Fukushima Nuclear Accident and Roadmap for Decommissioning

~A TEPCO Nuclear Engineer's Perspective~

Presentation for Program on U.S.-Japan Relations
Harvard University

Cambridge, Massachusetts
December 3th, 2013

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TEPCO

My Background

- **'90~'96: Kyoto University**

  BS/MS in Nuclear Engineering

- **'96~: TEPCO**

  '96~'00: **Fukushima Daini NPS**

  '00~'02: **Nuclear Engineering Dept., Tokyo-H/Q (severe accident analysis)**

  '02~'04: **MBA, Stanford Graduate School of Business**

  '04~'05: **Nuclear Engineering Dept.**

  '05~'11: **International Affairs Dept.**

  Mar.~Sept.'11: **Fukushima Response Int'l Team, Tokyo-H/Q**

  Sept. '11~: **Washington DC Office**

TEPCO class of '96 in Naraha-town, Fukushima (Jan. 2000)

Pursued "Nuclear Renaissance" in Texas (June 2010)

My Background (cont'd)

- '90~'96: Kyoto University

  BS/MS in Nuclear Engineering

- '96~: TEPCO

  '96~'00: **Fukushima Daini NPS**

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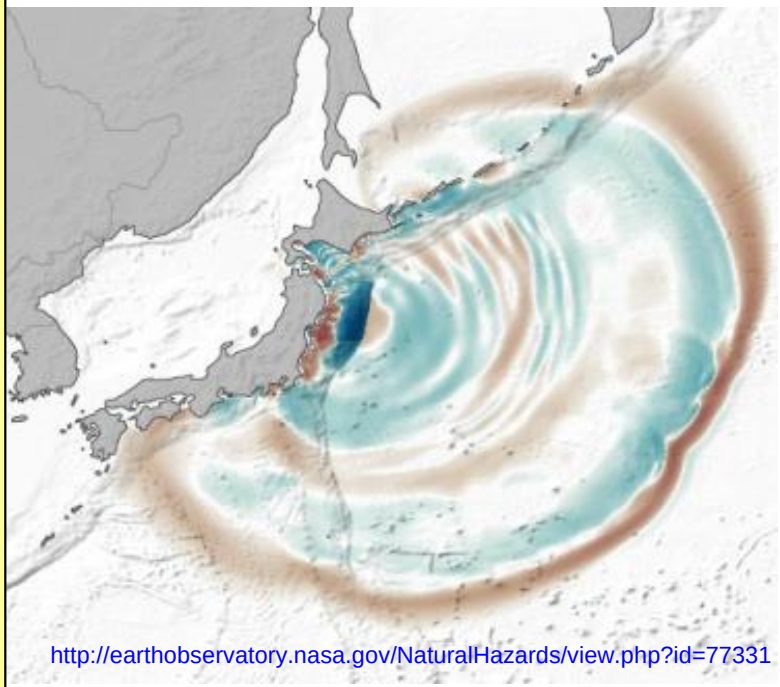
  Mar.~Sept.'11: **Fukushima Response Int'l Team, Tokyo-H/Q**

  Sept. '11~: **Washington DC Office**

Then, everything changed…



http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=77331

Great East Japan Earthquake (March 11, 2011)

My Post-Accident Activities

IAEA Preliminary Mission (4/6/2011@Fukushima Daiichi NPS)

IAEA: International Atomic Energy Agency

My Post-Accident Activities (cont'd)

Preparation for IAEA Fact-Finding Mission (5/21/2011@Fukushima Daiichi "*Bedroom*")

My Post-Accident Activities (cont'd)

IAEA Fact-Finding Mission (5/27/2011@Fukushima Daiichi)

My Post-Accident Activities (cont'd)

U.S. INPO-Led Industry Support Team (8/19/2011@Fukushima Daini)

INPO: Institute of Nuclear Power Operations

Reinforcing US-Japan Ties
(6/15/11@U.S. Ambassador Roos' Residence)

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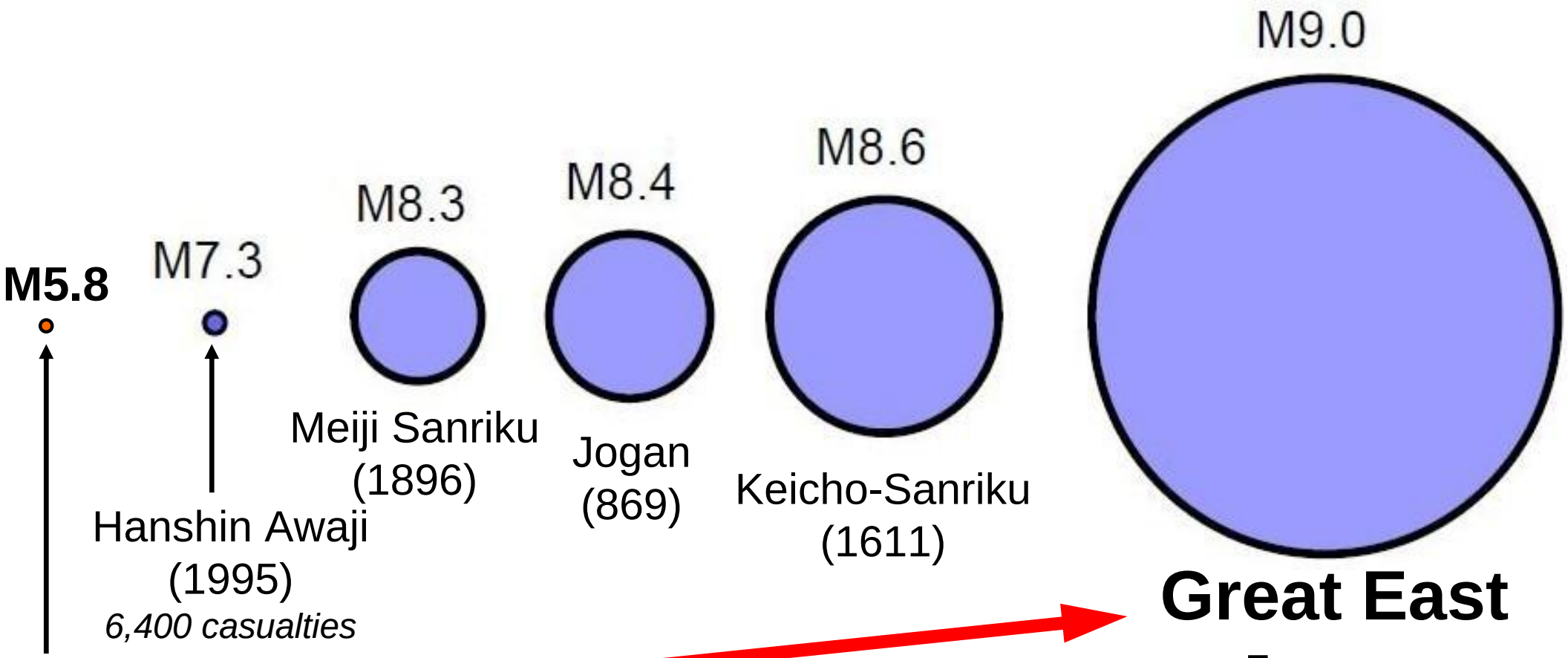
Damage Due to Great East Japan Earthquake (GEJE)

- ***Largest** earthquake (M9.0) and tsunami (M9.1) in recorded history of Japan*
- ***20+ m** tsunami run-up in coast line spanning **200 km***
- ***560 km^2** flooded (10x Manhattan)*
- ***19,000 dead/missing***

Comparison of Seismic Energy (Magnitude)



http://wcrnews.wordpress.com/2011/08/23/5-9-earthquake-rocks-virginia-d-c/

Impact of GEJE to TEPCO Facilities

Shutdown:

- Nuclear power: **7** units
- Thermal power: **12** units
- Hydro power: **25** units
- Substations: **8**

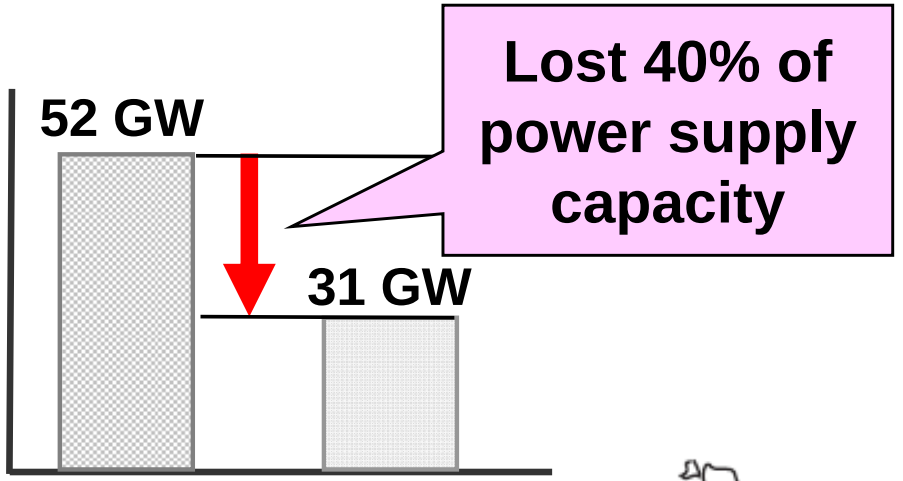
Power outage:

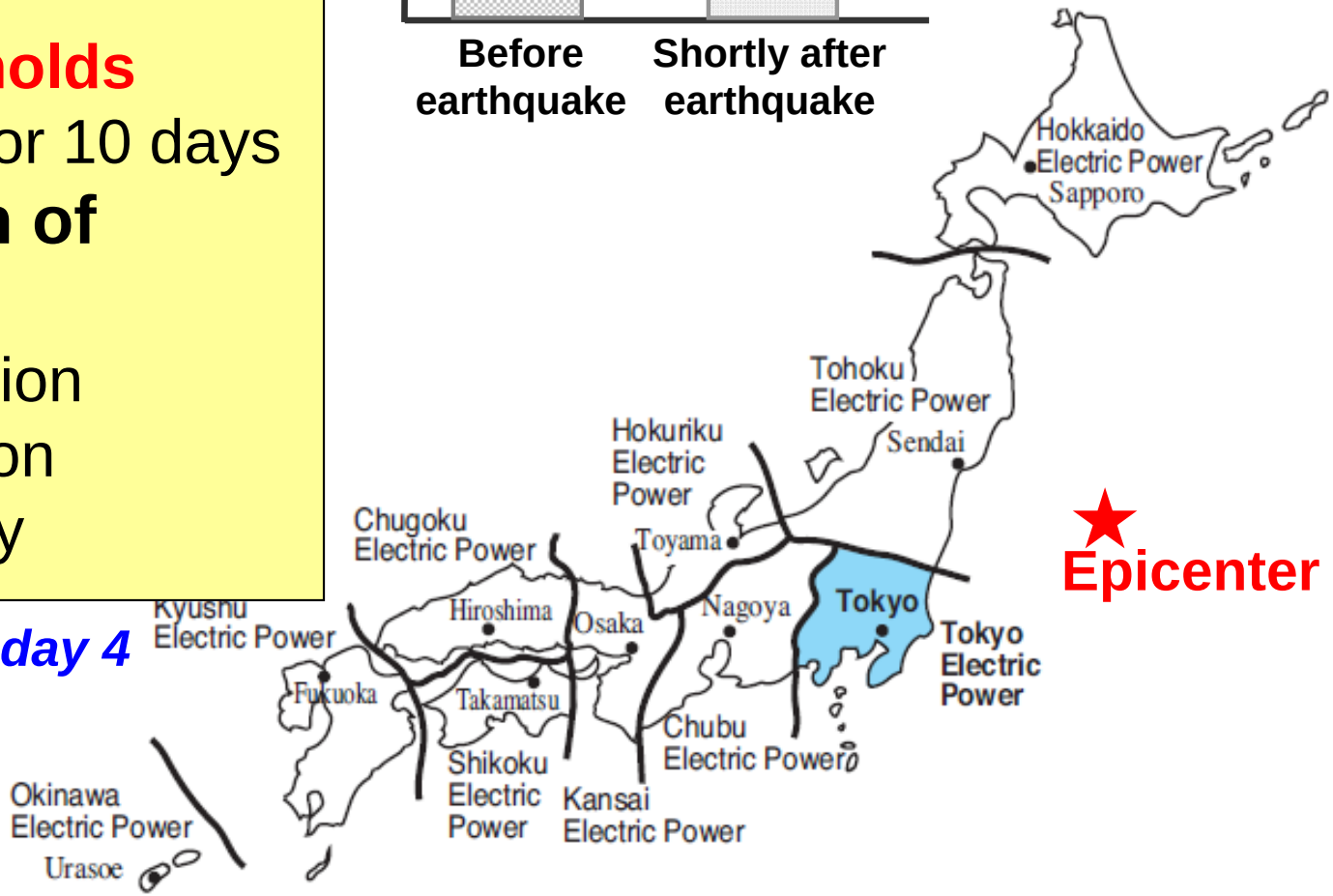
- **4 million households**
- Rolling blackout for 10 days

Massive interruption of infrastructure:

- Public transportation
- Telecommunication
- Food/water supply

>99% of power restored by day 4





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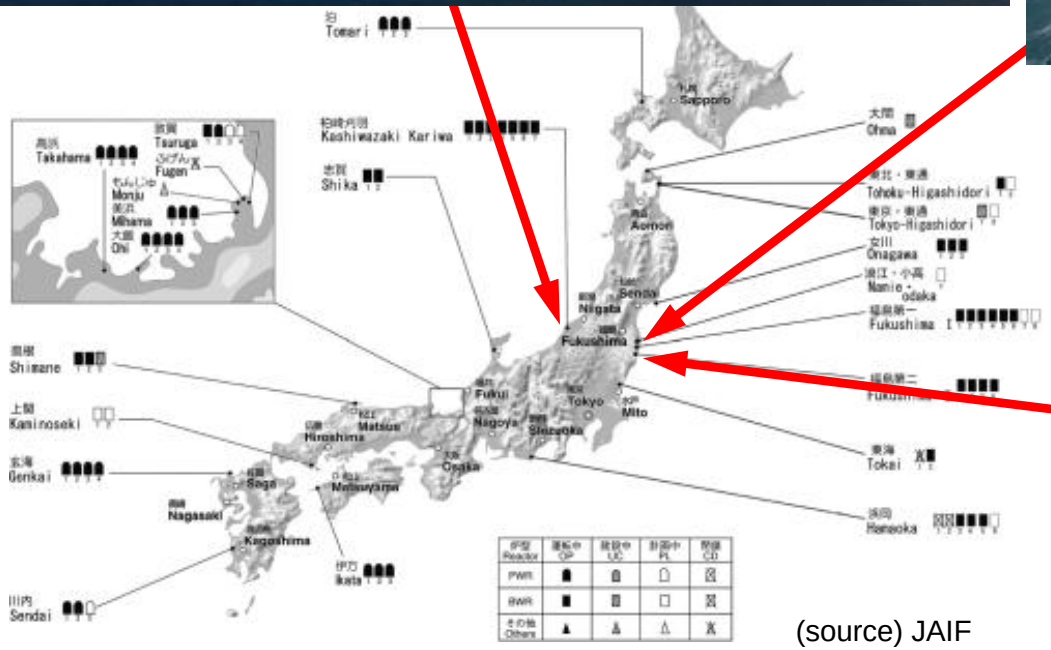
TEPCO's Nuclear Power Stations (17 BWR Units)



