IHTC-15 : The 15th International Heat Transfer Conference

Panel on "The Role of Thermal Science for Nuclear Disaster Resilience"

Resilience Related Lessons Learned from Fukushima Daiichi Accident

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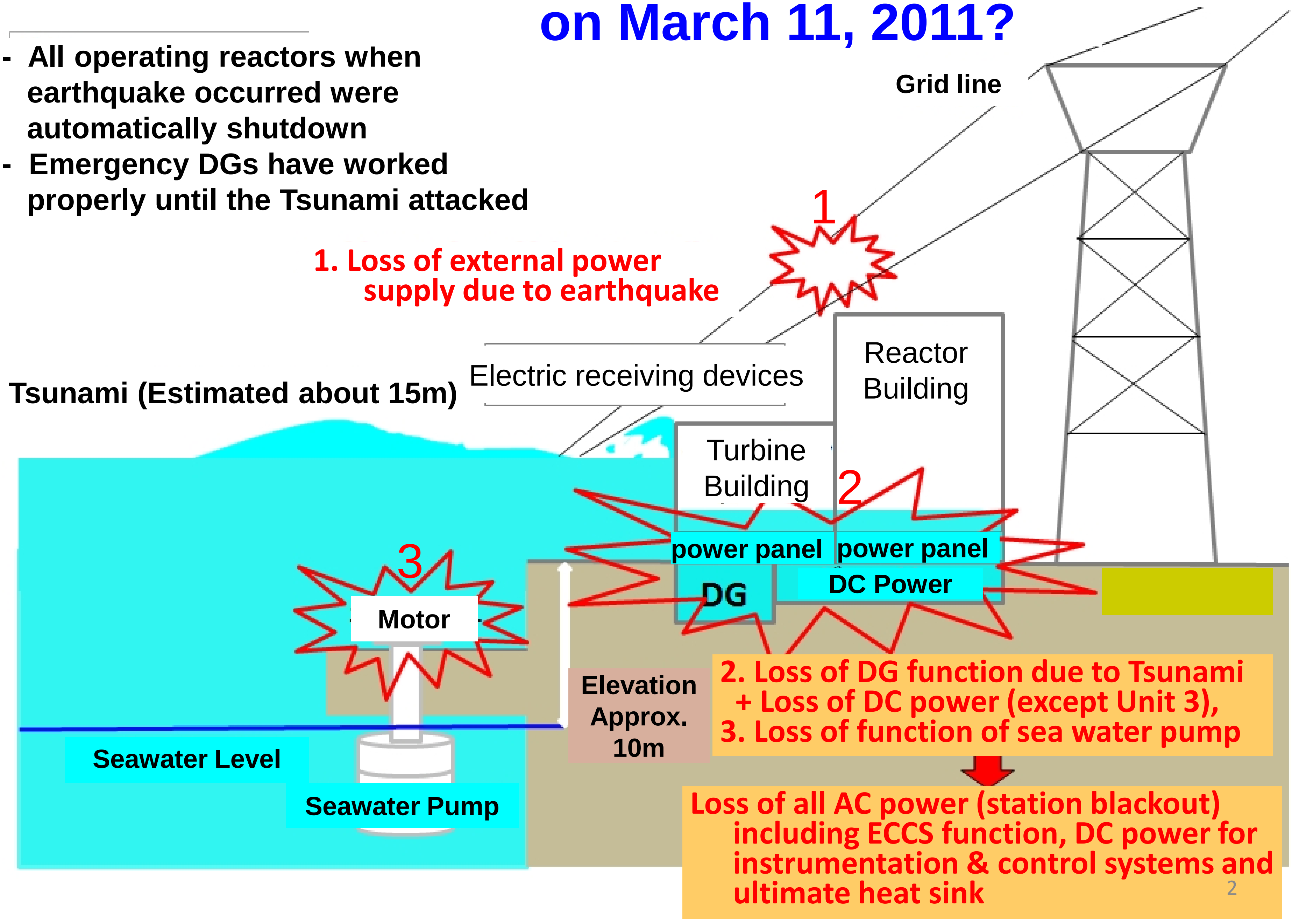
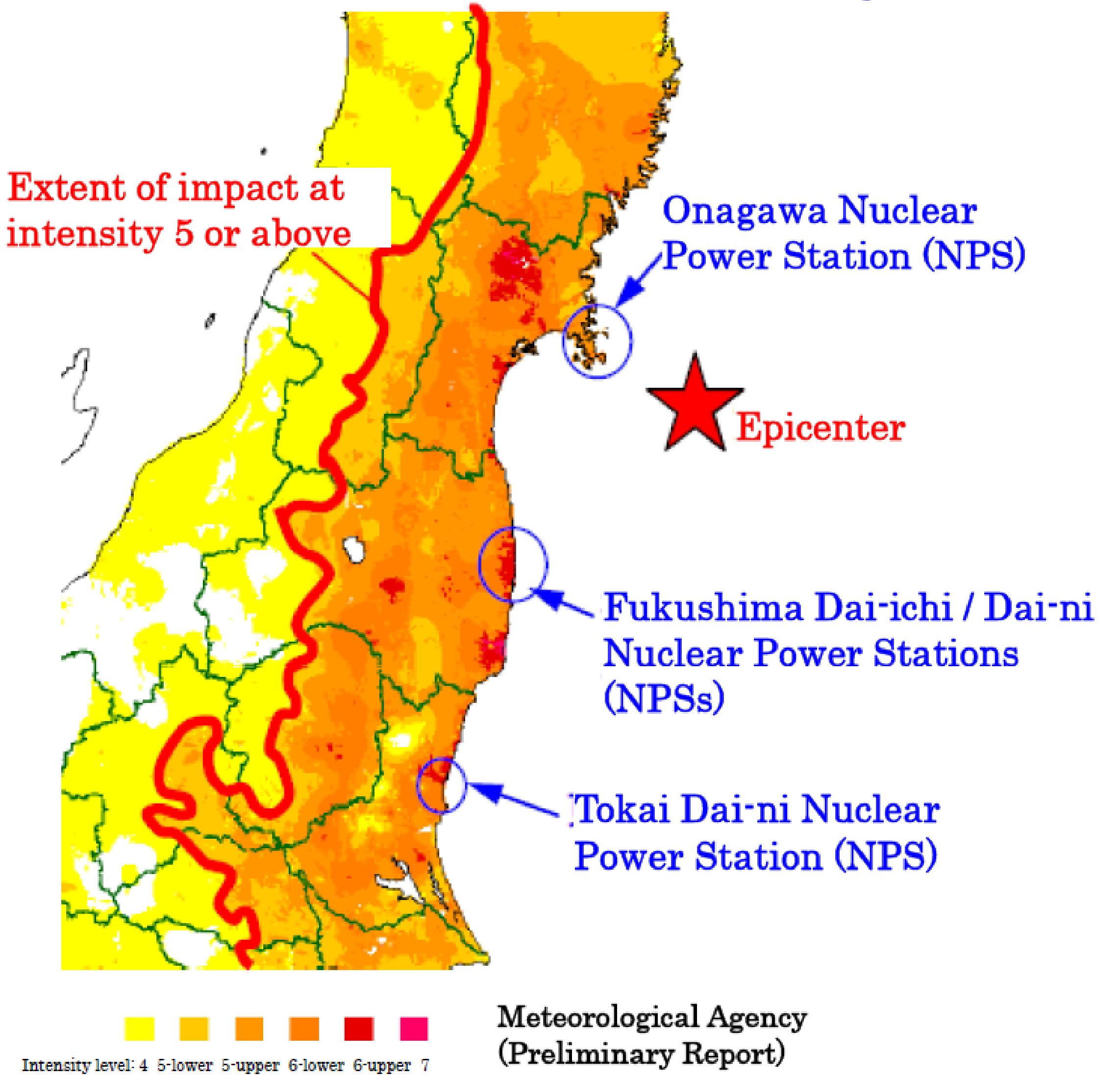
What happened at Fukushima on March 11, 2011?

