Study on Severe Accident Progression and Source Terms in Fukushima Dai-ichi NPPs

October 27, 2014

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1. Investigation Reports

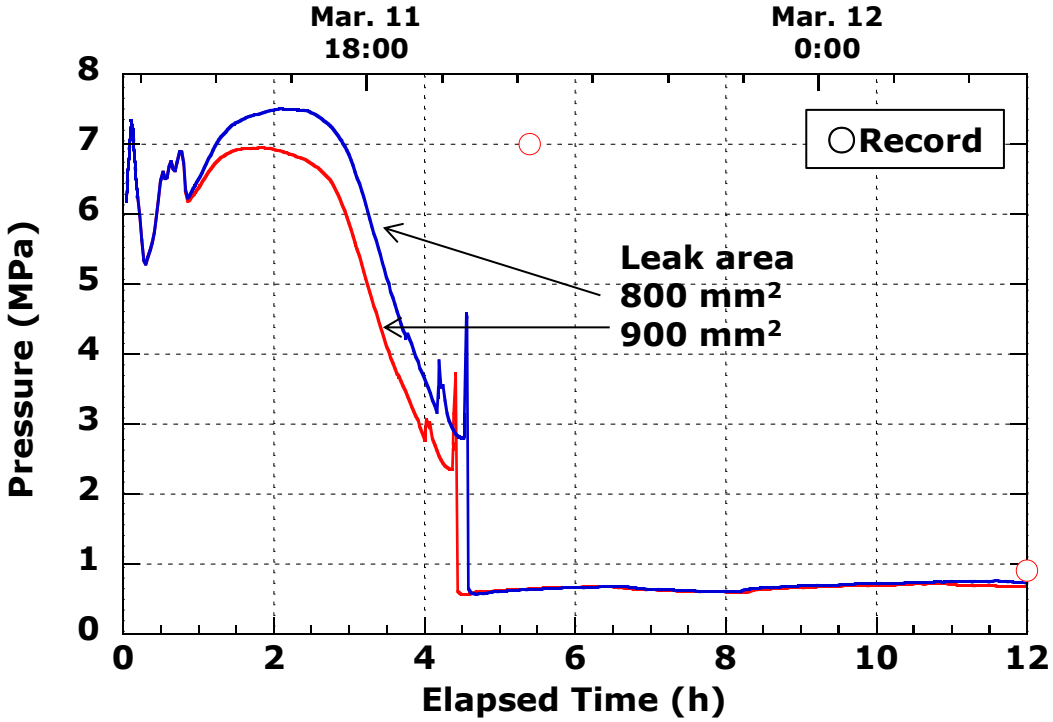
- **After Fukushima Daiichi accident, several investigation reports were published**
- **These reports pointed out lessons learned from the accident**
- **New regulation, reflecting the lessons, was enacted last year**
- **NRA launched new committee to investigate unsolved issues**

New Investigation Committee

- Possibility of small break LOCA at Unit 1
- Activation of S/RV at Unit 1
- Flooding on 4th floor of Unit 1
- Isolation condensers of Unit 1
- SFP of Unit 3
- Hydrogen explosion at R/B of Unit 4

Possibility of SBLOCA at Unit 1

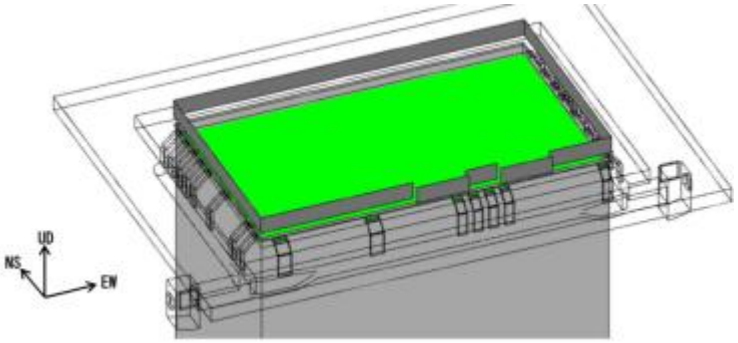
- **Diet investigation report pointed out possibility of small break LOCA and S/RV was not activated**
- **If SBLOCA occurs, RPV pressure decreases rapidly and is inconsistent with observed data**

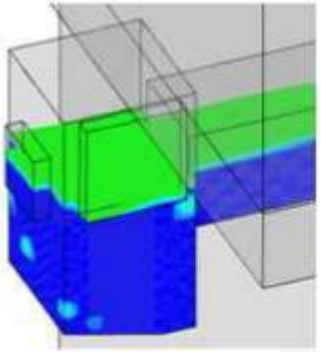


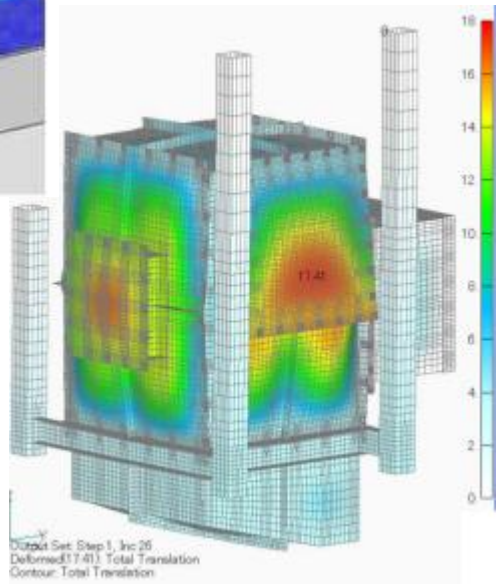
Ref.: WWW.nsr.go.jp/comittee/yuushikisha/jiko_bunseki/data/004_05.pdf (in Japanese)

