



# Lessons Learned from the Fukushima Daiichi Accident to Establish Resilience Technology for Nuclear Power Plants Based on the Defense in Depth Philosophy

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President of Japan Society of Maintenology

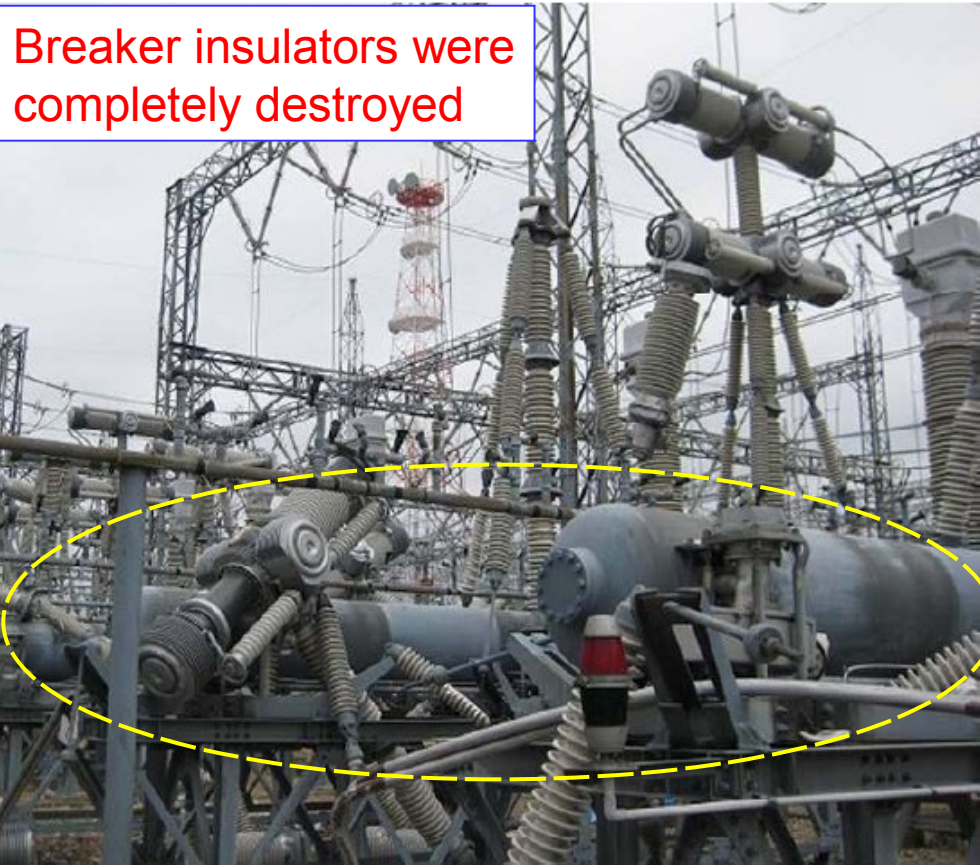
Professor, Hokkaido University



# Damaged External Power

■ External AC Power was lost in Fukushima Daiichi

Breaker insulators were completely destroyed



Damaged ABB(Air Blast Breaker)  
Fukushima Daiichi Unit 1-4

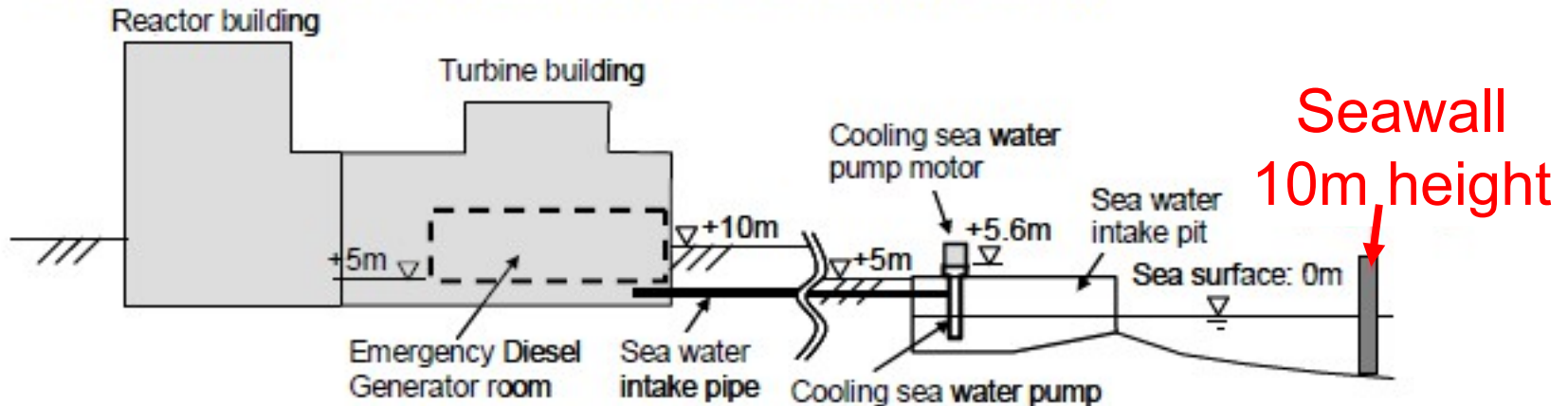


GIS : Gas Insulated Switchgear  
Onagawa Unit 1-3 were OK



# Tsunami getting over seawall at the Fukushima Dai-ichi NPS

## Cross section of Fukushima Dai-ichi (Unit-1)

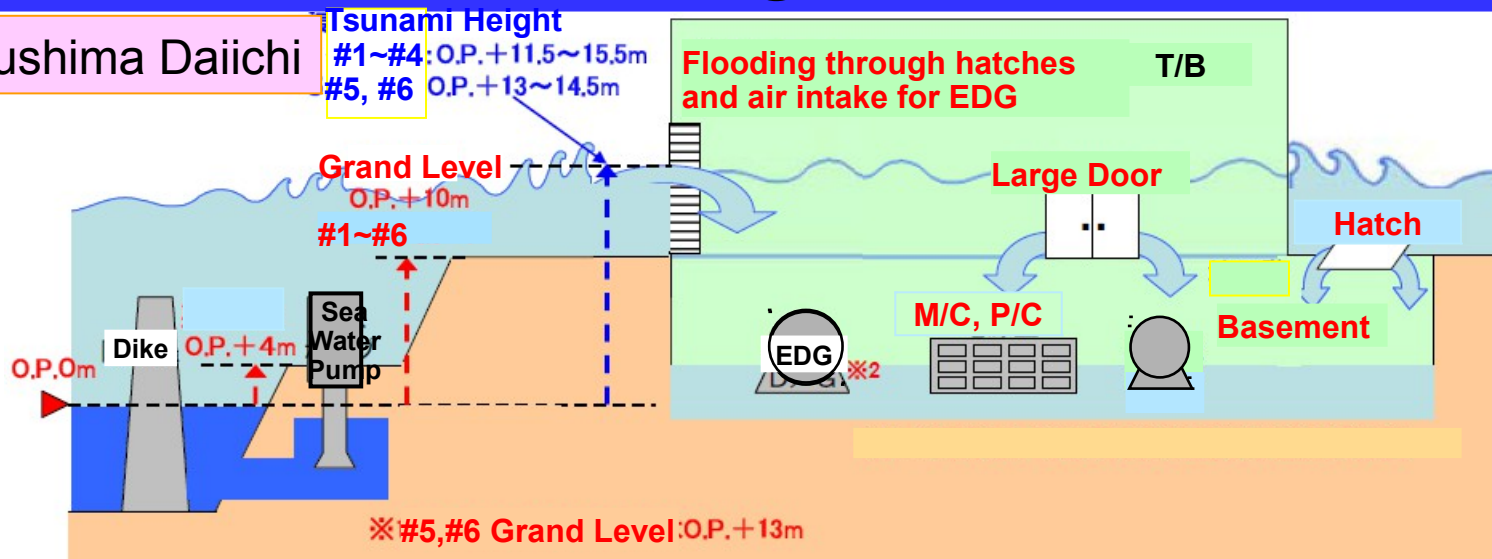


Reference: The Tokyo Electric Power Co., Inc. Release

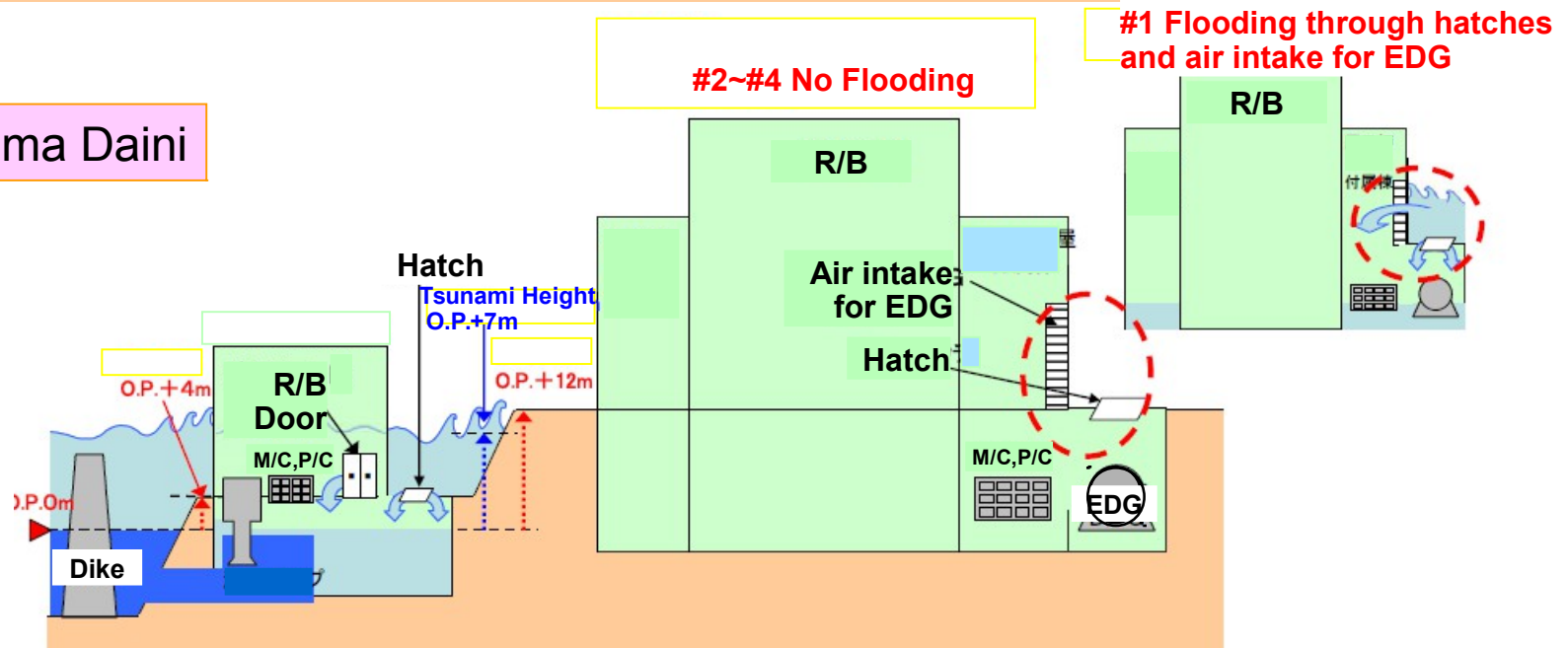
[Online]. <http://www.tepco.co.jp/tepconews/pressroom/110311/index-j.html>

# Tsunami Flooding Area in each NPP

## Fukushima Daiichi



## Fukushima Daini





# Cause of SBO in Fukushima Daiichi

Damages of heat exchanger room and heat exchanger (Unit 1)

Sea water heat exchanger room



Metal Crad SW

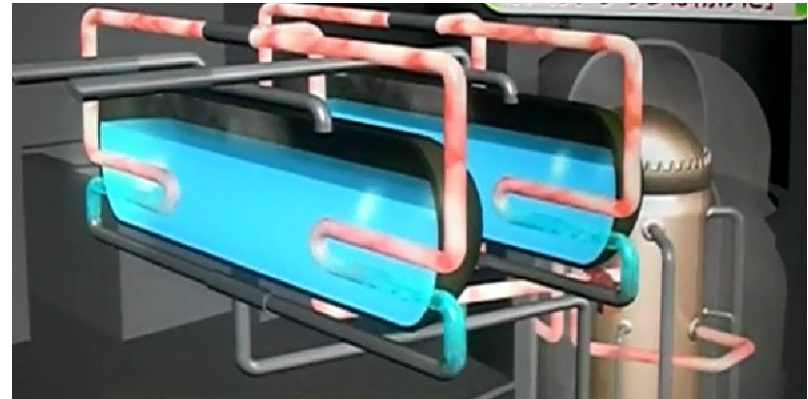
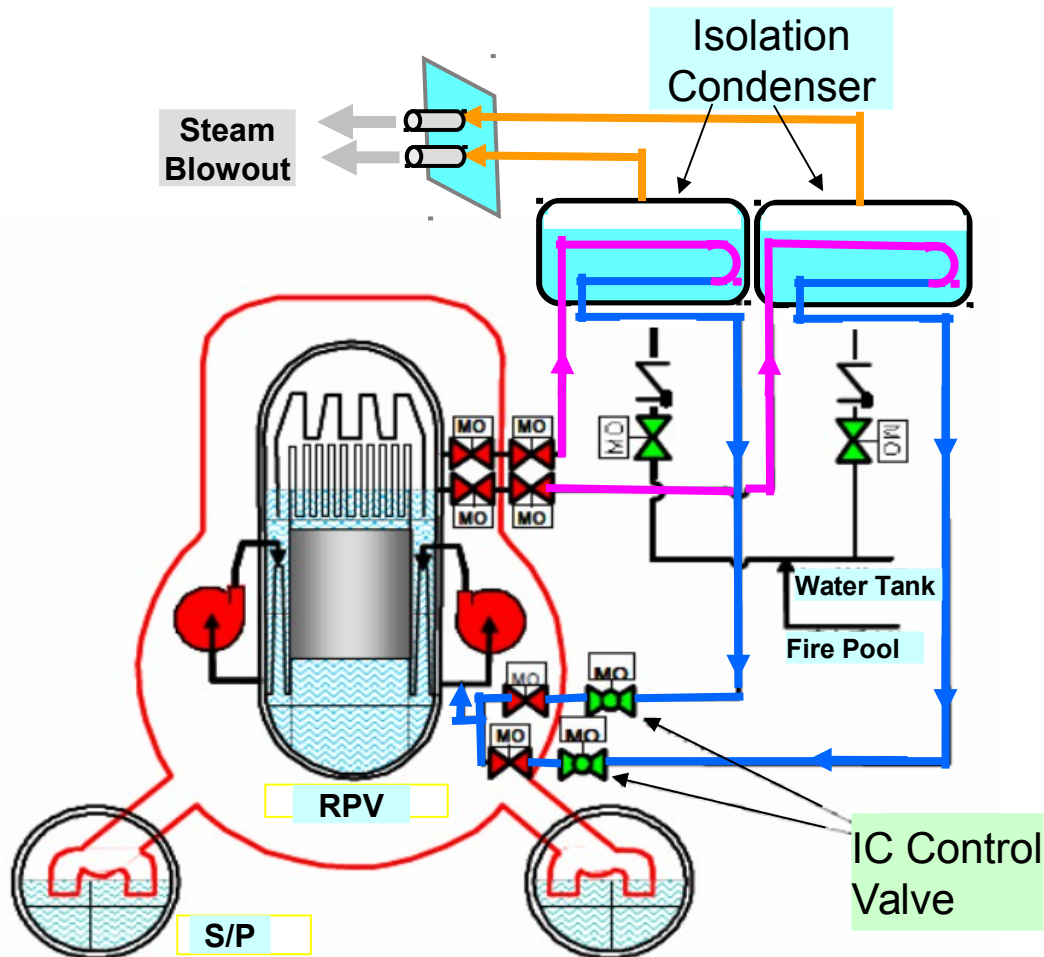


Sea water

Damages of reactor building and emergency diesel generator (Unit 1)

# ICs in unit 1 were tripped by FC

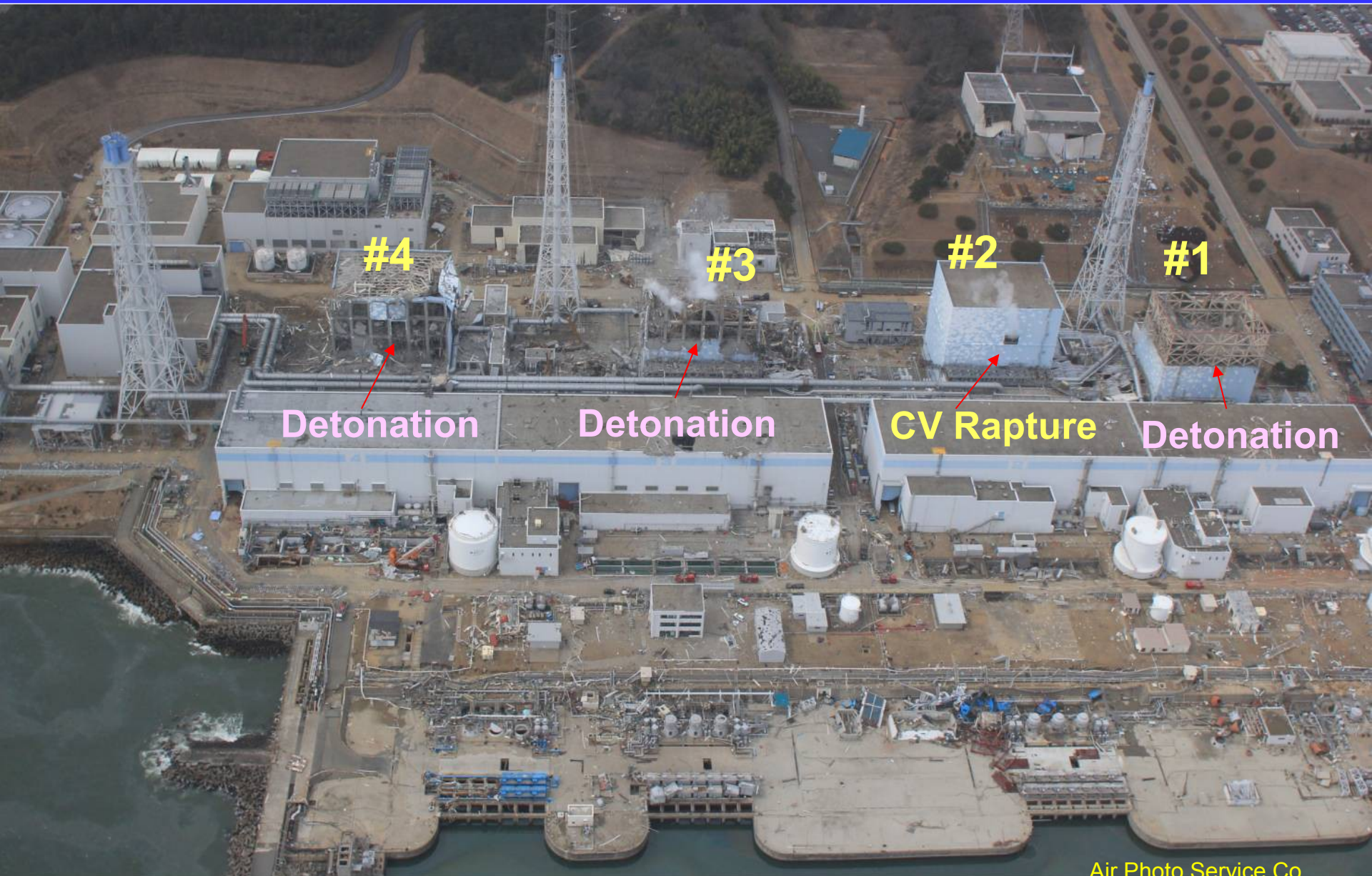
- Loss of battery power for main control room caused the **fail-close action** to MO isolation valves to cut off the IC cooling.
- **It was act as a fail-dangerous system under the loss of DC.**
- If the IC continue to operate, the accident would be terminated.