- All operating reactors when earthquake occurred were automatically shutdown
- Emergency DGs have worked properly until the Tsunami attacked



Distribution of seismic intensity



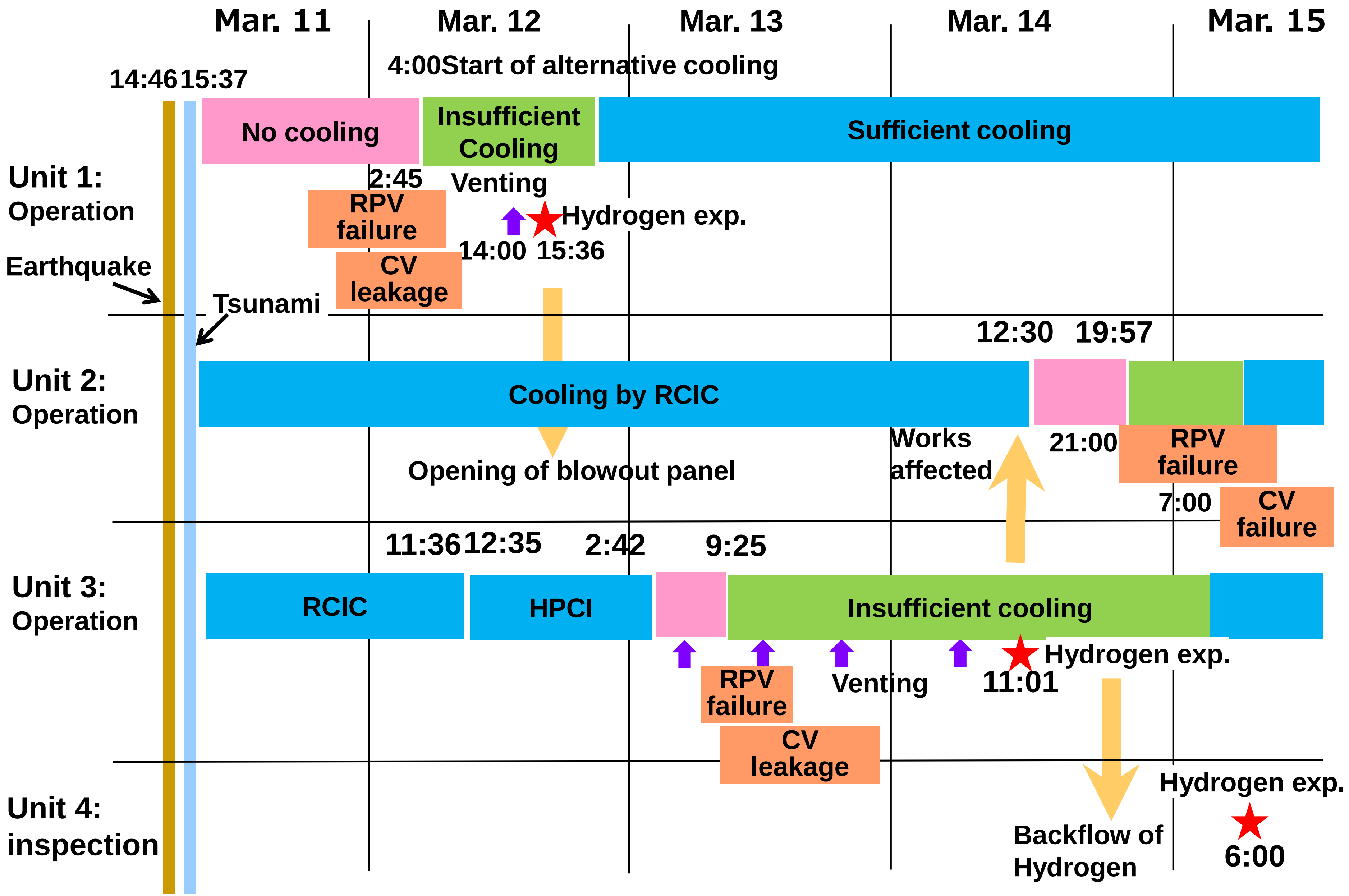
Source: Meteorological Agency "Preliminary Report" into the 2011 off the Pacific coast of Tohoku Earthquake ([Online] http://www.jma.go.jp/jma/index.html)

[http://www.nisa.meti.go.jp/english/press/2012/06/en20120615-1.html]

Loss of external power supply due to damage of power receiving devices, collapse of power supply tower, caused by earthquake (14:46)

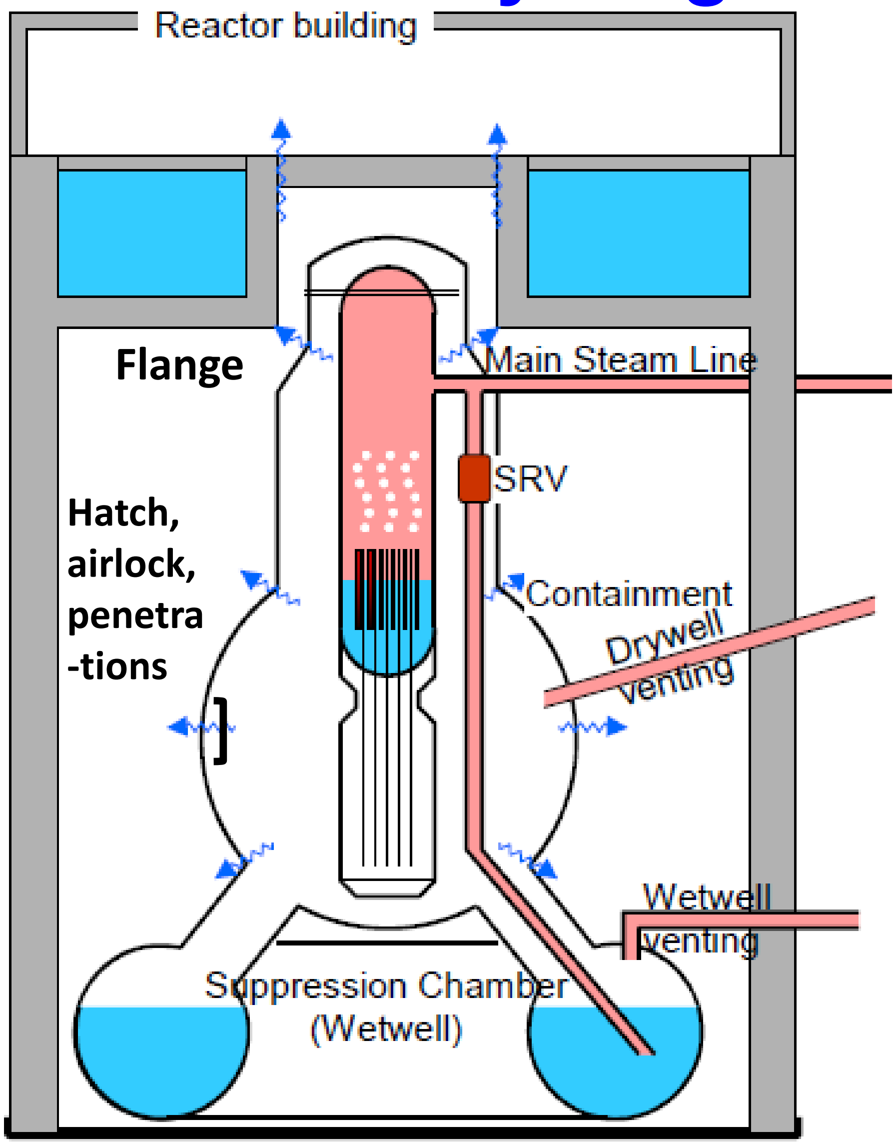
Emergency diesel generators, automatically activated after the scrum, were terminated due to water inundation by tsunami (15:37)

