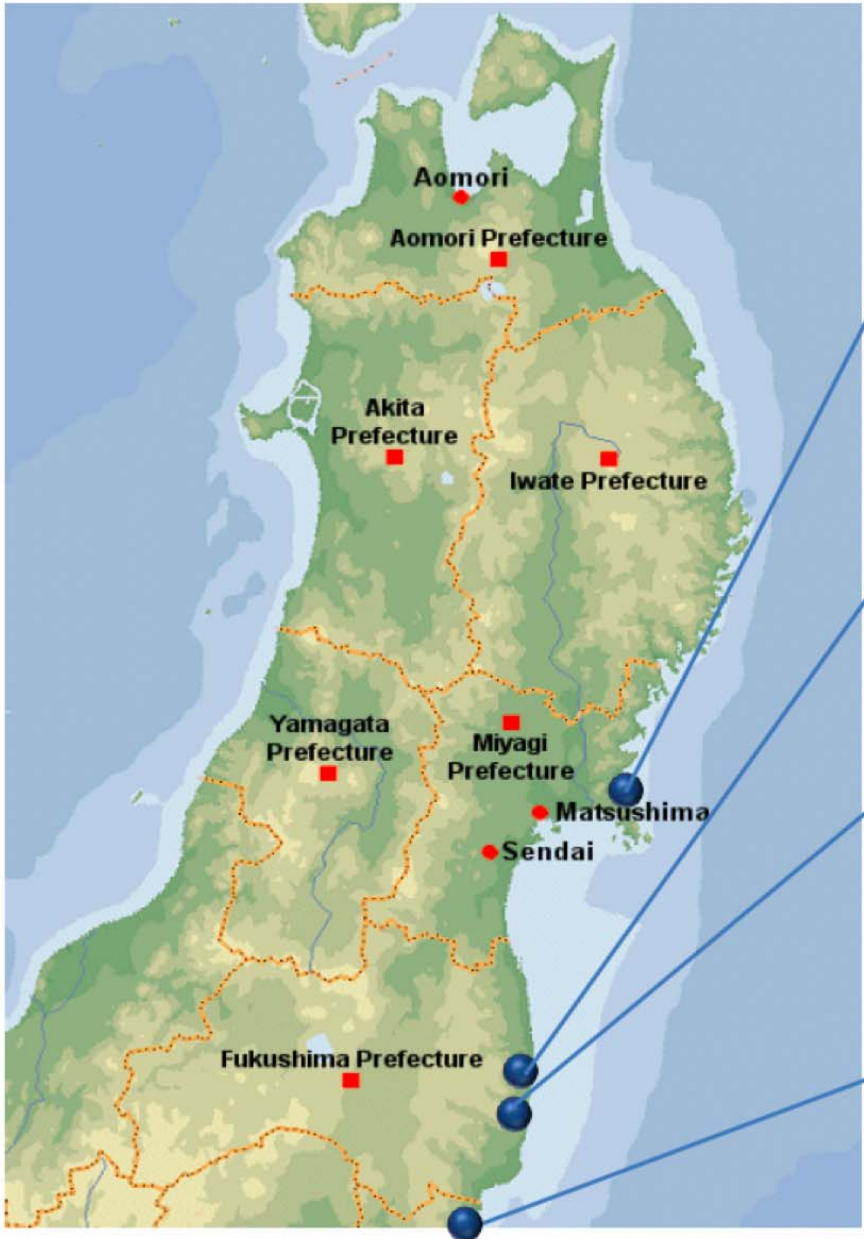


[SOURCE] T. Annaka, "A method of Probabilistic Tsunami Hazard analysis, 12th Civil Engineering Society, 2006

Kanamori paper (Earth Planets Space, 2006)

Implication for the long-term seismic hazard in northeastern Japan….These observations suggest: (1) Three quarters of the plate motion is taken up by aseismic slip which was not resolved by the GPS analysis, or (2) The plate boundary is coupled 100%, and the accumulated strain will be eventually released by either large megathrust events, large tsunami earthquakes, or large silent earthquakes.

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

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

Simply said,

(1) Elevation vs. Tsunami height

- Site ground level→ saved Onagawaand 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)

Key Lessons Learned (2)