Flooding on 4th floor of Unit 1

- **S/NRA/R calculated sloshing of SFP (Unit 1) and structure**
- **Analyses suggest below**
  - **Water flooded from SFP to duct due to sloshing**
  - **Water leaked from duct due to break by dynamic loading**



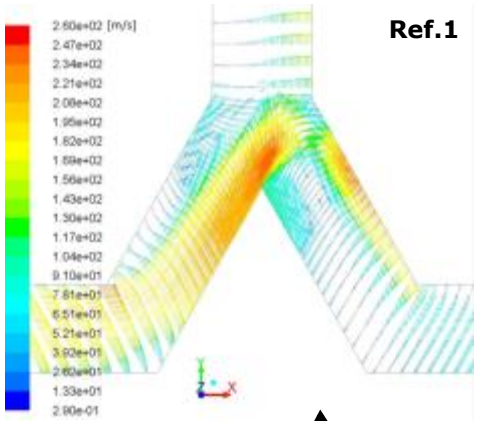


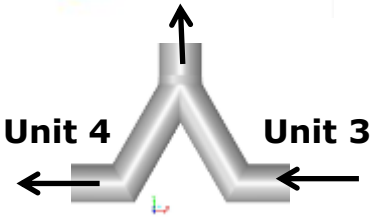


Ref.: WWW.nsr.go.jp/comittee/yuushikisha/jiko_bunseki/data/003_01.pdf (in Japanese)

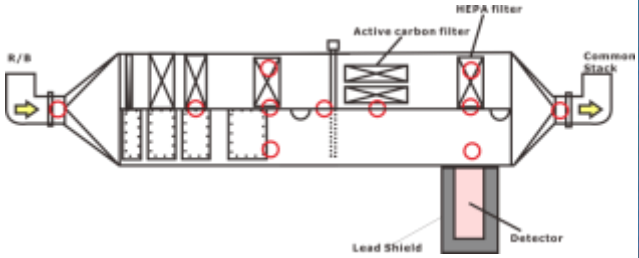
Hydrogen Explosion at Unit 4

- **CFD calculations suggest hydrogen flow from Unit 3 to Unit 4 through common stack**
- **Outlet of STGS (Unit 4) was contaminated higher than inlet**
- **NRA investigated R/B of Unit 4 and found ducts were significantly damaged**





Dose rate of filters in Unit 4 were measured



Damaged ducts in Unit 4

4th floor

2nd floor

Ref.2

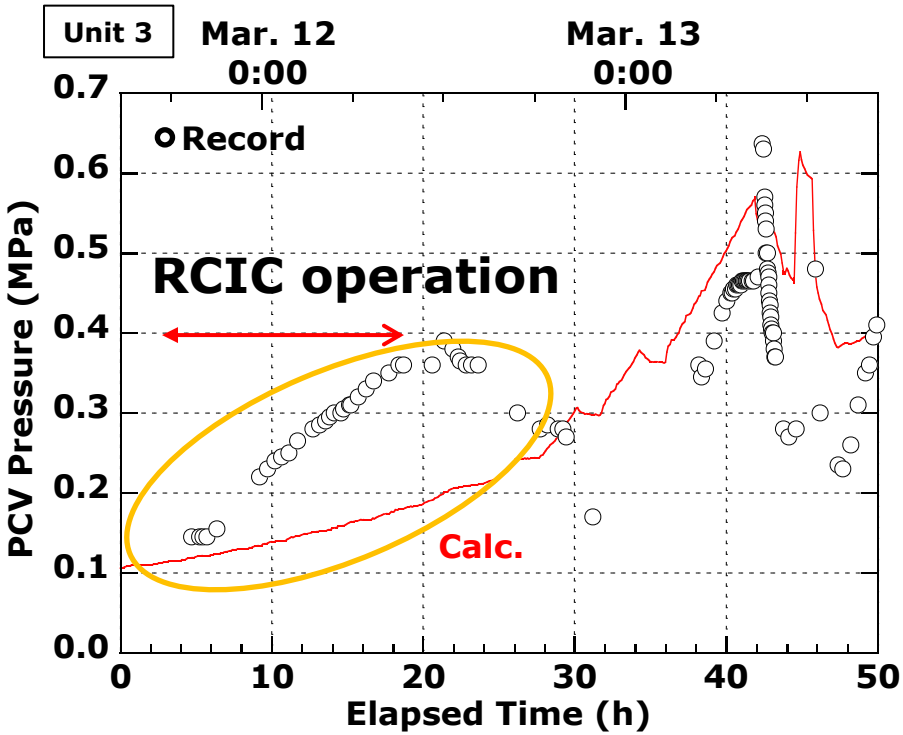
Ref.1: WWW.nsr.go.jp/archive/jnes/content/000125907.pdf
Ref.2: WWW.nsr.go.jp/comittee/yuushikisha/jiko_bunseki/data/004_01.pdf