Estimation of failures of reactor pressure vessel and containment vessel



[Ref] Government Investigation Committee, July 2012

Possible Hydrogen Leakage Route and Hydrogen Explosion



Unit 1: 3/12 15:36

Unit 3：3/14 11:01

Unit 4：3/15 6:00

Estimated fission products released to Environment

Organization	I-131	Cs-137
NSC/JAEA (August, 2011) *	130	11
JAEA (March, 2012) *	120	9
NISA/JNES (June, 2011) **	160	15
NISA/JNES (February, 2012) **	150	8.2
TEPCO (June, 2012) *	500	10
(Ref）Chernobyl Accident*	1760	85

（10^{15}**Bq**）

*** Estimated with environmental monitoring data and diffusion analysis (SPEEDI/DIANA etc)**

**** Estimated with reactor accident progression analysis (MELCOR)**

Major technical causes of accident occurrence and escalation

- **Optimistic assumptions against external events (earthquake, tsunami)**
- **Insufficient measures against station blackout (including loss of DC power)**
- **Insufficient severe accident management measures (alternative cooling, CV venting)**
- **Insufficient measures against common-cause events at multiple units site**
- **Lack of appropriate severe accident progression prediction tools**
- **Insufficient education and training for severe accident situations**

Investigation reports on Fukushima accident issued in Japan:

- **Independent Investigation Commission, Feb 2012**
  Chaired by Prof. Kitazawa
- **Tokyo Electric Power Company, June 2012**
  Chaired by Vice-president Yamazaki
- **National Diet Investigation Commission, July 2012**
  Chaired by Prof. Kurokawa
- **Government Investigation Committee, July 2012**
  Chaired by Prof. Hatamura
- **Atomic Energy Society of Japan, April 2014**
  Chaired by Prof. Tanaka

General meaning of "Resilience"

- the ability of people or things to feel better quickly after something unpleasant, such as shock, injury, etc [Oxford]
- the ability to become strong, healthy, or successful again after something bad happens [Webster]

Four elements in "Resilience Engineering"

(Prof. Kitamura)

- ➢ Respond
- ➢ Monitor
- ➢ Anticipate
- ➢ Learn

Resilience related lessons learned from Fukushima accident (1)

Independent Investigation Commission, Feb 2012

Final Chapter "Lessons of the Fukushima Daiichi Nuclear Power Station Accident and Quest for Resilience"

"There can be no resolution of the Fukushima crisis until we study the causes of the accident and the havoc it wreaked, learn the lessons of the steps taken to respond to it, and forge a new national consensus. Those have been the key objectives of our investigation. Above all, we must strive to enhance Japan's resilience: the resilience of Japan's government, its institutions and its people."

Resilience related lessons learned from Fukushima accident (2)

Government Investigation Committee, July 2012

Chairperson's Final Remarks

"(5) Everything changes, respond flexibly to changes"

"…the only way to stop situations such as this from happening is to consider that all matters will change, pay scrupulous attention to observation, show humility in being open to external ideas, and continue to respond appropriately"

Resilience related lessons learned from Fukushima accident (3)

Atomic Energy Society of Japan, April 2014

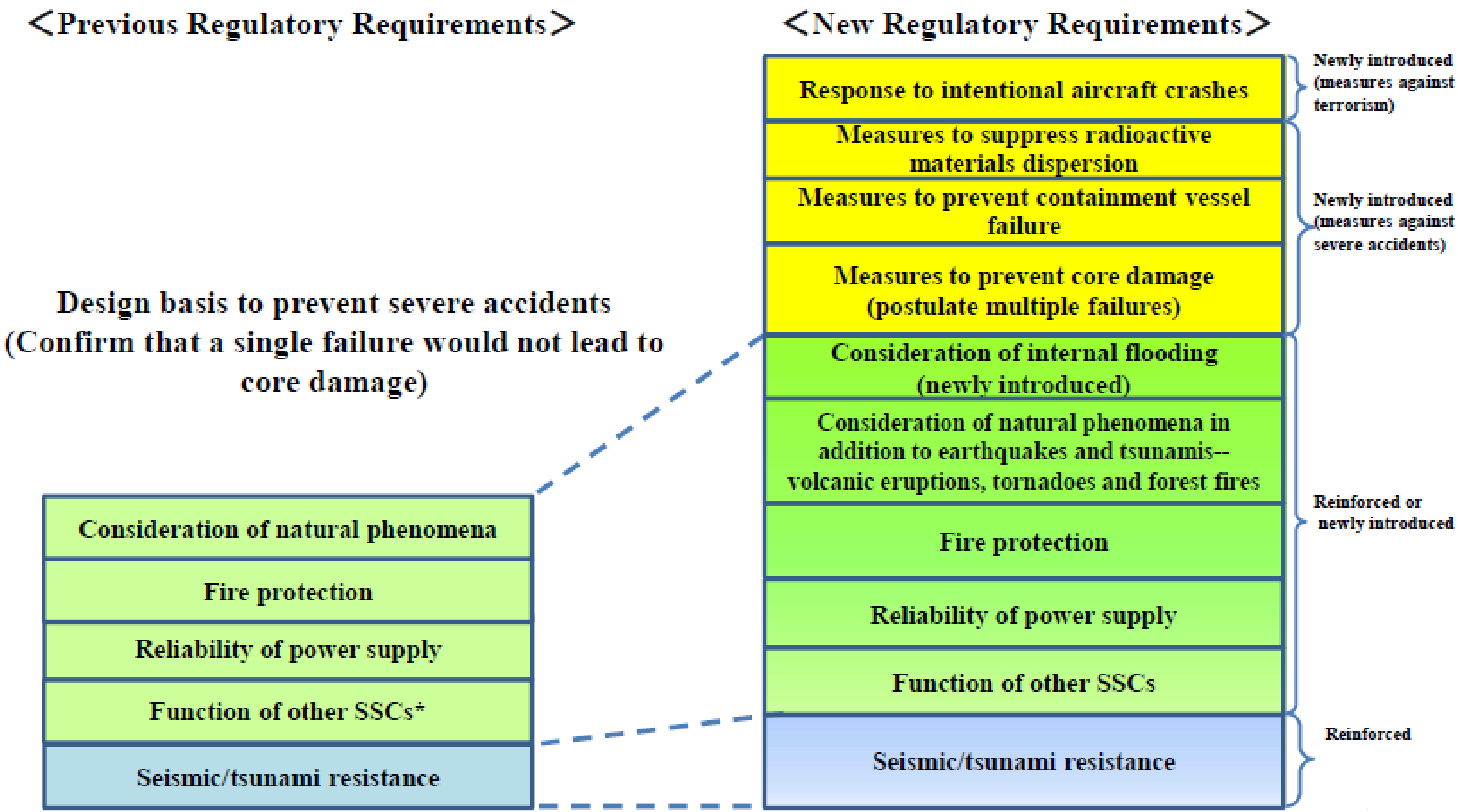
Recommendation 8.2.2

"(2) Strengthen severe accident measures"

"Since the event does not always proceed as expected in severe accident condition, an ability to respond flexibly to cope with the situation such as a management is necessary. In order to enhance this ability, improvement activities should be continuously conducted through training and practices."