(source) JAIF

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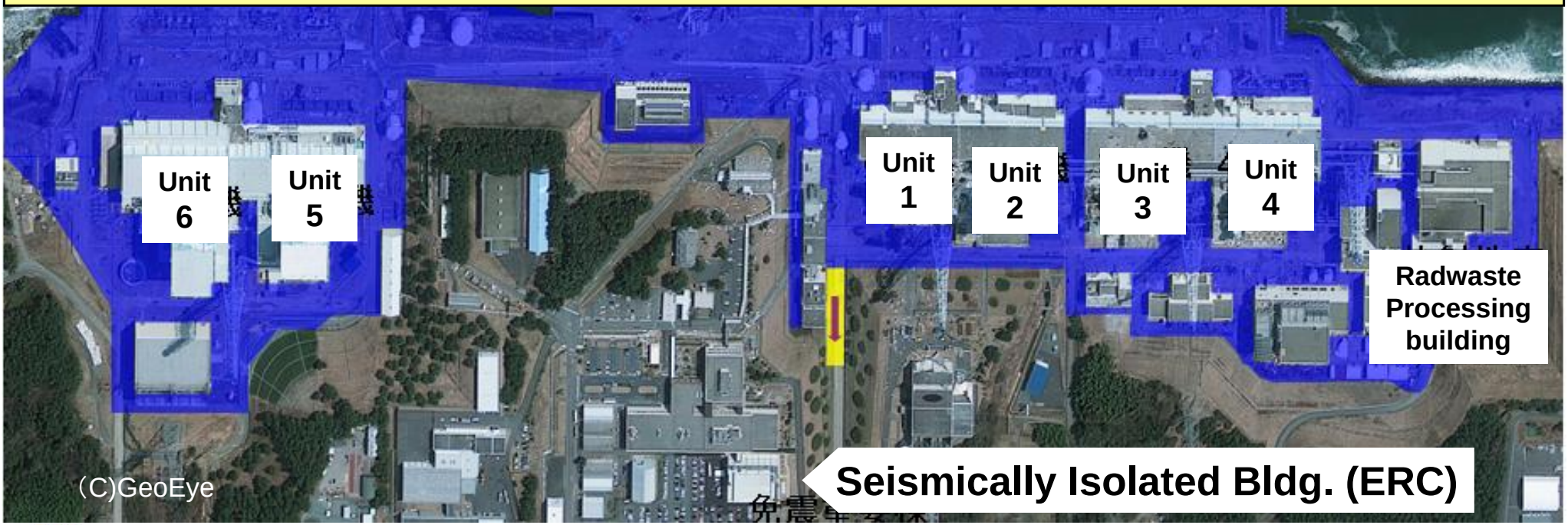
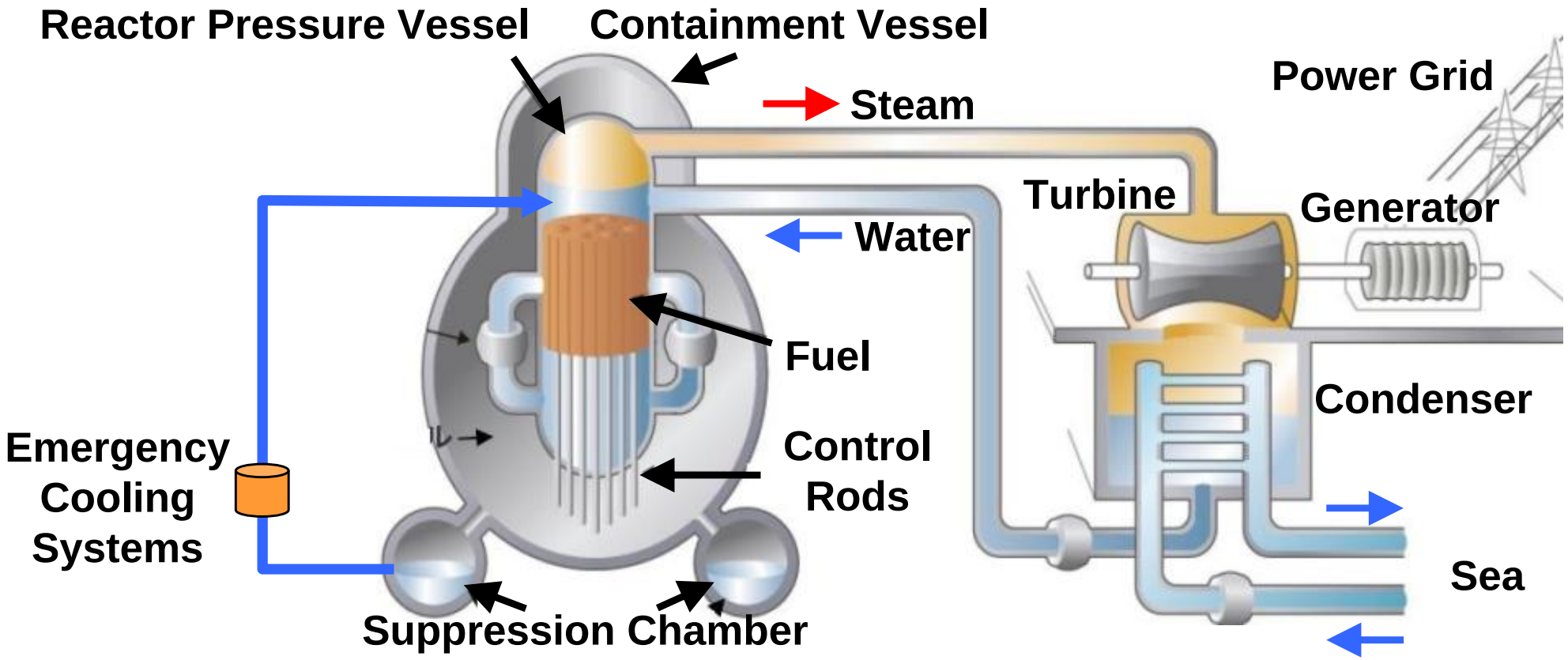
Tsunami Observed at Fukushima Daiichi (1F)

Impact of Earthquake/Tsunami at 1F

- **After the Earthquake (near design-basis):**
  - ✓**Loss of all off-site power**
  - ✓**Plant responded as designed (automatic shutdown of operating units; startup of emergency diesel generators)**
- **After the Tsunami (beyond design-basis):**
  - ✓**Tsunami height (13.1 m): 4x historical-high and 2x design-basis**
  - ✓**Station Black Out (SBO) for 5 out of 6 units**
  - ✓**Loss of almost all safety system, instrumentation, lighting, etc.**



Nuclear Safety 101

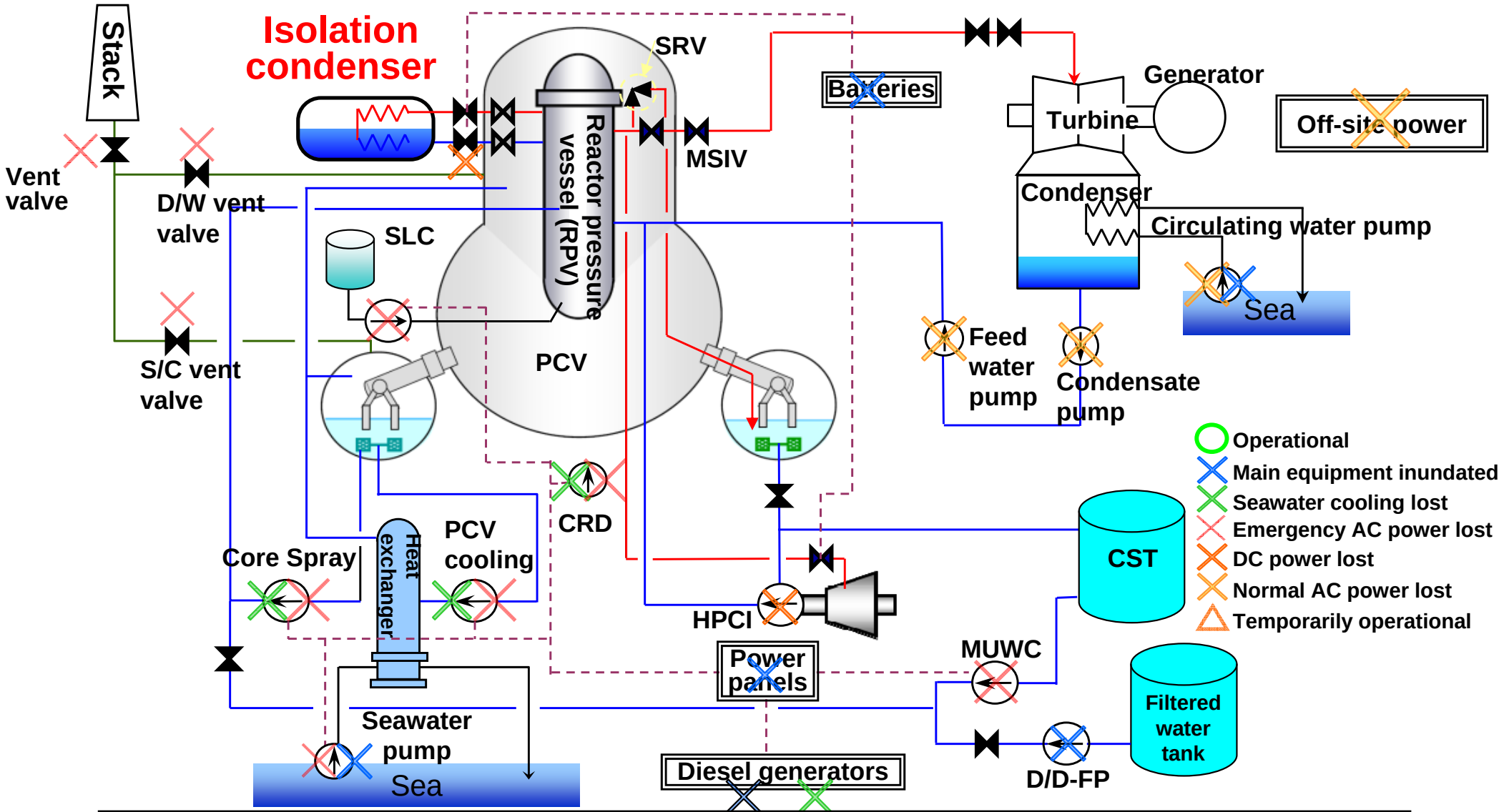


[Sources of Heat] a. **Nuclear Fission** (during operation)
b. **Radioactive Decay** (after shutdown)

$E=mc^2$ *(massive heat generated from very little mass)*

3 Safety Principles: (1) **Shutdown**, (2) **Cool**, (3) **Contain**

Plant Status After Tsunami (1F Unit 1)



- Reactor automatically shutdown after earthquake
- Loss of all AC/DC power + core cooling capability due to tsunami
- Core melt and Zr-water reaction led to H2 explosion in reactor bldg.
- Stabilization by sea water injection via fire trucks

Accident Response at 1F: In the Field

Roads damaged by earthquake

Roads blocked by tsunami debris

Continual aftershocks, tsunami alerts, open manholes, etc. exacerbated the situation

Accident Response at 1F: In the Main Control Room

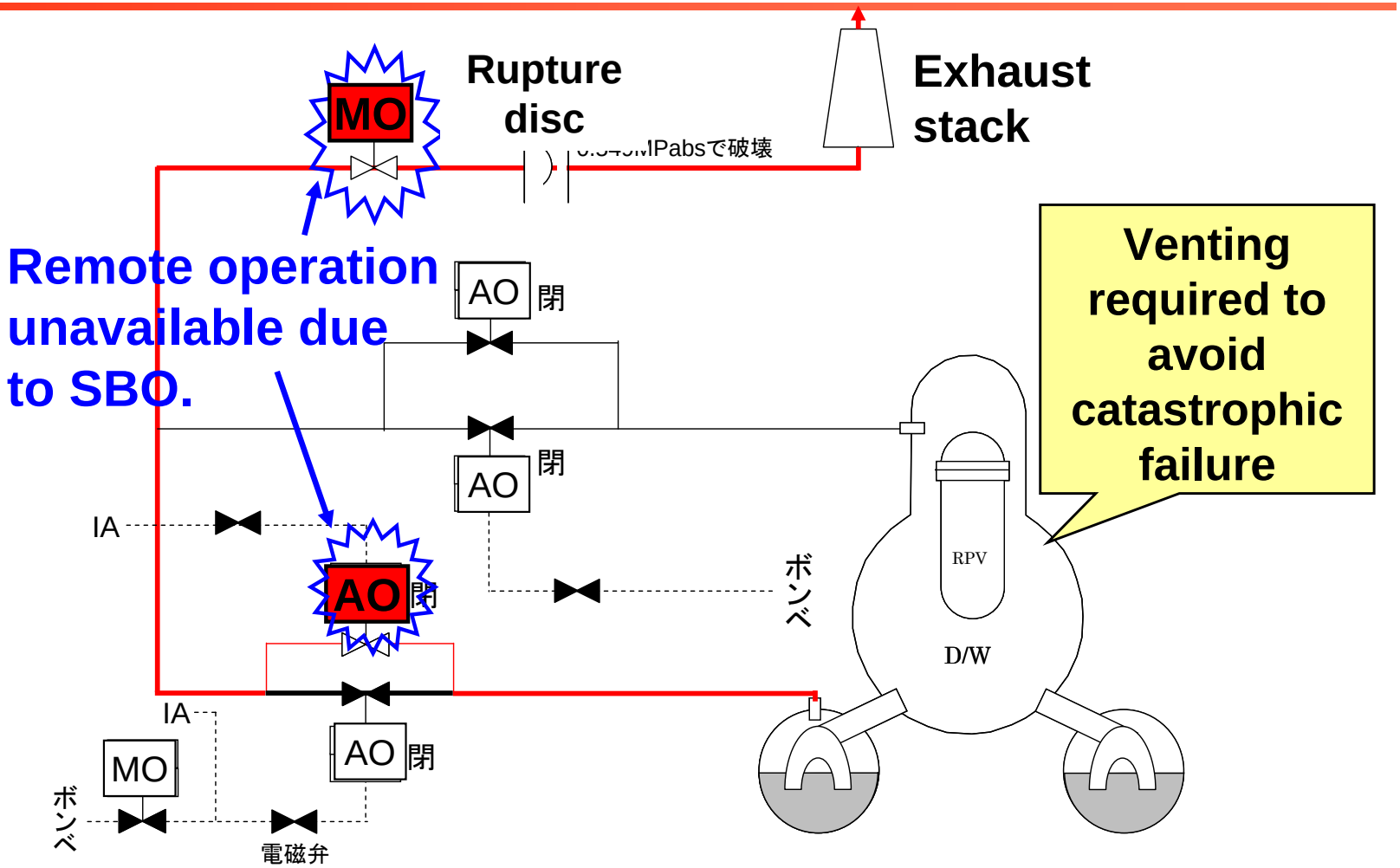
Checked instrumentation in near-complete darkness

Supervised operation wearing full-face mask

Brought in heavy batteries to restore instrumentations

- **Lack of:**
  instrumentation, communication means, lighting, food, water, sleep, ...
- **Increase in:**
  radiation level, fatigue, fear, despair, ...