- RCIC steam turbine also stopped by loss of battery power in Unit 3.
- S/P temperature and pressure were so high that AM water injection took a lot of times.



# Hydrogen Detonation and CV Rapture



Air Photo Service Co.



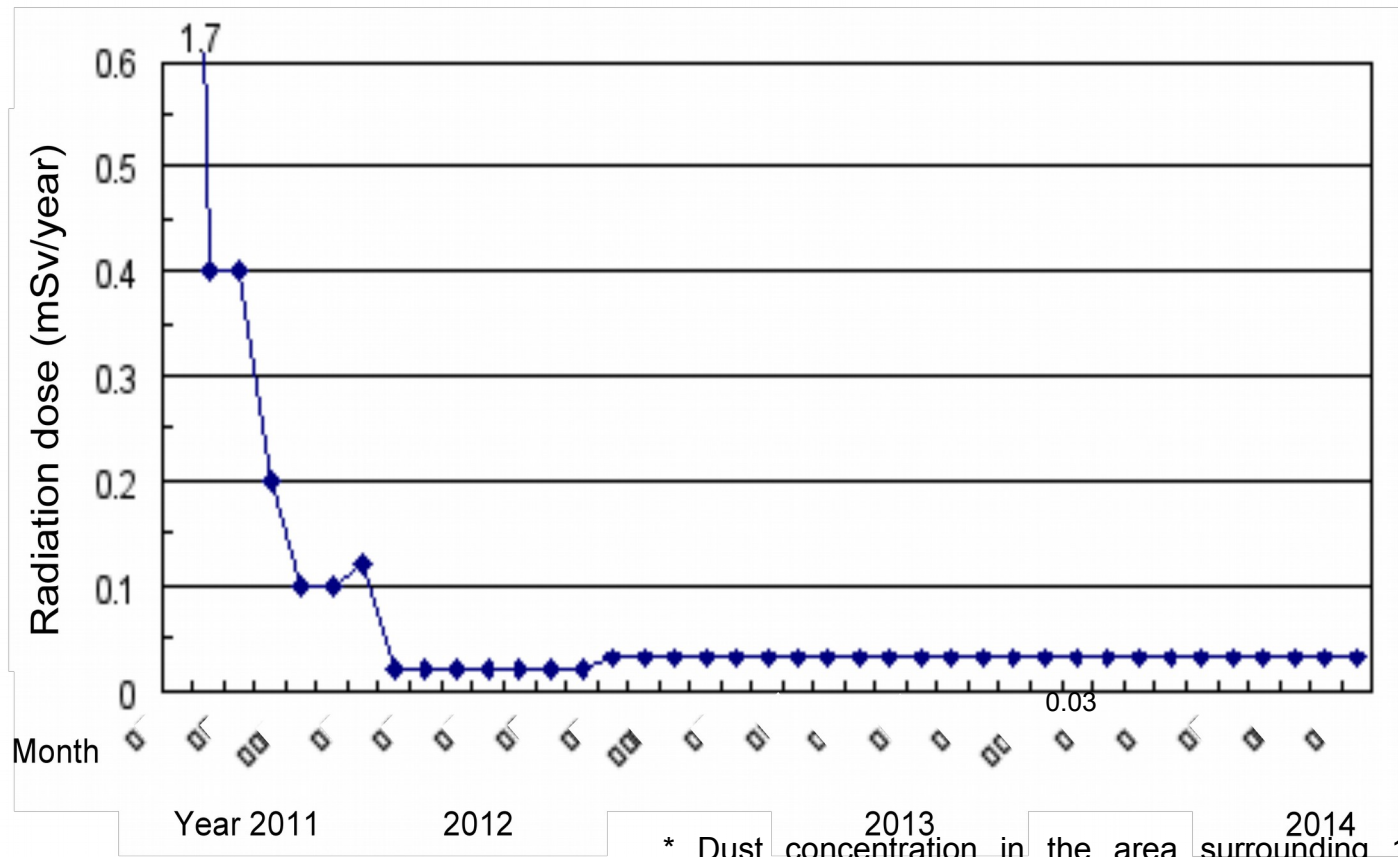


- H2 detonation were occurred after vent operation (#1, #3, #4)
- Radiation level increased soon after #2 CV rapture



# Status of airborne radioactive materials

## Annual dose on the site boundary by radioactive materials (cesium) released from R/B in Units 1 to 4



### ( Reference )

\* Concentration limit in the air of environment surveillance area boundary :

[Cs-134] :  $2 \times 10^{-5} \text{Bq/cm}^3$

[Cs-137] :  $3 \times 10^{-5} \text{Bq/cm}^3$

\* Dust concentration in the area surrounding 1F site boundary :

[Cs-134] : ND ( Detection limit: approx.  $1 \times 10^{-7} \text{Bq/cm}^3$  ) ,

[Cs-137] : ND ( Detection limit: approx.  $2 \times 10^{-7} \text{Bq/cm}^3$  )





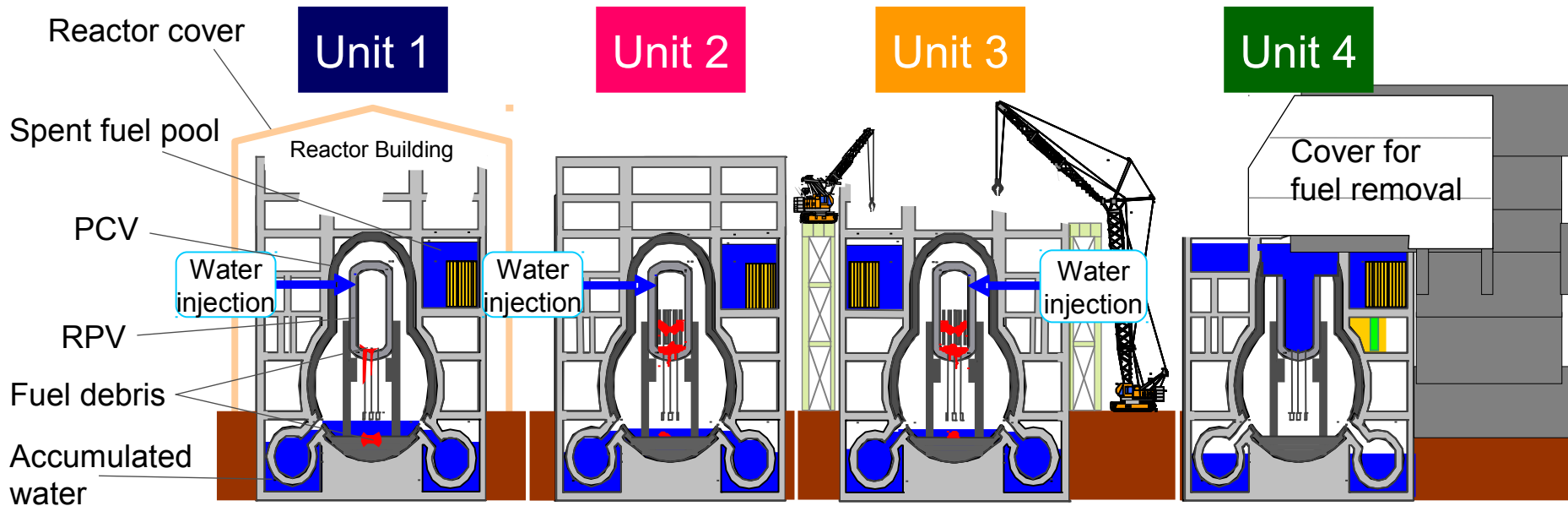
# Fukushima Daiichi Now





# Status of the Reactors at Units 1 to 4

**Cold shutdown is being maintained at all reactors**

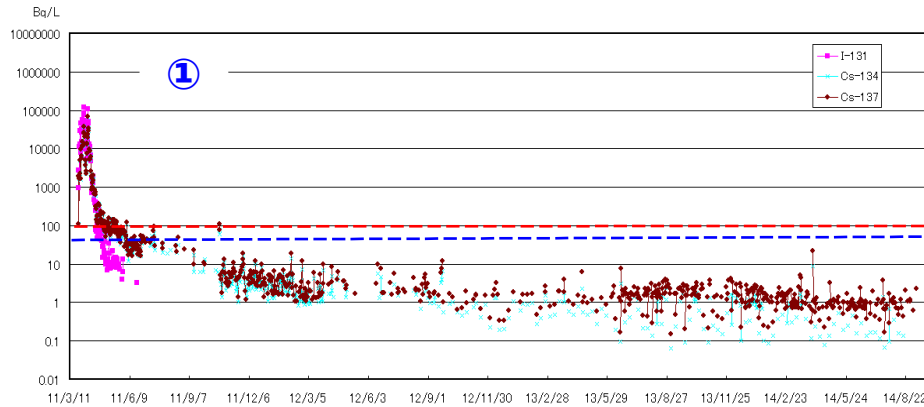


	Unit 1	Unit 2	Unit 3	Unit 4
RPV bottom temp.	About 29°C	About 36°C	About 34°C	-
PCV internal temp.	About 29°C	About 37°C	About 34°C	-
Fuel pool temp.	About 26°C	About 22°C	About 21°C	About 22°C
Reactor cooling water injection volume	About 4.6m <sup>3</sup> /h	About 4.5 m <sup>3</sup> /h	About 4.3 m <sup>3</sup> /h	-

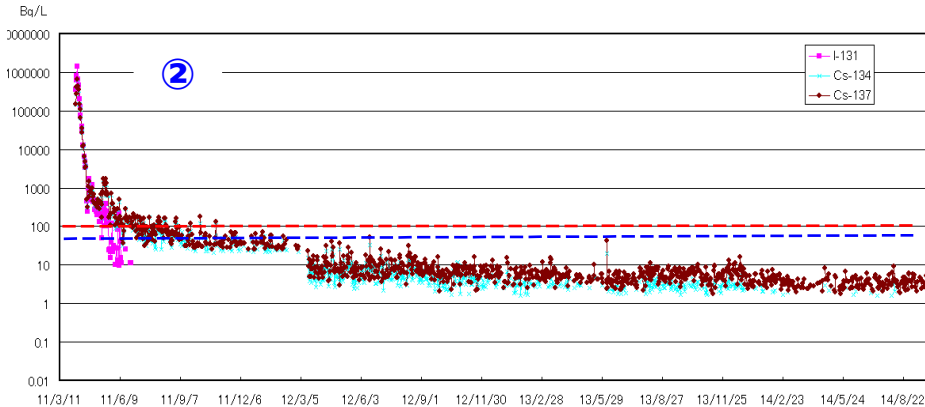
(as of Sept. 24, 2014)



# Concentration of FP in seawater



North side of water outlets at Units 5 and 6



Front of cargo unloading wharf

Concentration limits for water outside environmental monitoring area

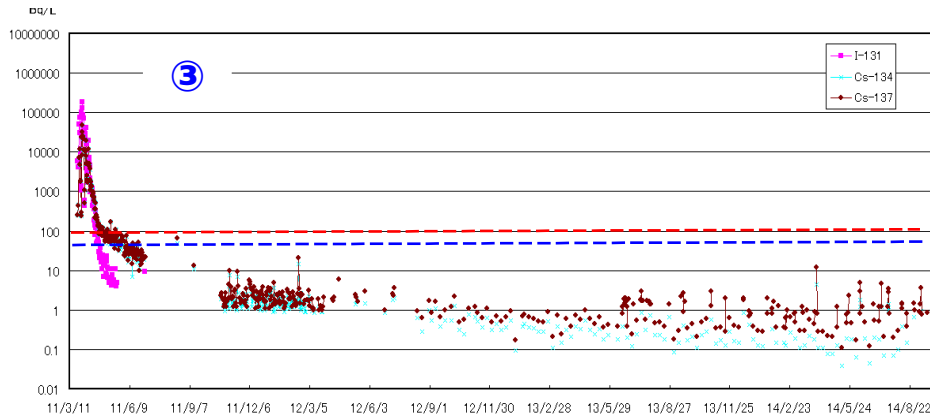
- □ Cesium 137: 90 Bq/L — — — — —
- □ Cesium 134: 60 Bq/L — — — — —



①



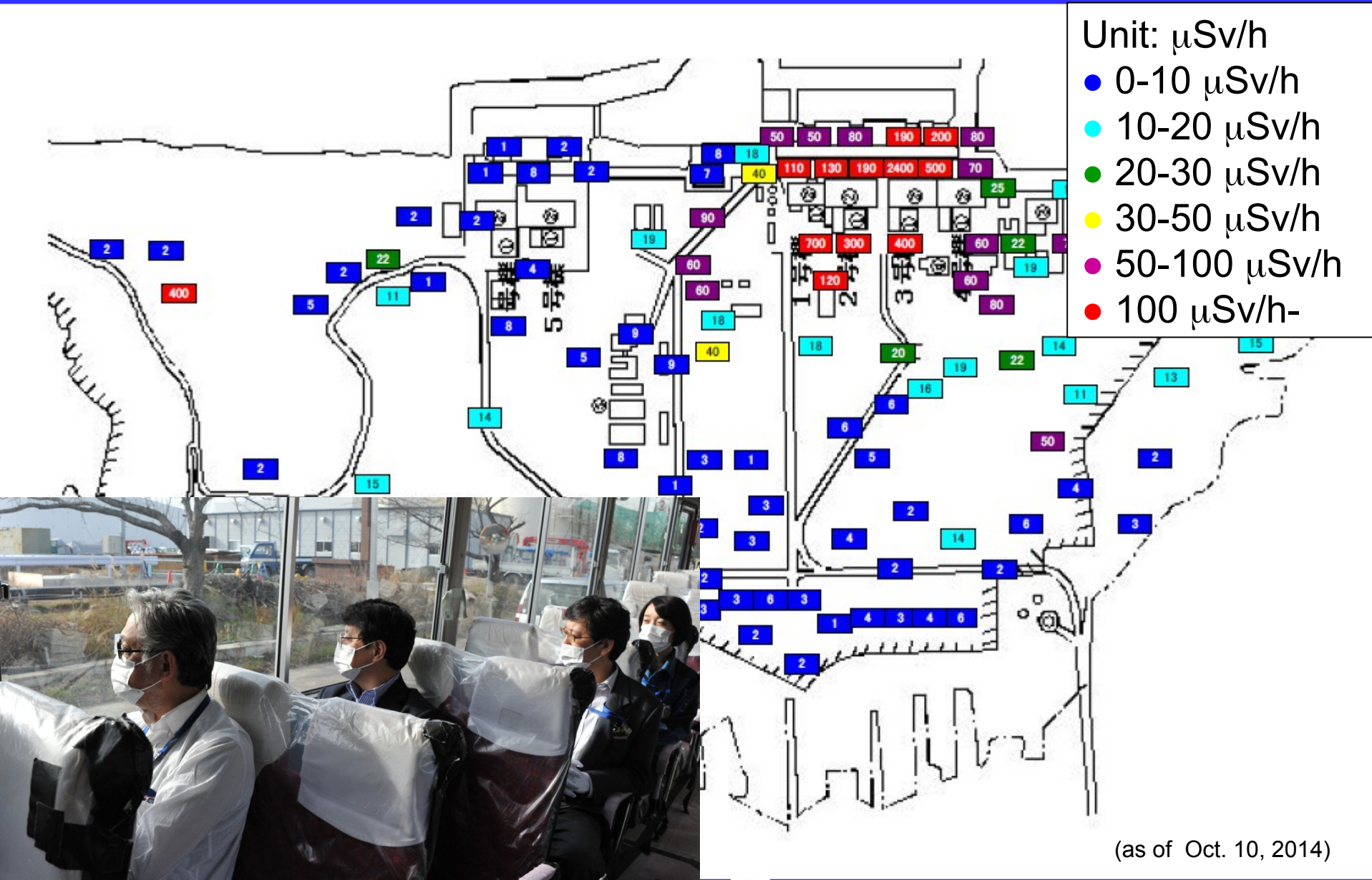
②



Vicinity of south side of water outlet



# Radiation Dose Map around Unit 1 to 4

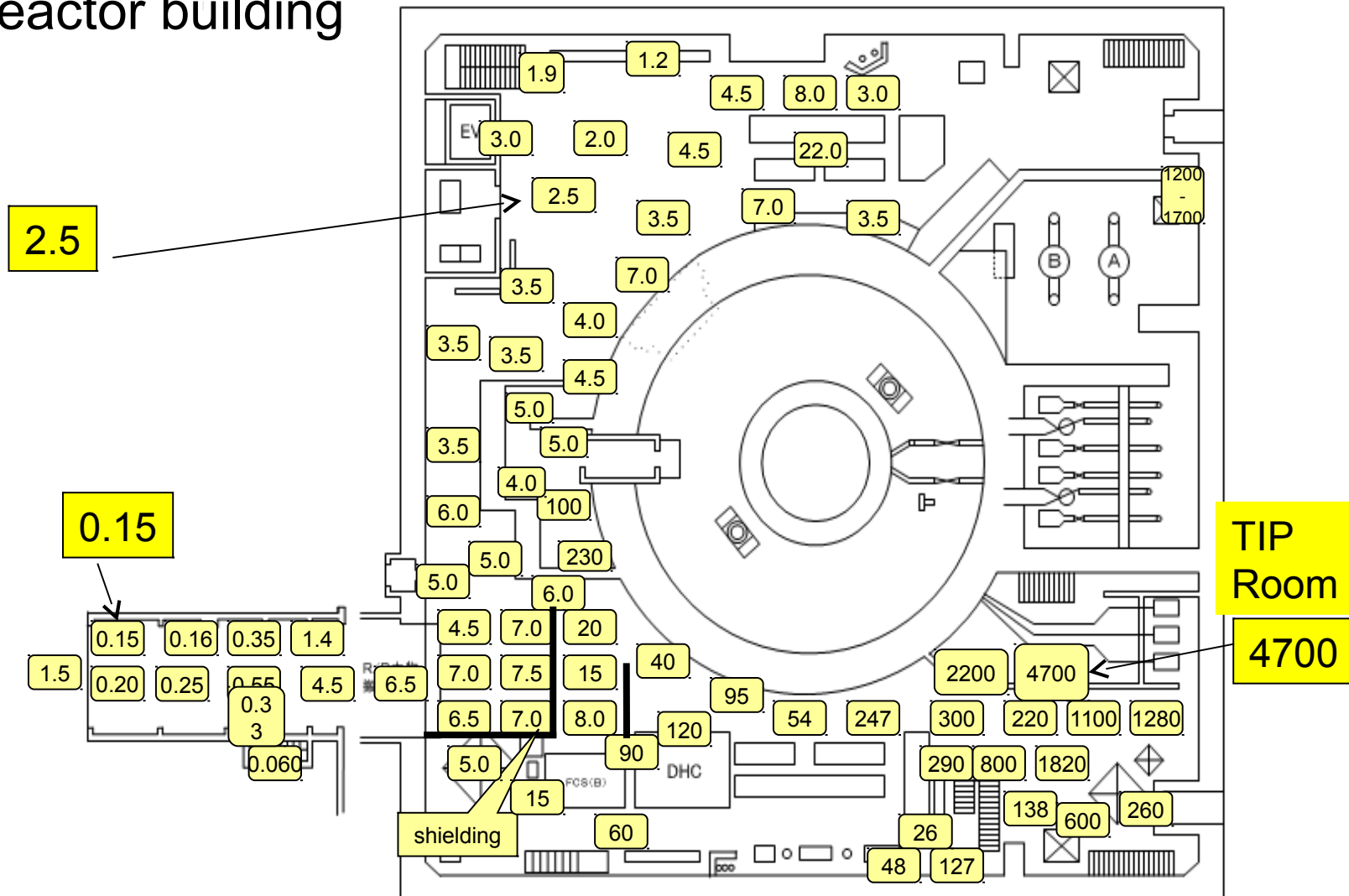




# Radiation Dose Map in Unit 1 Building

Unit 1: Reactor building  
1<sup>st</sup> Floor

Unit : mSv/h



(as of Mar. 27, 2014)