Comparison between Previous and New Regulatory Requirements

- The New Regulatory Requirements tighten measures to prevent or deal with severe accidents and acts of terrorism



* SSC: Structure, Systems and Components

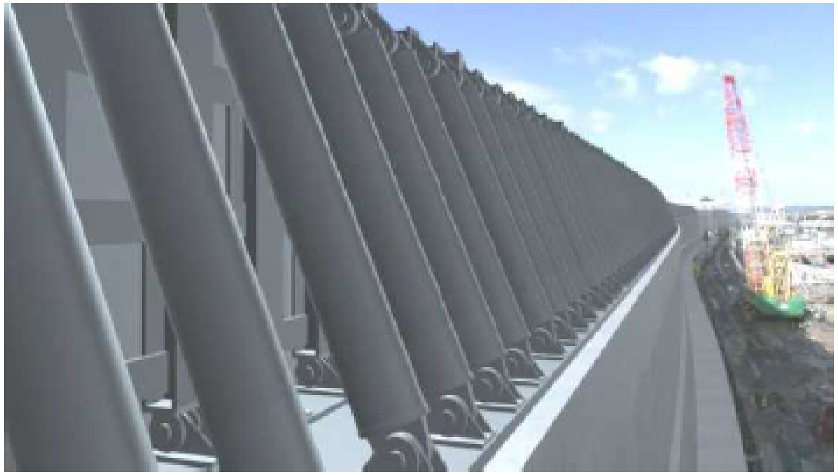
https://www.nsr.go.jp/english/e_news/data/13/0912.pdf

Significant Enhancement of Measures against Tsunamis

- The Standards define a "Design Basis Tsunami" as one which exceeds the largest ever recorded. The Standards require protective measures such as seawalls to combat such a phenomena.
- The Standards require SSCs for tsunami protective measures to be classified as Class S, the highest seismic safety classification applicable to RPV, to ensure that they continue to prevent inundations even during earthquakes.

<Examples of multi-layered protective measures against tsunamis>

○Installation of a seawall to prevent site inundation



○Installation of water-tight doors to prevent the flooding of buildings

https://www.nsr.go.jp/english/e_news/data/13/0912.pdf

Importance of “Resilience” for Future Reactor Safety

1. Safety measures have been greatly improved based on lessons learned from Fukushima accident both in hardware and software (including management and training).
2. However unexpected event still may lead to disastrous situation as we encountered in TMI-2, Chernobyl and Fukushima accidents.
3. It is highly expected that the application of resilience engineering can cope with unexpected event that has extremely low probability but has extremely high consequences.

Concluding Remarks

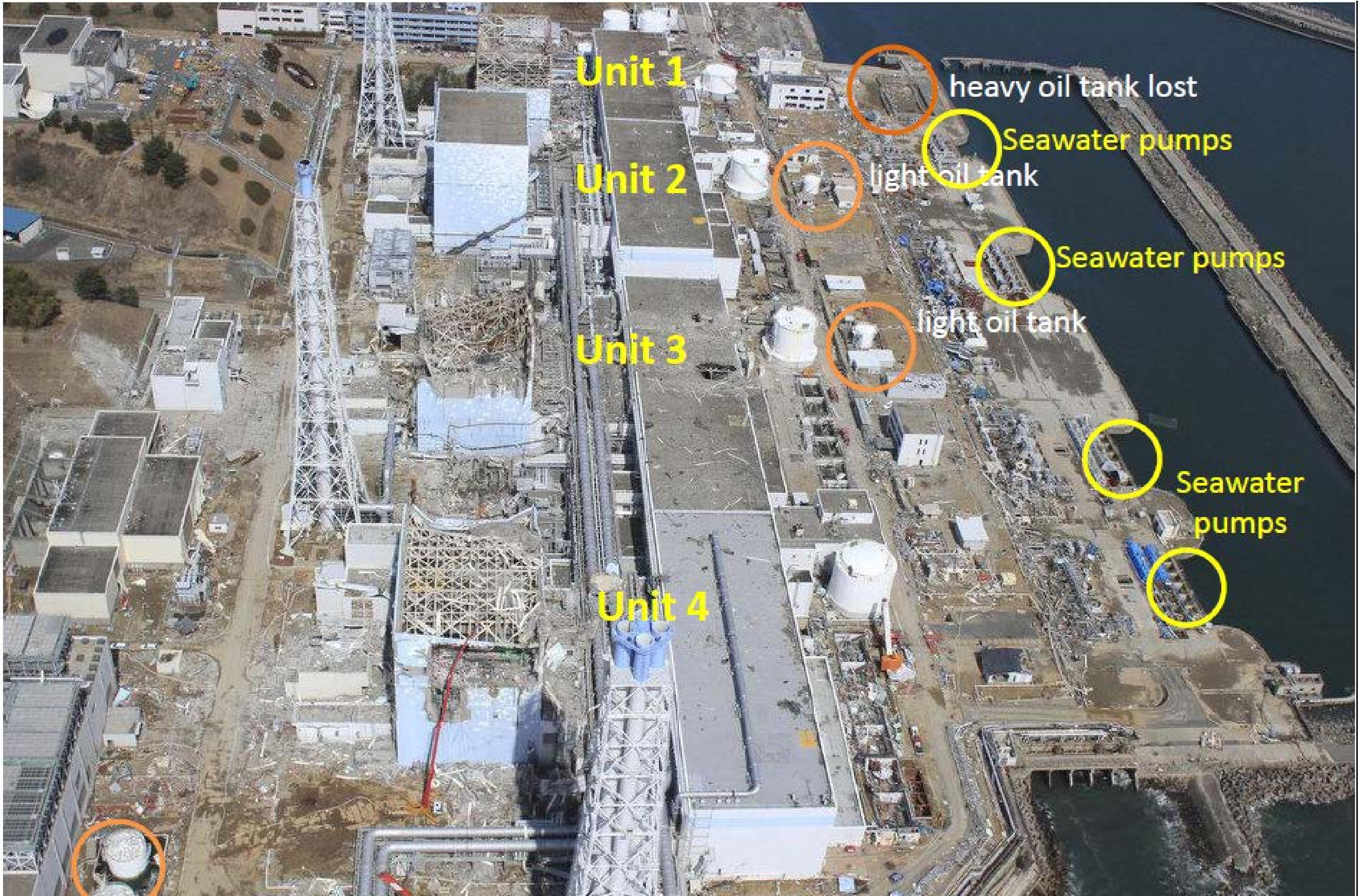
- **Some investigation reports on Fukushima accident in Japan emphasize the importance of "resilience" in lessons learned.**
- **Although the safety level has been greatly enhanced based on these lessons, unexpected event with extremely low probability may still lead to disastrous situation. It is expected that the application of resilience engineering can cope with this situation.**
- **Keywords to characterize TMI and Chernobyl accidents are internationally recognized as "human error" and "safety culture", respectively. That for Fukushima accident may be "resilience", depending on the outcome of the present panel.**

Thank you for your attention!