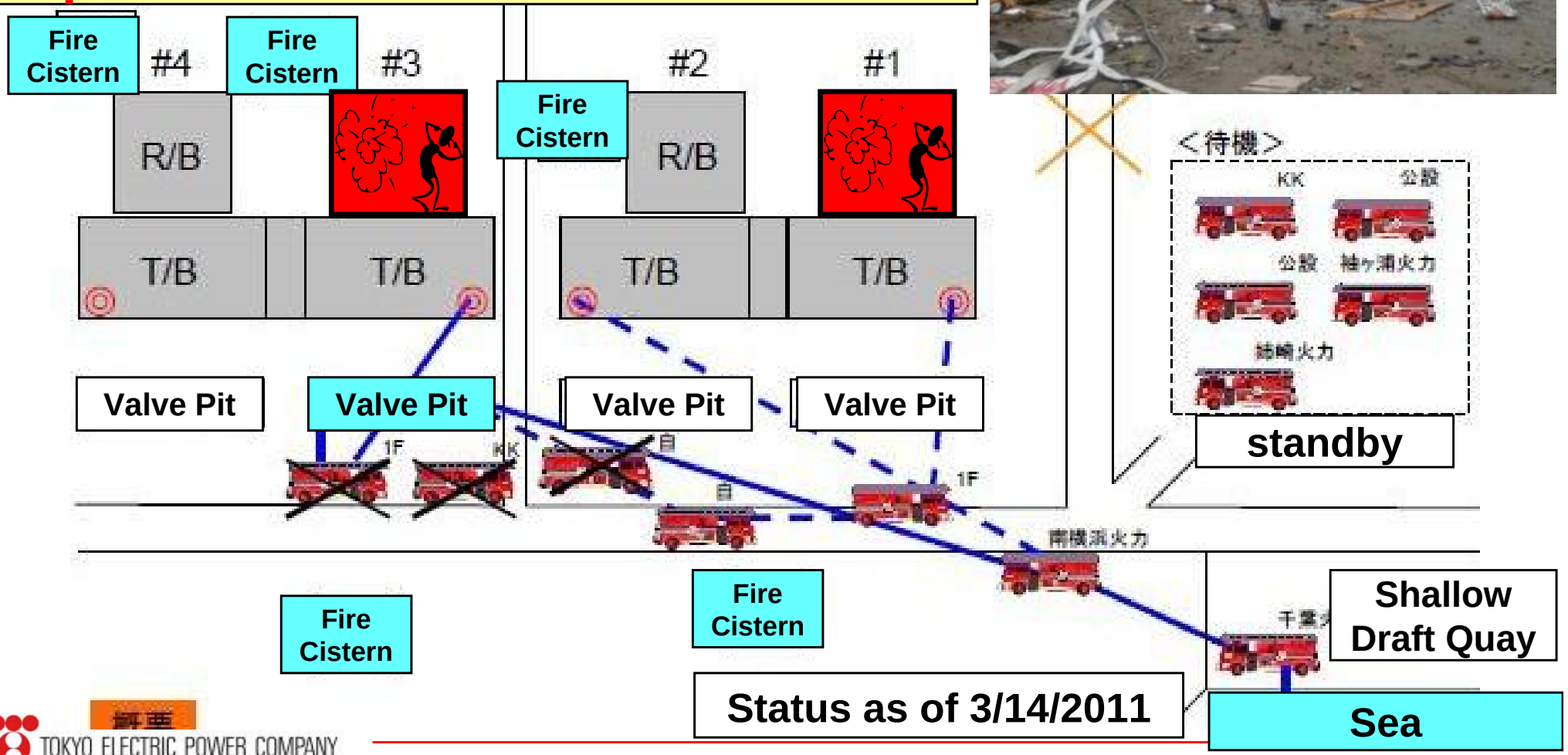
Accident Response at 1F: Unit 1 Containment Venting



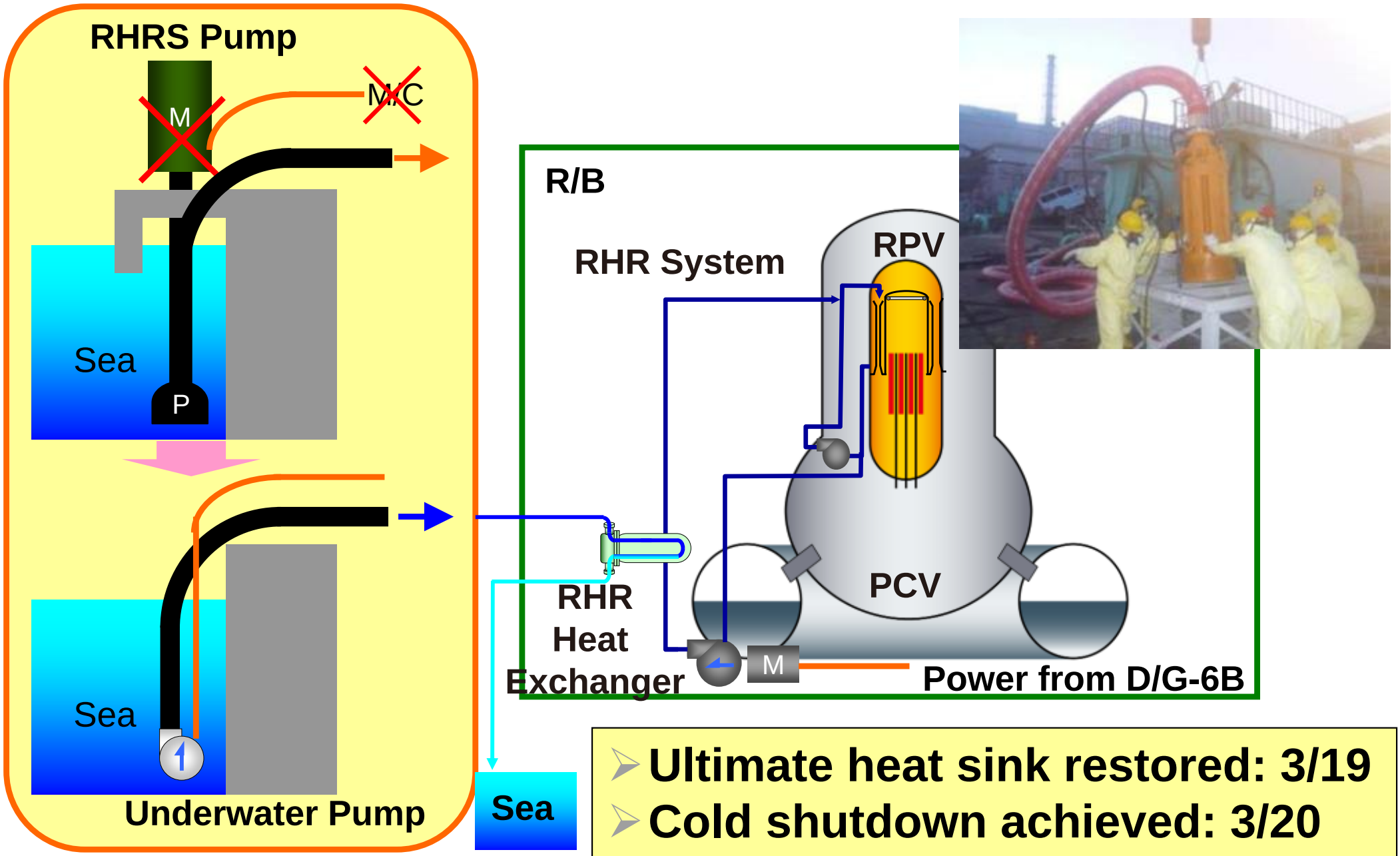
- Six men formed 3 “last-resort teams” to manually open 2 valves in highly-radioactive area
- Core damage already progressing by this time (3/12 9:04-9:30)

Accident Response at 1F: Water Injection by Fire Trucks

- Fire trucks played critical role in injecting water into reactors
- Fire brigade operated fire trucks amidst high radiation/successive explosions



Accident Response at 1F: Protecting Units 5&6



- Ultimate heat sink restored: 3/19
- Cold shutdown achieved: 3/20

→Determination to save Units-5/6

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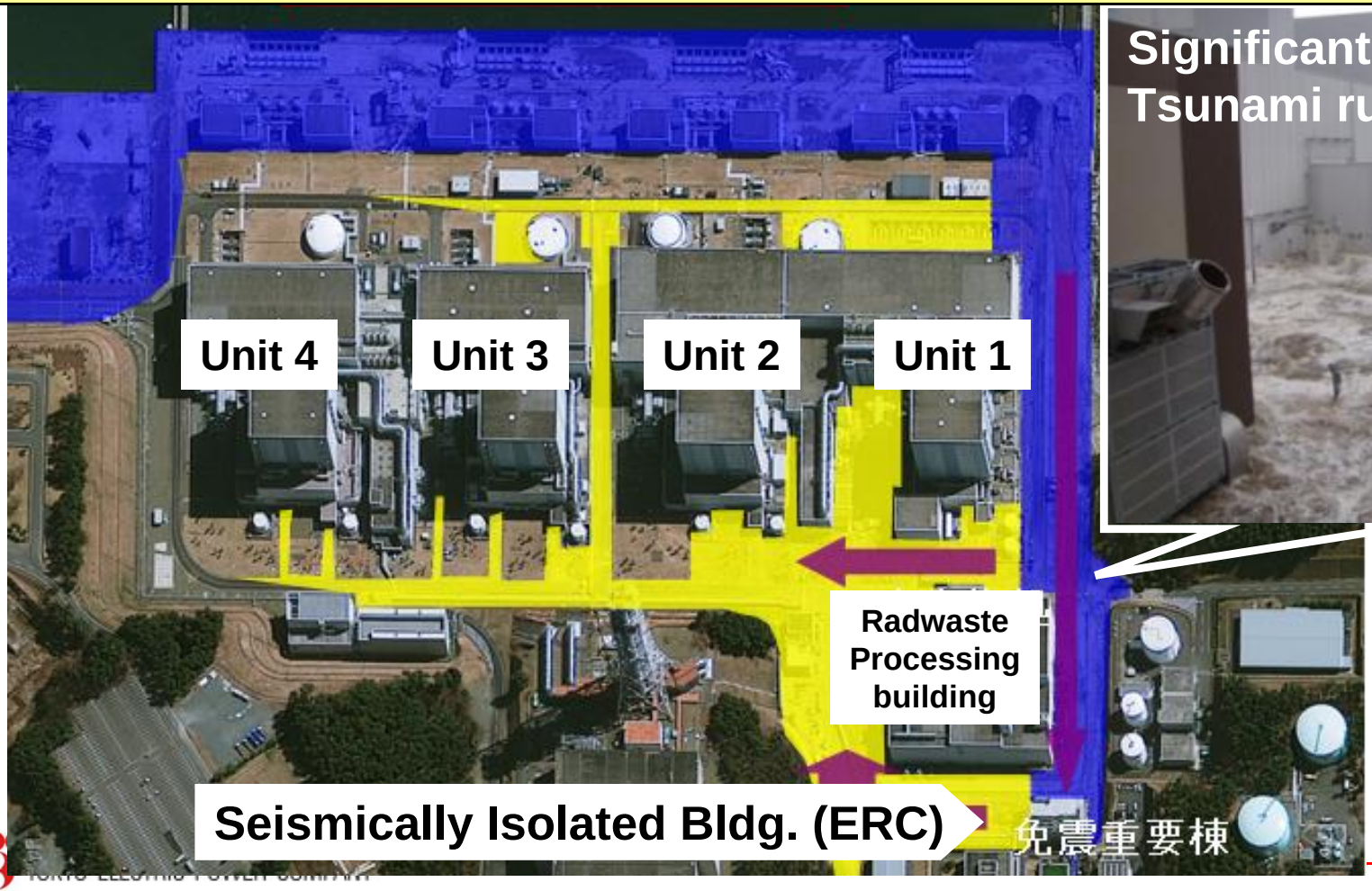
Impact of Earthquake/Tsunami at 2F

- **After the Earthquake (smaller than design-basis):**
  - ✓**Loss of all but one line of off-site power**
  - ✓**Plant responded as designed**
- **After the Tsunami (beyond design-basis):**
  - ✓**Loss of Ultimate Heat Sink for 3 out of 4 units**

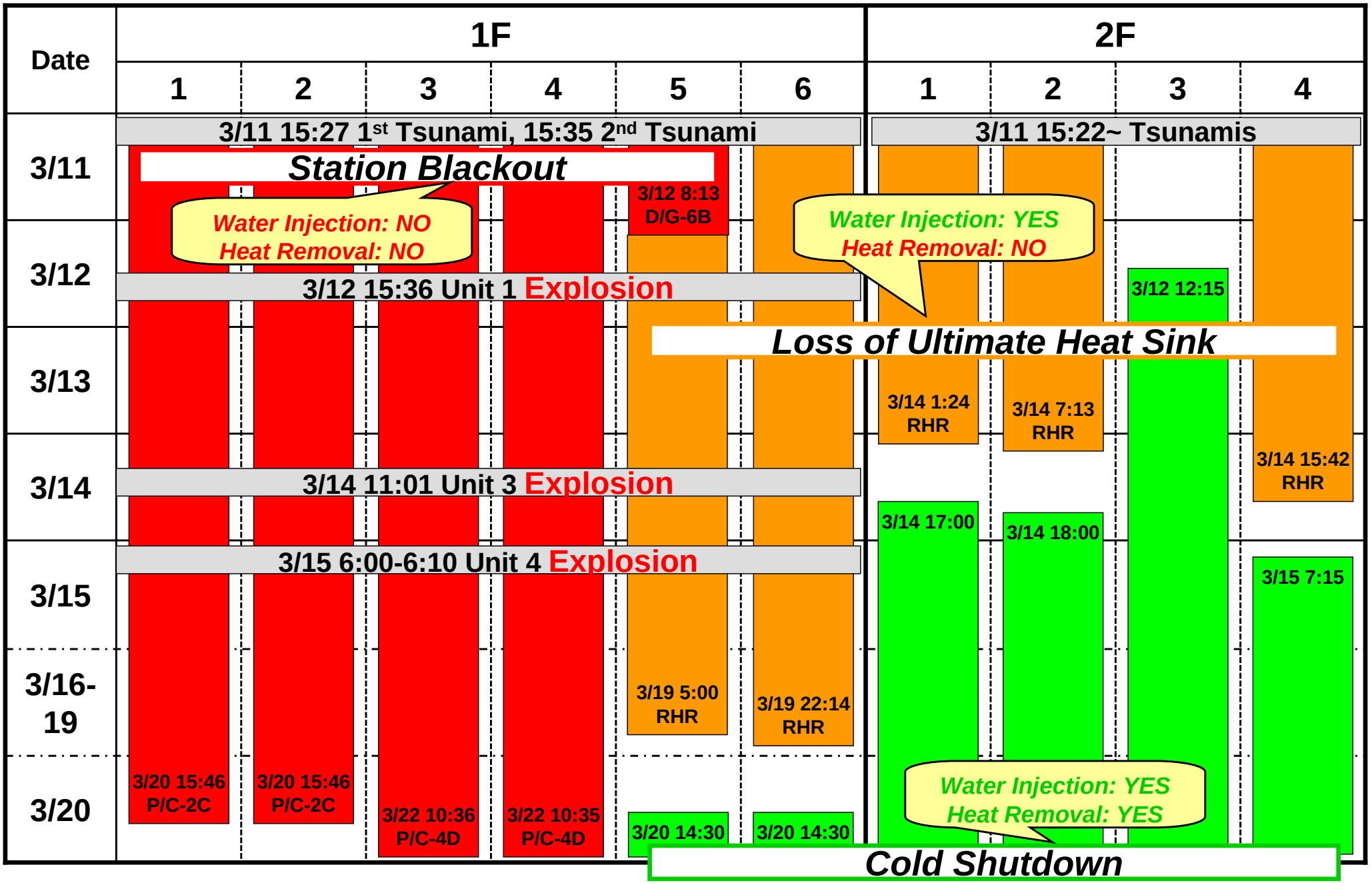


(C)GeoEye

Accident Response at 2F: Recovery from Tsunami

- **Restored ultimate heat sink by:**
  - ✓ **Laying 9 km of heavy power cables by hand**
  - ✓ **Rapidly procuring and replacing motors**
- **Executed "FLEX On-The-Fly"**