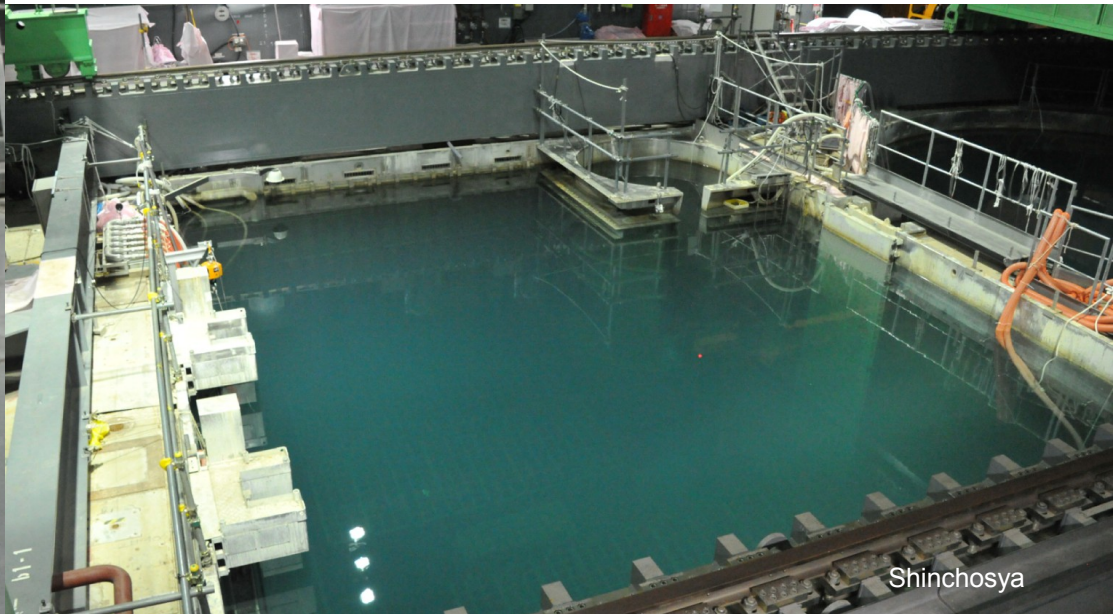
# Tour to each unit





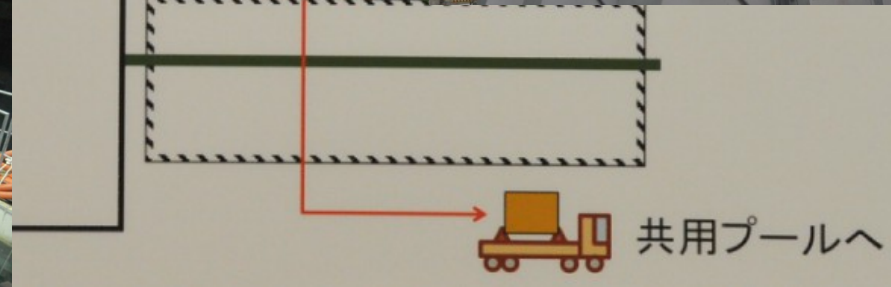
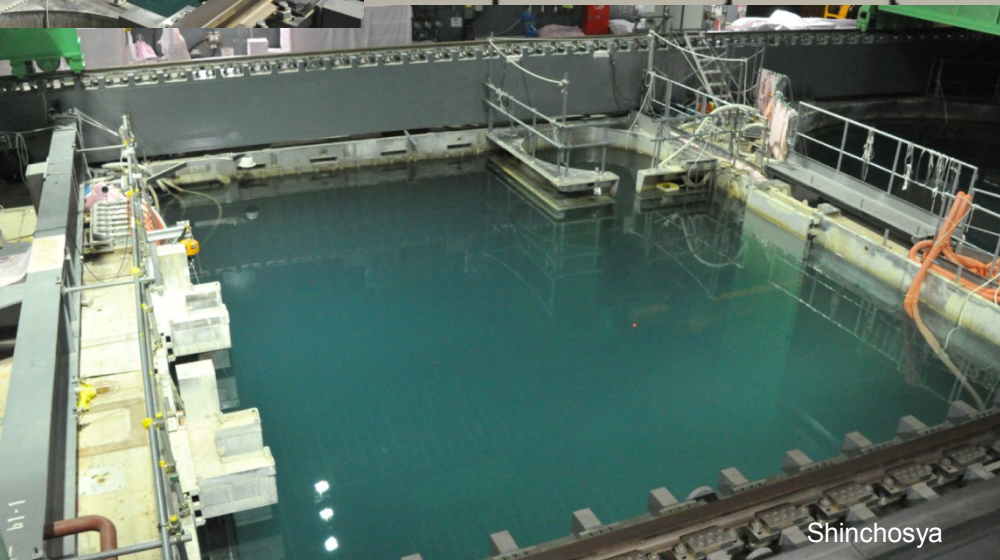
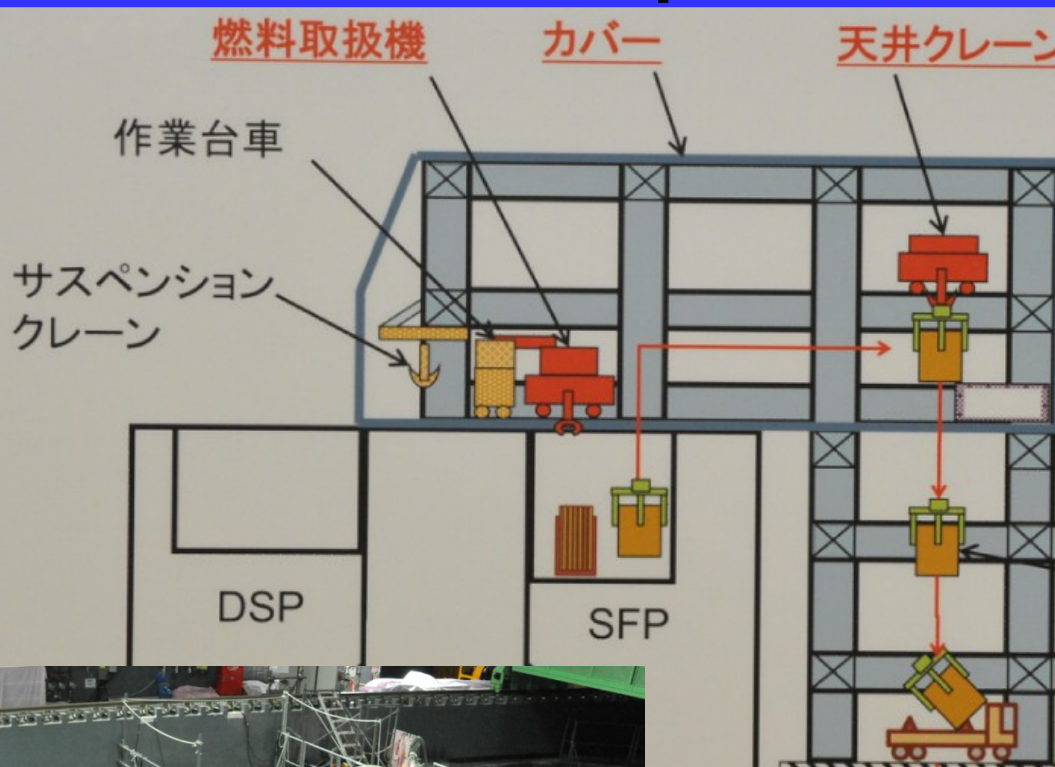
# Current Status of Unit 4

**All the fuels removed from spent fuel pool by the end of 2014**



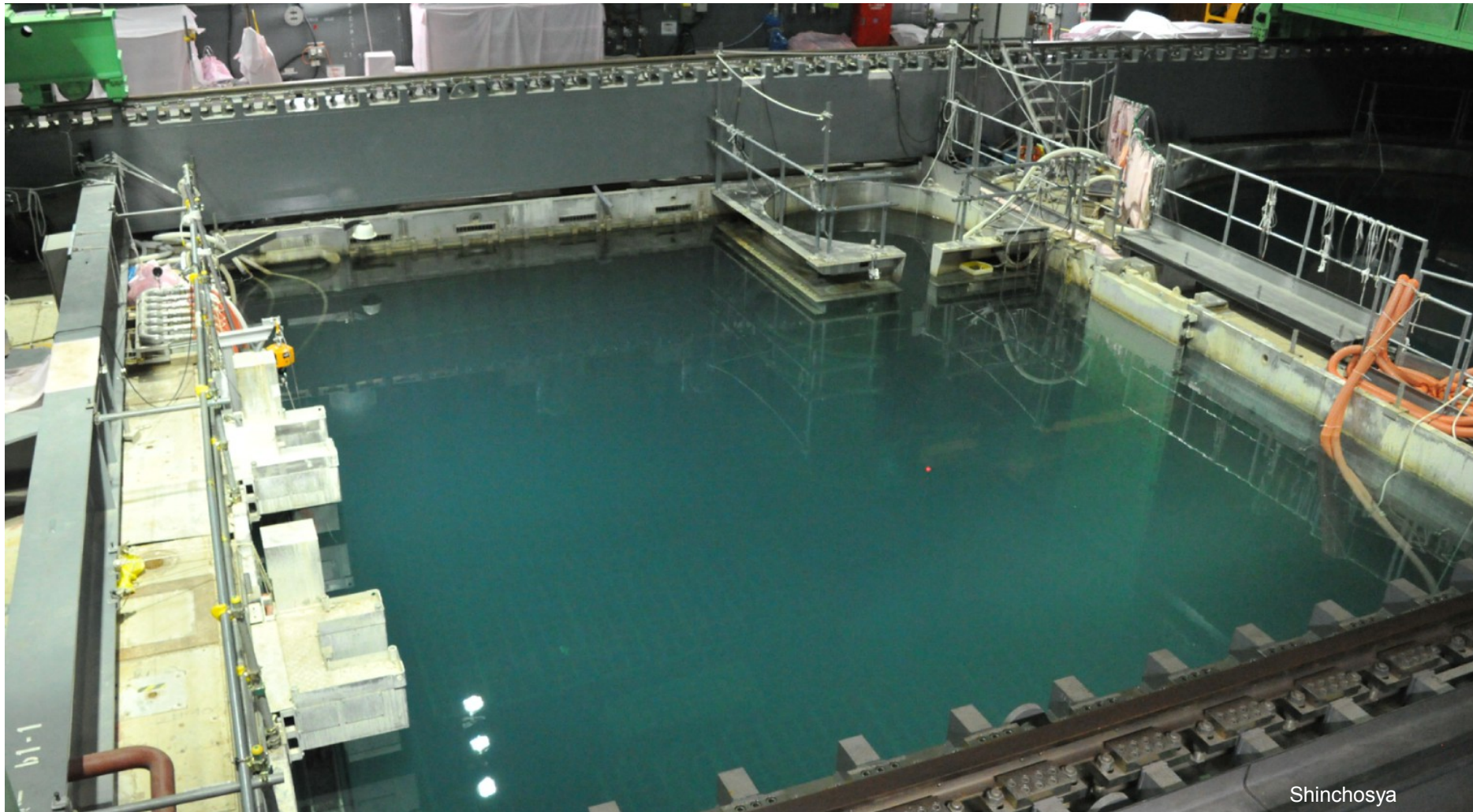


# No fuels in the spent fuel pool





# No fuels in the spent fuel pool



Shinchosya



# Current Status of Unit 3

**Rubble removal from the top of the reactor building completed. Installation of fuel removal cover and fuel handling facility planned**



**Damaged by  
Hydrogen Explosion  
As of Feb. 12, 2012**

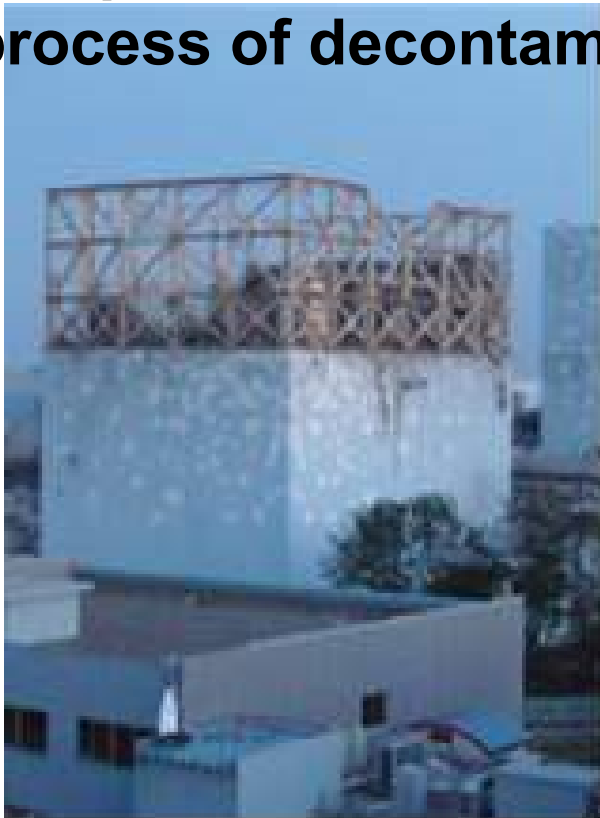




# Current Status of Unit 1

**Sustained stable reactor cooling.**

**The protective cover will soon be removed to continue the process of decontaminating.**



**Damaged by  
Hydrogen Explosion  
As of Mar. 12, 2011**



**Completion of Cover Structure  
As of Oct. 28, 2011**

# Current Status of Unit 2

**No hydrogen explosion inside the Reactor Building due to opening of the Blowout Panel.**  
**Very high radiation level in the building.**

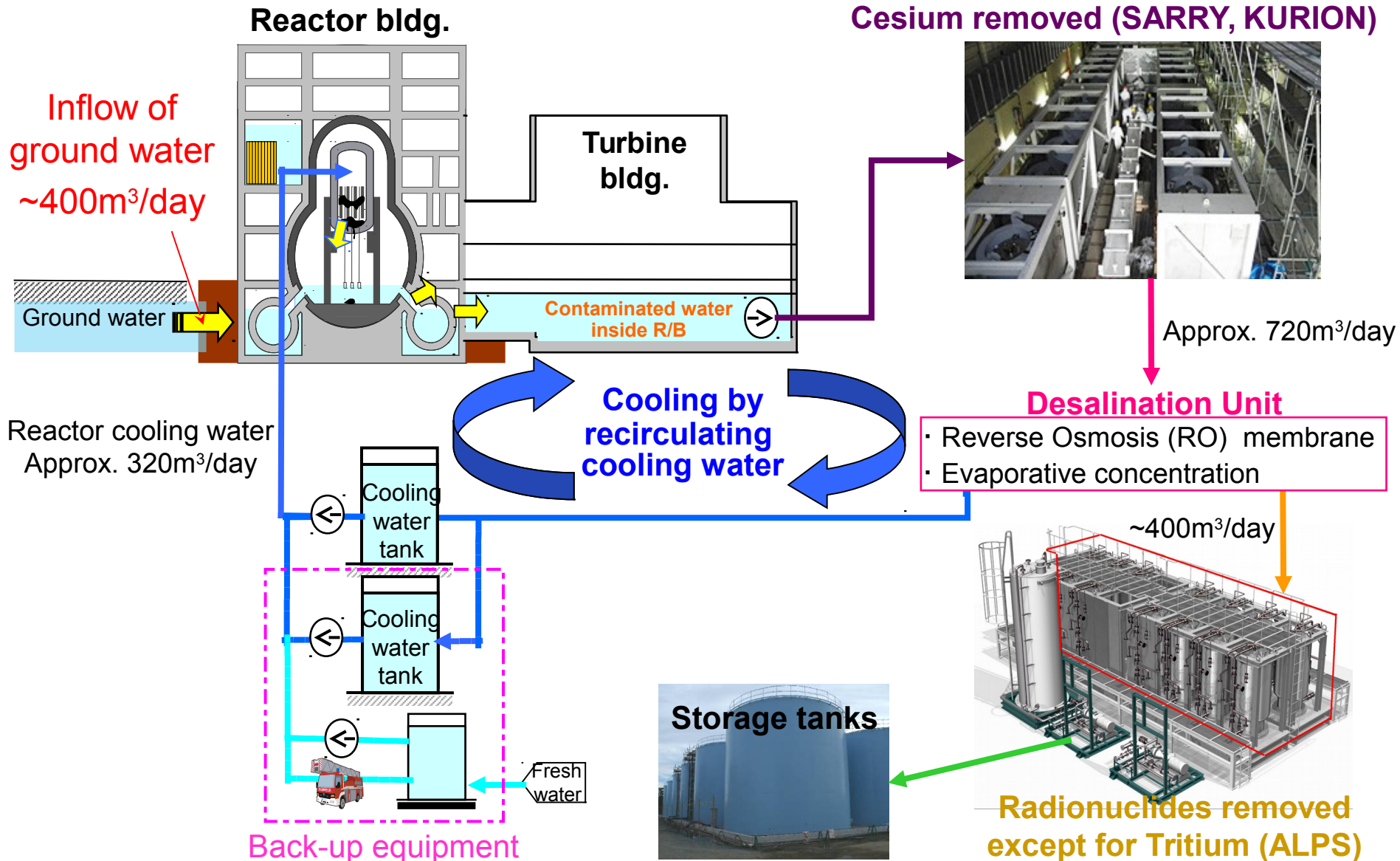
**Opened Blowout Panel**



**Opened Blowout Panel**  
**As of Apr. 10, 2011**

**Closing the Opening Section**  
**As of Mar. 11, 2013**

# Contaminated Water Management





# Current site layout in Fukushima Daiichi



# Advanced Liquid Processing System (ALPS)



**Treat the contaminated water  
by removing radionuclides**

**750**

Tons/day in first installed system

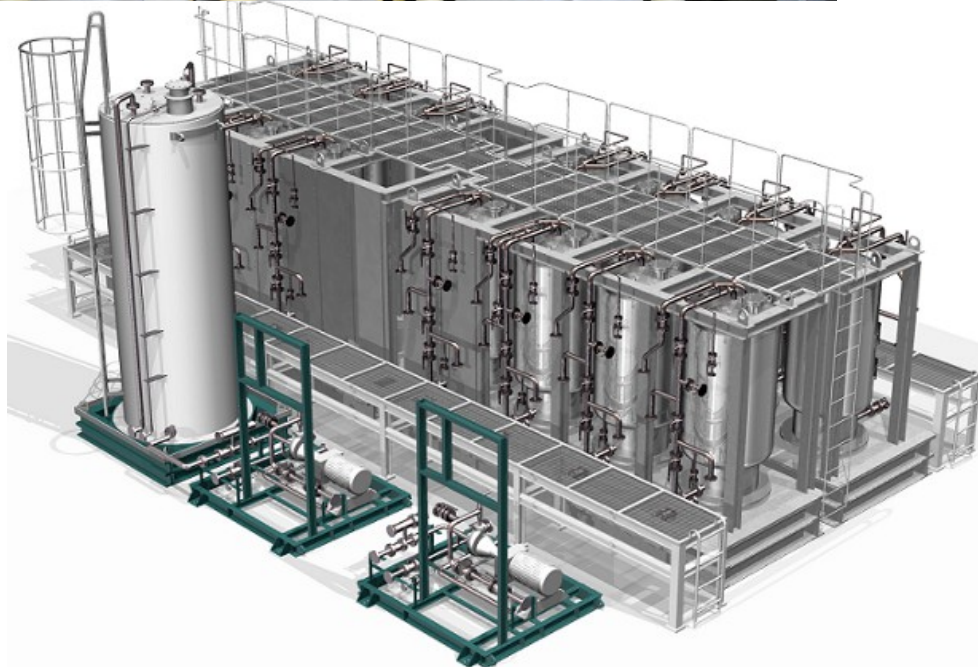
**2,000**

Tons/day with first installed system  
+ additional system  
+ high-performance system