Summary of Damage after Tsunami Attack

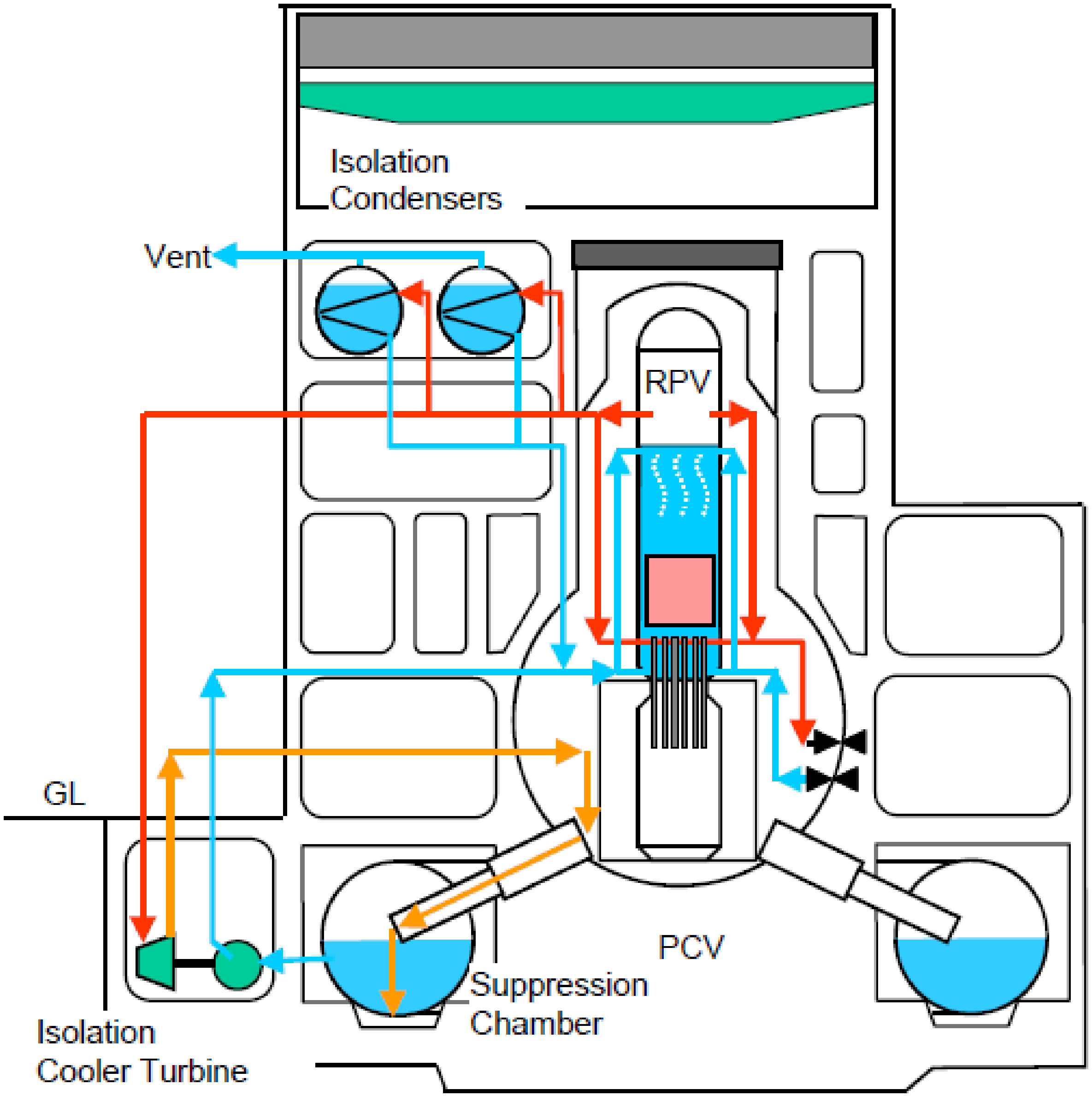
Unit	1	2	3	4	5	6
Operation Status	Full-power operation			Under inspection		
Off-site power	×	×	×	×	×	×
Emergency diesel generator A : Air-cooled	× ×	× ×[A]	× ×	× ×[A]	× ×	× ○[A] ×
Emergency power panel	×	×	×	×	×	○
Normal power panel	×	×	×	×	×	×
DC Power source	×	×	○	×	○	○
Sea-water cooling pump	×	×	×	×	×	×