Overview of the 10-Unit Simultaneous Accidents



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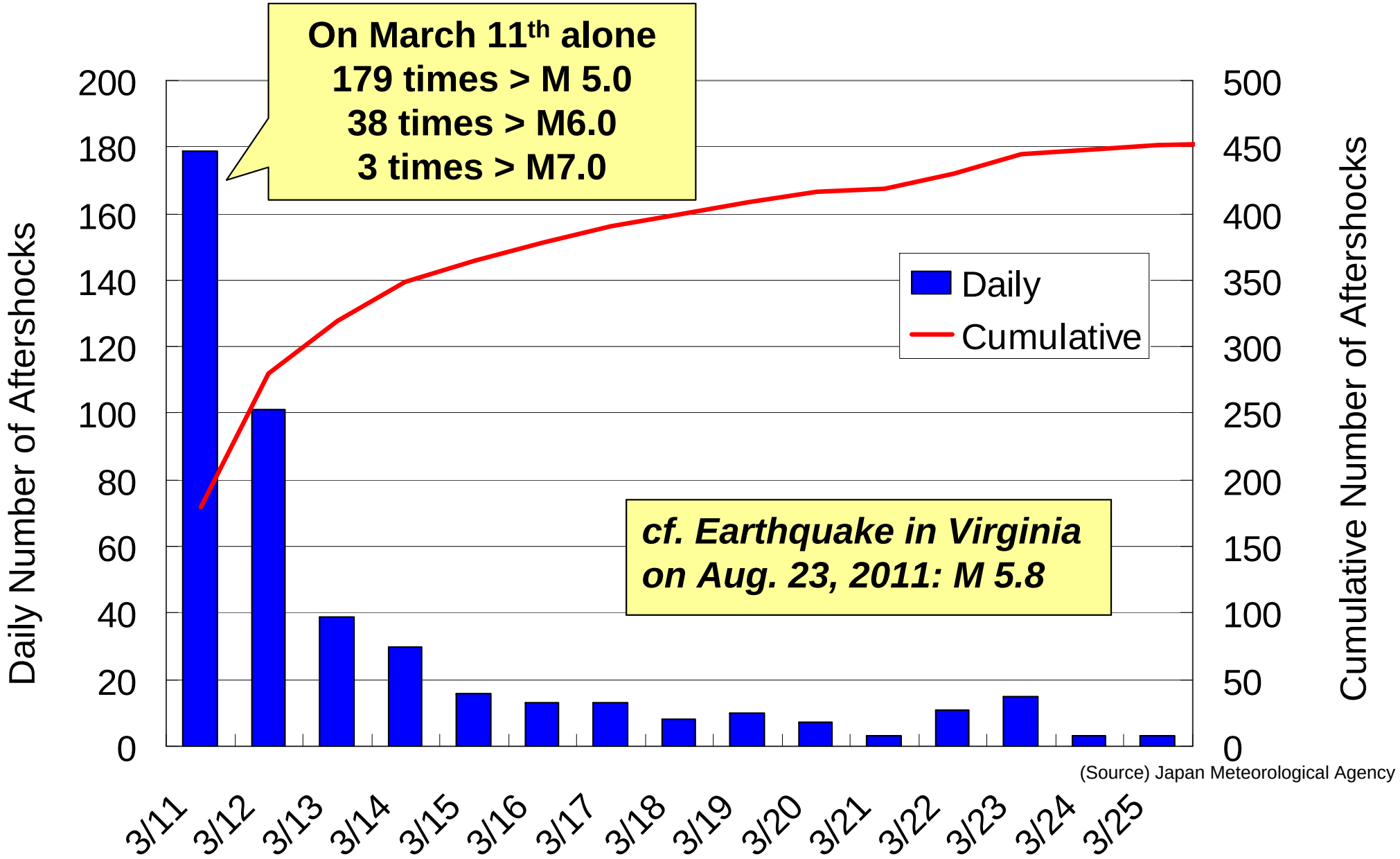
Hundreds of Aftershocks Greater than M 5.0



(Source) Japan Meteorological Agency

Visualization of earthquakes in 2011

http://www.youtube.com/watch?v=eKp5cA2sM28

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Voices from the Field

- **"In an attempt to check the status of Unit 4 D/G, I was trapped inside the security gate compartment. Soon the tsunami came and I was minutes away from being drowned, when my colleague smash opened the window and saved my life."**
- **"In total darkness, I could hear the unearthly sound of SRV dumping steam into the torus. I stepped on the torus to open the S/C spray valve, and my rubber boot melted."**
- **"Unit 3 could explode anytime soon, but it was my turn to go to the main control room. I called my dad and asked him to take good care of my wife and kids should I die."**

Torus Room

Unit 1 Main Control Room

D/G: Diesel Generator
SRV: Safety Relief Valve
S/C: Suppression Chamber

Voices from the Field (1F)

"At that time, I was conjuring up faces of fellow colleagues who would die with me."
(Masao Yoshida, Site Superintendent)

"I was determined to stay behind to my death; however I was resolved to send my men back home alive."
(Ikuo Izawa, Shift Manager)

"Let me go and vent the containment.
I know where the valve is and I can run fast.
Let me protect the unit that I love."
(Kazuhiro Yoshida, Deputy Shift Manager)

"The Man Who Saw The Brink of Death"

"Book reveals human drama in Fukushima No. 1 crisis"
The Japan Times 12/11/2012
http://www.japantimes.co.jp/news/2012/12/11/national/book-reveals-human-drama-in-fukushima-no-1-crisis/

TEPCO Internal Investigation Committee Final Report

➢ Issued on June 20, 2012

http://www.tepco.co.jp/en/press/corp-com/release/2012/1205638_1870.html

"Tangible" Countermeasures

- Flood Protection
- High-pressure Injection System
- Depressurization System
- Low-pressure Injection System
- Heat Removal/Cooling System
- Power Supply for Instrumentation
- Post-Core Damage Mitigation
- Common Items
- Mid-to-Long Term Items

"Intangible" Countermeasures

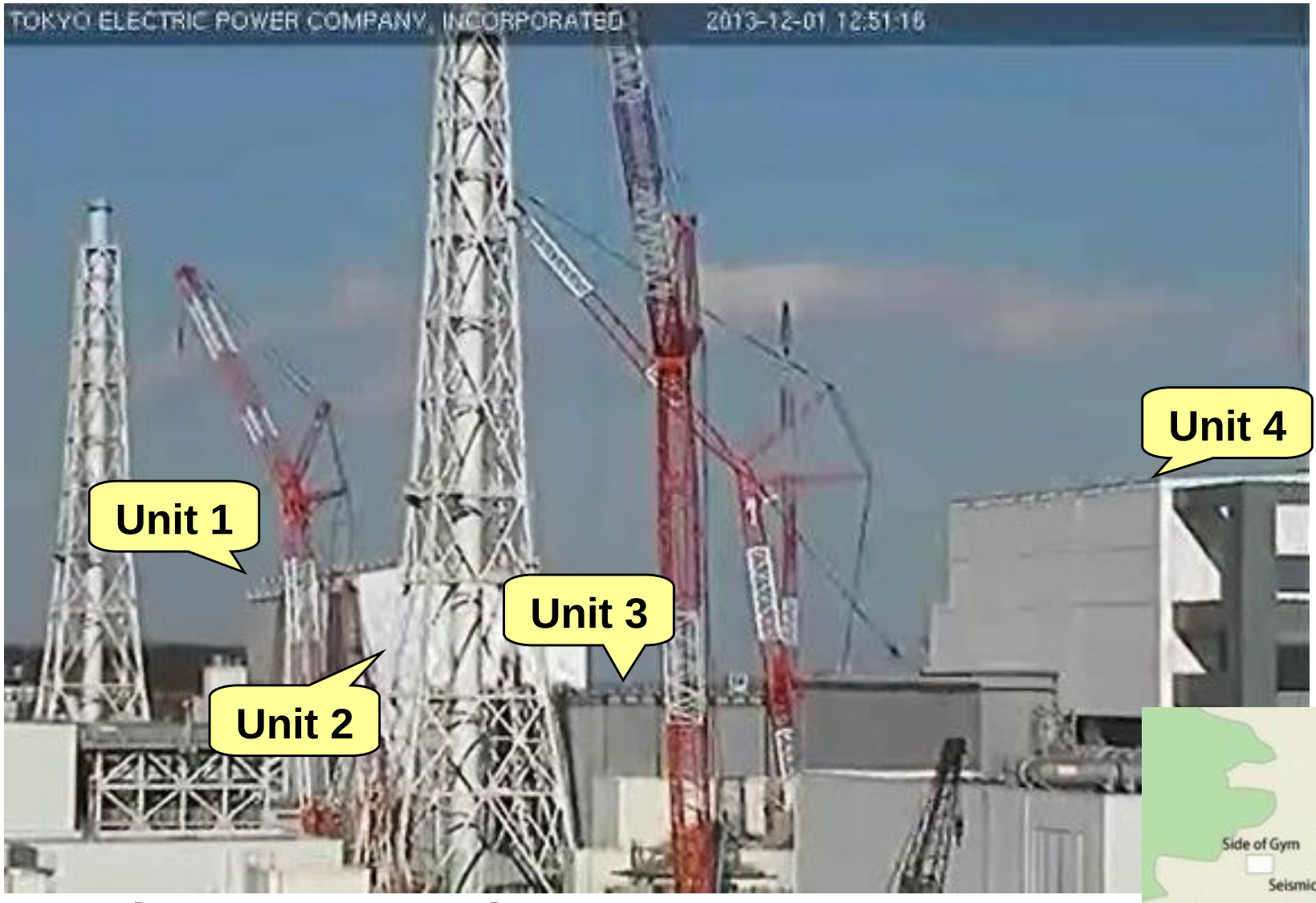
- Operational Measures in Relation to Tangible Modifications
- Emergency Preparedness
- Info. Dissemination and Sharing
- Roles and Responsibilities
- Information Disclosure
- Transportation of Resources
- Access Control
- Radiological Protection
- Plant Status Recognition
- Suggestions to the Government

Major Lessons Learned:

➢ Recognize large uncertainty in external events

➢ Prepare for the unexpected

Current Status of Fukushima Daiichi (1F) NPS



Live Camera View (as of 12/1/2013)

http://www.tepco.co.jp/en/nu/f1-np/camera/index-e.html

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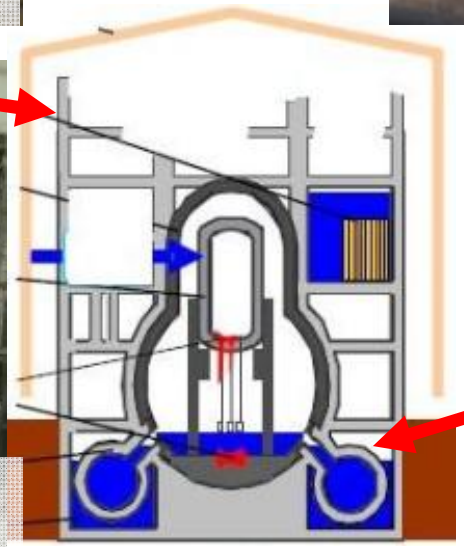
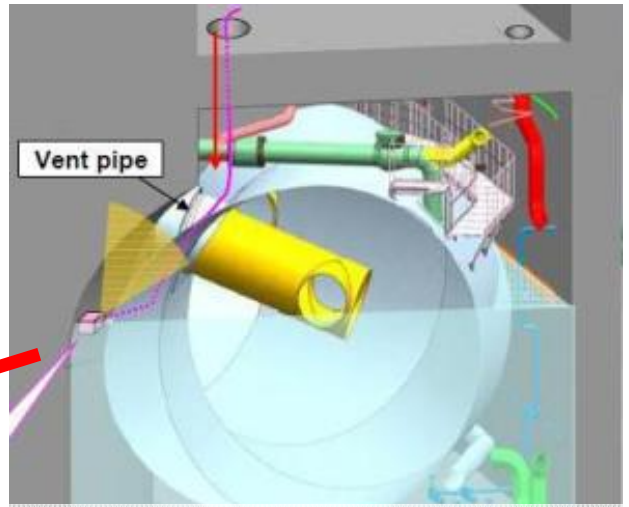
Progress Made at 1F Unit 1


Reactor Building (3/15/2011)


Reactor Building Cover (installed in Oct. 2011)


Refueling Floor (10/24/2012)



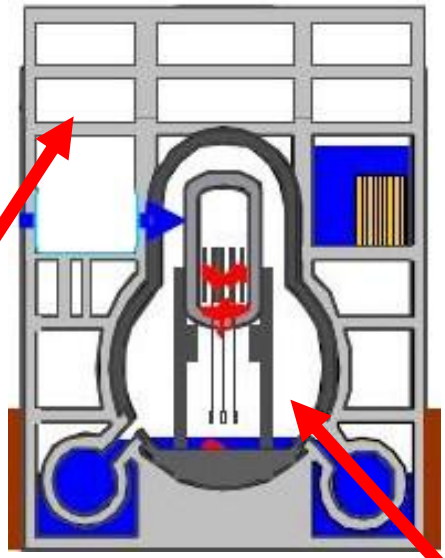


Torus Room (11/13/2013)

Reactor building cover to be dismantled to enable rubble removal work to be conducted on refueling floor

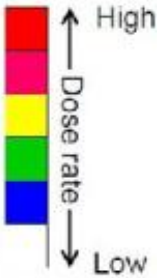
Progress Made at 1F Unit 2

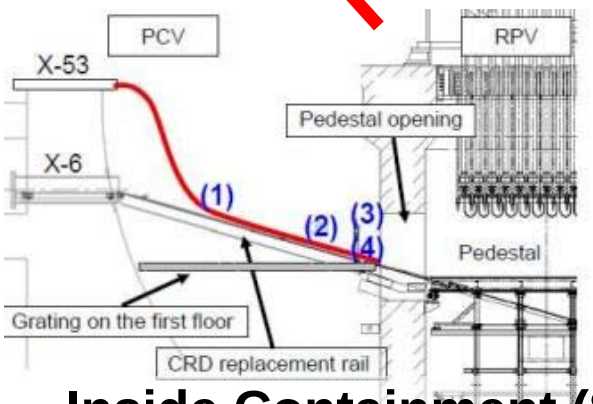
Steam Coming Out From Blow-out Panel (4/10/2011)



Blow-out Panel Closed (3/11/2013)

Gamma Camera Image of Refueling Floor (2/21/2013)





Inside Containment (8/12/2013)

Attempt to investigate inside reactor pressure vessel by borescope via TIP guide tube