**120,000+**

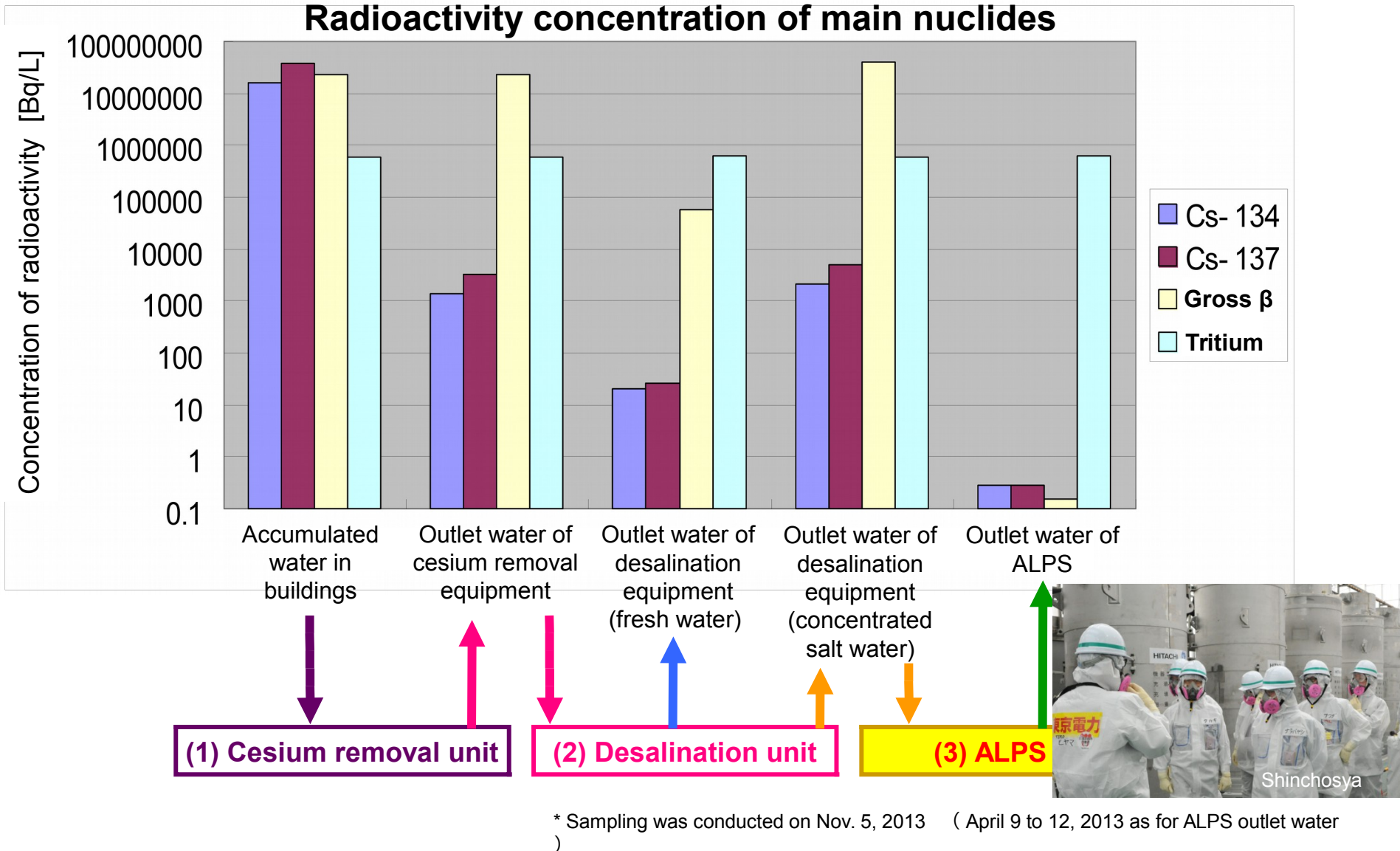
Tons of contaminated water  
processed so far

**REMOVE SOURCES OF  
CONTAMINATION**



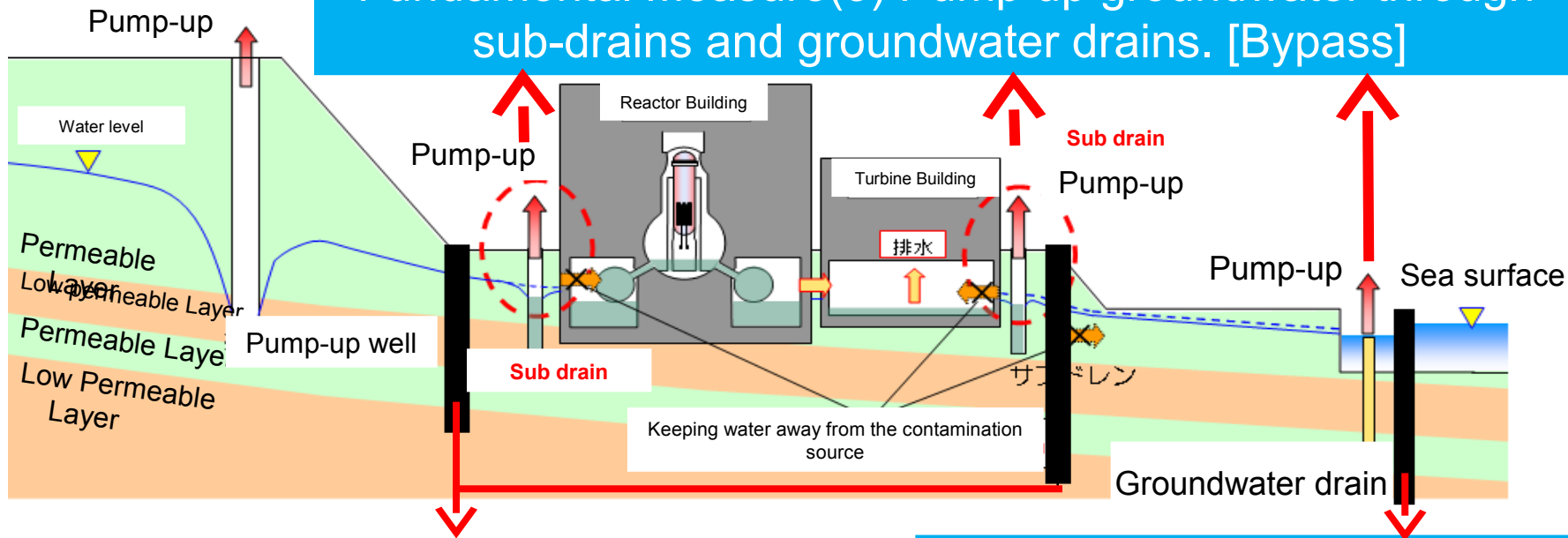


# Contaminated Water Status

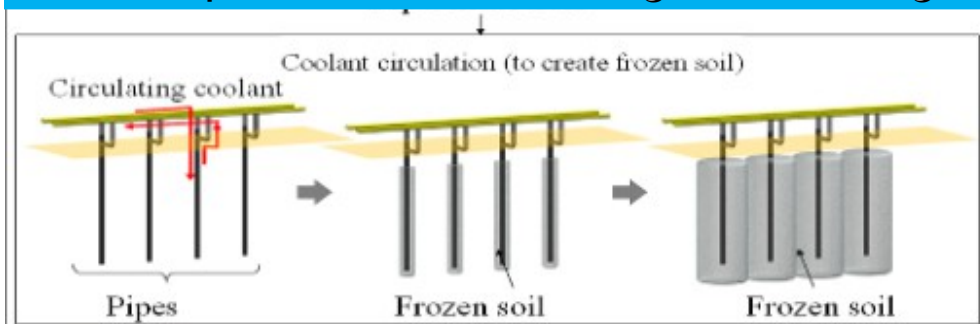


# Fundamental Measures

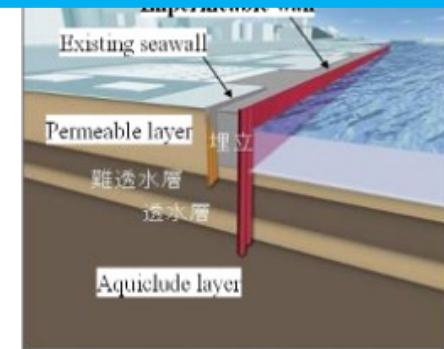
Fundamental Measure(3) Pump up groundwater through sub-drains and groundwater drains. [Bypass]



Fundamental Measure (2)  
Install the land-side water-shielding frozen walls to prevent water flowing into buildings



Fundamental Measure (1)  
Install the sea-side water-shield walls to prevent leakage

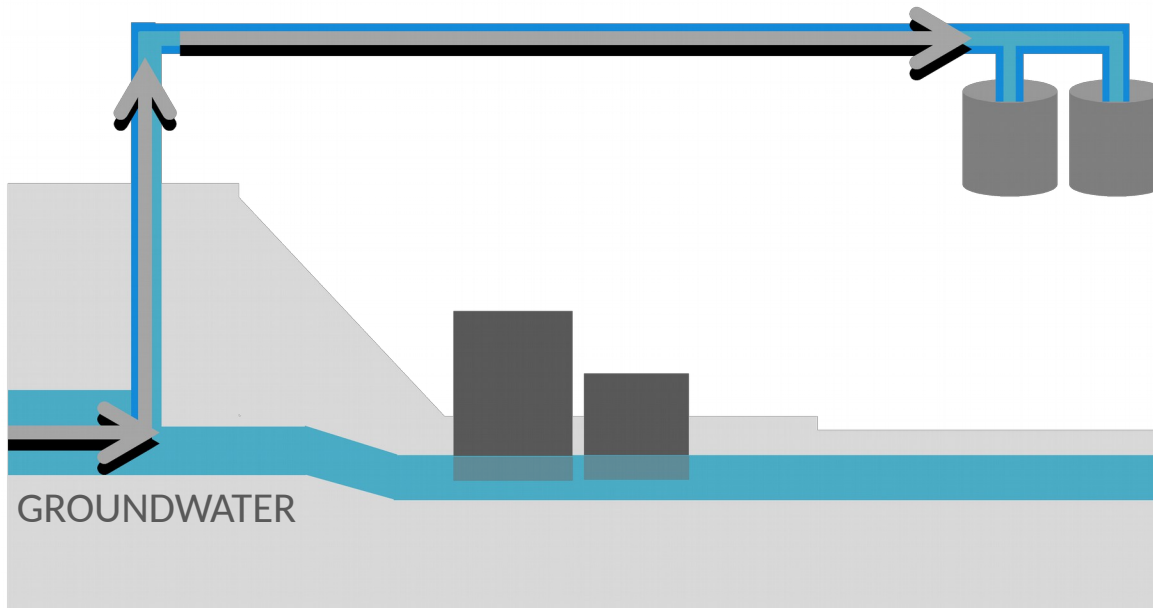




# Groundwater Bypass



**Pumps collect groundwater bypassing reactor buildings and divert it safely to the sea**



**300-350**

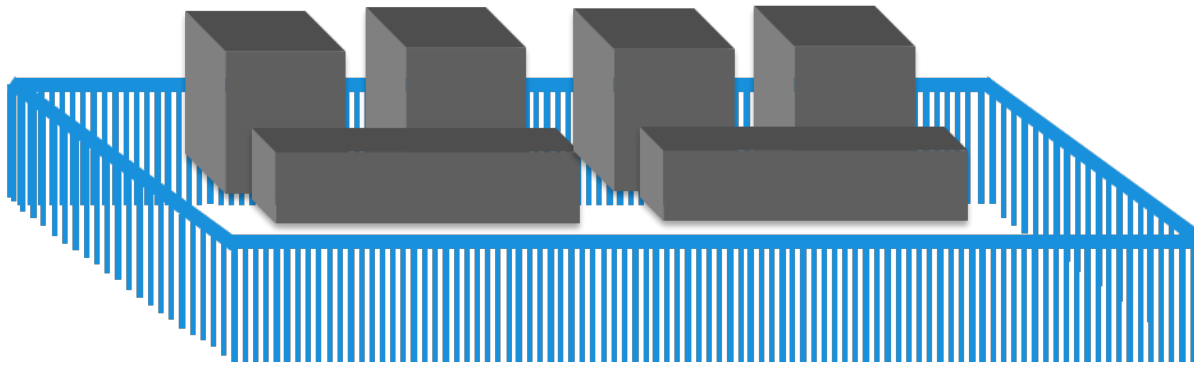
Tons/day pumped up

**50-80**

Tons/day estimated amount of water reduced flowing into reactor buildings

# Landside Impermeable “Frozen Wall”

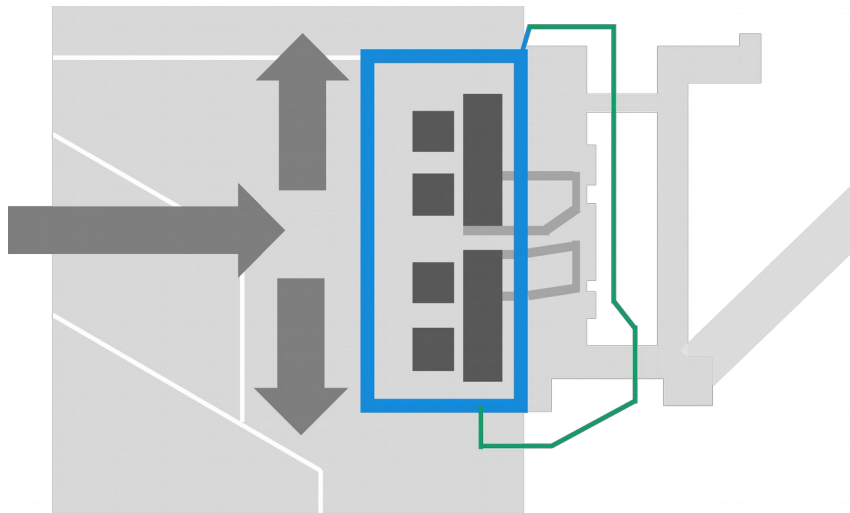
**Block groundwater from entering the units and becoming contaminated**



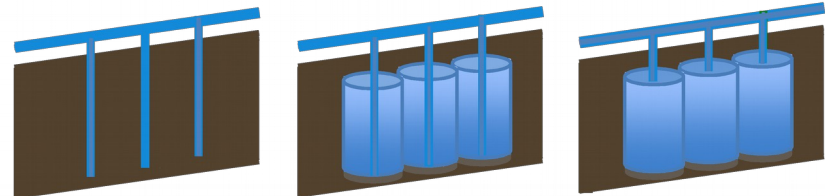
1.5km  
Long

1,545

Vertical pipes delivering  
soil-freezing coolant



PROGRESSION OF SOIL FREEZING (Begins March, 2015)

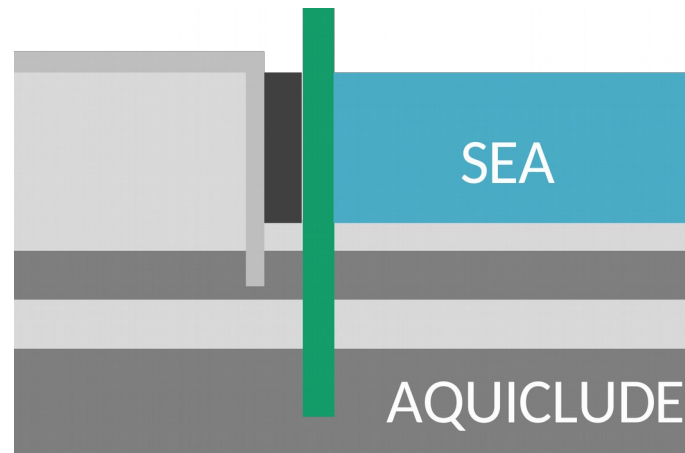
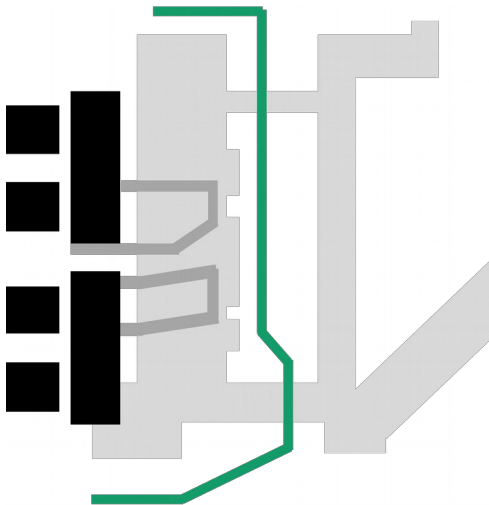


ISOLATE WATER FROM  
CONTAMINATION

# Seaside Impermeable Wall



**Block groundwater flowing between the facility and the sea**



**PREVENT LEAKAGE OF  
CONTAMINATED WATER**



# Robotics for Resilience Action at Fukushima Daiichi NPS

QB Quince2 2012/06/13 11:17:36

File Window

Accessory Control

Speed Mission Timer

L 60:31

Capture

Lock Rewinder

No Gyro

0 Set

Forward [Sync]

前足

後足

9432

前方カメラ

At temperature, humidity

24.3C 70.1%

Rewinder count

793.6

Heading: 204.625

Battery: 2.9[V] 19.4[Ah]

Temp

Motor-R	40
Motor-L	39
R-SC-R	37
R-SC-L	30
F-SC-R	31
F-SC-L	31

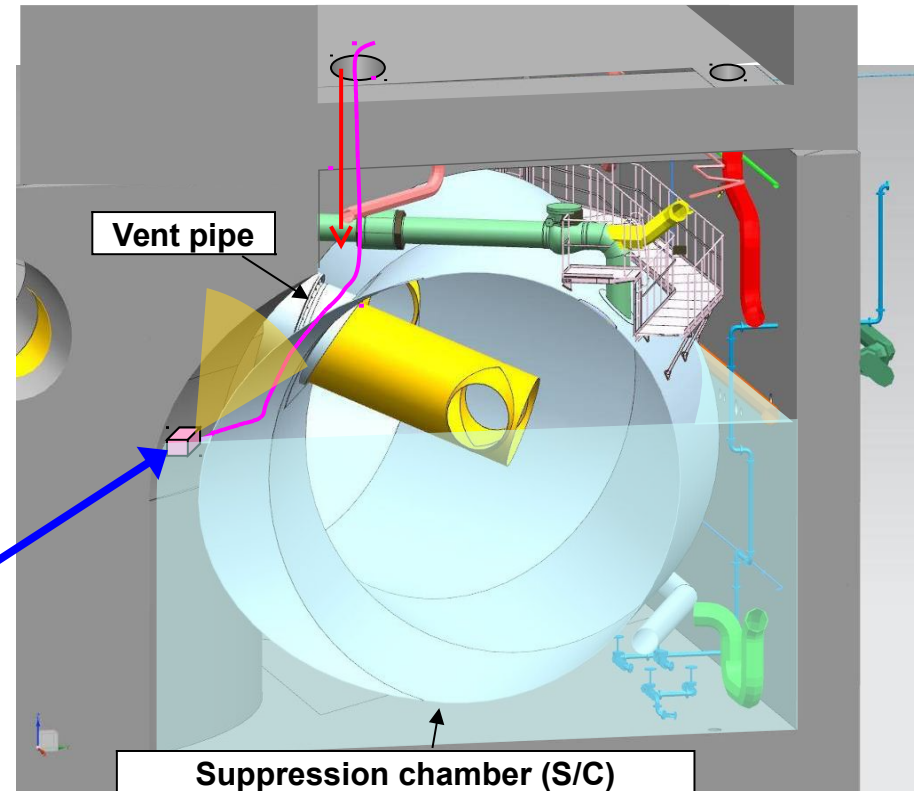
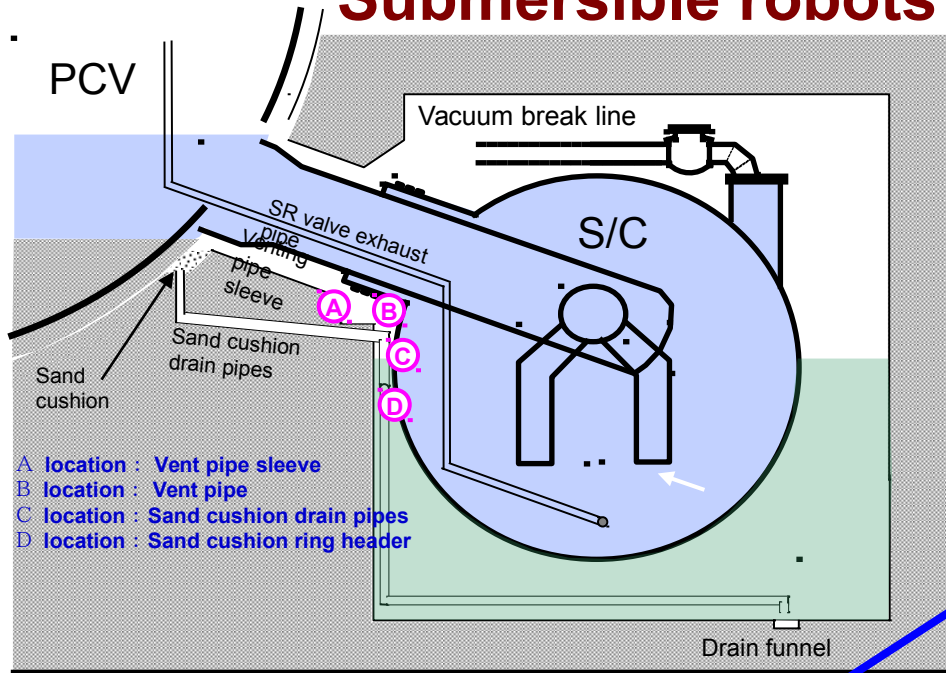
Edge Mode Zoom In Zoom Out Home