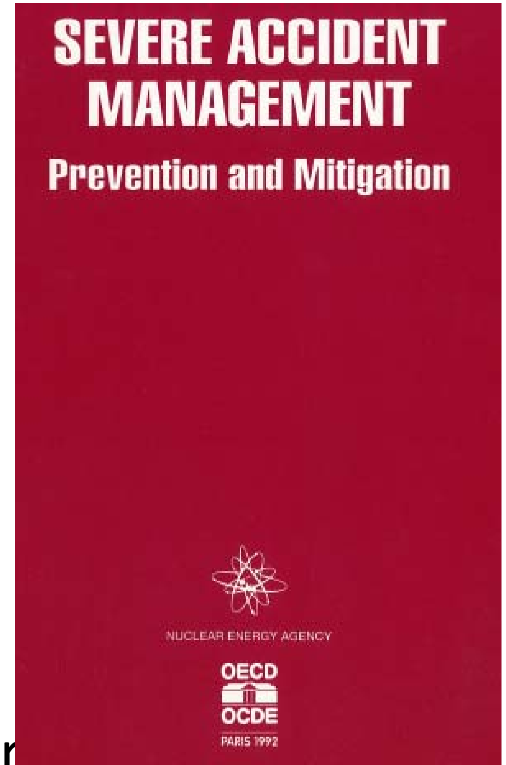
3. Workable/effective Severe Accident Management

- *Provisions of Onsite or National/Regional Nuclear Crisis Management Center for storage of mobile equipments & drill*
- *Implementation of recovery actions in harsh radiation environment*
- *Hydrogen detonation/deflagration outside of the CV*
- *Real-time simulation of plant behaviour as a decision aid*
- *Accident instrumentation*
- *SAMG not robust enough to cover plant damage conditions*
  - → *Consider integration of three Gs (internal event, external event and security-related event*

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)

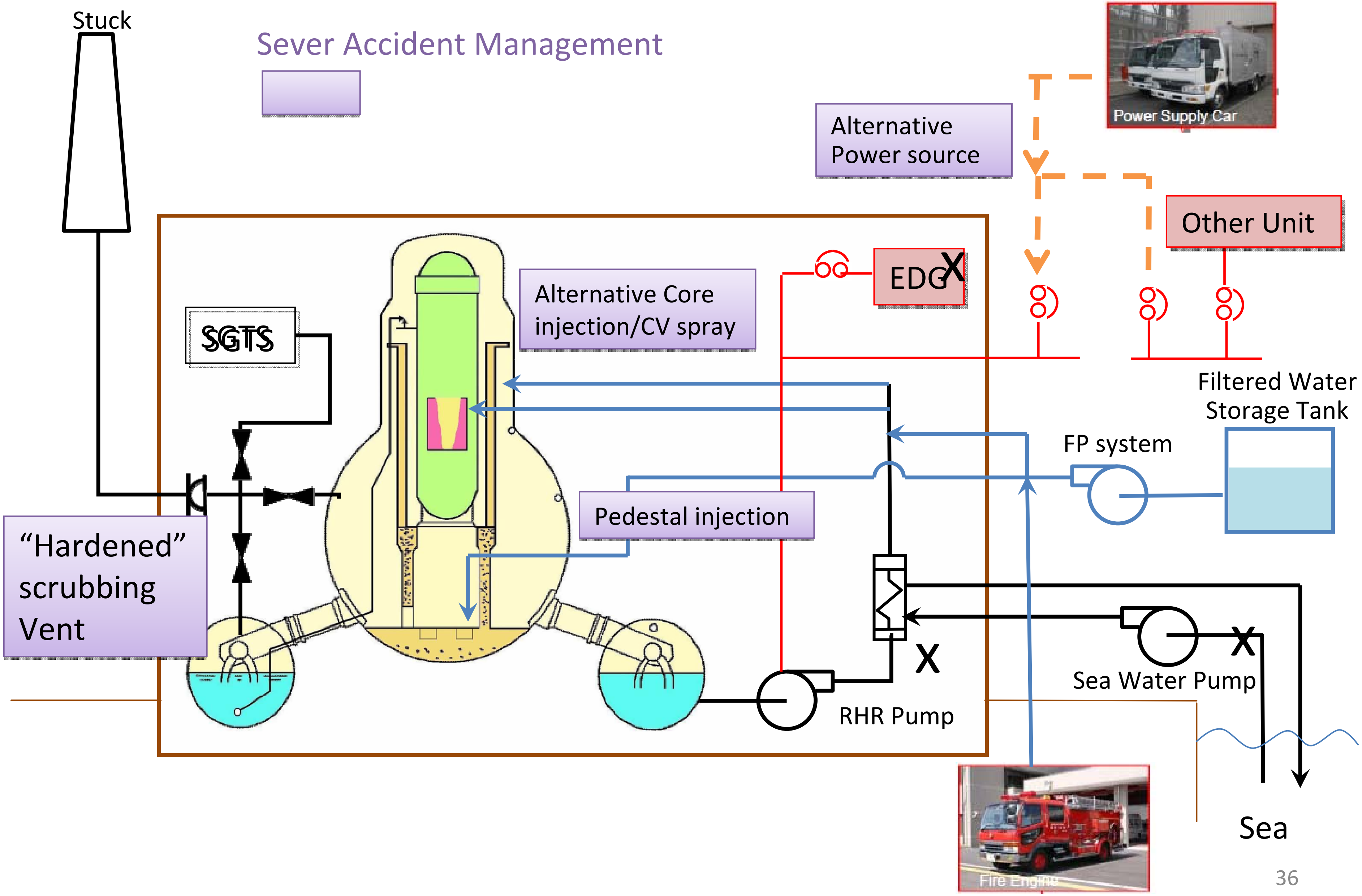
"Severe Accident Management": published in 1992
"Implementing Severe Accident Management in Nuclear Power Plants", published in 1996



(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

What SAM (Severe Accident Management) was in place?