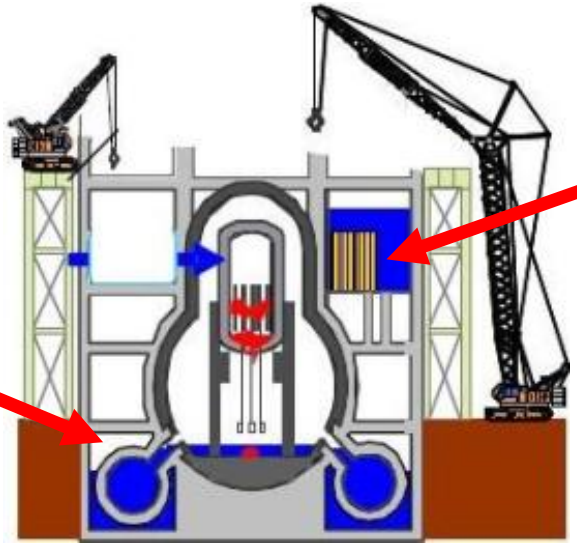
TIP: Traversing In-core Probe

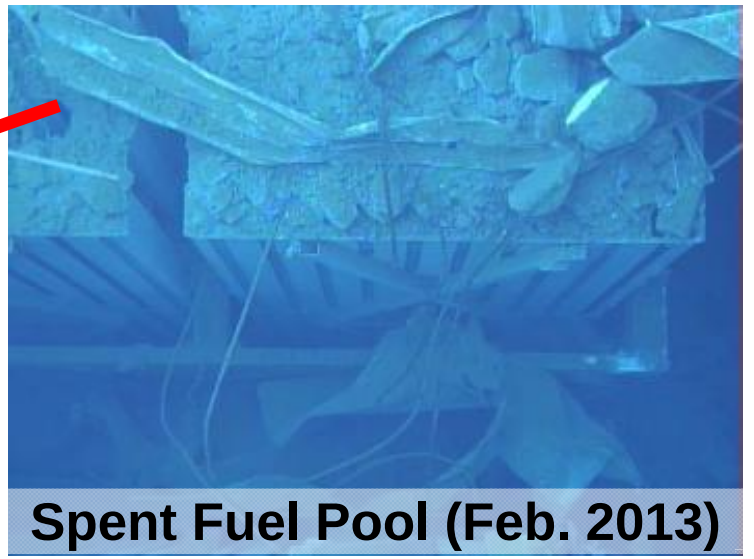
Progress Made at 1F Unit 3


Crippled Reactor Building (3/15/2011)


Large Rubble Removed (10/11/2013)


Torus Room (7/11/2012)



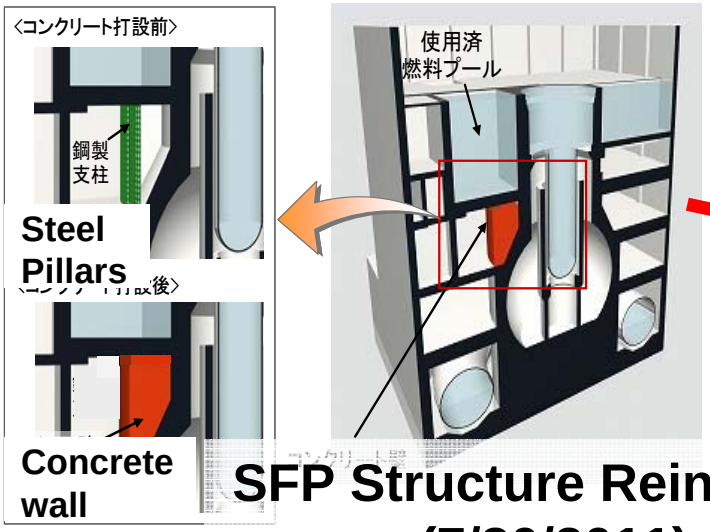

Spent Fuel Pool (Feb. 2013)

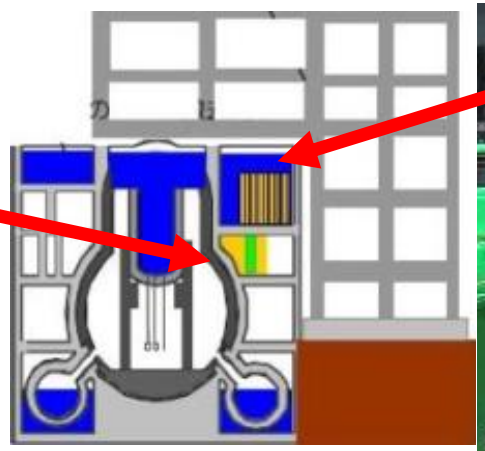
Preparation work underway to install fuel removal structure

Progress Made at 1F Unit 4

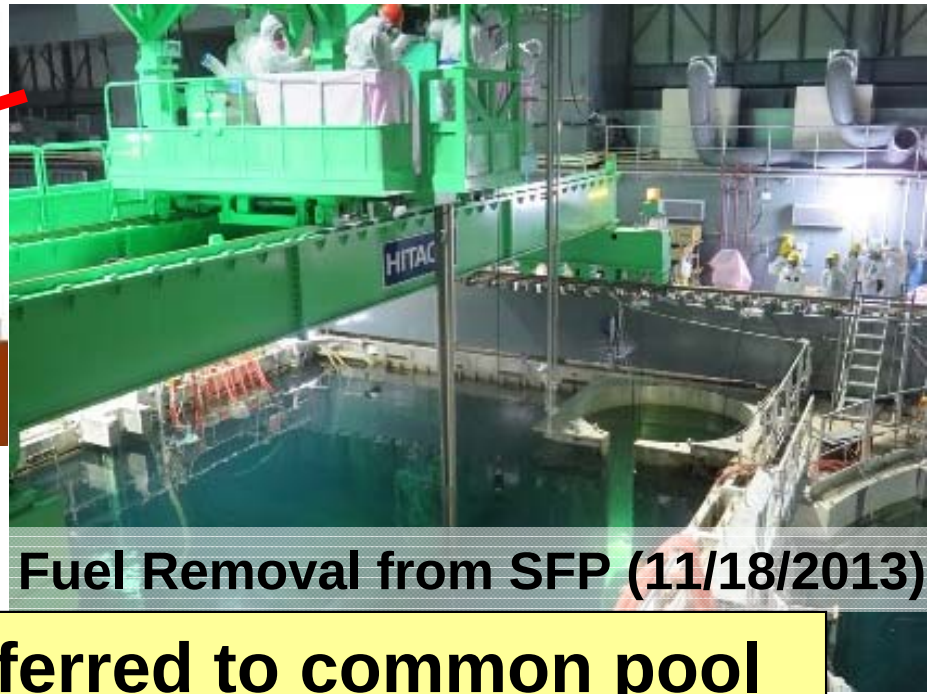
Water Injection by Concrete Pumper (3/22/2011)

Fuel Removal Structure (7/1/2013)





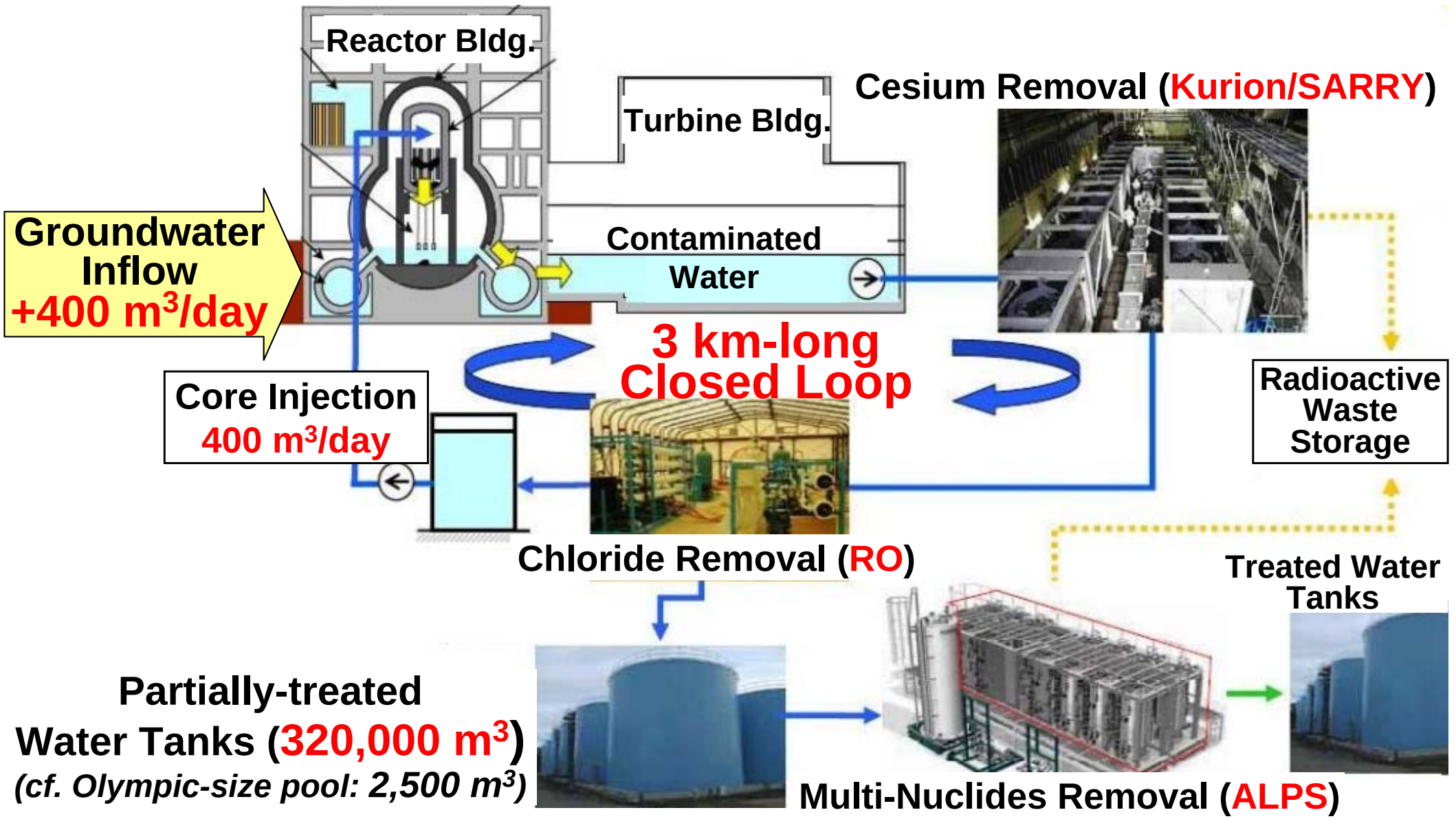
SFP Structure Reinforced (7/30/2011)



Fuel Removal from SFP (11/18/2013)

1,533 fuel bundles being transferred to common pool

Circulating-Water Core Cooling System



- All reactor cores stably cooled
- Increasing water inventory posing challenge

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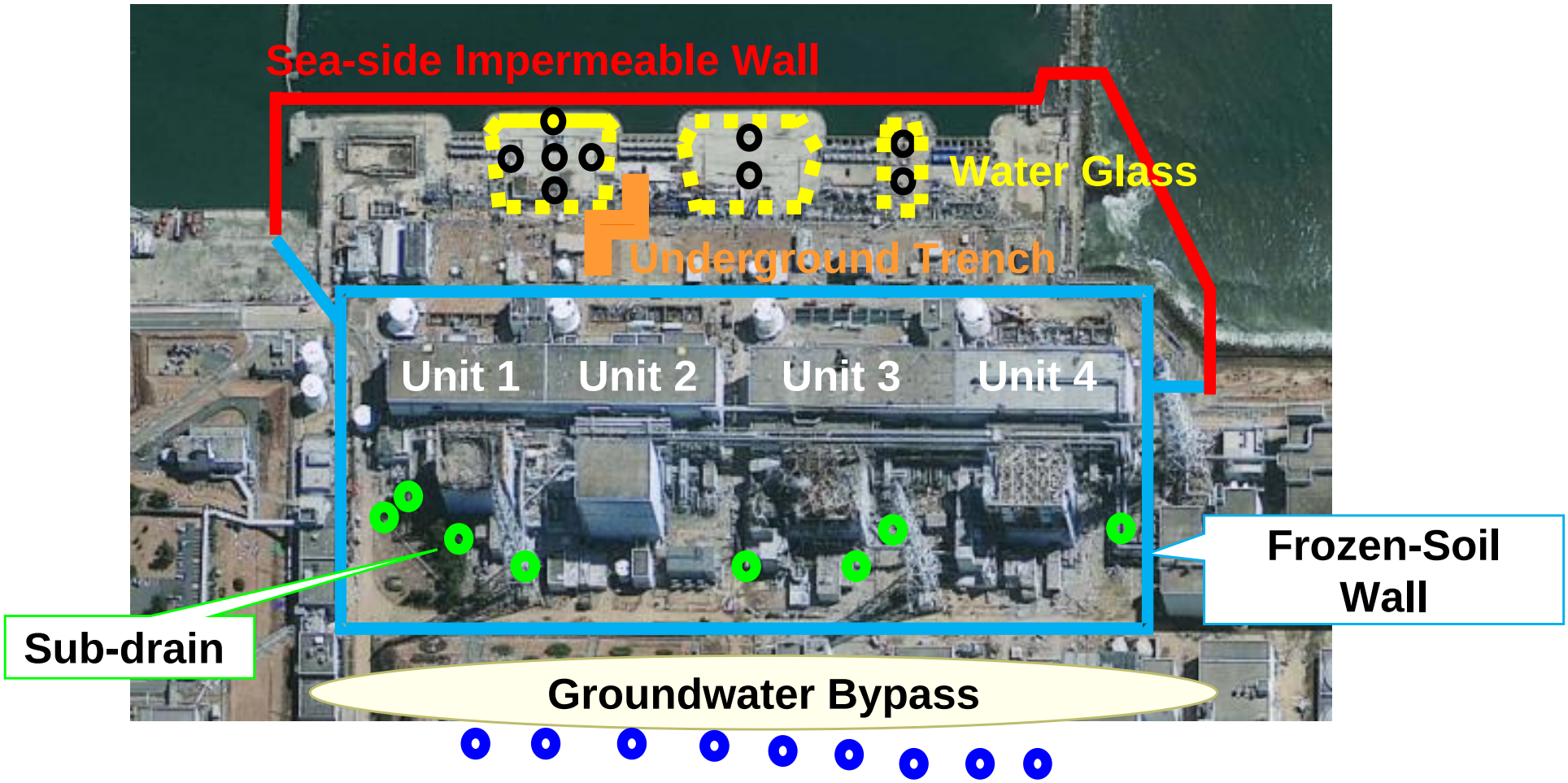
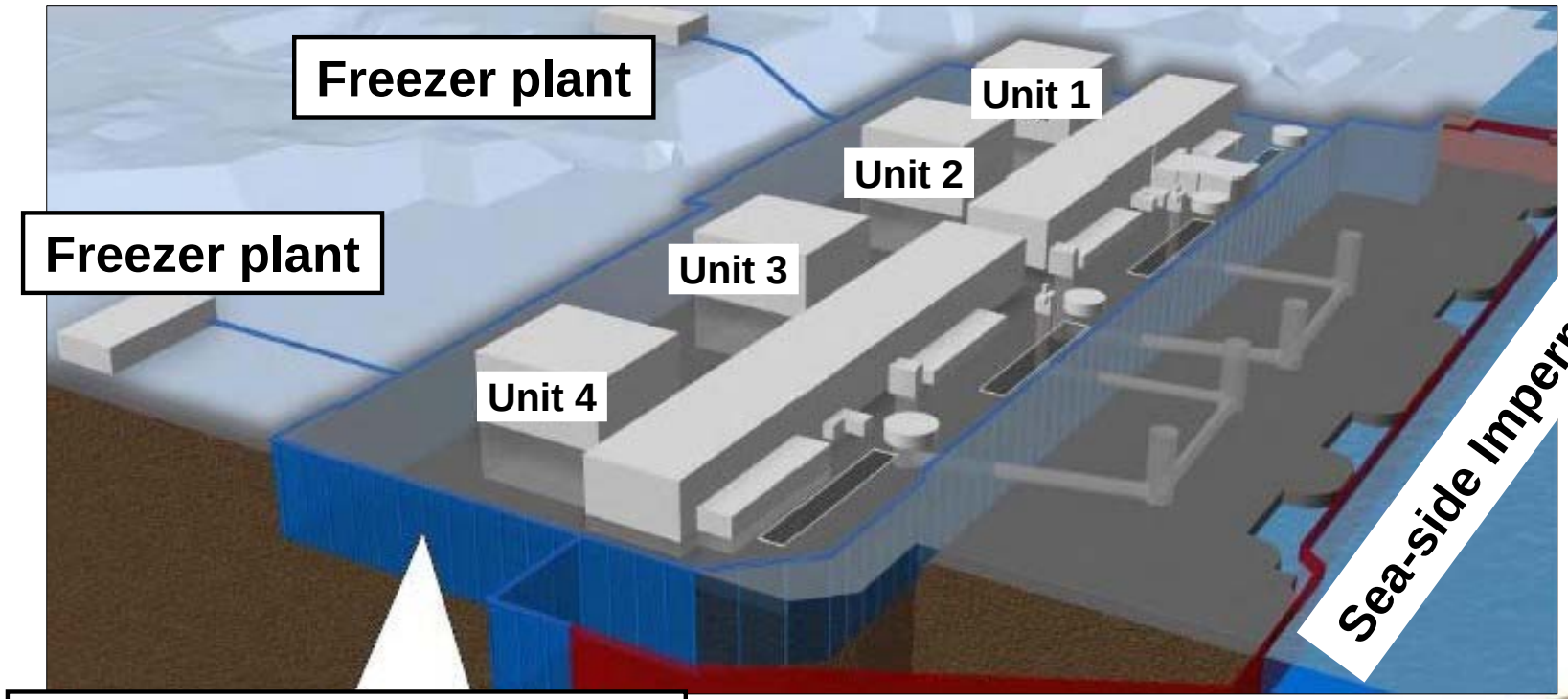
Groundwater Contamination Near the Sea