Edge Mode Zoom In Zoom Out Home



# Survey by Boat at Basement Floor of Unit 1 Reactor Building

## Survey and repair toward filling PCV with water - Submersible robots

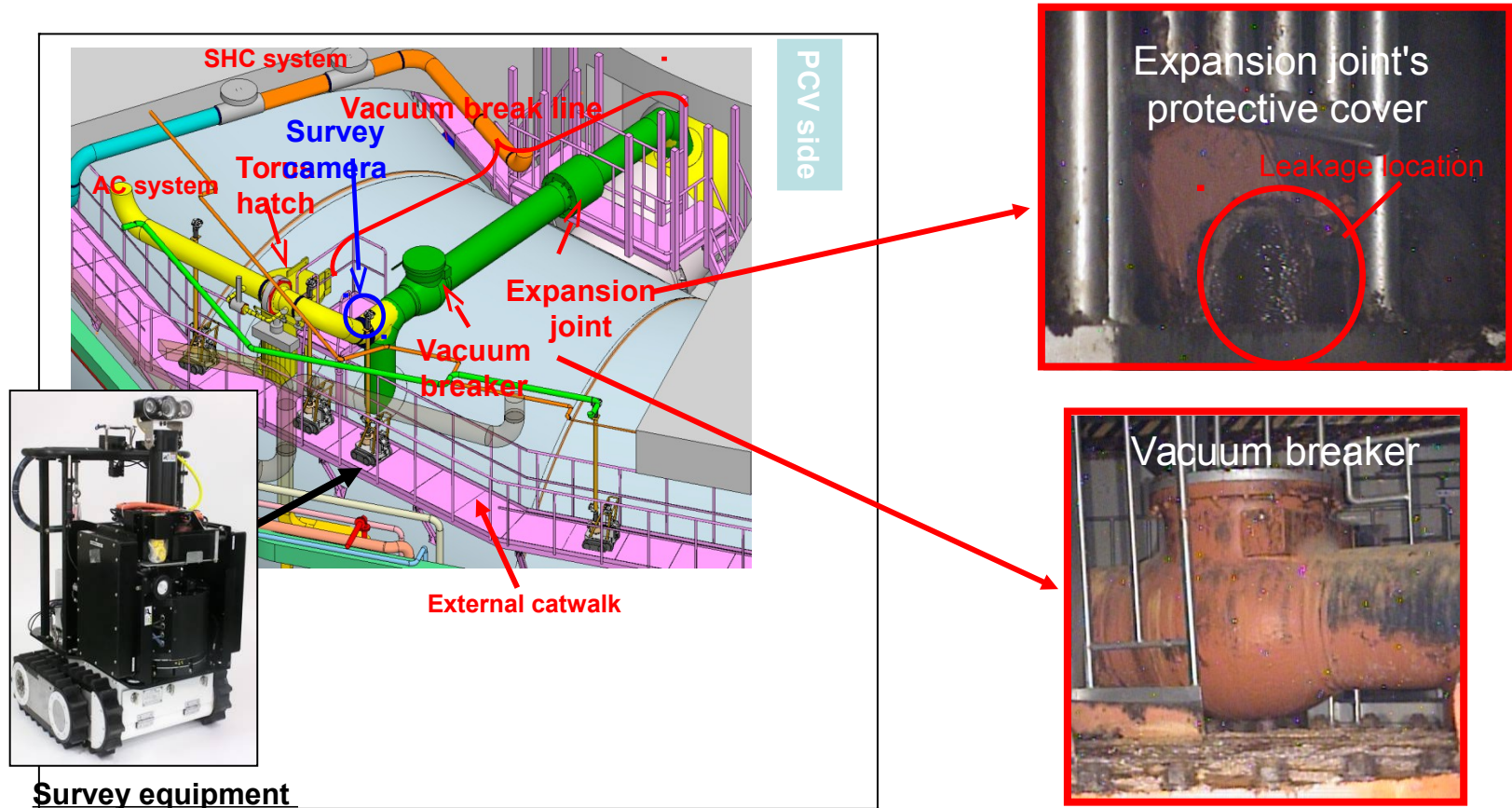


Cross-section of basement  
floor of R/B (torus room)



# Survey at Basement Floor of Unit 1 Reactor Building

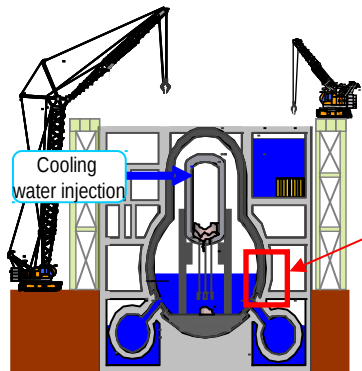
Robots Survey and repair toward filling PCV with water



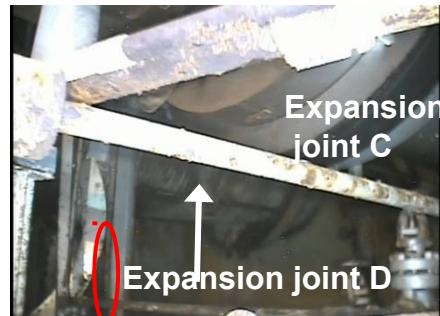


# Investigation into Unit 3 Leakage Location

## Finding of water leakage

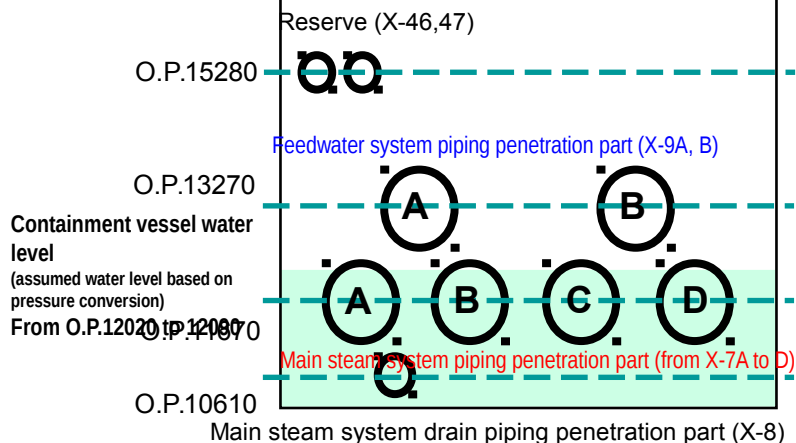


MSIV room  
Piping penetration part



Main steam piping D

(Drawing seen from the containment vessel's interior)



Main steam isolation valve (MSIV) piping penetration part  
Cross-section schematic diagram

Note: the radiation monitor for the main steam pipe process is located between water pipes A and B and main steam pipes B and C.

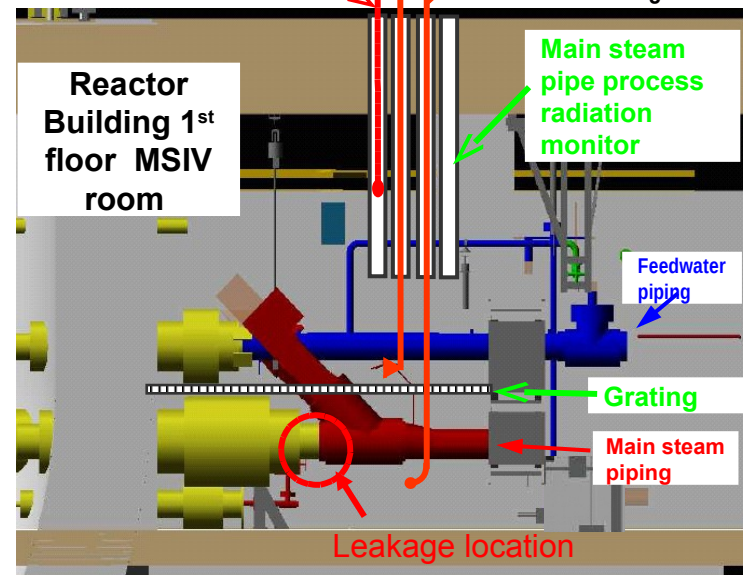
## Comprehensive view survey camera (pan tilt camera)

Survey endoscope camera

Dosimeter  
(hot spot dosimeter)

Reactor Building 2nd floor -  
Floor space of the air  
conditioning machinery room

(Containment vessel side)

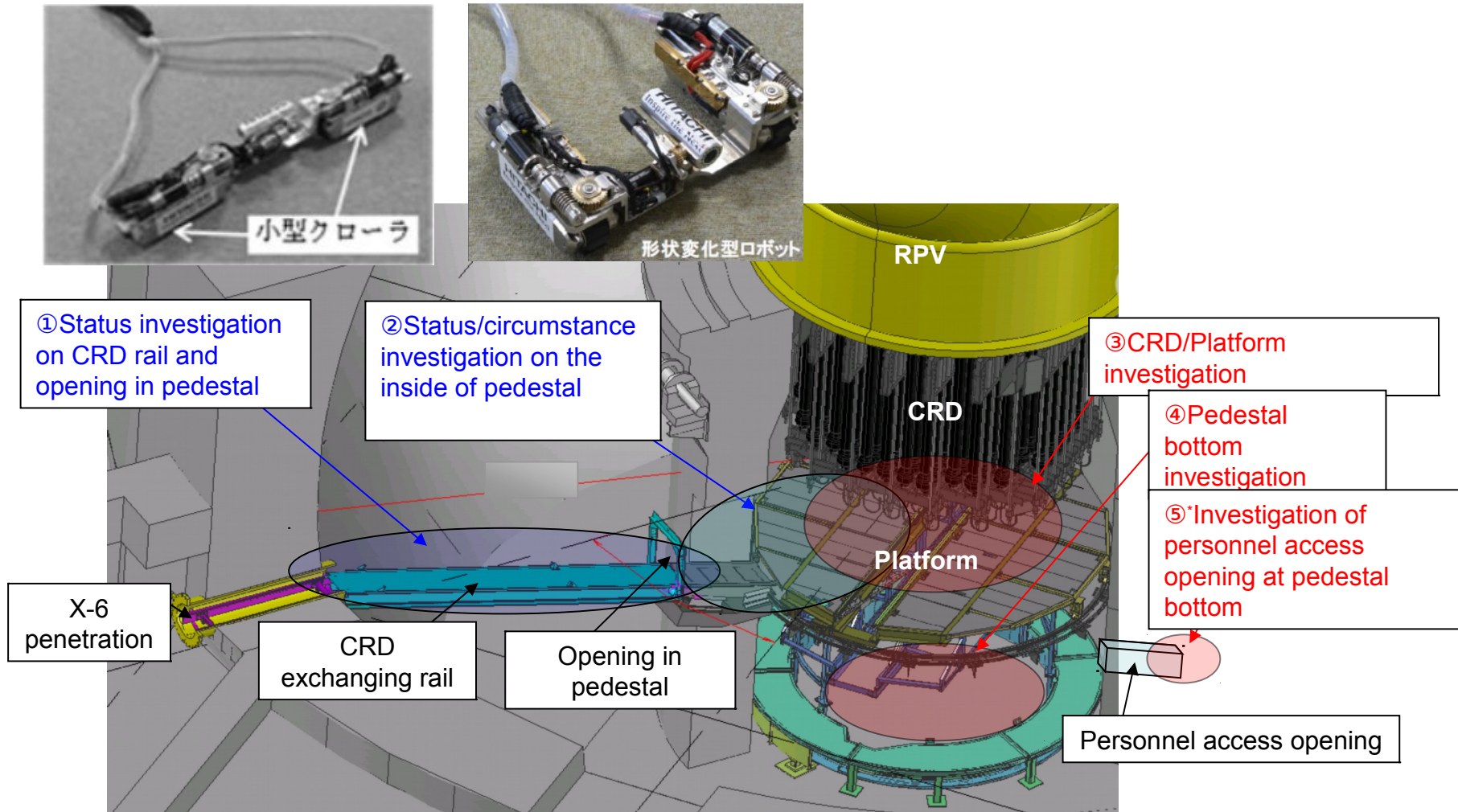


Reactor Building 1st floor MSIV (cross-section)



# Investigation into Bottom of Unit 2 RPV

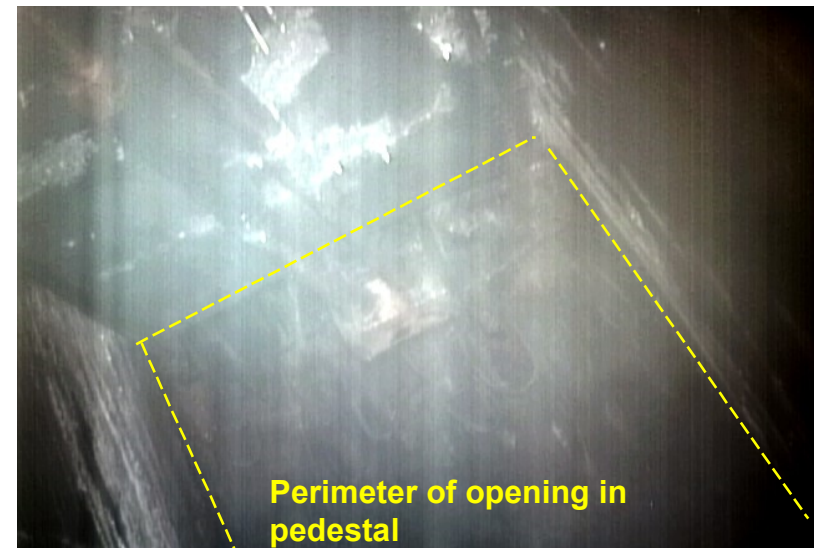
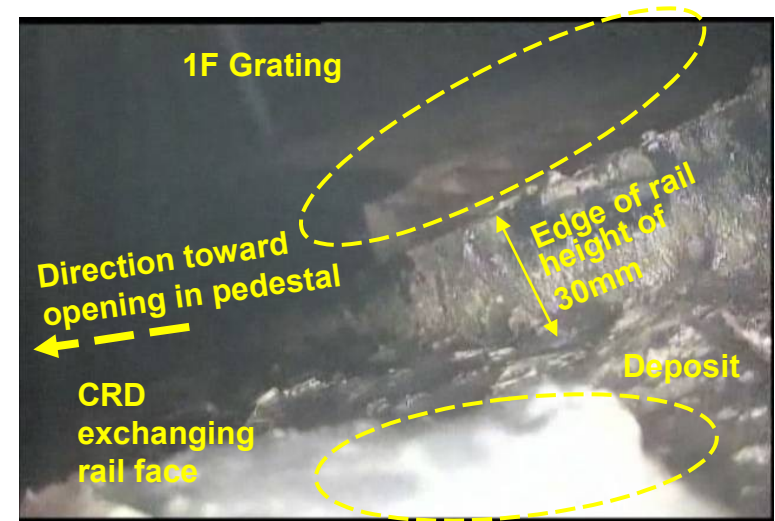
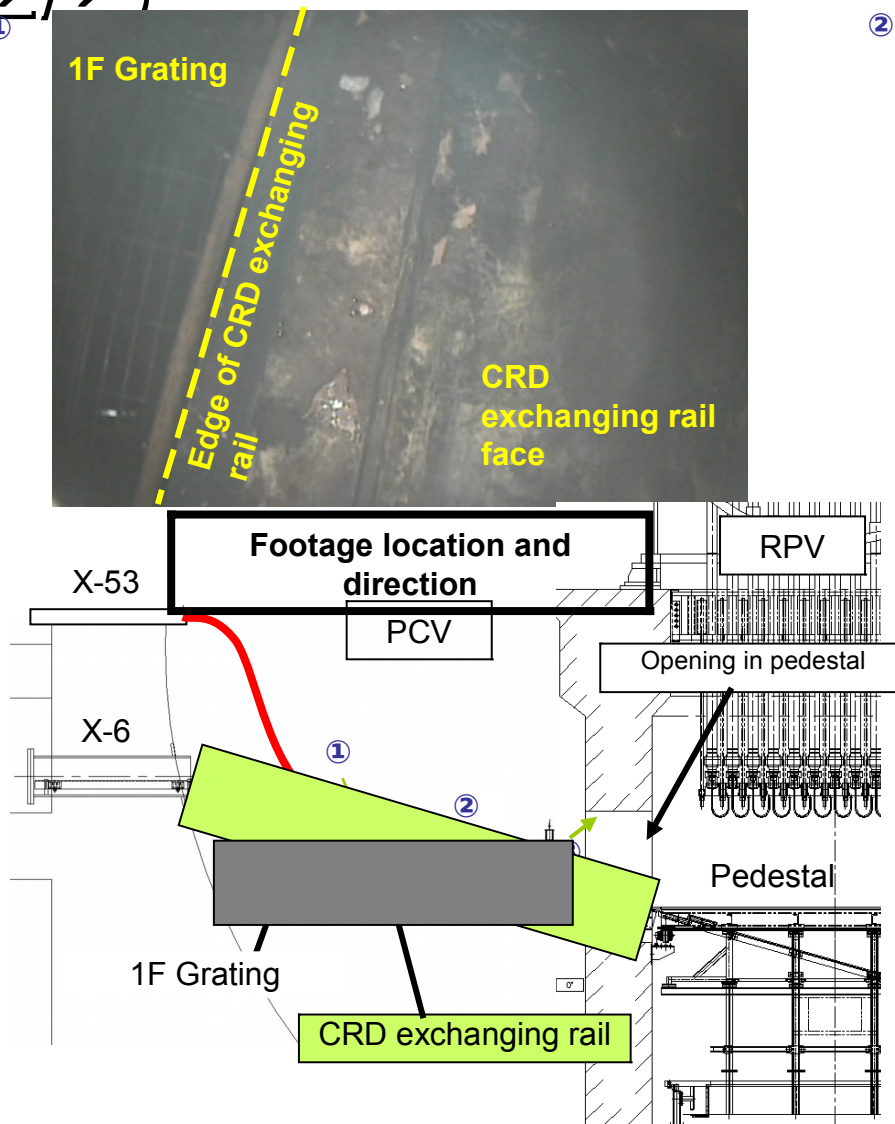
## (1/2) Transformer Type Robot for Investigation debris at pedestal



\* As for ⑤, access from the outside of pedestal is also considered.