Key Lessons Learned (3)

4. Safety regulation and safety culture

Regulatory standards, Independence, human resources

5. Multi-unit installation

6. SFP design

Location, Early transfer to storage facilities

7. Emergency Management

- ✓*Who is in charge?,*
- ✓*Offsite center,*
- ✓*Use of SPEEDI code (Prediction of Dose using realtime release source term data) [http://www.bousai.ne.jp/eng/*

8. International aspects

- ✓*Dissemination of information*
- ✓*Issues that would be considered in international safety standards and practices*
- ✓*Cooperation on safety including peer review over design, site, safety culture*

Safety Culture

Three-level model of Safety Culture

Artefacts-Visible Signs

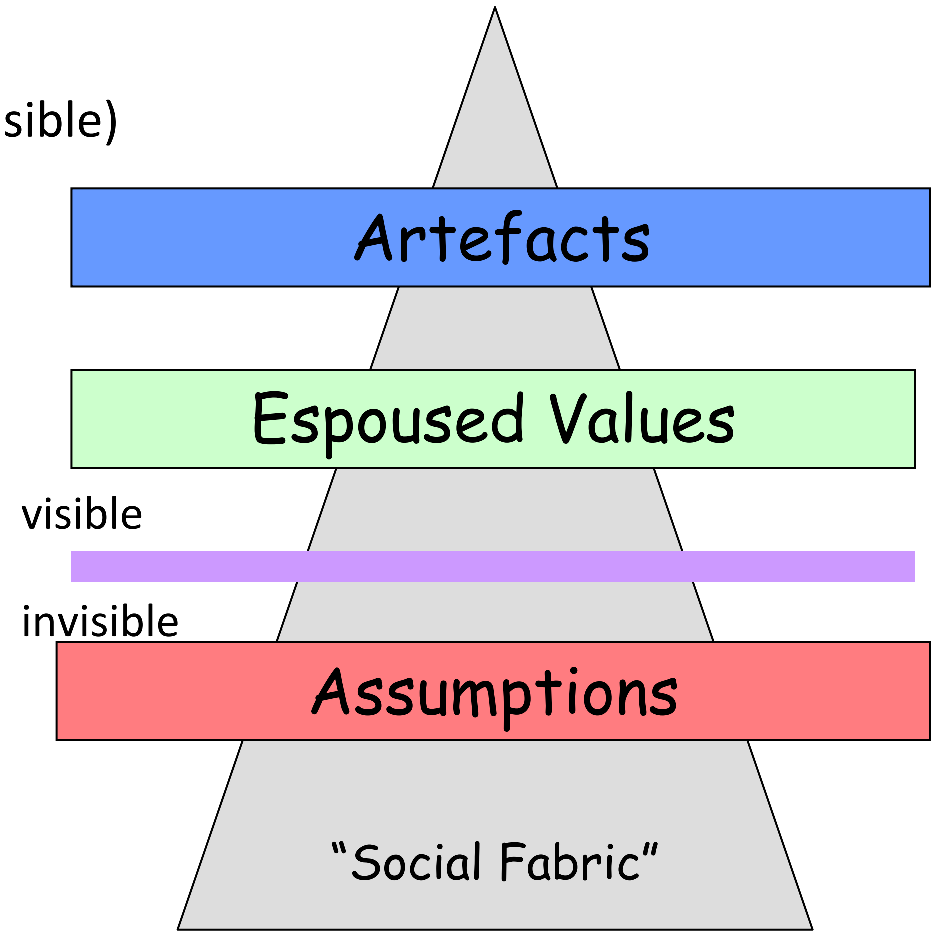
(greeting rituals, dress, housekeeping – visible)

Espoused Values

(values that are adopted and supported by a person or organization based on strategies/ goals)

Basic Assumptions

(Such as "human nature good or evil")



[SOURCE] Edgar Schein, former professor at the
MIT Sloan School of Management, expert on organizational culture

Change in nuclear safety regulatory system (1)

1. Decision by Cabinet (2011Aug15):

   - Integration of nuclear safety/security under Ministry of Environment
   - Nuclear Safety Agency and Advisory Committee

(Transfer)