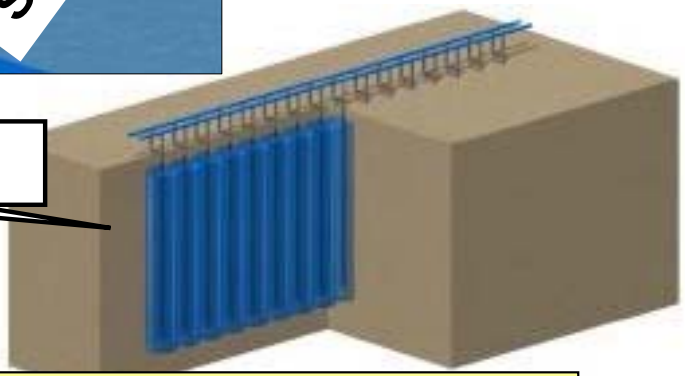


Contamination detected in groundwater near sea bank;
Suspected leakage of contamination into sea;
Immediate and fundamental measures taken to:

- **Prevent groundwater from being contaminated**
- **Prevent contaminated groundwater from flowing into sea**
- **Reduce groundwater inflow into buildings**

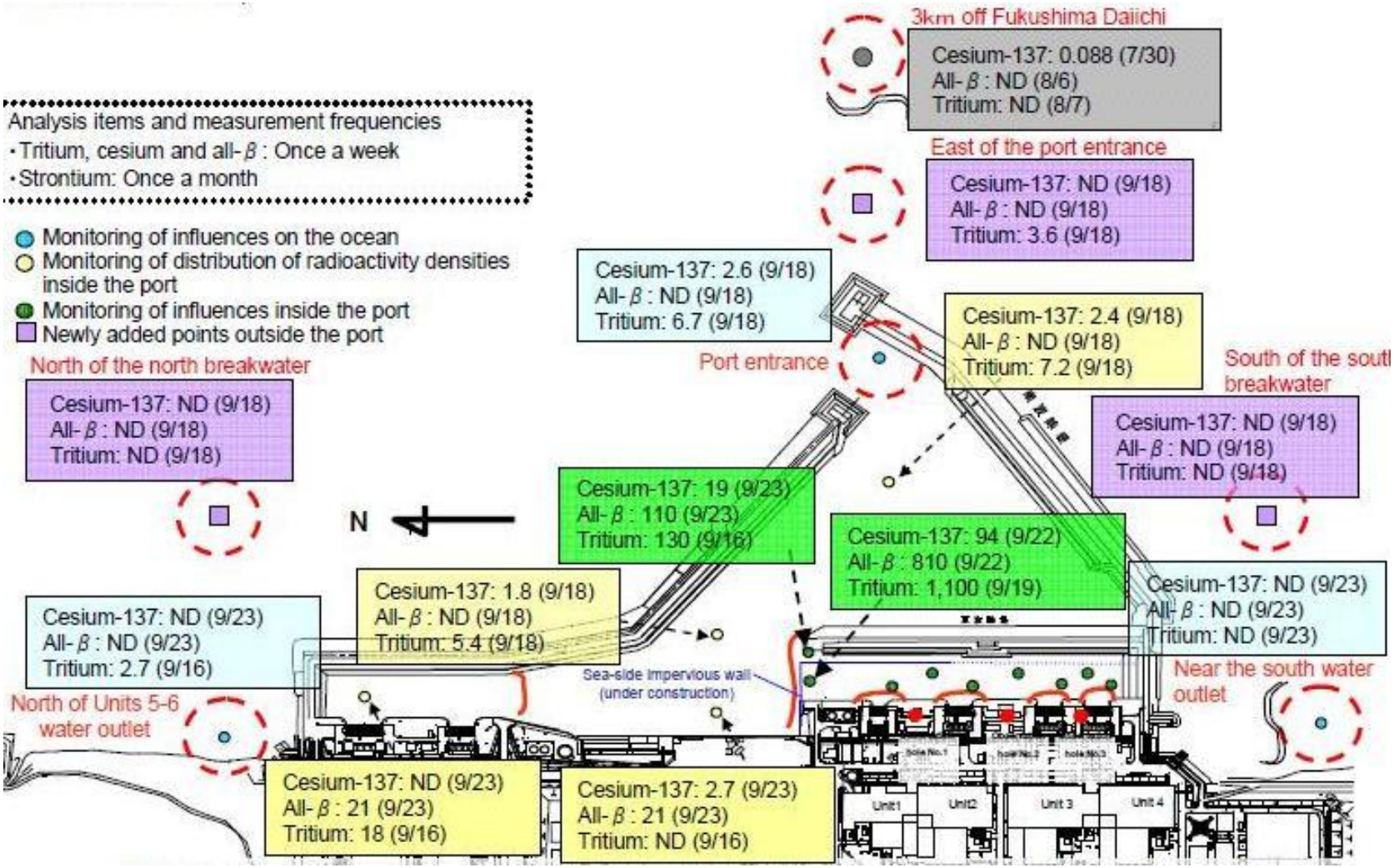
Conceptual Drawing of “Frozen-Soil Wall”





- Surround bldg. with frozen-soil wall to prevent groundwater inflow
- Feasibility study on technical challenges

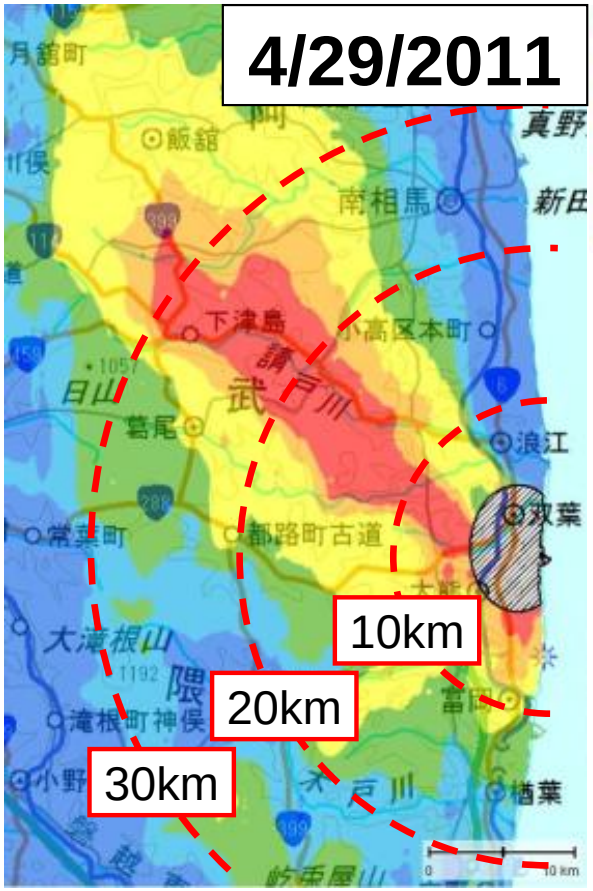
Seawater Contamination Limited to Small Area

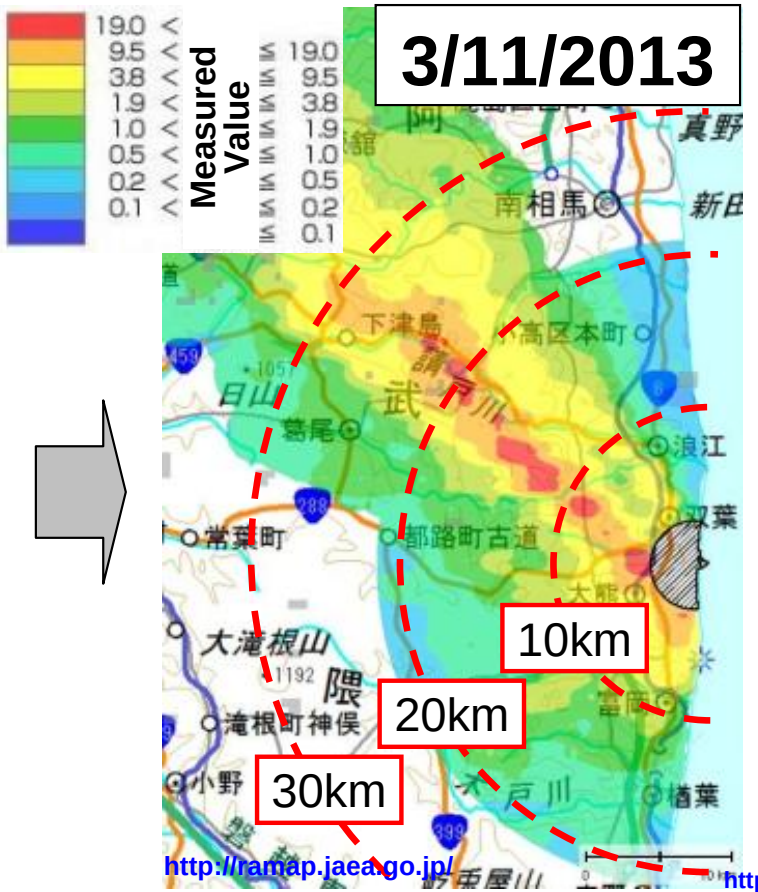


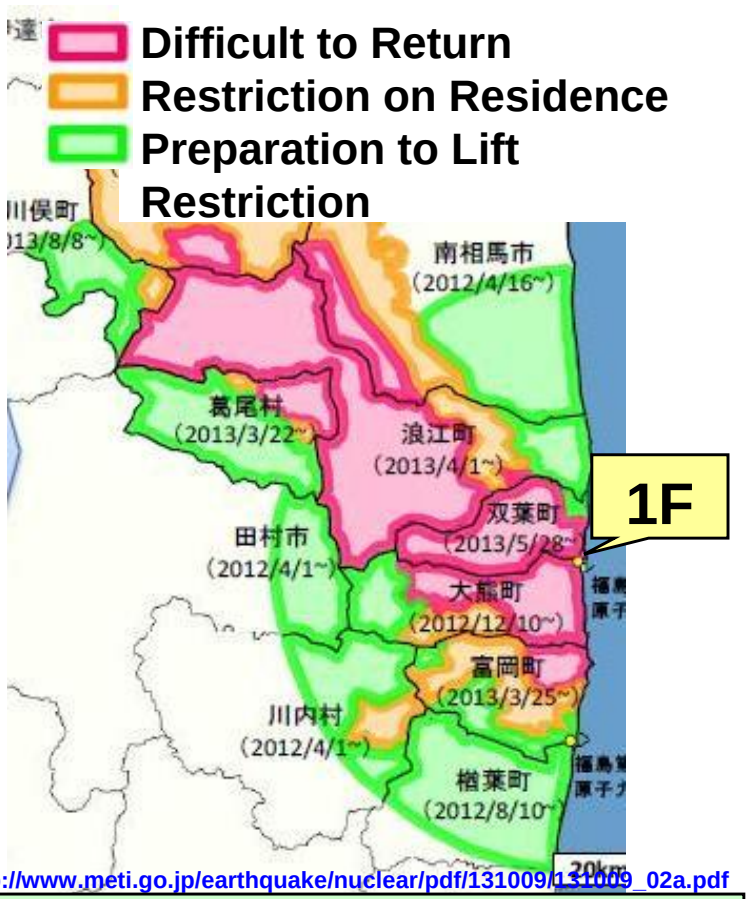
Seawater measurement results as of Sept. 2013 (unit: Bq/liter)

Seawater contamination limited to immediate vicinity of Units 1-4 intake structure

Off-site Radiation Dose and Evacuation Zones







Aerial Radiation Dose Map
(μ Sv/h at 1 m above ground)

Evacuation Zones
(as of 8/7/2013)

- **Off-site dose decreased significantly; evacuation zones gradually relaxed**
- **Int'l consensus on health impact of low-dose radiation critical to relieve anxiety of evacuees**

Mid- to Long-Term Road Map Towards Decommissioning

Cold Shutdown Condition Achieved (Dec., 2011)