# Investigation into Bottom of Unit 2 RPV

(2/2)





# Improvement of Facilities for Workers



**New Office facilities must evolve to meet the needs of NPS workers**



# Causes of SA and Countermeasures

(P) Protection (R) Resilience

Loss of external Power  
by Earthquake



(P) Enhance aseismic device  
(R) Recover Ext. Power Cable

Loss of EDG, P/C DC  
Battery, I&C and phone



(P) Water proof door, hatches  
(R) Mobile power/pump on hill

Loss of water in Core  
Meltdown, Hydrogen



(P) Diversity of water injection,  
(R) Recover heat sink and PAR

Loss of containment  
function, heat damage



(P) CV cooling, FCVS  
(R) Water Cannon, R/B Cover

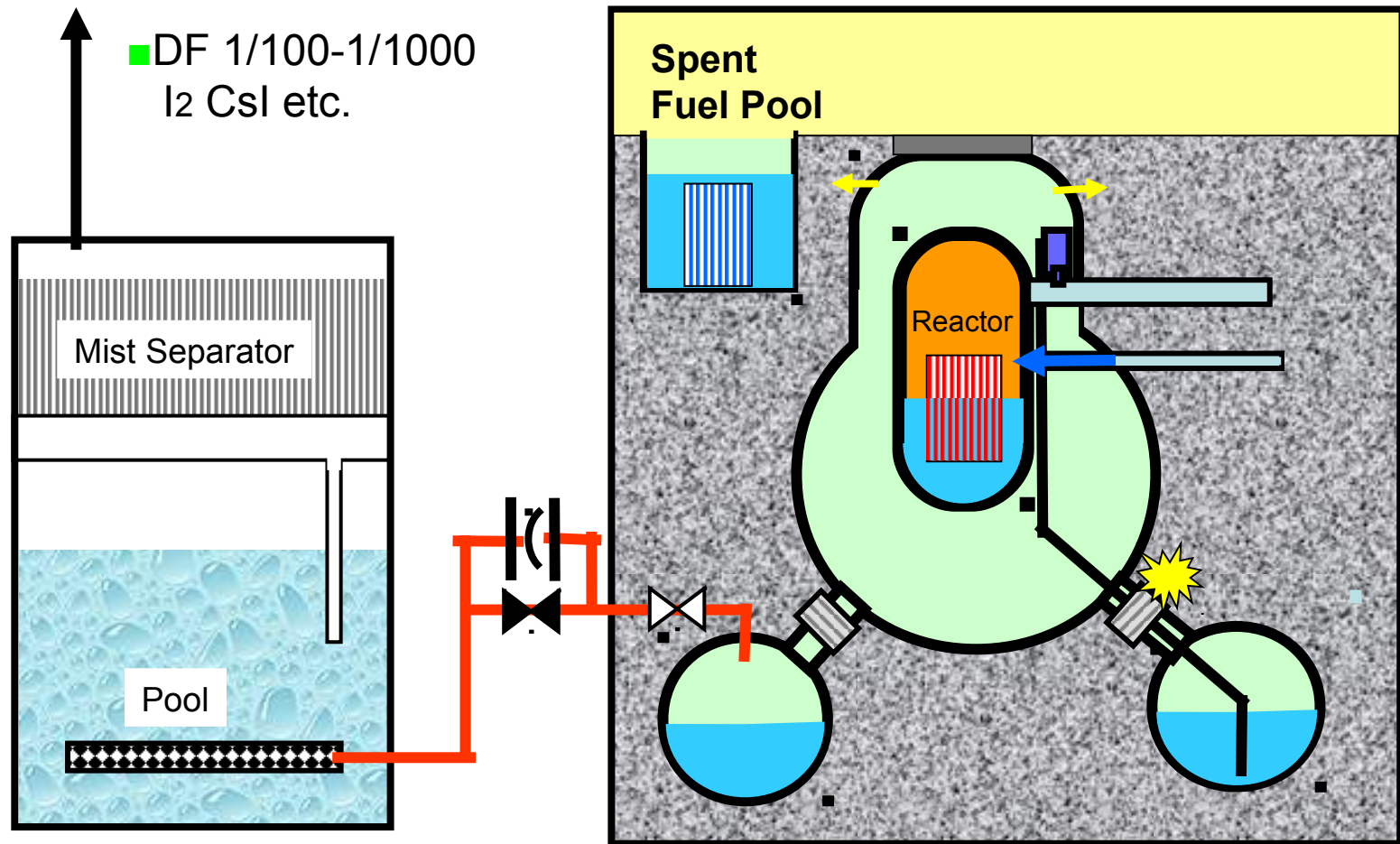
Slow judgment to protect  
against nuclear disasters



(P) New nuclear regulatory  
(R) Quick action by response center

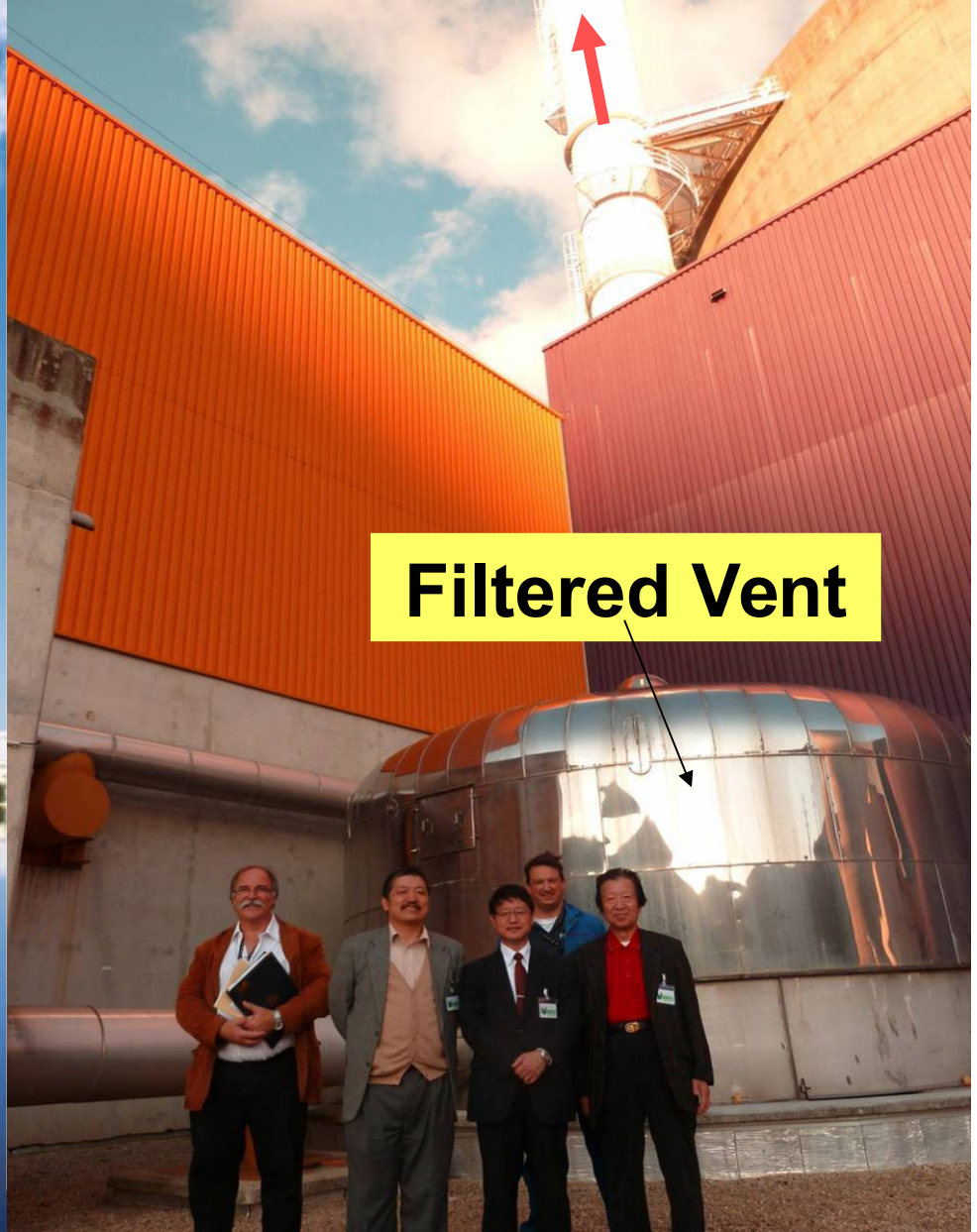
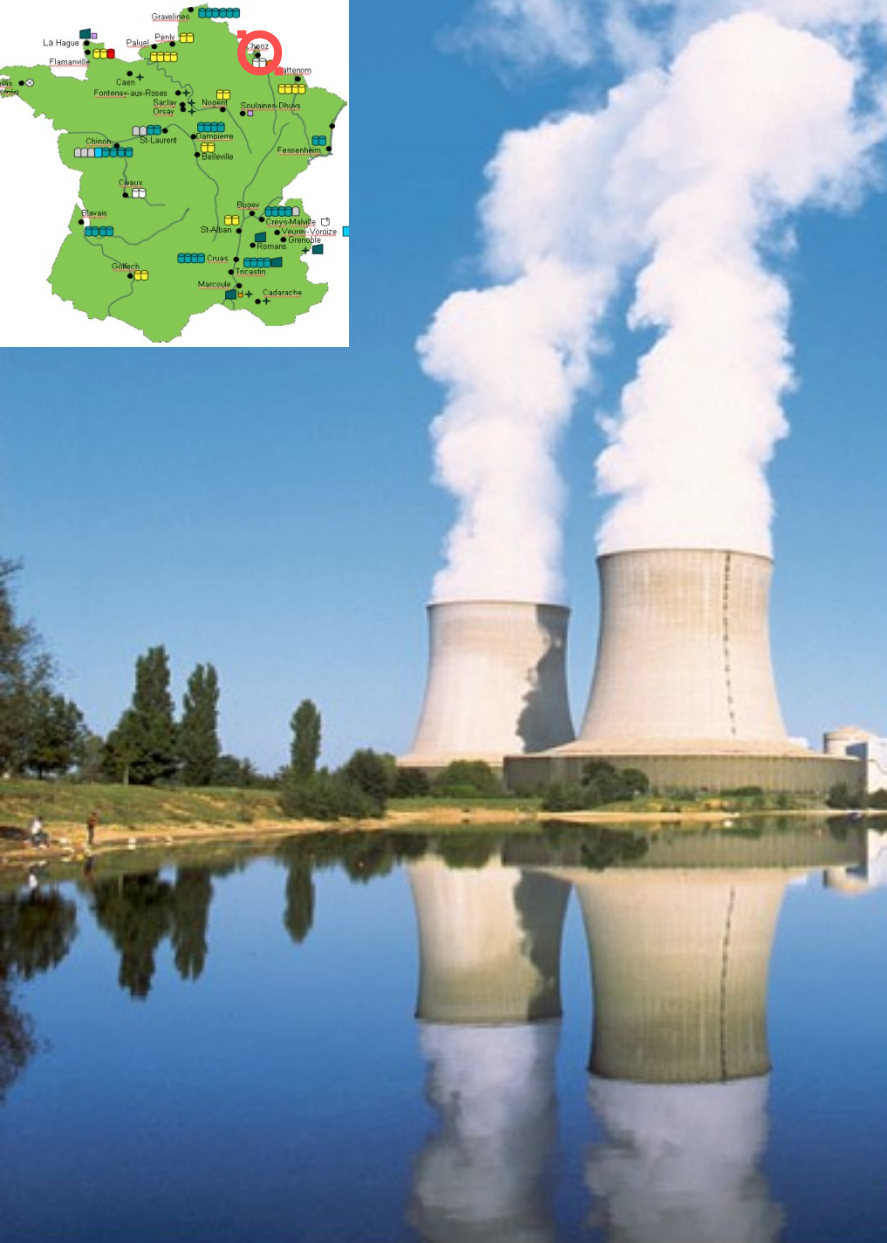
# Countermeasure : Filtered Vent

- Lessons of Chernobyl NPP Accidents promoted the installation of Filtered Vent System to protect radioactive materials exhaust.  
( French, German, Switzerland, Finland, Sweden )





# Visit Chooz NPP, EDF France



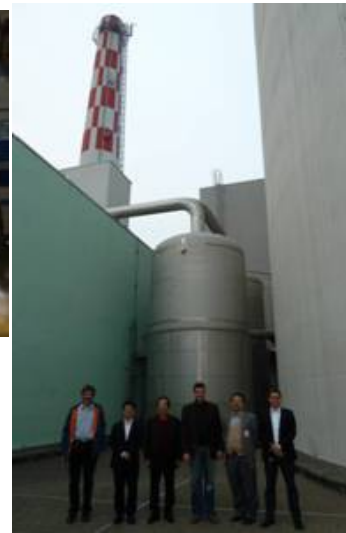
# Visit Leibstadt NPP, KKL, Switzerland



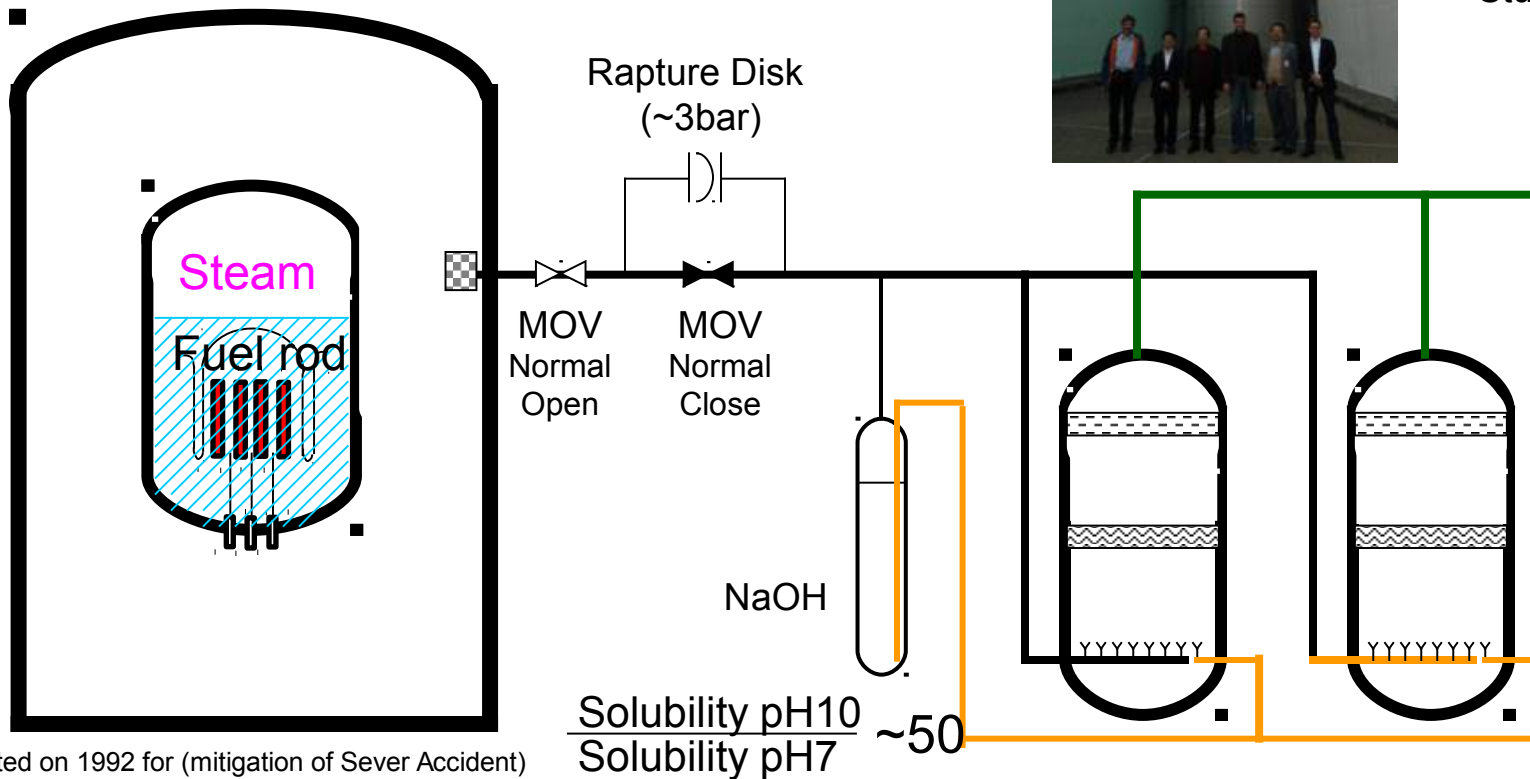
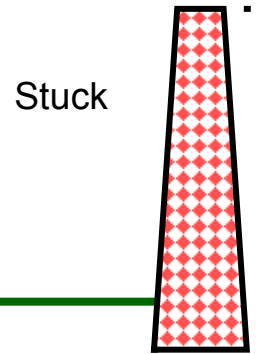


# FCVS: Filtered Containment Venting System

■ Vent valve will be open by manual shaft when SBO



DF  
 > 1000 Aerosol  
 > 100 I<sub>2</sub>

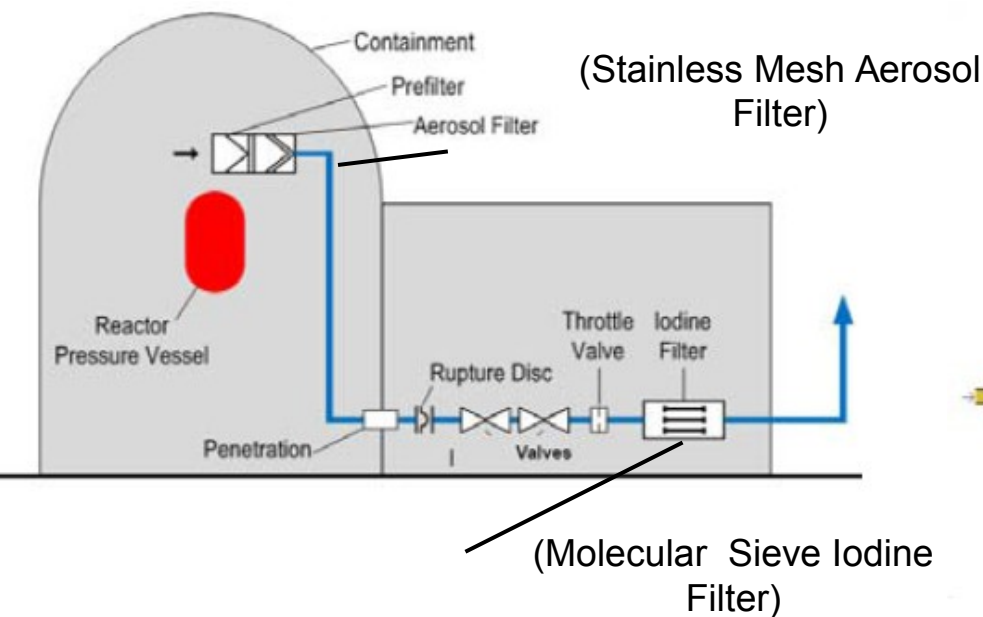


Back fitted on 1992 for (mitigation of Sever Accident)