- Safety regulation of commercial reactors: METI to MoE
- Safety regulation of research reactors: MEXT to MoE
- Nuclear Safety Commission: Cabinet office to MoE
- Nuclear security: Cabinet office (AEC) to MoE
- Environmental monitoring : MEXT to MoE

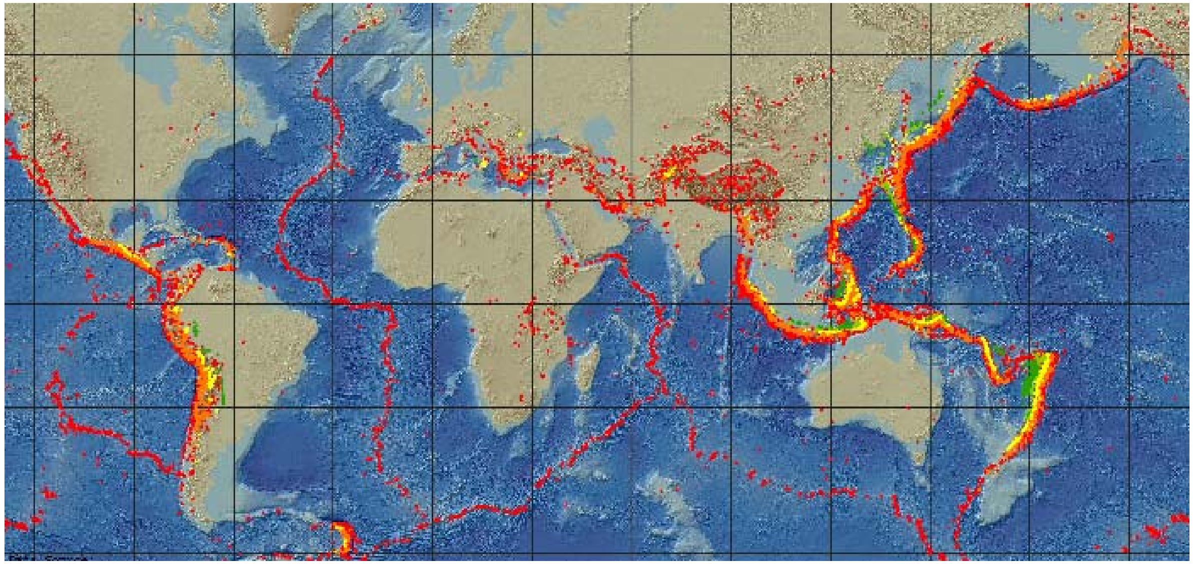
Change in nuclear safety regulatory system (2)

2. AEC statement (2011Aug30): expectations to the new organization

- ✓ Safety first and Independence to pursue “safety first” policy,
- ✓ Leadership,
- ✓ With advisory committee,
- ✓ Technical competence and use of TSO,
- ✓ Public trust
- ✓ Sharing information with the public,
- ✓ Learning organization,
- ✓ Decision-making based on Defense-in-depth supplemented by risk information and with clarity,
- ✓ Non-prescriptive regulatory standards,
- ✓ Use of consensus standards by the professional societies,
- ✓ Internationally proactive and harmonization with internationally well-recognized standards

Regional Cooperation
FNCA (Framework of Nuclear Cooperation in Asia)

- 1st meeting in Bangkok in 2000, now 12 countries as members, predecessor since 1990
- Decided on working together on protection against natural hazard in Asian region where earthquake, Tsunami, volcano eruption, typhoon are frequent (Ministerial meeting, November 2010, Beijing)
- 3rd "study panel" on nuclear power (July 2011, Jakarta)
  Shared information on;
  - ✓Fukushima Accident
  - ✓External event PSA (Earthquake, Tsunami)
  - ✓Consideration of natural phenomena in siting of NPP



Further on international implications

Personal observations

- Had shaken public confidence on NP (IAEA)
- Phase-out in a few countries
- Seemingly, no immediate significant change in nuclear power programmes in many countries (USA, China/India, New entrants)

- International nuclear community may need to consider;
  1. to strengthen support to new entrants for building nuclear infrastructure to enable safe operation
  2. to strengthen/implement international scheme in;
     - ✓ peer review in the area of safety
     - ✓ providing emergency support
     - ✓ liability system (Convention of Supplementary Compensation)
  3. to revisit defense-in-depth for its completeness/effectiveness,

while utilizing insights from risk assessment, such as;

- ✓ line 1 (material)
- ✓ line 2 (protection against CCF by natural and man-made hazard)
- ✓ line 3 (enhanced passive safety features)
- ✓ line 4 (considerations: beyond-DBE/protection against soil contamination)

Never, Ever Again
anywhere in the world

http://www.asahi.com/photonews/gallery/fukushimagenpatsu/