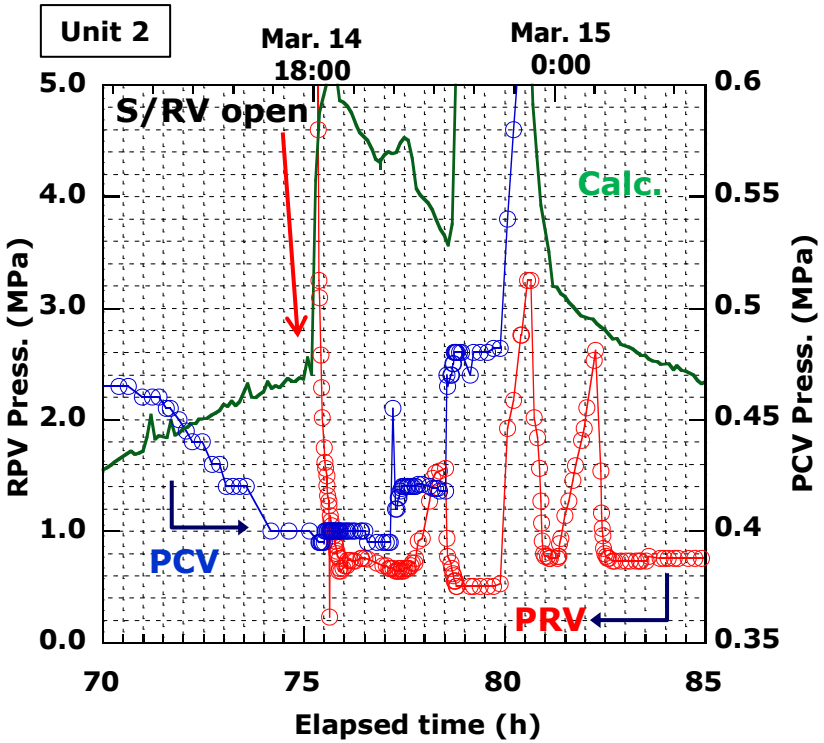
2. Research on Fukushima in S/NRA/R

- **Experimental programs**
  - **Pool scrubbing test**
  - **Sea water injection**
- **Computational analyses**
  - **Accident progression (lumped parameter code)**
  - **CFD approach**
    - **Containment integrity**
    - **Hydrogen distribution**
    - **Diffusion of fission products**

Thermal Stratification of S/P

- **Calculations of lumped S/P model (uniform temperature distribution) show significant difference from actual measurement**
- **These calculations imply thermal stratification of S/P under long term SBO**





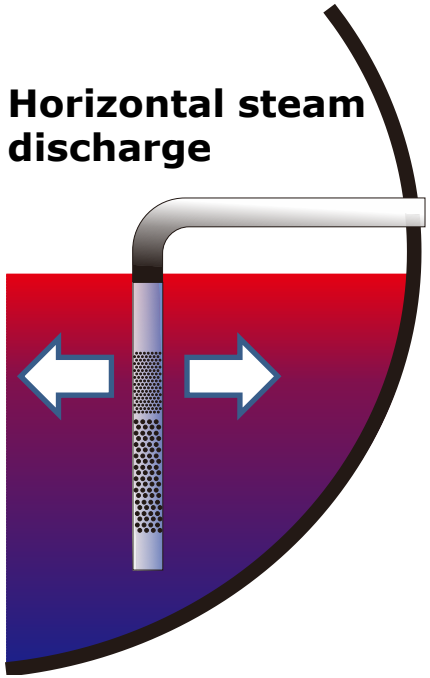
Calc. shows slow pressurization

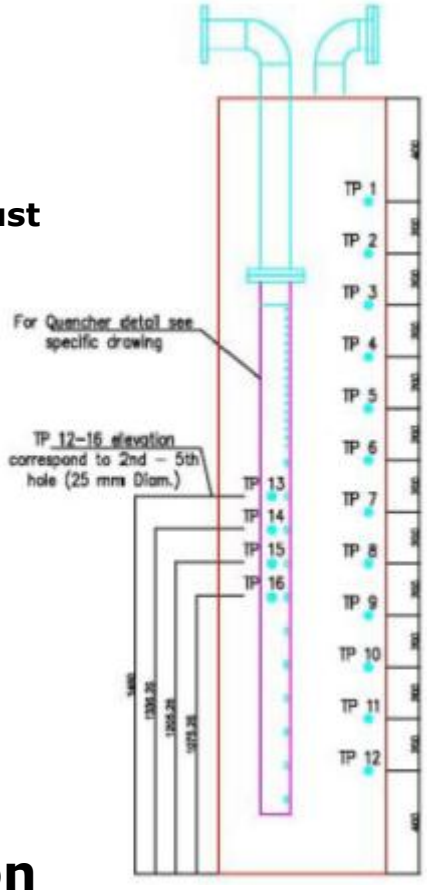
Calc. shows D/W pressure quickly increases

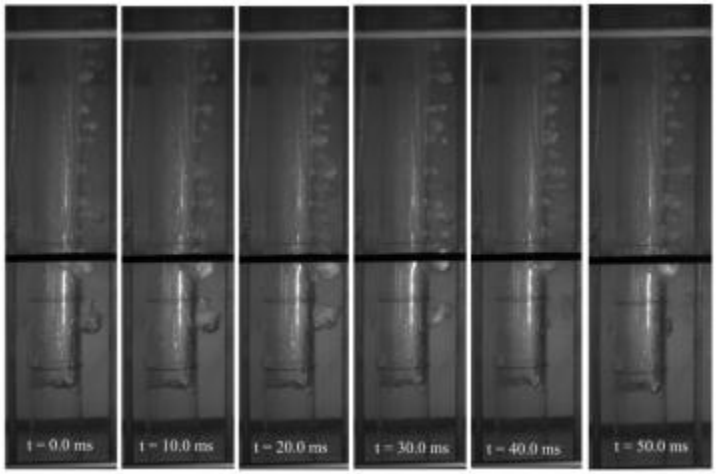
Ref.: Nuclear Emergency Response Headquarters Government of Japan, "Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety - The Accident at TEPCO's Fukushima Nuclear Power Stations - ," June 2011