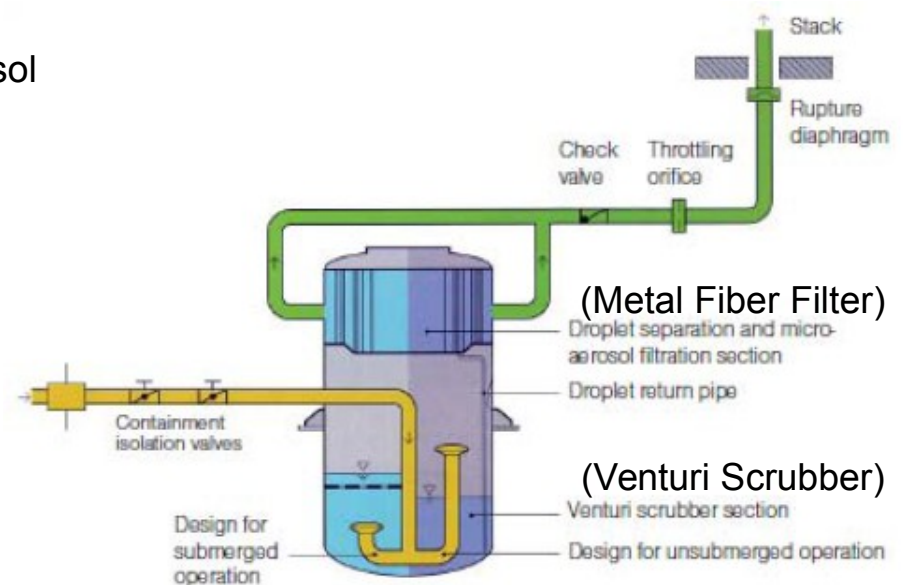


# The Examples of FCVS Configuration Planned to install in Japanese nuclear plants

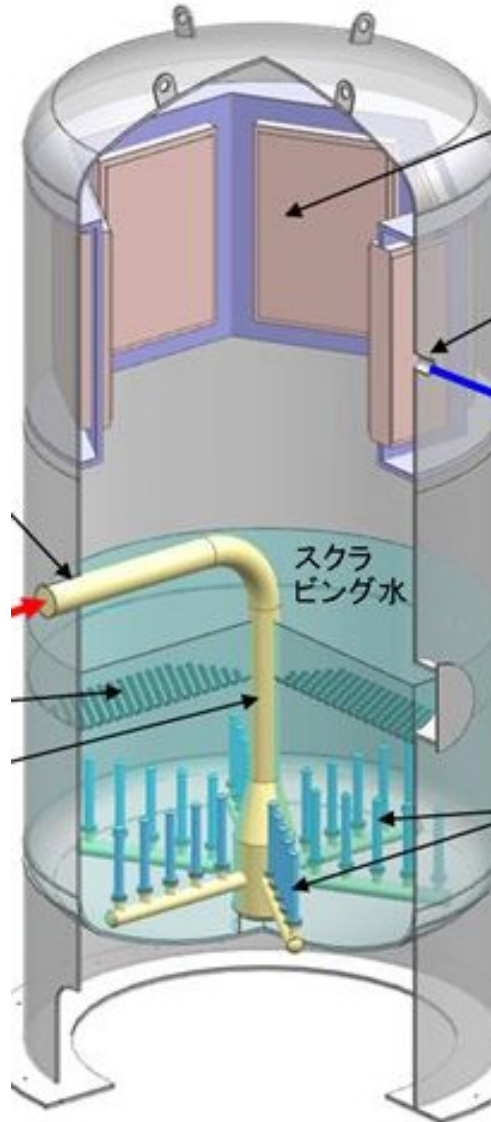
(Dry Type)  
Stainless Mesh Aerosol Filter + Molecular Sieve Iodine Filter



(Wet Type)  
Venturi Scrubber + Metal fiber Filter



# FCVS Test Facility at Hokkaido Univ





# FCVS Installation Chubu and TEPCO





# Tsunami Protection

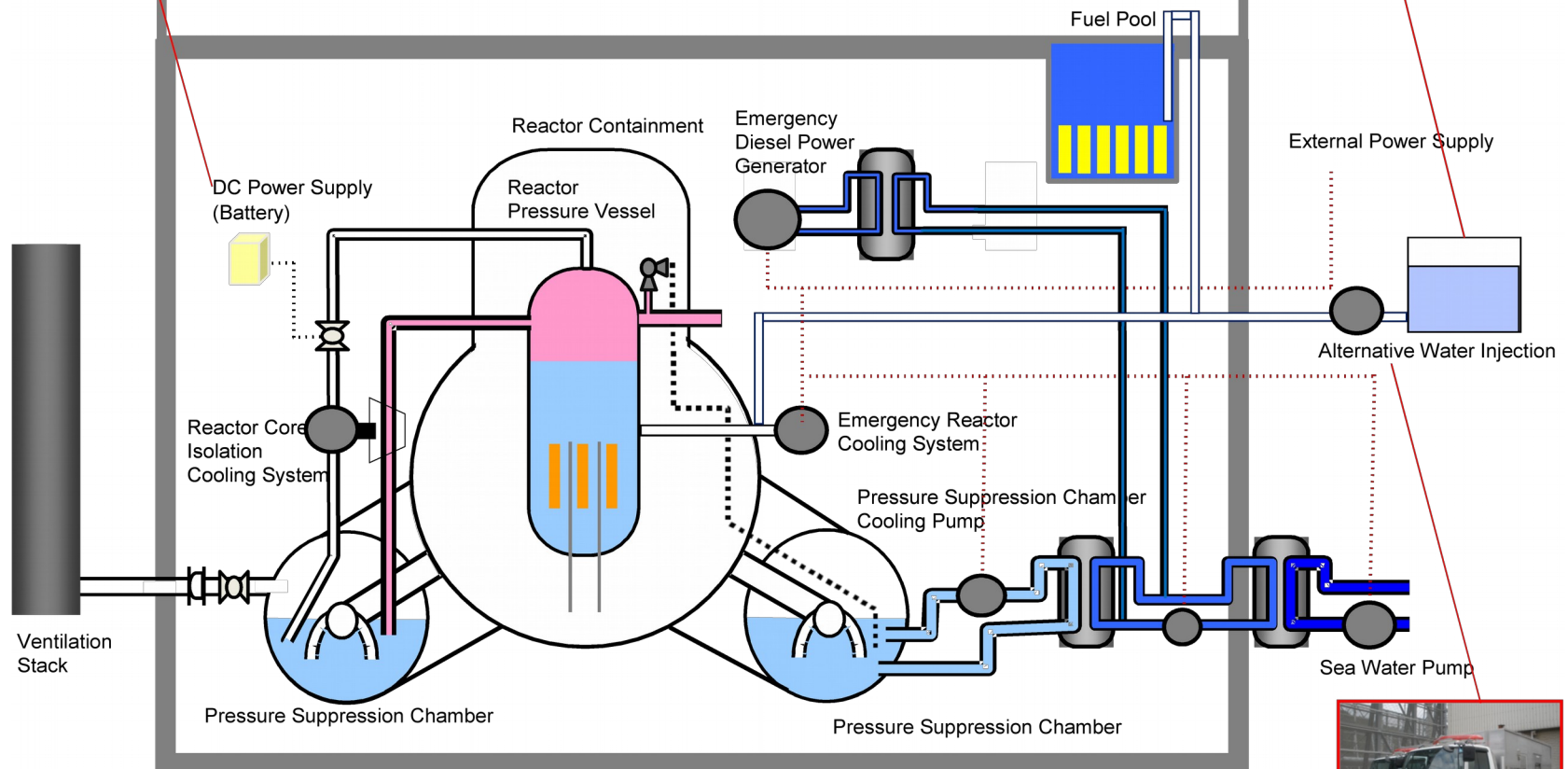
## Diablo Canyon NPP, USA



# Peach Bottom has Water Proof Doors



# Resilience after Tsunami: Recover Core/PCV cooling for BWR





# Countermeasure for Tsunami, based on the Defense in Depth Philosophy

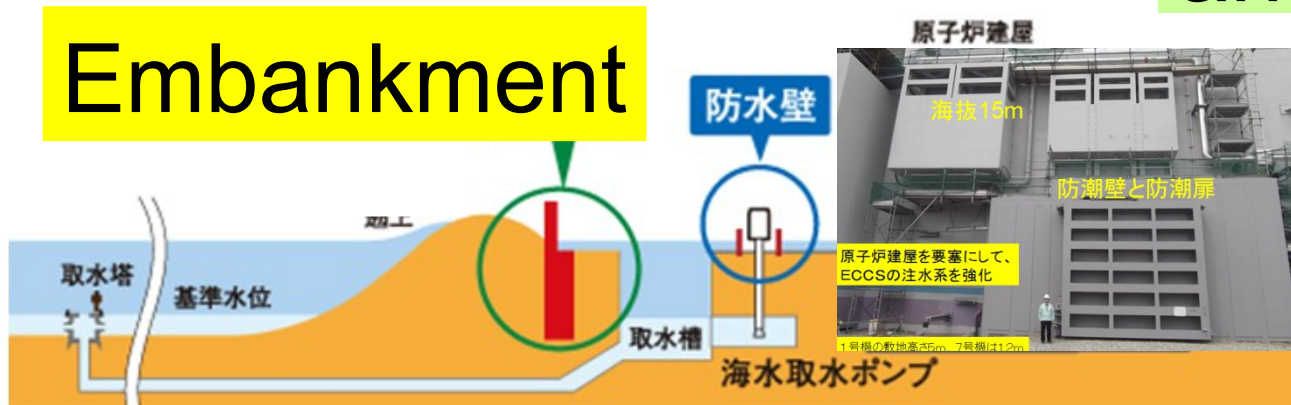
Mobile Cars on Hill



Water Proof Wall and Doors

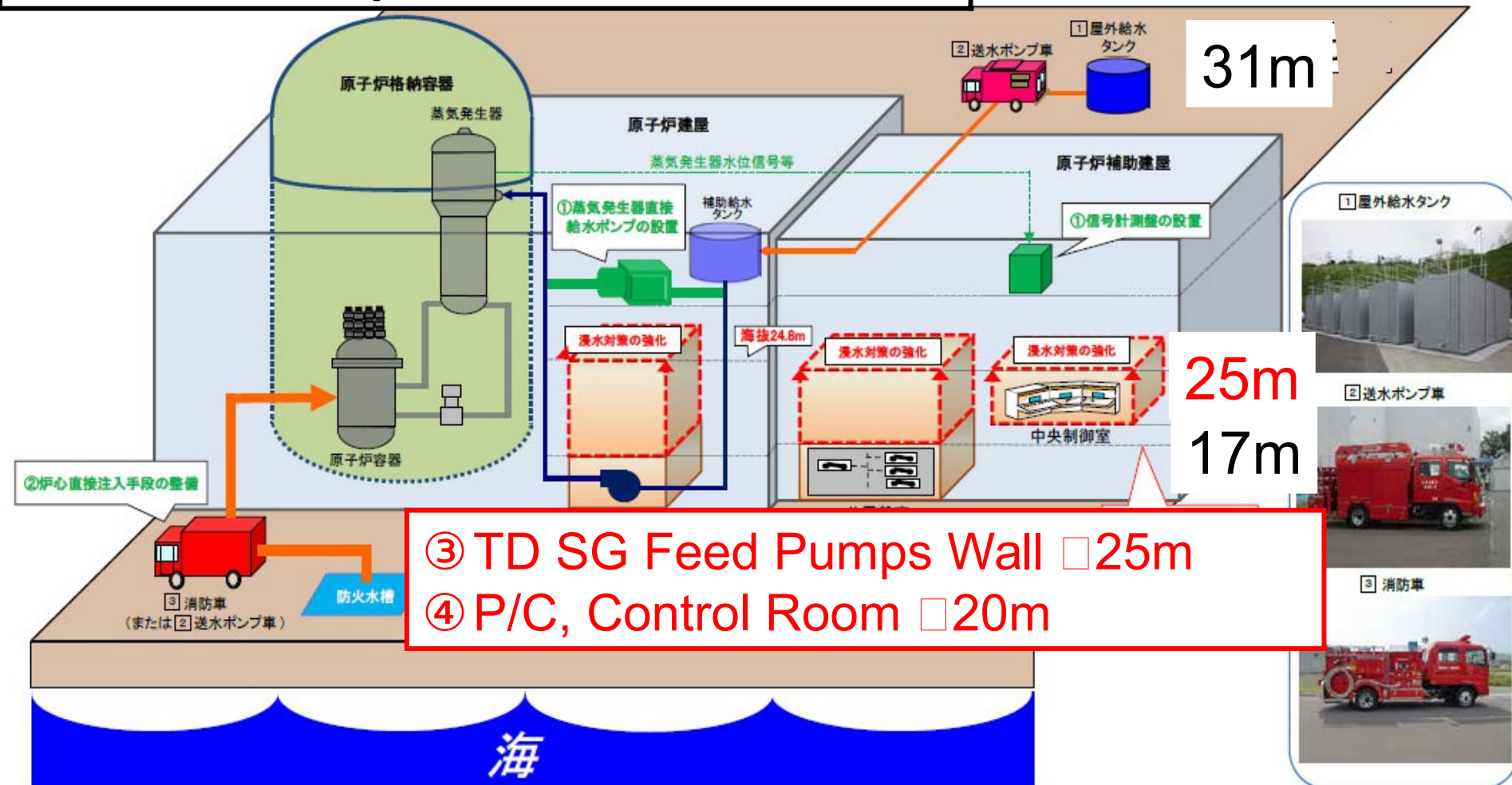
Water Proof Door for EDG and Pumps

Embankment



# Countermeasure for Tsunami, based on the Defense in Depth Philosophy

- ① SG Feed Water Pump at 31m
- ② Core Direct Injection Mobile Car at 31m





Elevation 15m

Large wall and door

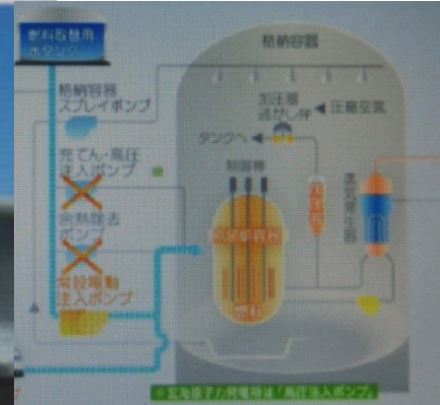
Reactor building was enforced to be a castle for ECCS survival.

Unit 1 elevation 5m, Unit 7 12m in Kashiwazaki-Kariwa NPS



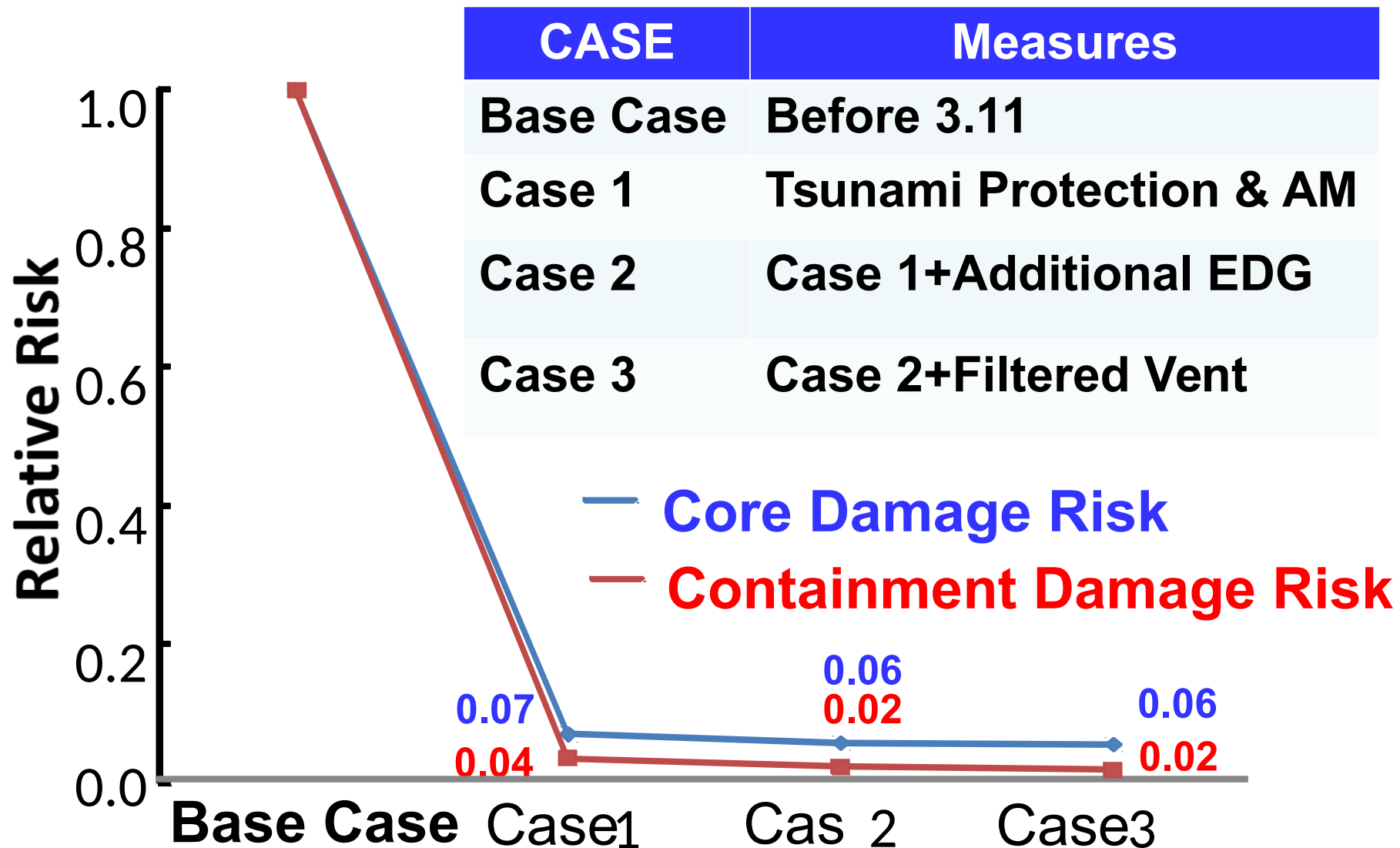
# Resilience for AC Power at Genkai NPS

	最大津波高さ	敷地高さ
川内 1・2号機	海拔 約4m <sup>※1</sup>	海拔 約13m
玄海 3・4号機	海拔 約3m <sup>※2</sup>	海拔 約11m

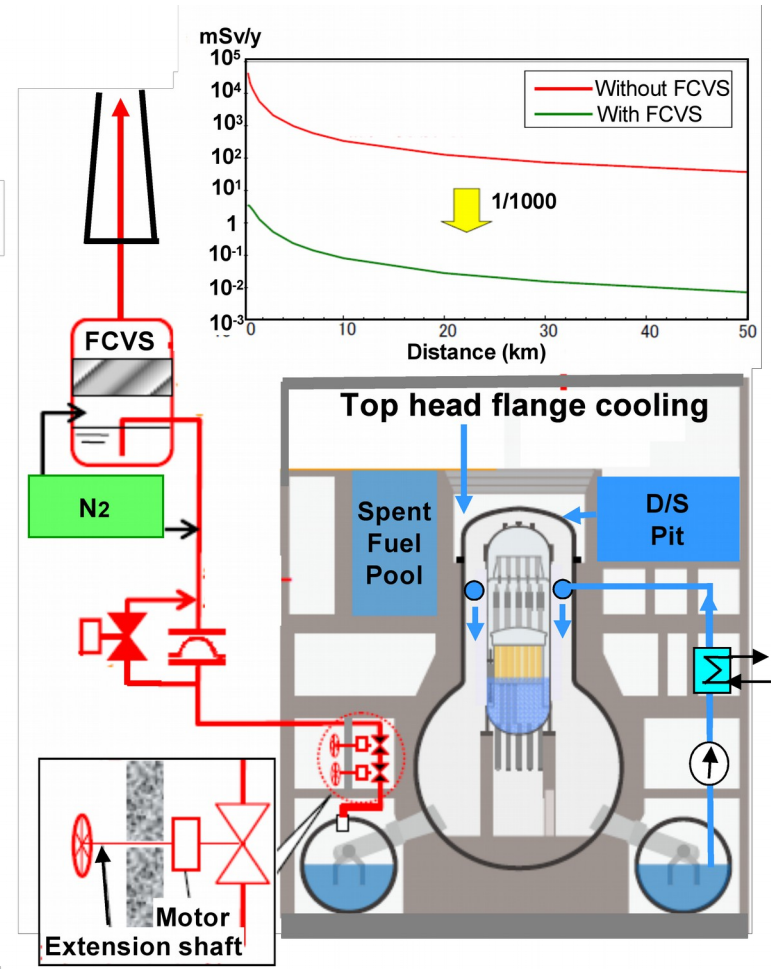
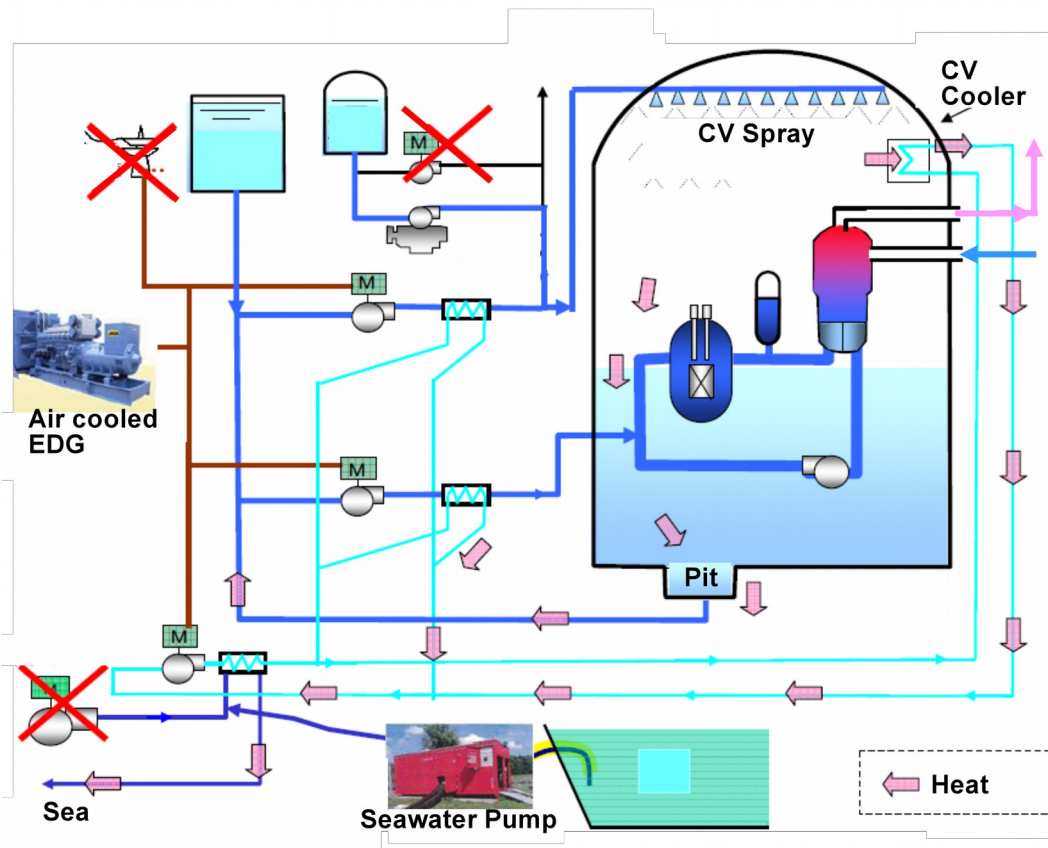