Within 2 years

Within 10 years

30 to 40 years

Phase-1

Begin removal of fuels from spent fuel pools

Unit 4: Nov. 2013

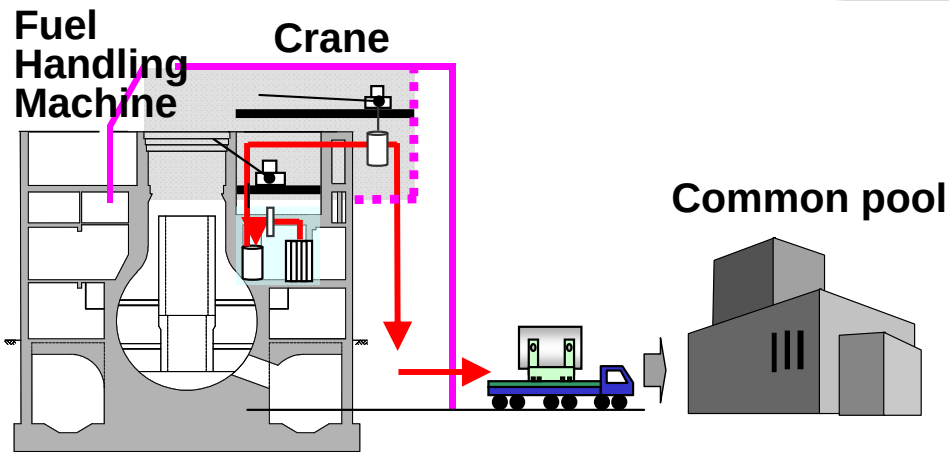
Phase-2

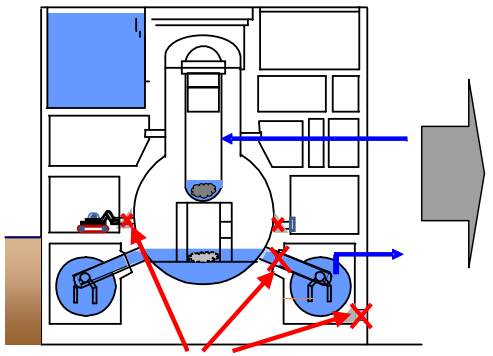
Begin removal of fuel debris

Endeavor to push schedule forward

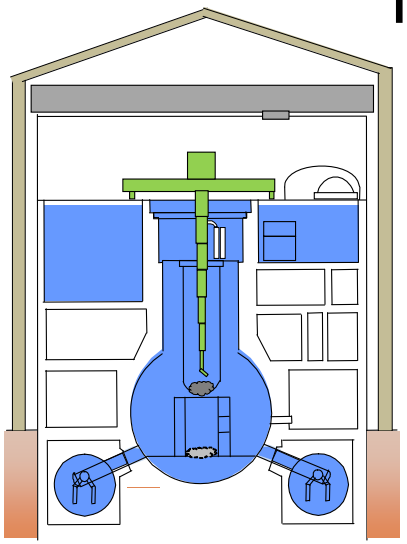
Phase-3

Complete decommissioning





Stop Leakage



Flood PCV and Remove Fuel Debris

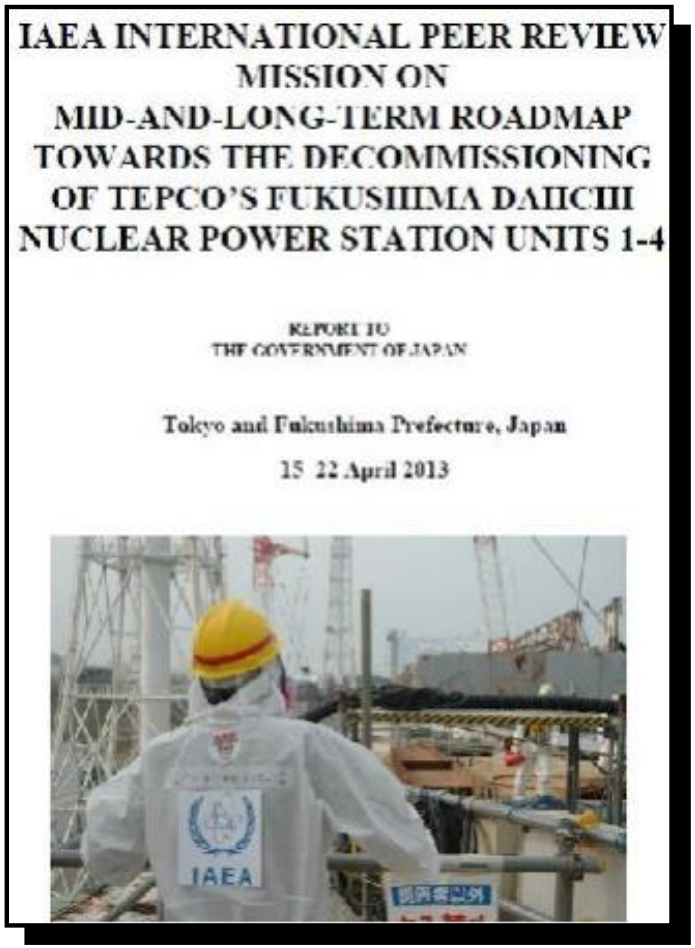
Global collaboration vitally important to tackle this unprecedented undertaking

Global Collaboration

TEPCO

- **Feasibility Study Agreement with U.S. Nat'l Labs to identify their expertise applicable to decommissioning at 1F (Sept. 2012-March 2013)**
- **Pursuing further collaboration in following areas:**
  Groundwater contamination; reactor bldg. water-proofing; radioactive waste disposal; fuel debris recovery/storage; contaminated water treatment

Global Collaboration (cont'd)


IAEA INTERNATIONAL PEER REVIEW MISSION ON MID-AND-LONG-TERM ROADMAP TOWARDS THE DECOMMISSIONING OF TEPCO'S FUKUSHIMA DAIICHI NUCLEAR POWER STATION UNITS 1-4

REPORT TO THE GOVERNMENT OF JAPAN

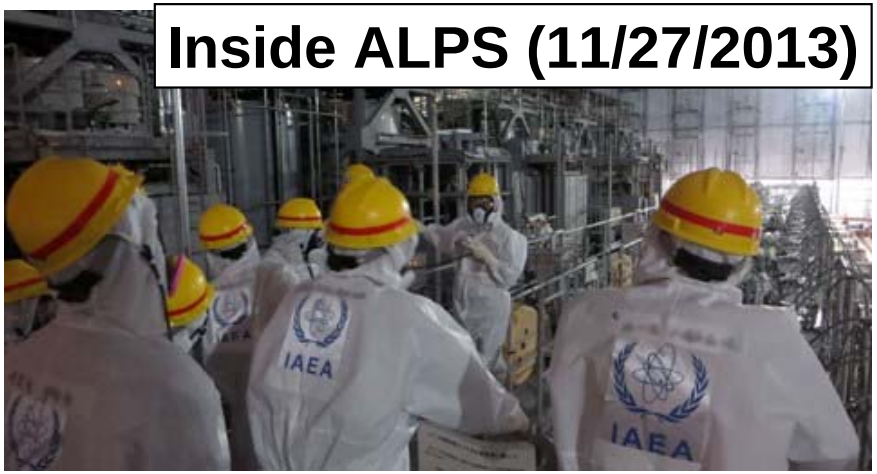
Tokyo and Fukushima Prefecture, Japan

15–22 April 2013

http://www.meti.go.jp/press/2013/05/20130523001/20130523001-4.pdf

Unit 4 Fuel Removal (11/27/2013)

Inside ALPS (11/27/2013)



- **IAEA Peer Review Missions on Decommissioning Roadmap**
- **April 15-22 and Nov. 25- Dec. 4, 2013**

Global Collaboration (cont'd)

Council for Decommissioning 1F (chaired by METI minister)

Utility Companies Reactor Vendors

TEPCO

Integrated Management of Decommissioning Technologies

IRID

http://www.irid.or.jp/en/

Int'l Experts Group Mtg. (Sept. 2013)

Advices from Domestic and Int'l Organizations

Joint Studies/R&D with Research Organizations

- **International Research Institute for Nuclear Decommissioning (IRID) established in Aug. 2013**
- **Soliciting information for technologies in: Contaminated water issues; Fuel debris removal**

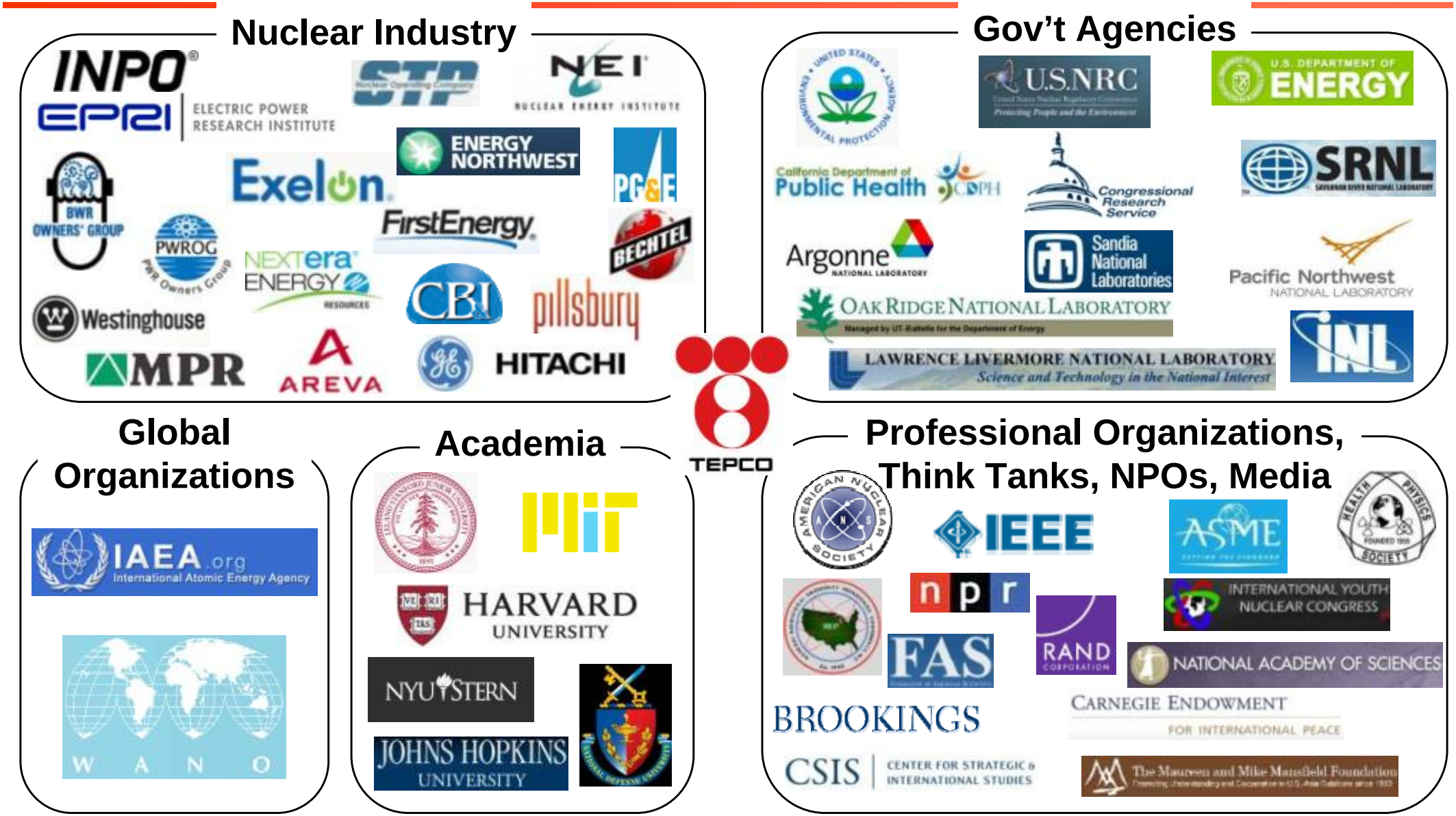
Other Activities

- **Compensation for afflicted people:**
  ¥3.1 trillion (approx. $31 bil.)
  (paid out as of Nov. 2013)

- **Cooperation with gov't in off-site radiation survey, decontamination work, etc.**

- **Assistance in temporary return of evacuees to homes**

TEPCO's Post-Accident Activities in the U.S.



Committed to disseminating lessons learned globally and working together to make nuclear power plants safer

References

[Japan]

- Tokyo Electric Power Company (TEPCO)
  http://www.tepco.co.jp/en/nu/fukushima-np/index-e.html
- Nuclear Reform Monitoring Committee of TEPCO
  http://www.nrmc.jp/en/index-e.html
- Ministry of Economy, Trade and Industry (METI)
  http://www.meti.go.jp/english/earthquake/
- Nuclear Regulation Authority (NRA)
  http://www.nsr.go.jp/english/
- Japan Atomic Industrial Forum (JAIF)
  http://www.jaif.or.jp/english/
- Japan Nuclear Safety Institute (JANSI)
  http://www.genanshin.jp/english/index.html

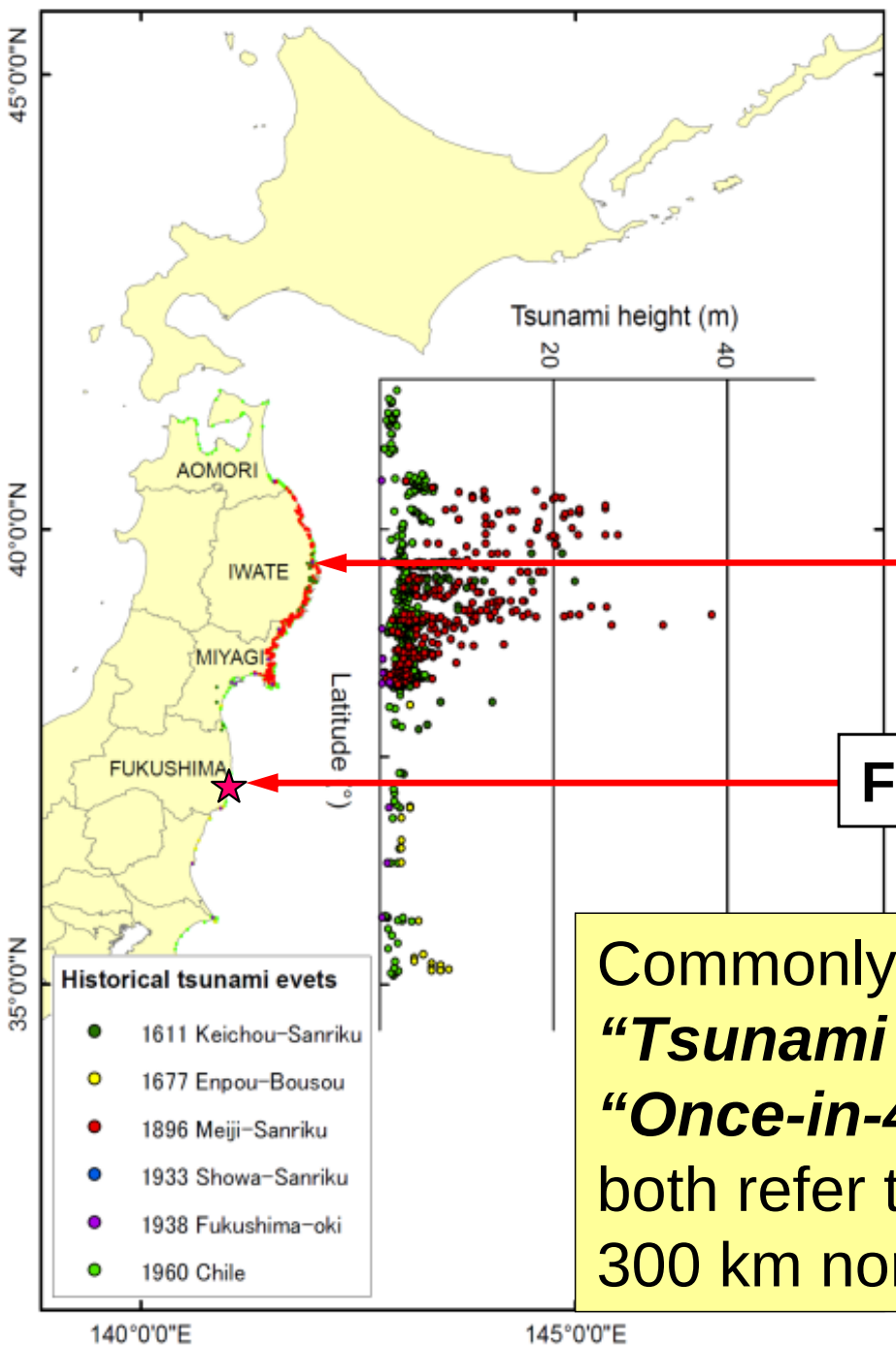
[USA]

- Institute of Nuclear Power Operations (INPO)
  http://www.nei.org/filefolder/INPO_11-005_Fukushima_Addendum_1.pdf
- Electric Power Research Institute (EPRI)
  http://www.epri.com/Pages/Default.aspx
- Nuclear Energy Institute (NEI)
  http://safetyfirst.nei.org/japan/
- National Academy of Science—Fukushima Lessons Learned Committee
  http://www8.nationalacademies.org/cp/projectview.aspx?key=49465

[International]

- International Atomic Energy Agency (IAEA)
  http://www.iaea.org/
- World Association of Nuclear Operators (WANO)
  http://www.wano.info/
- World Health Organization (WHO)
  http://www.who.int/entity/ionizing_radiation/pub_meet/fukushima_report/en/index.html

No Historical Evidence of Huge Tsunamis Near Fukushima NPSs



Tsunami Warning Stone
(Miyako, Iwate Pref.)