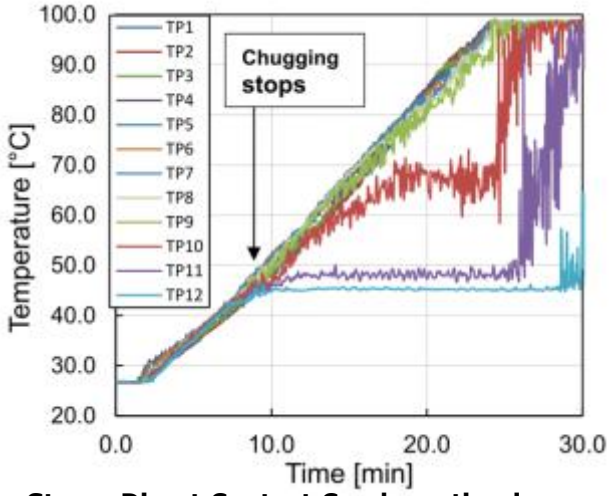
Early Pressurization of PCV

PCV is pressurized due to thermal stratification of S/P during RCIC operation







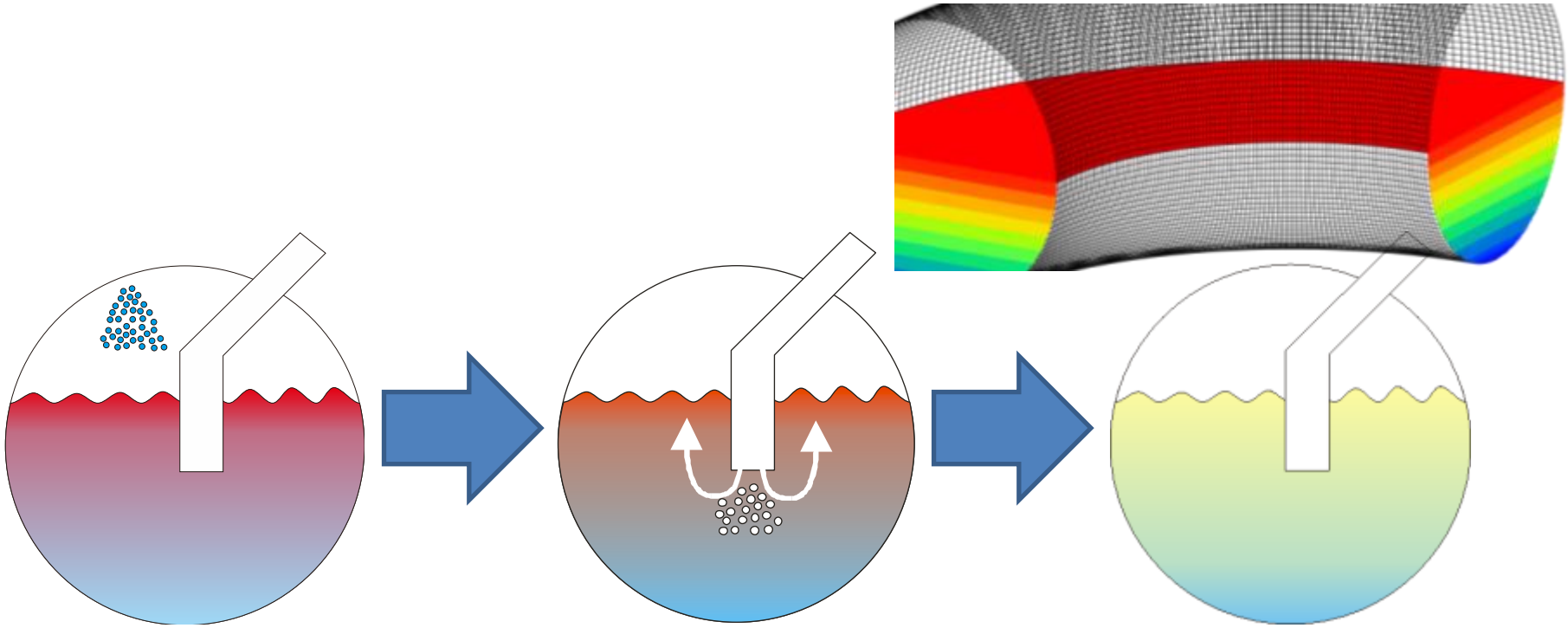


Experimental results show nonuniform temperature distribution

Ref.: M. Pellegrini, et al., "Suppression pool testing at the SIET labs (3) Experiments on Steam Direct Contact Condensation in a Vertical Multi-holes Sparger," Proc. of The 10th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-10), Okinawa, Japan, December 14-18, 2014 (provided by the senior author)

Depressurization of W/W

- Depressurization of W/W due to activation of spray system
- Discharge from D/W to W/W through vent pipe
- Enhance mixing of S/P and break thermal stratification



- Spray activation
- Steam condensation
- Depressurization

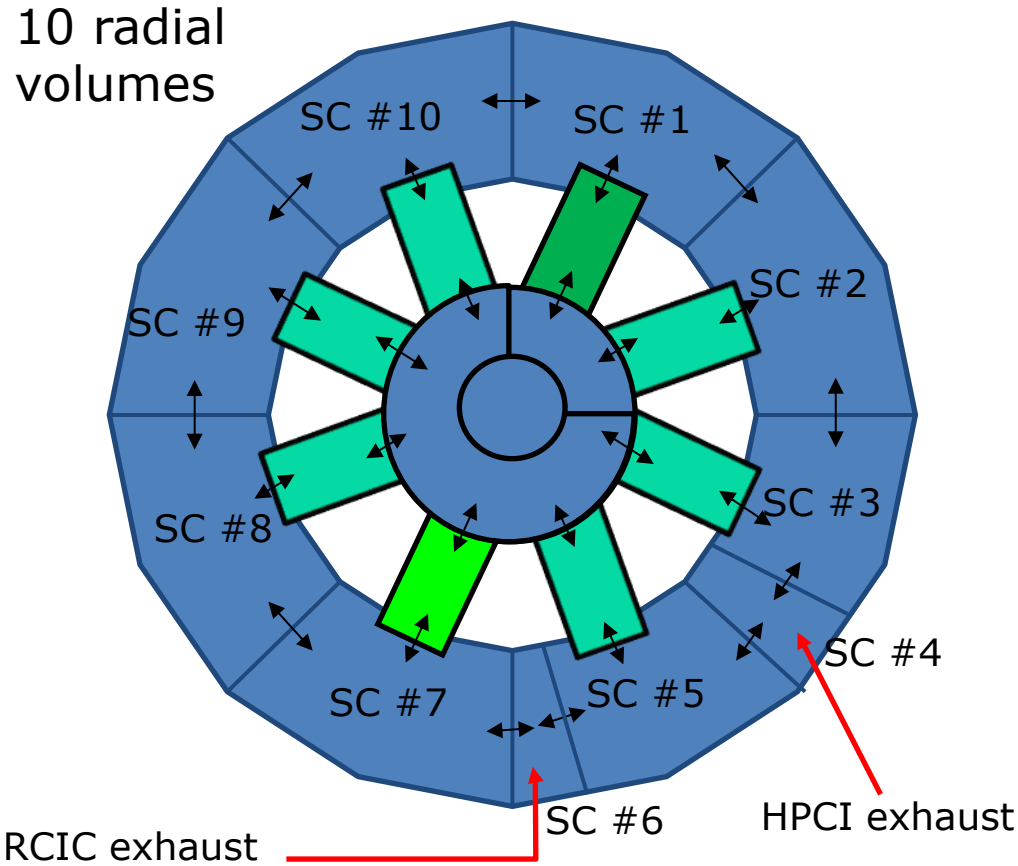
- Discharge from D/W to W/W through vent pipe
- Mixing of S/P