# Risk Reduction by Countermeasures

■ Base Case: Relative Risk=1.0



# Resilience to recover CV cooling

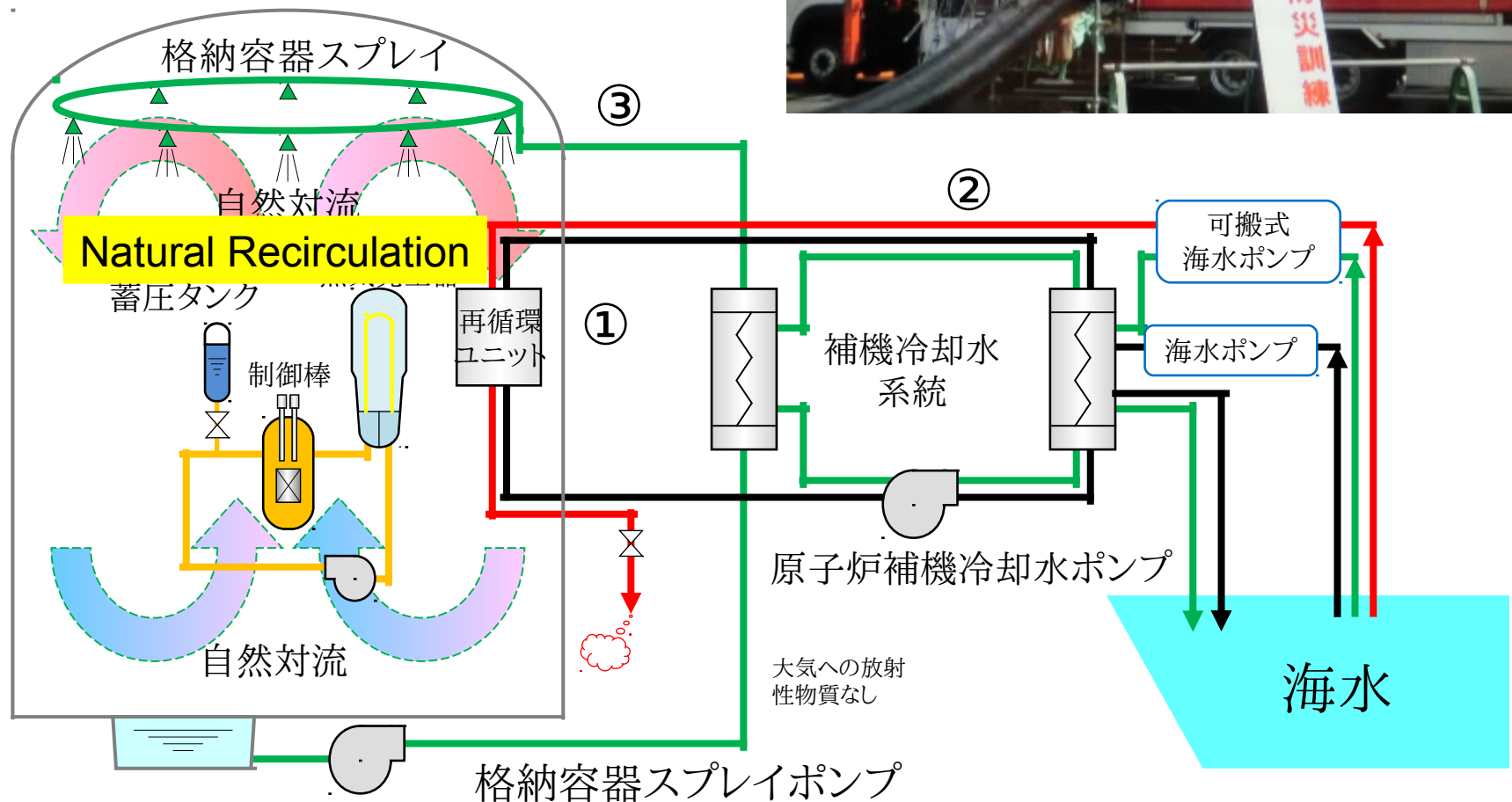




# Resilience for CV Cooling:

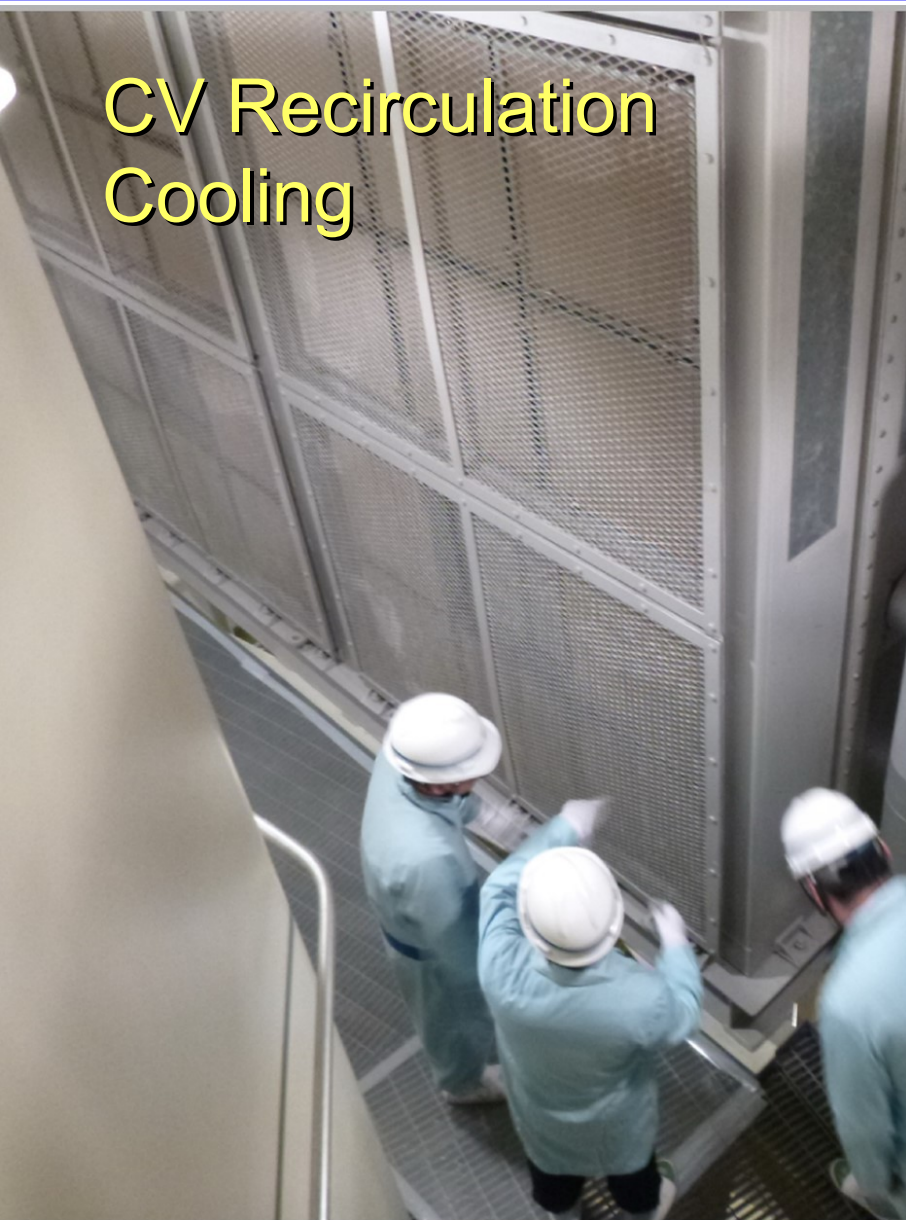
## Mobile Pump at Sendai NPS

- ① CV Cooling unit
- ② CV Spray



# Resilience for CV Cooling

CV Recirculation  
Cooling



CV Spray by mobile pump





# Resilience for H<sub>2</sub> Accumulation

Hydrogen Passive  
Autocatalytic  
Recombiner



Heated Igniter





# Tsunami Protection: Water proof door





# Resilience for Water Injection

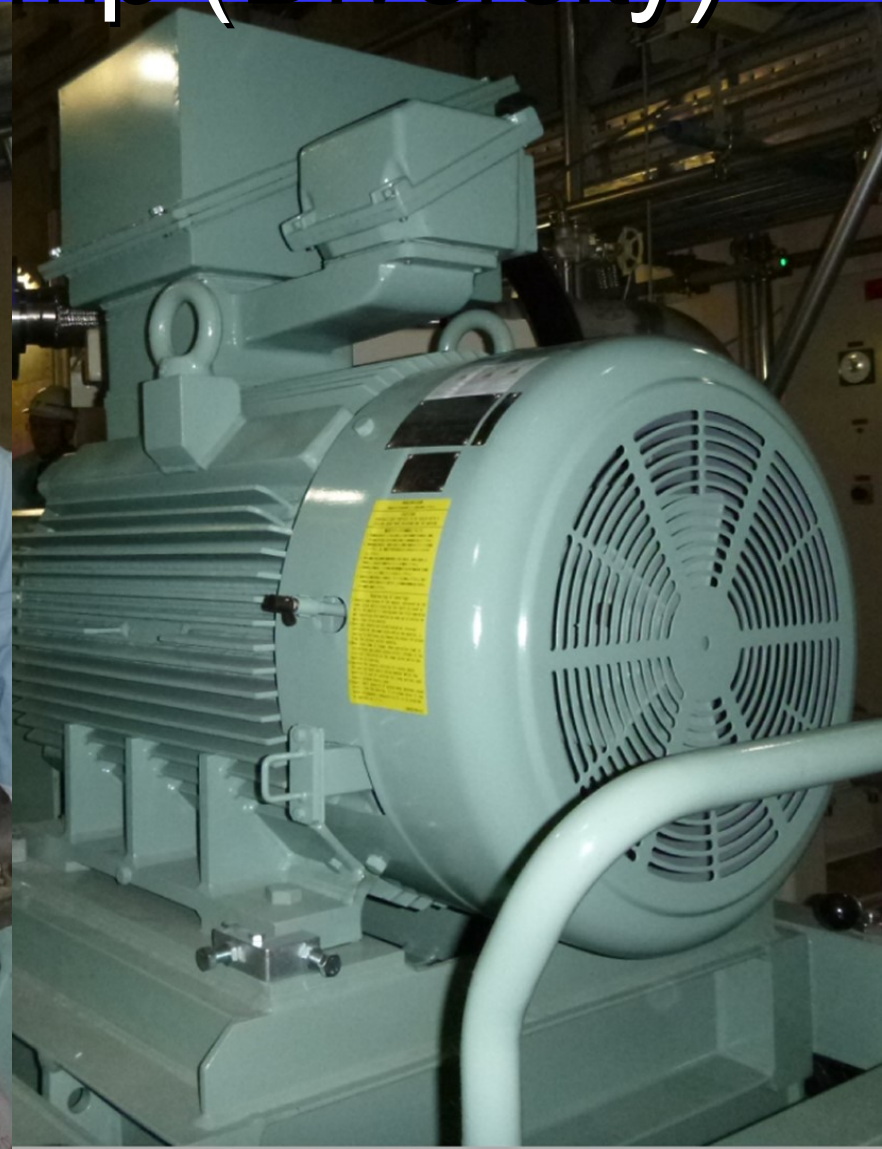


# Resilience for Water Injection: Diesel Engine Driven Pump (Diversity)





# Resilience for Water Injection: Moter Driven Pump (Diversity)

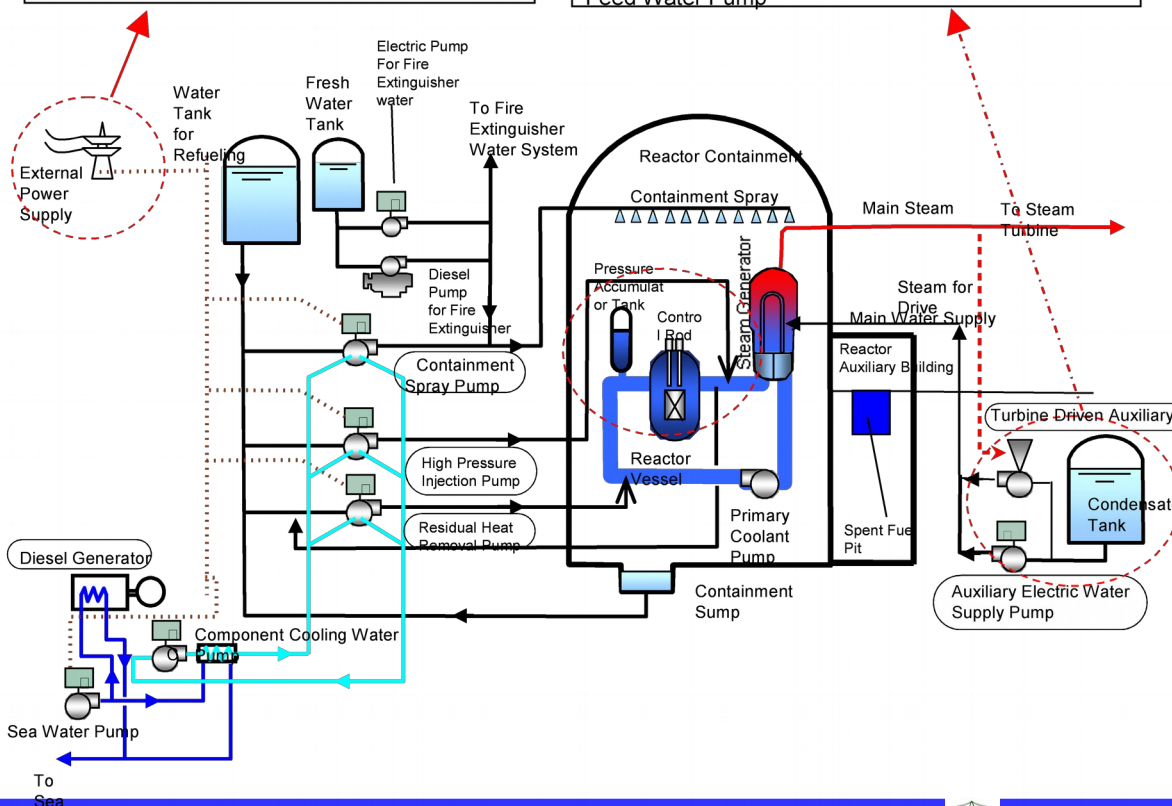
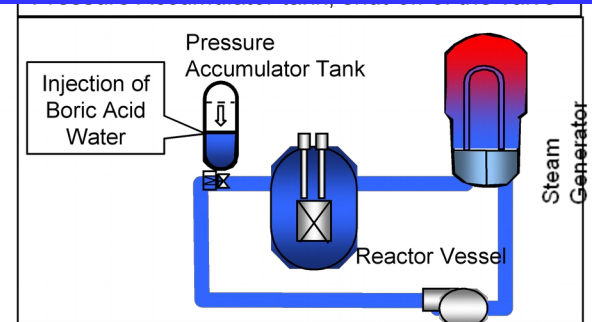
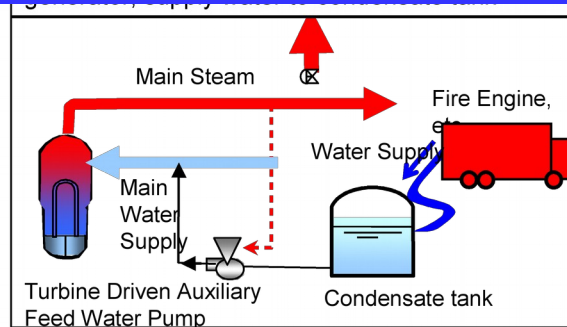
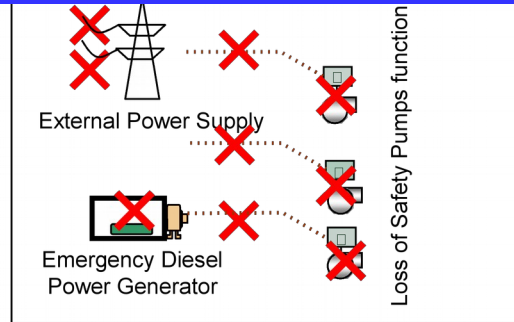




# Resilience for Heat Sink: Mobile heat sink car and fire engines



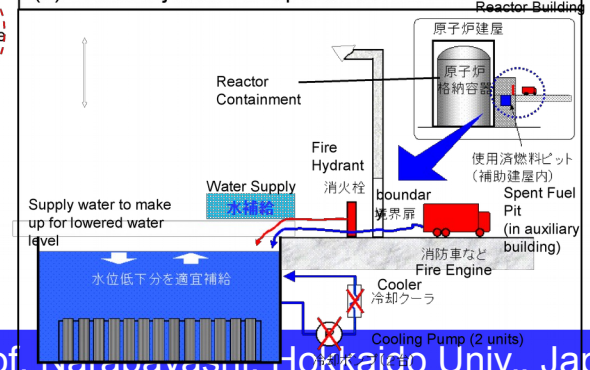
# Series of Events and Countermeasures in case of tsunami, for PWR



(6) Connection of Power Supply Car



(7) Water Injection to Spent Fuel Pit





# Electric Power Supply Car at Ikata NPS



# Portable Water Supply Pumps for Resilience Action at Ikata NPS





# Under Water Pumps for Resilience Action at Ikata NPS





# Resilience for CV damage: Water Cannon



# People in Fukushima met the Mayer of Slavutich City on Sep. 2013





# Fukushima's People Learned the Good Practice of Slavutich





# The Dreamy Town Slavutich in Ukraine





# The Dreamy Town Slavutich in Ukraine





# A Plan to construct the Dreamy Town in Fukushima should start ASAP





# Conclusion

- Fukushima Daiichi NPP accident would be terminated, if **protection/ resilience measures** installed for tsunami, such as water proof door/mobile power, etc.
- In Europe, it had already installed the Heat Removal System and Filtered Venting System from the lessons of **TMI and Chernobyl Accidents**.
- From the Lessons of Fukushima-Daiichi Accidents, we should prepare **protection and resilience actions** based on the **defense in depth strategy** for the world NPPs.
- Nuclear education is very important to improve the resilience learned from Fukushima Daiichi Nuclear Accident and safety culture in the world