Sea water pumps lost all functions

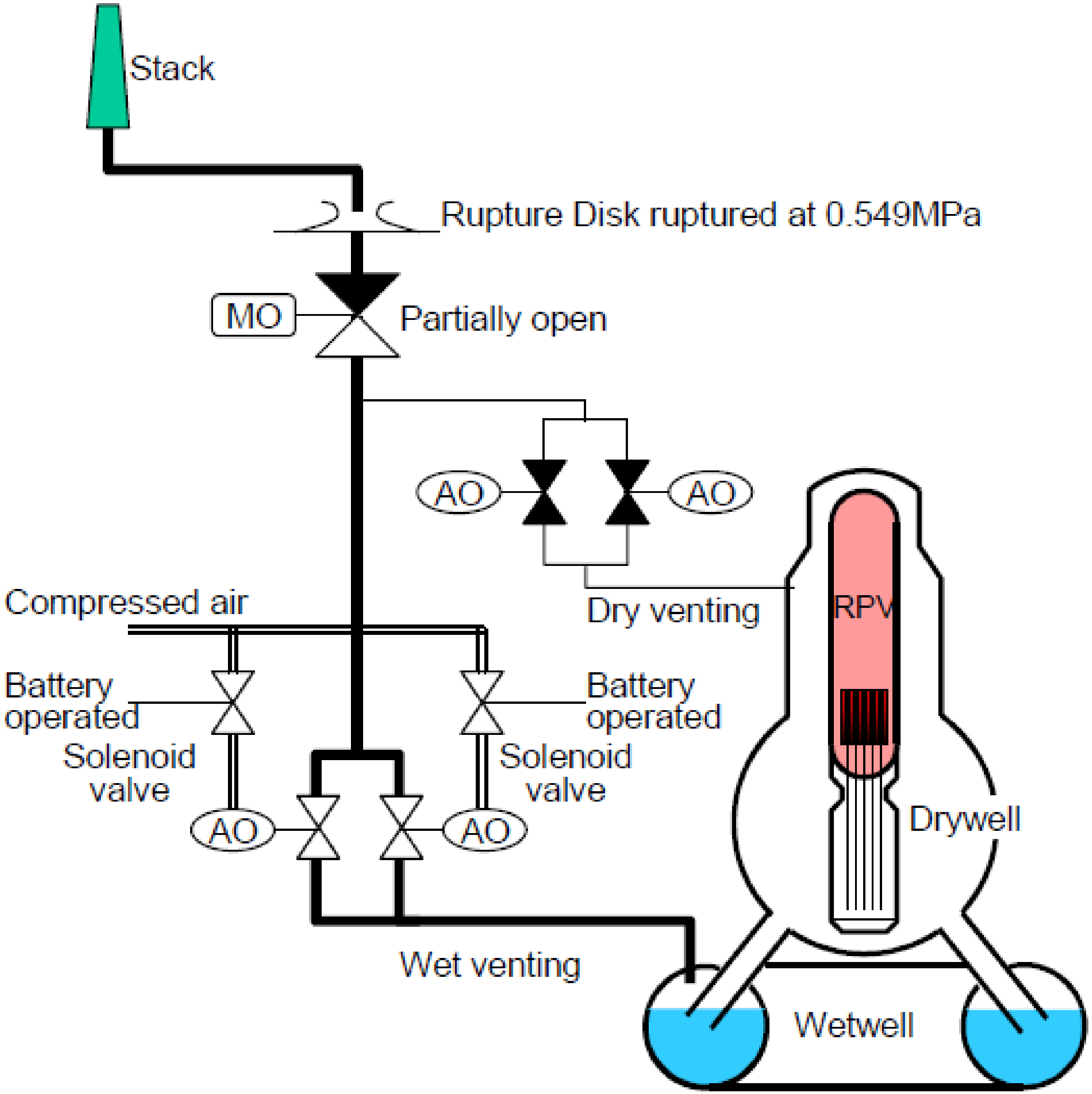


light oil tanks

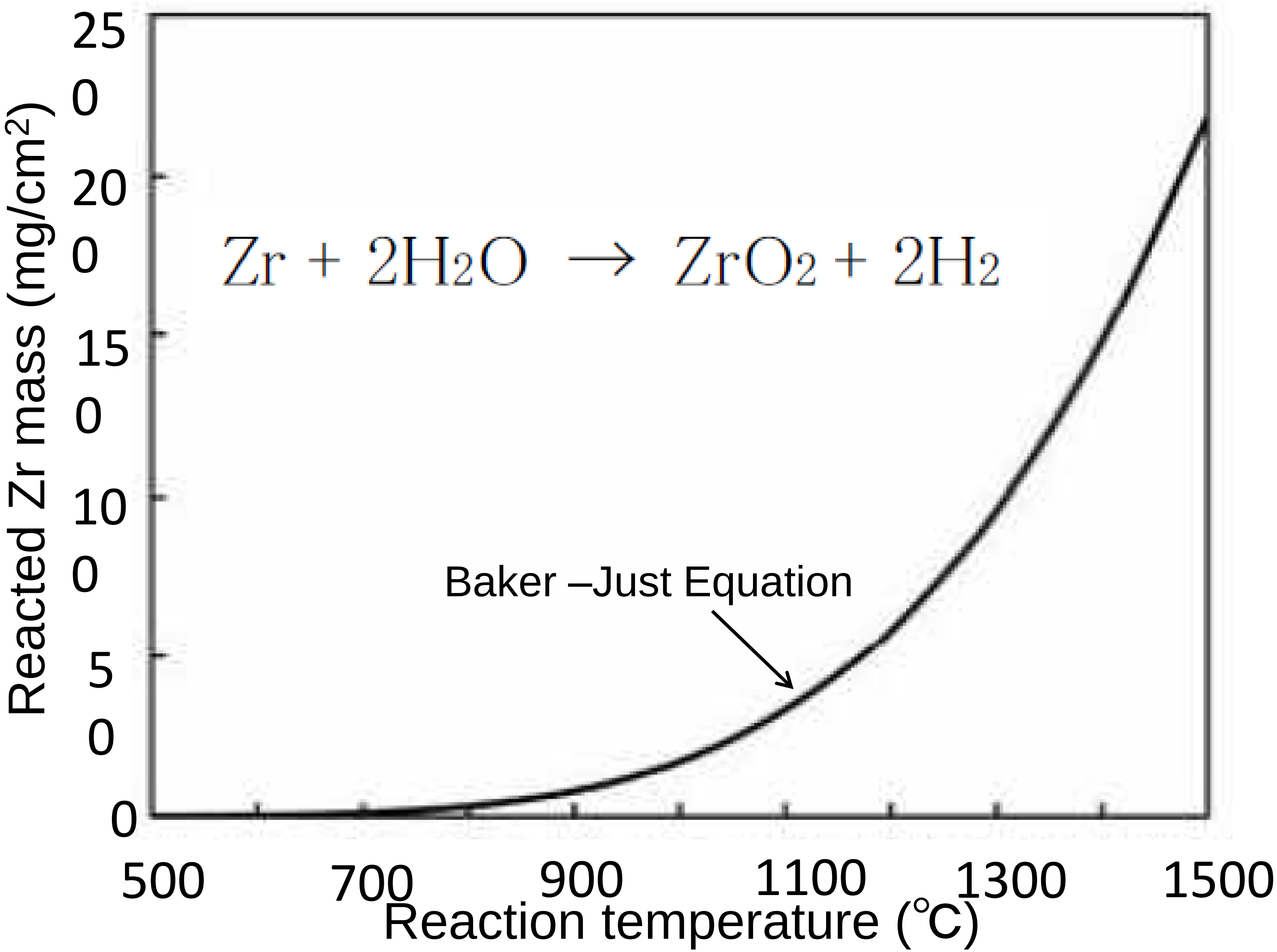
Isolation condenser (Unit 1)