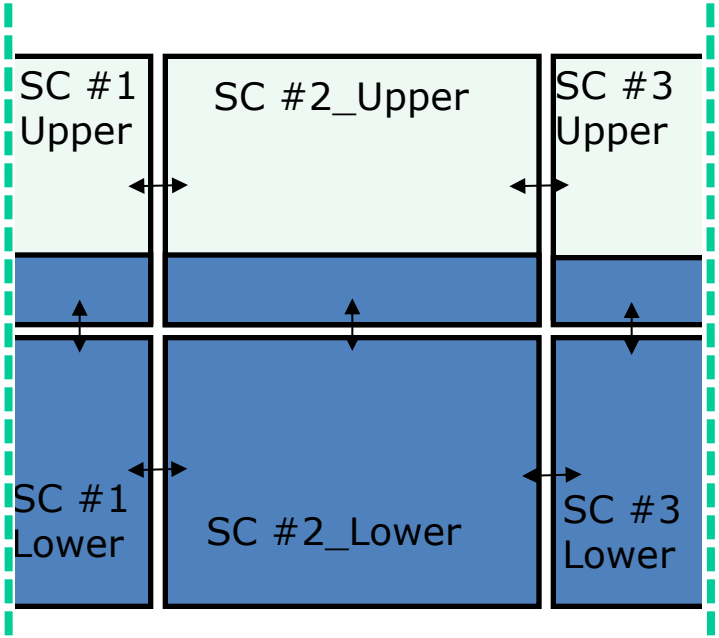
- Break of thermal stratification of S/P

New Attempt of S/C Nodalization

Divide Suppression chamber volume into 20 volumes for Unit 2,3.