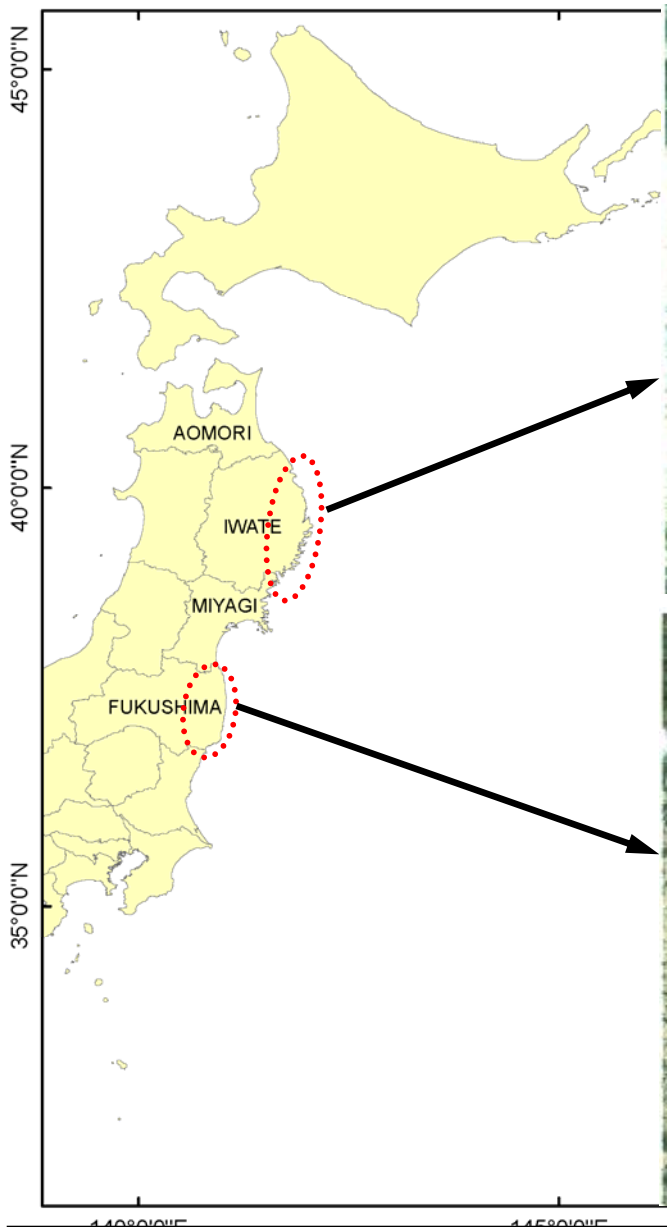
(source) http://blog.miyakomall.jp/2012/04/

Fukushima NPSs

Commonly misquoted
"Tsunami Warning Stone" and
"Once-in-400-year recurrence of 7-m tsunami"
both refer to locations in Iwate Prefecture,
300 km north of Fukushima NPS

TOKYO ELECTRIC POWER COMPANY
TEPCO

Tsunami Height Heavily Dependent on Coastal Topography



Iwate has deep-indented coastline that tends to magnify tsunami height

Fukushima has flat coastline and historically experienced significantly lower tsunami height compared to Iwate

However, we should have been prepared for the unexpected

TEPCO's Nuclear Safety Reform

TEPCO Board of Directors

Request ⇨ / ⇦ Proposal

Nuclear Reform Monitoring Committee

Supervision

Dr. Dale Klein, Chairman
(Former Chairman, U.S. Nuclear Regulatory Commission)
Lady Barbara Judge, Deputy Chairman
(Former Chairman, U.K. Atomic Energy Authority)
Dr. Kenichi Ohmae, Member
(CEO, Business Breakthrough, Inc.)
Mr. Masafumi Sakurai, Member
(Former Superintendent Public Prosecutor)
Mr. Kazuhiko Shimokobe, Member
(Chairman, TEPCO)
Mr. Kazuhiro Suzuki, Secretary-General
(CEO, Nuclear Fuel Transport Co.)





Observation

Reporting

Observation / Supervision

Reference Reporting

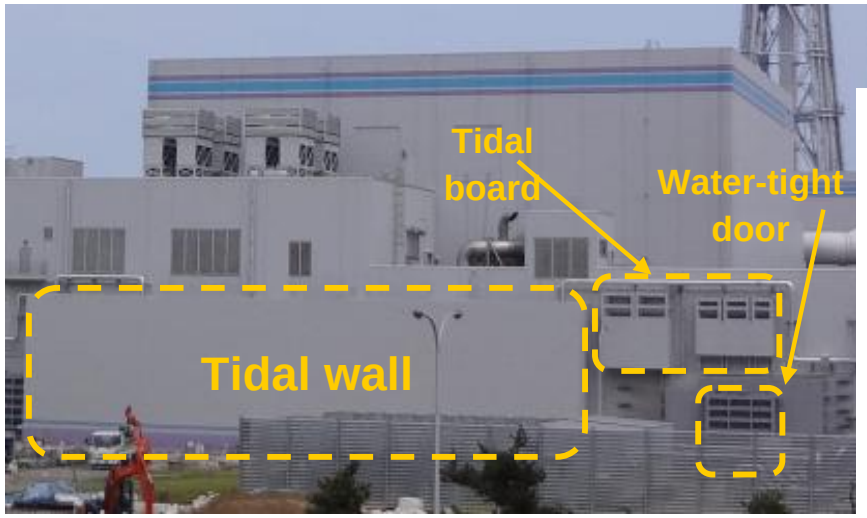
TEPCO Nuclear Reform Special Task force

Execution

Mr. Naomi Hirose (President); **Mr. Zengo Aizawa** (Chief Nuclear Officer)
Mr. Takafumi Anegawa (General Manager, Nuclear Asset Management Dept.)

Nuclear Safety Reform Plan issued on 3/29/2013
→Actions to revamp provision for accidents:
safety culture, technical capabilities, communication skills, etc.

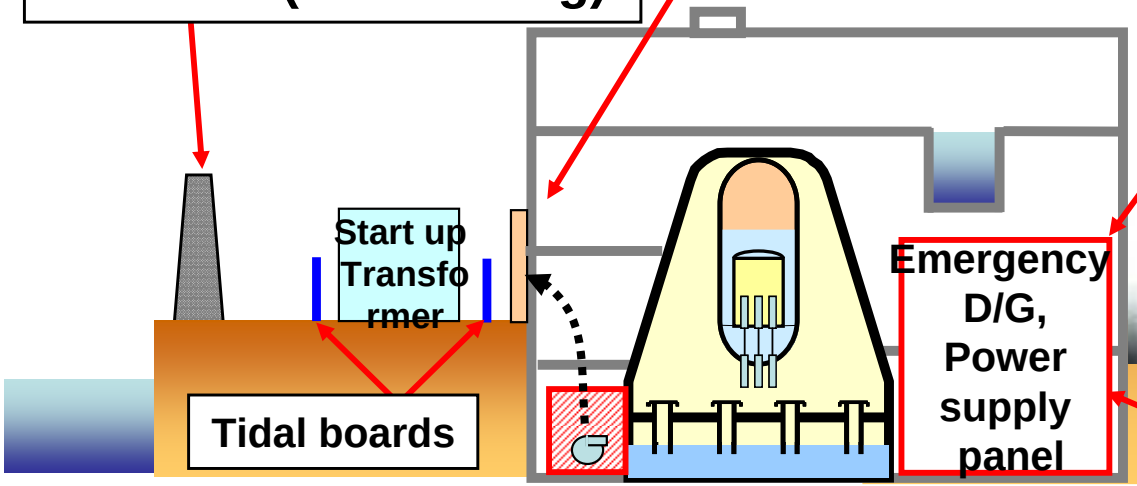
Safety Enhancement Measures at Kashiwazaki-Kariwa (KK) NPS



Tidal walls

Water-tight doors (~60 places)

Sea wall (1.5 km long)



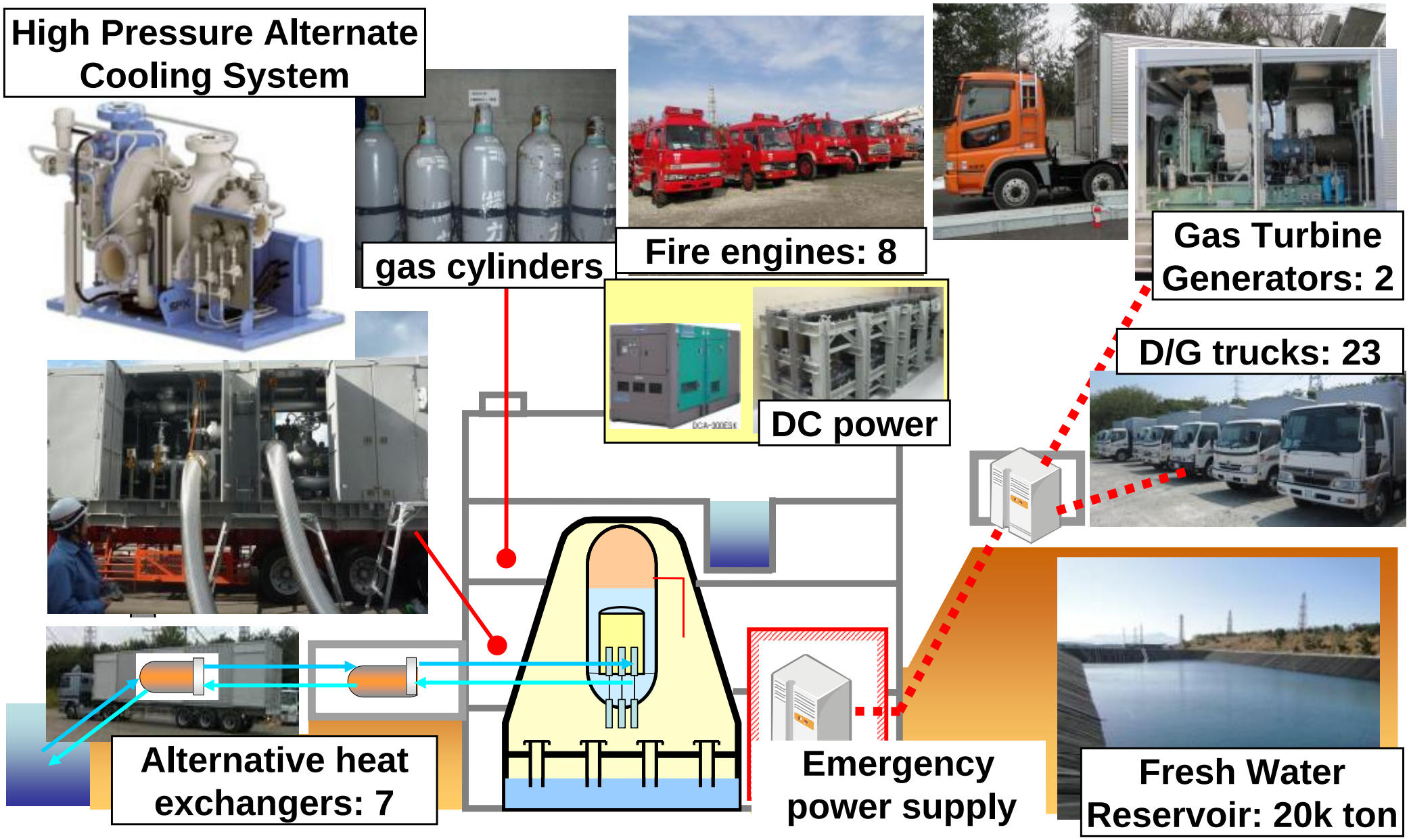
cable tray

piping

Waterproof treatment (~ 300 places)

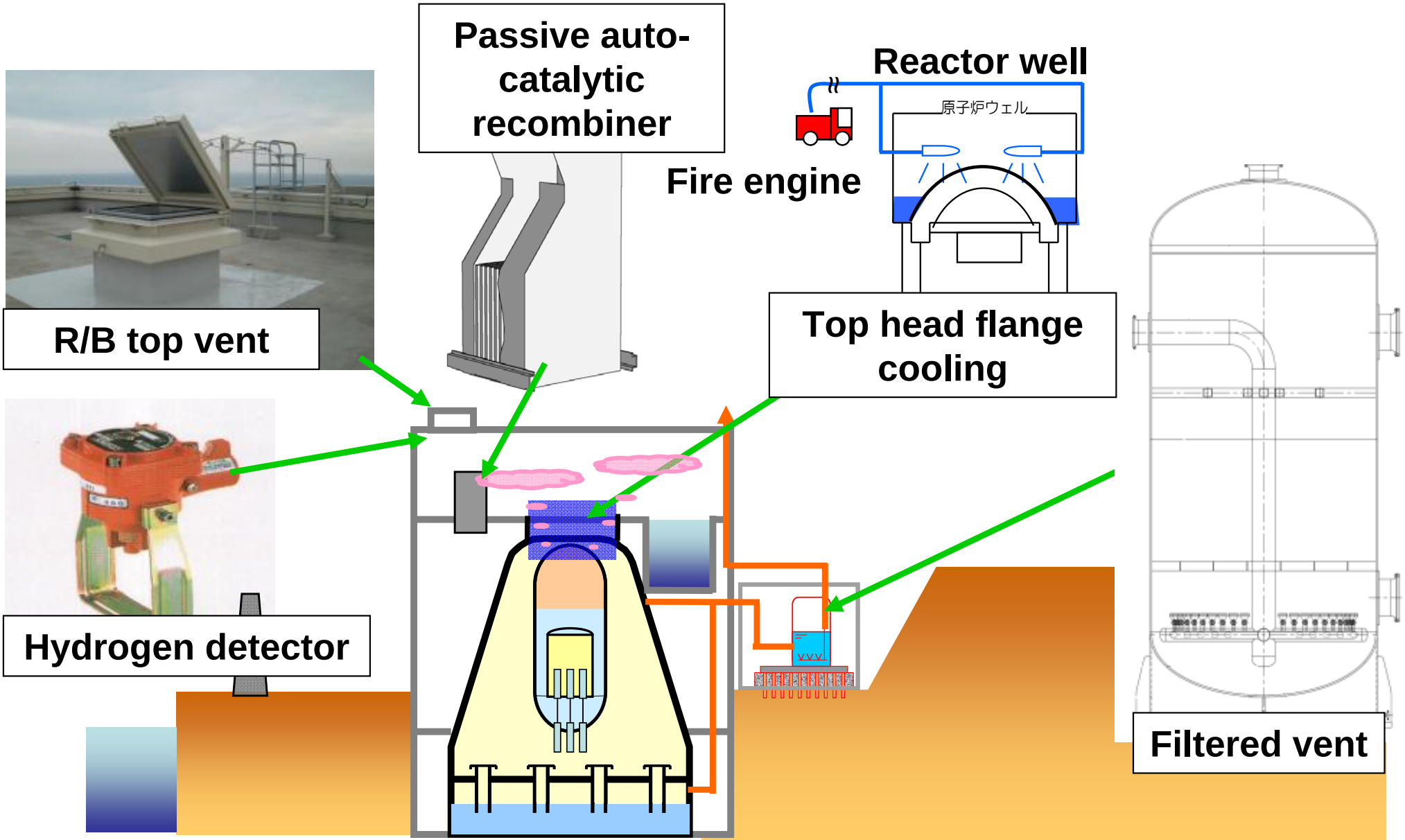
Prevention Measures for Tsunami-induced Accident

Safety Enhancement Measures at KK NPS (cont'd)



Core-damage Prevention Measures

Safety Enhancement Measures at KK NPS (cont'd)



Post Core-damage Mitigation Measures