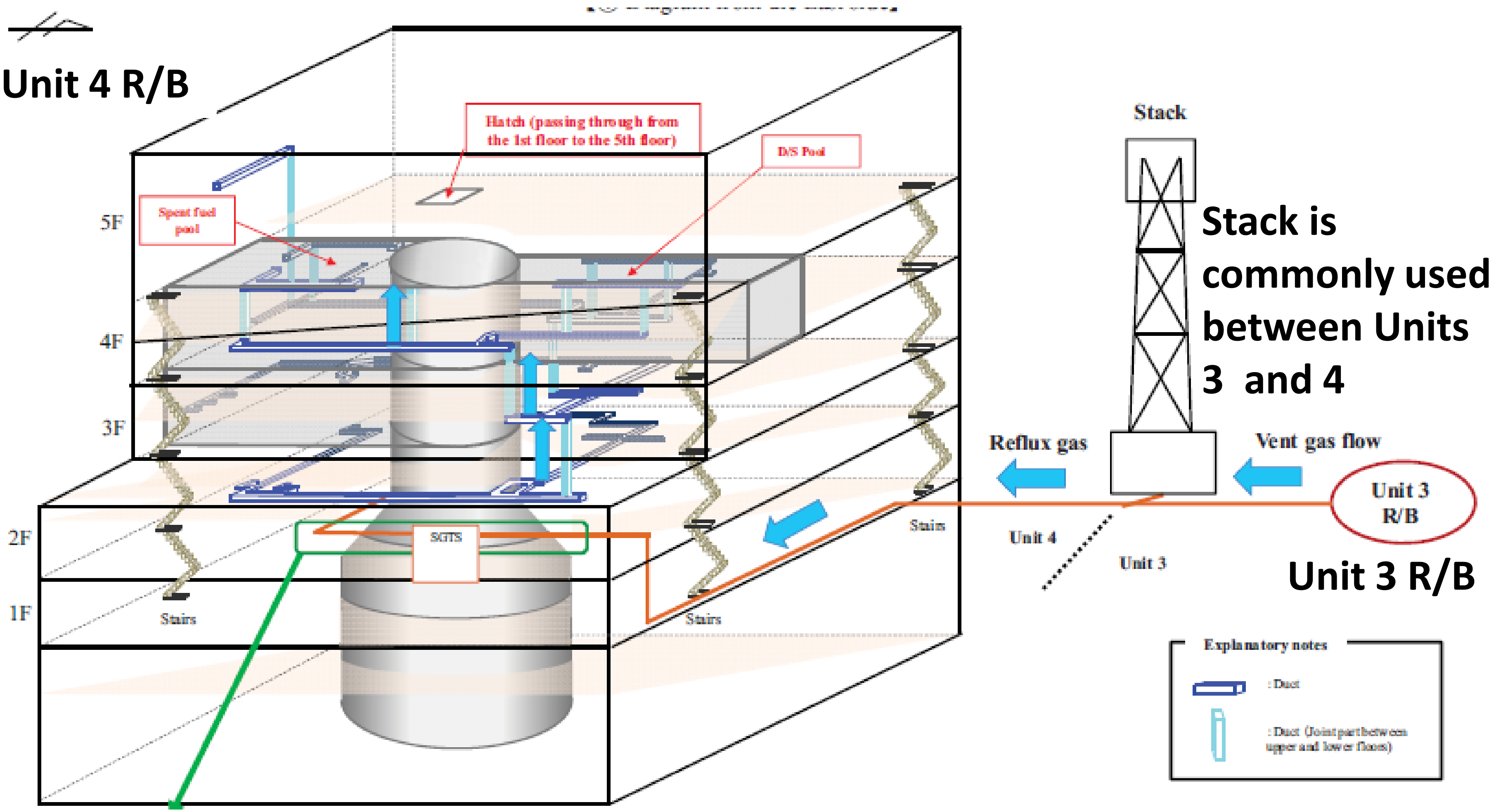
Containment Venting System



Zircalloy-water reaction



Possible Hydrogen Flow Path from Unit 3 to Unit 4

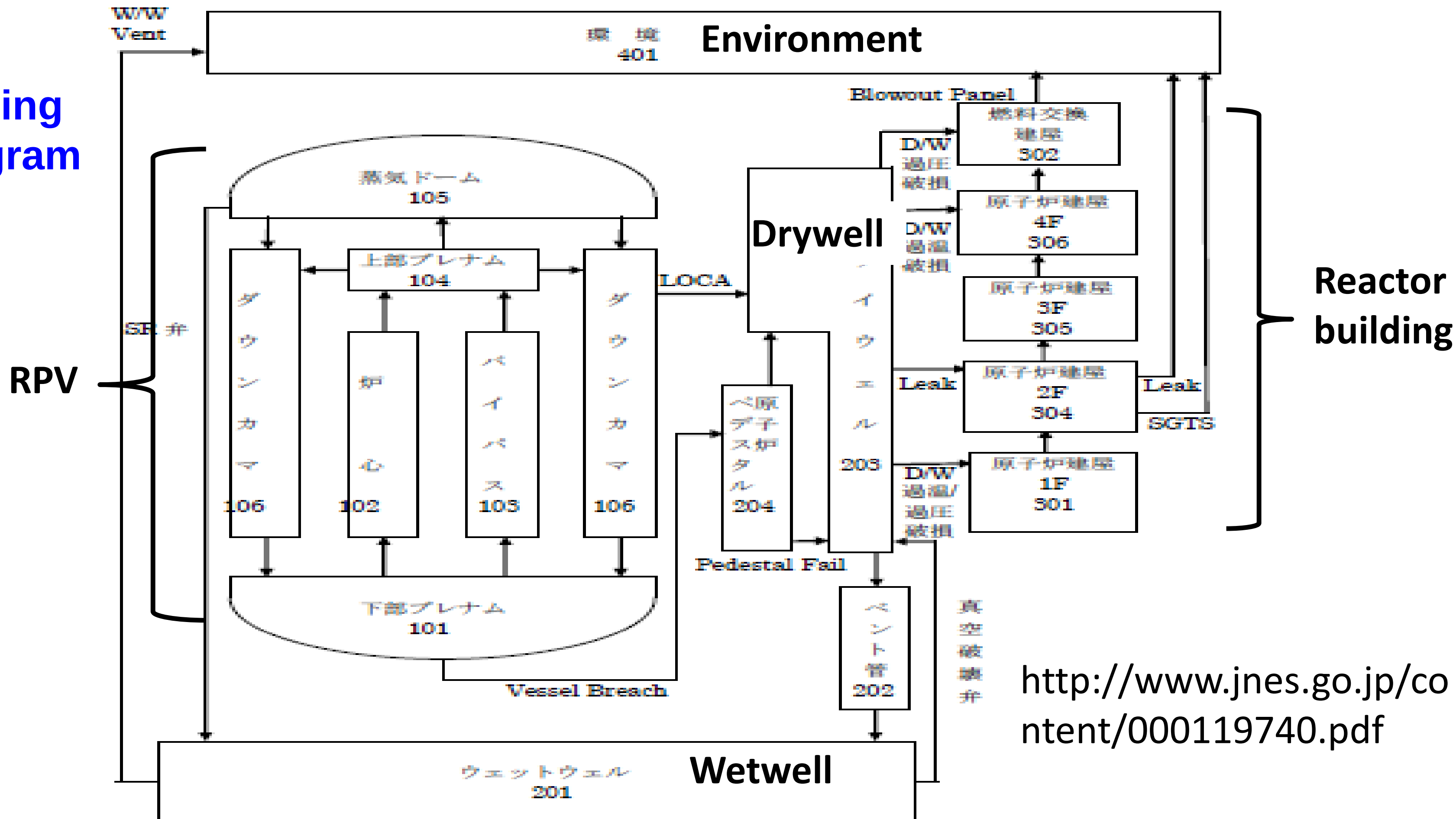


Government's Investigation Committee (July, 2012)

3. Release of fission products
Analysis results by JNES with MELCOR code

JNES: Japan Nuclear Energy Safety Organization
MELCOR: Severe accident analysis code developed by USNRC

Noding diagram



http://www.jnes.go.jp/content/000119740.pdf

Estimation of FP release from atmospheric diffusion –
–Inverse estimation with SPEEDI code–

Concept of inverse estimation

Calculated value
Assume 1 Bq/h release
Calculate air concentration and absorbed dose rate at measured locations