10 radial volumes

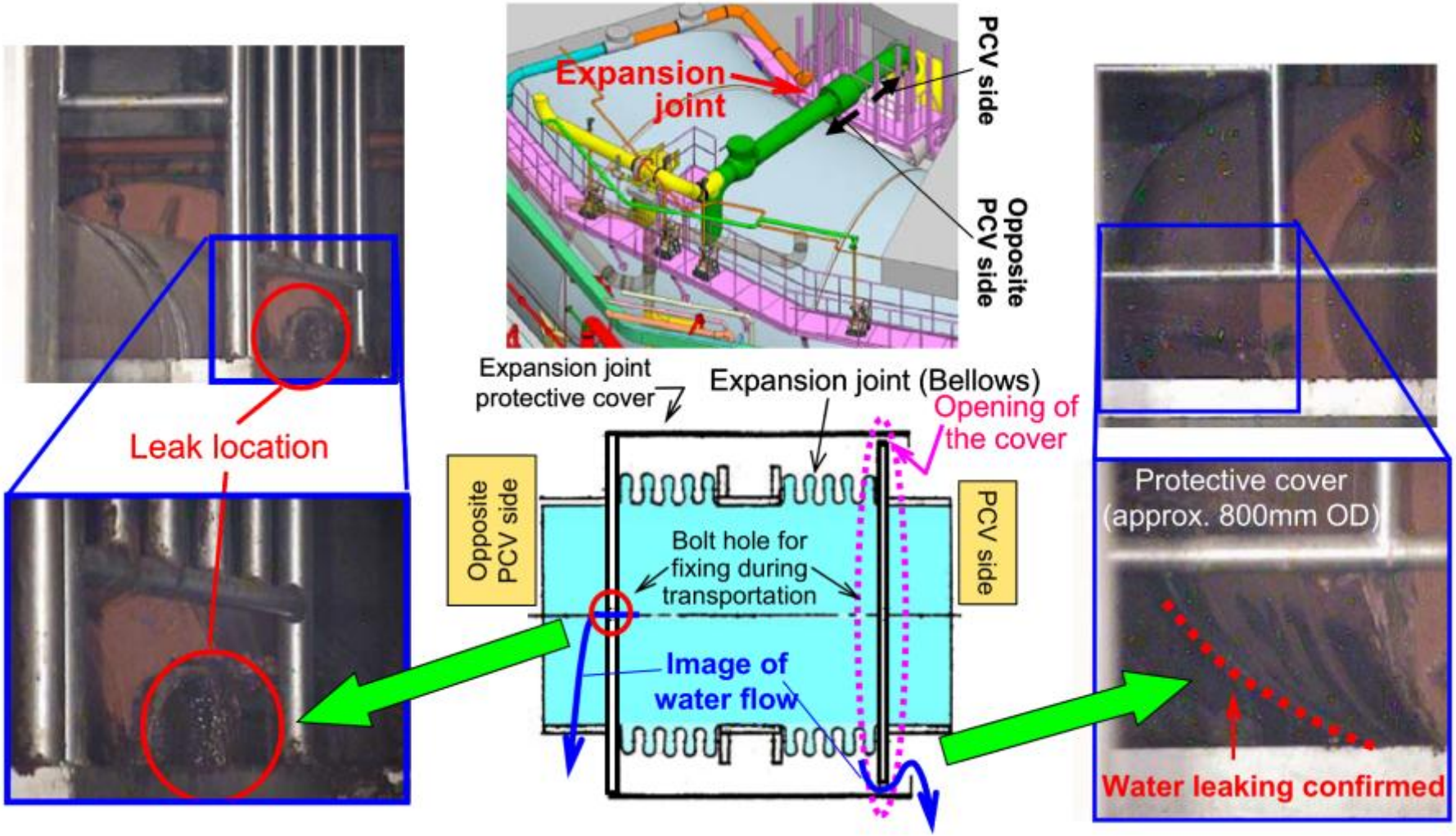




Each radial volume is divided into 2 volumes for the vertical direction.

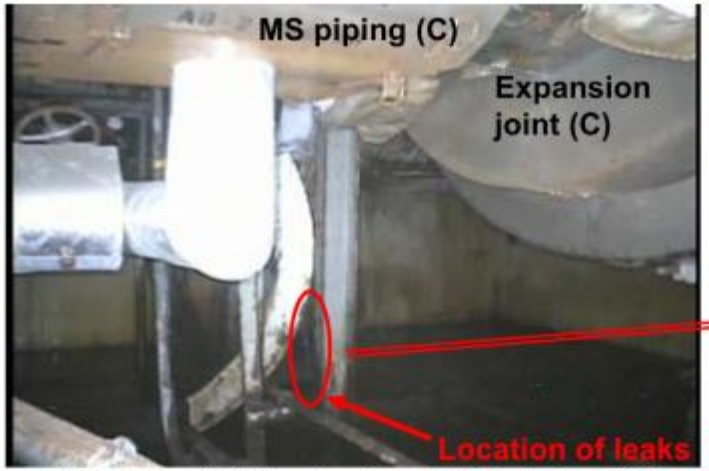
Consider radial thermal distribution and vertical thermal stratification

Leakage from PCV (1/2)



Ref.: TEPCO, "Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression Progress Report No. 2," Aug. 6, 2014

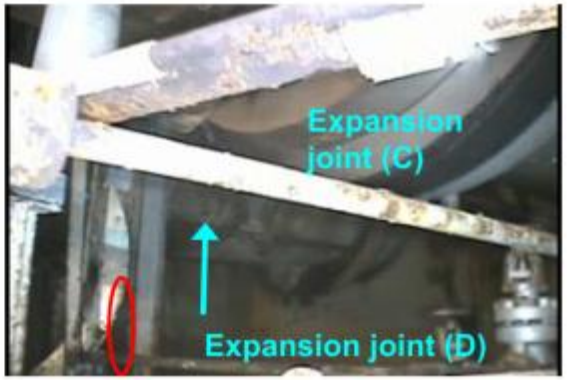
Leakage from PCV (2/2)



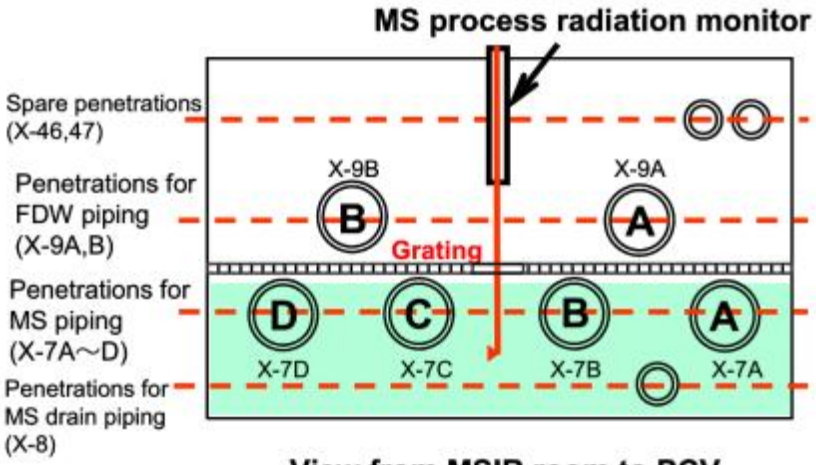
MS piping (D) (back side of MS piping (C))

* MS = Main Steam system, consists of 4 sub-systems (A) to (D)

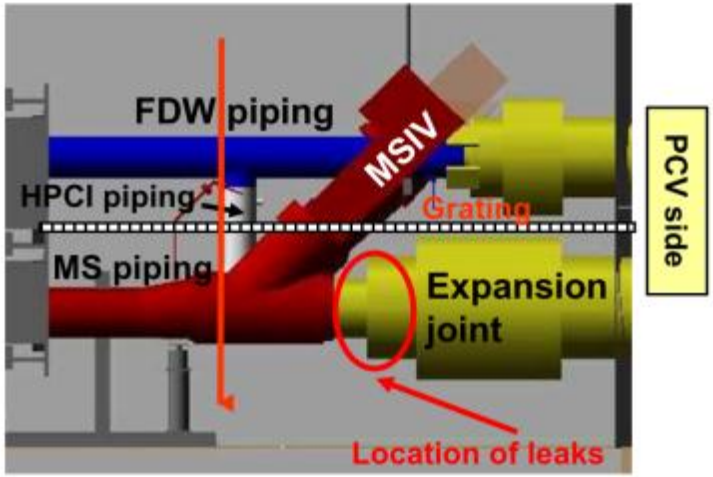
Location of leaks (enlarged)



MS piping (D)



View from MSIR room to PCV

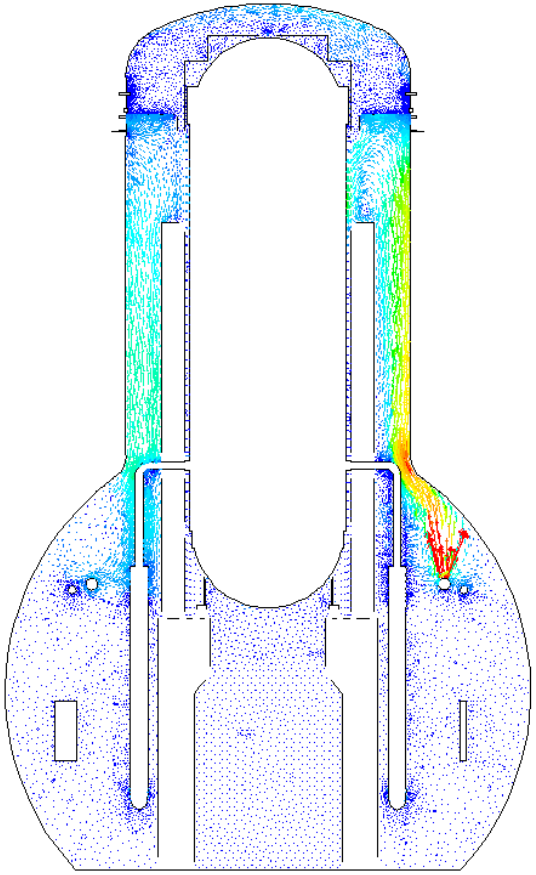


MSIV room image drawing

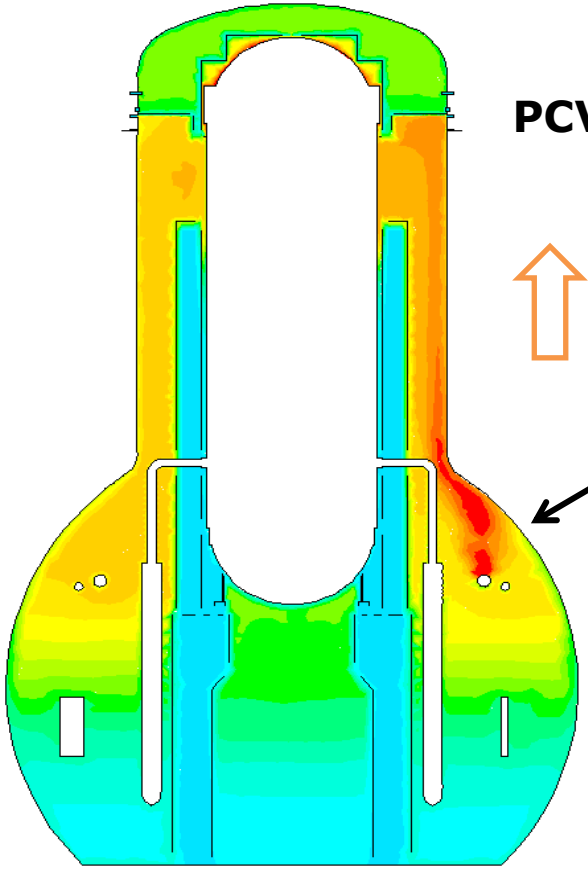
Ref: http://www.tepco.co.jp/en/press/corp-com/release/2014/1240140_5892.html

Leakage from PCV (Analysis)

Flow velocity



Temperature



PCV top head flange

Leakage from SRV gasket

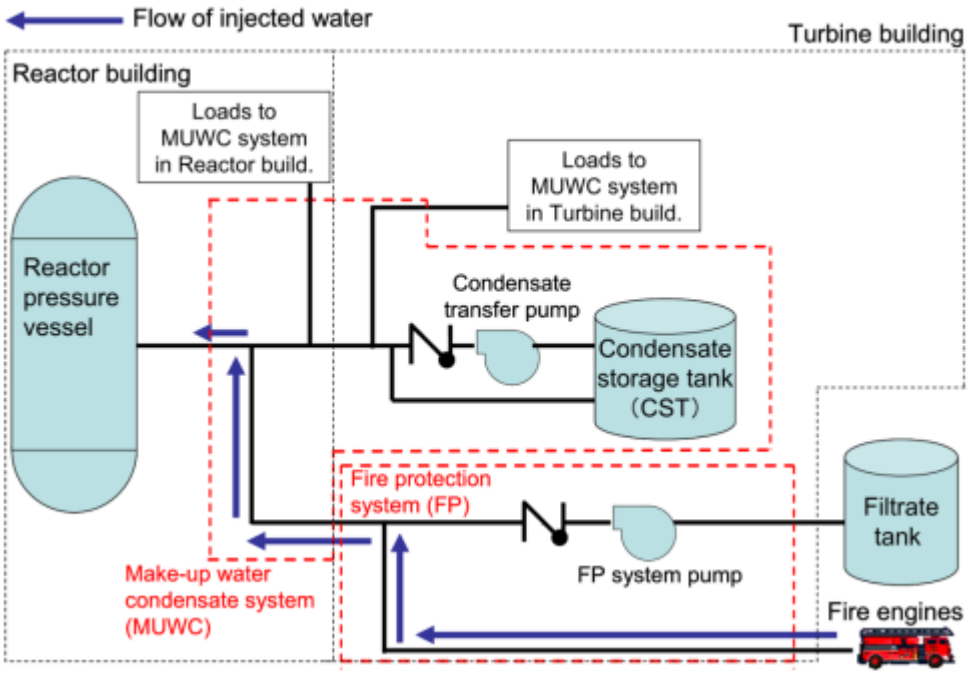
1800 sec after leakage from S/RV gasket

External Water Injection

- External water injection
- MCCI is important to estimate amount of external water injected to the core
- Core status