Measured value
Air concentration and absorbed dose rate

Release rate(Bq/h)= Measured/ Calculated

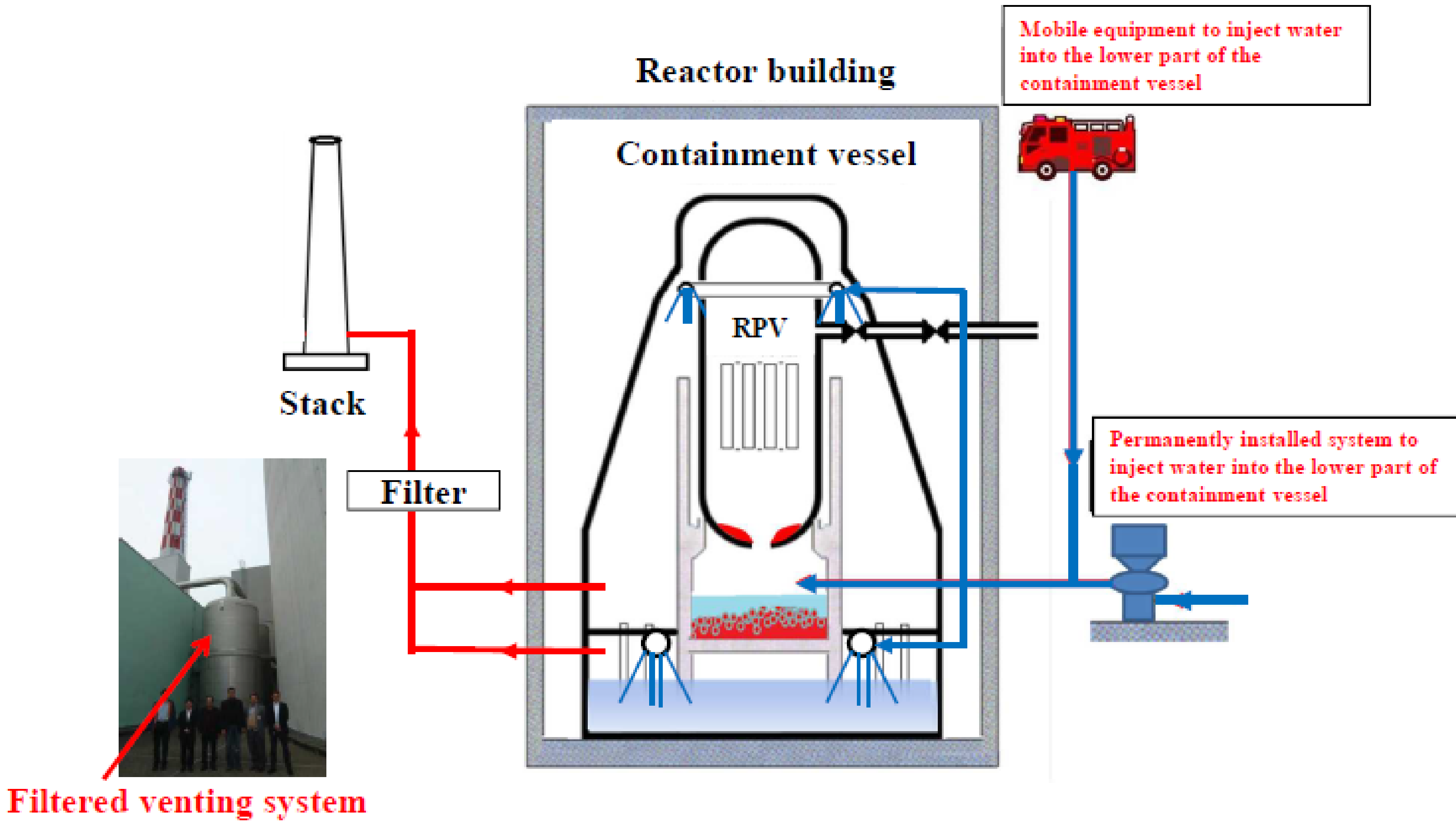
http://nsed.jaea.go.jp/ers/environment/envs/FukushimaWS/jaea1.pdf

Measures to Prevent Containment Vessel Failure

- Require measures to prevent containment vessel failure in the event of core damage

(Example 1) Install a filtered venting system to reduce the pressure and temperature inside the containment vessel and to reduce radioactive materials while exhausting (BWR)

(Example 2) Prepare a system (mobile pumps, hoses, etc.) to inject water into the lower part of the containment vessel to cool down the core to prevent containment vessel failure due to a molten core



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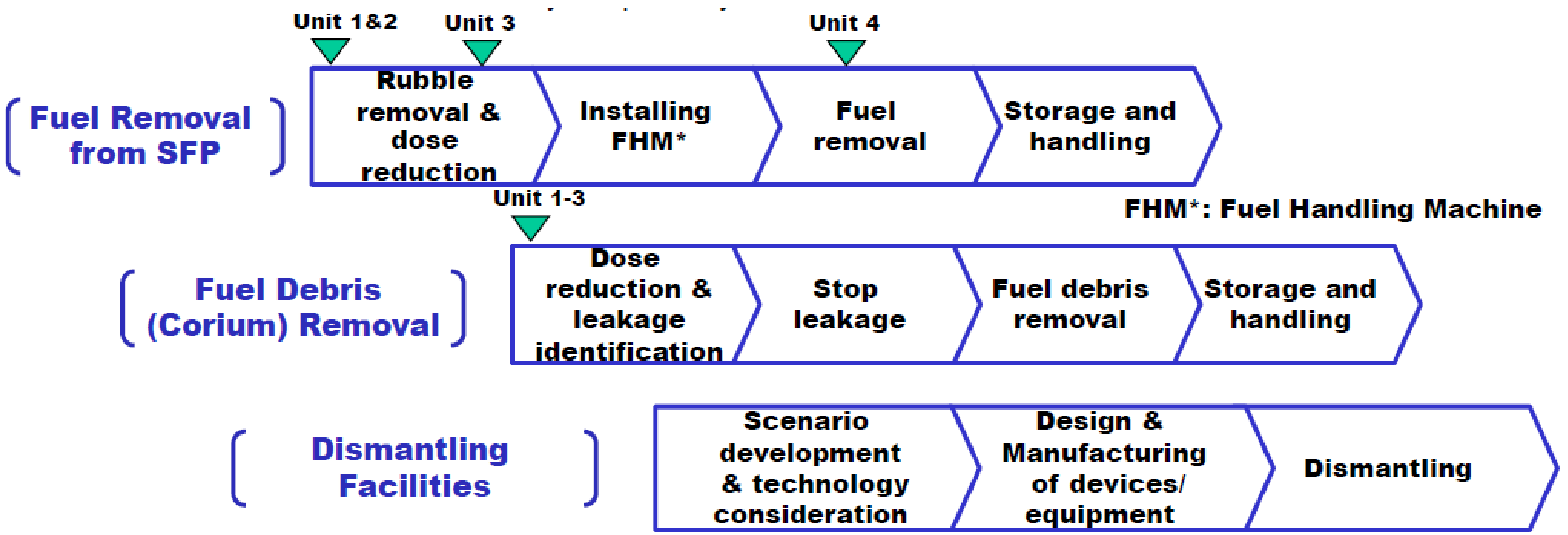
Main works and steps for the decommissioning



- Fuel removal from Unit 4 spent fuel pool (SFP) has been underway since Nov. 18, 2013. The work at Unit 4 will be accomplished around the end of 2014.
- Preparatory works for fuel removal from Unit 1-3 SFP and fuel debris removal are ongoing.
- It is said that it will take 30 to 40 years for the completion of the final decommissioning.

Important HRD for Nuclear Safety in the Light of Lessens Learned from Fukushima Accident

(1)Top professional at the plant to cope with unexpected event
(2)Operators under top professional to properly conduct necessary procedures

(1)Top professional at the plant to cope with unexpected event

- No manual exist to cope with unexpected event
- Need to understand what happens with limited information
- Need to properly predict what will happen next
- Need to develop effective measures to prevent disastrous situations

How to develop HR?

- ✓ Physics-based essentially in-depth knowledge
- ✓ Dispatch of personnel to research institutes
- ✓ Extensive team training without scenario
- ✓ Systematic training on leadership

(2) Operators under top professional to properly conduct necessary procedures

- No manual exist to cope with unexpected event
- Need to understand technical reasons of the directions by the top professional
- Need to properly conduct necessary actions
- Need to precisely report the results to top professional

How to develop HR?

- ✓ In-depth knowledge on plant behaviors
- ✓ Extensive team training without scenario
- ✓ Systematic training on communication