Bypass of External Water Injection

- **If whole external water, fed by fire engine, was injected to the core, core ought to have been cooled.**
- **External water injection, to the core, is less than the record**
- **TEPCO identified potential bypass path**
  e.g. 10 paths for unit 1
- **Actual amount injected to the core significantly affects core status, hydrogen generation, MCCI, etc.**

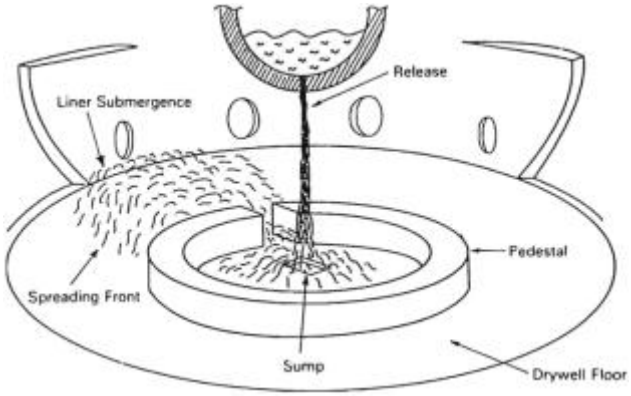


Path No.	Leak path	Pipe diameter	Remarks
1	Seal water line of condensate pump	3/4"	Flow to condenser
2	Minimum flow line of condensate transfer pump	4"	Flow to condensate storage tank
3	Evaporator make-up water line	2"	Flow to condenser
4	Seal water of valves	1/2"	Flow to system line
5	Seal water line of liquid waste neutralization pump	3/4"	Flow to system line
6	Seal water line of condenser vacuum breaker valve	3/4"	Flow to condenser
7	Mechanical seal water line of PLR pump	3/4"	Flow to equipment drain sump
8	Seal water line of feedwater pump	1"	Flow to condenser
9	Condensate demineralizer	8"	Flow to condensate demineralizer column
10	Seal water line of low- pressure heater drain pump	3/8"	Flow to equipment drain sump

Ref.: TEPCO, "Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression Progress Report No. 2," Aug. 6, 2014

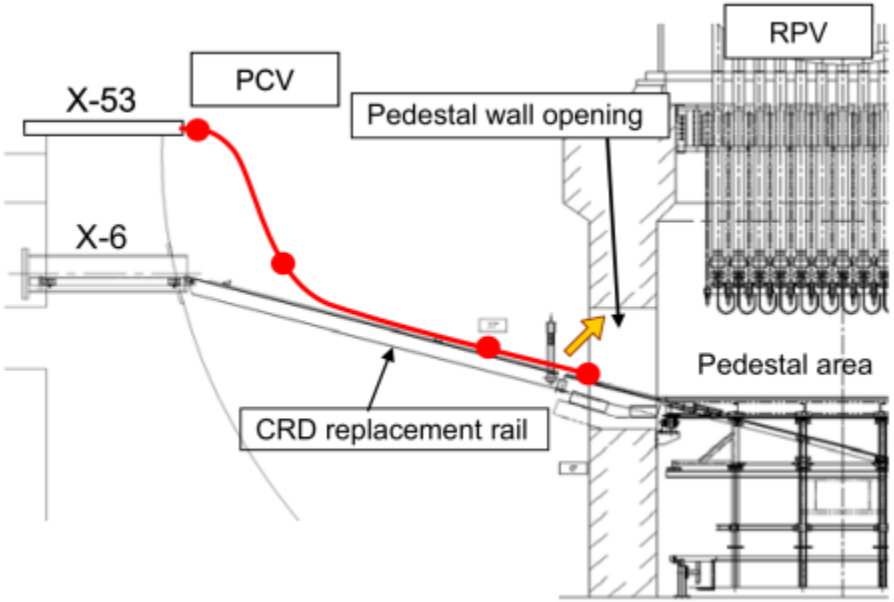
Melt Spread in PCV

- **Shell attack, direct melt-attack of the liner, is identified as one of the important PCV failure modes for Mark-I containment**
- **Investigation of inside PCV is in progress by TEPCO**



Ref.: U. S. NRC, "Probability of Mark-I Containment Failure by Melt-Attack of the Liner," NUREG/CR-6025, 1993

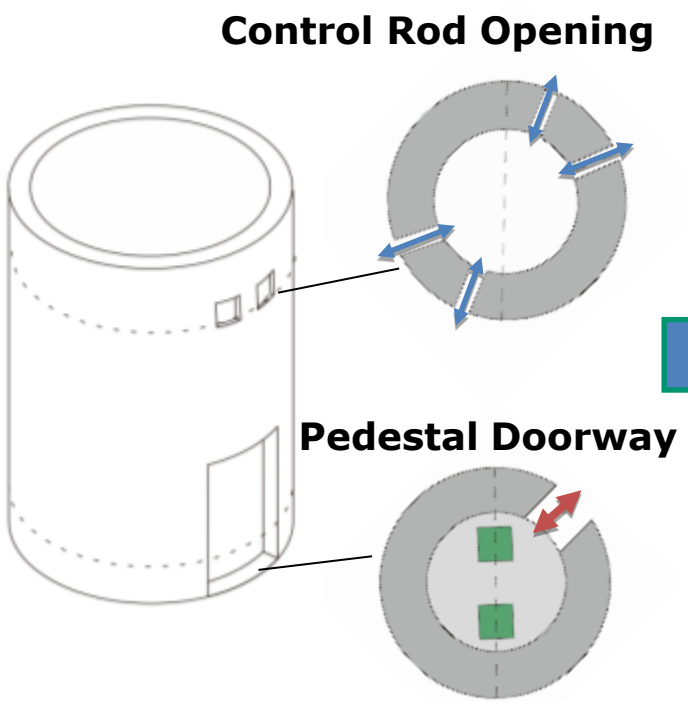
Investigation inside of PCV (Unit 2)

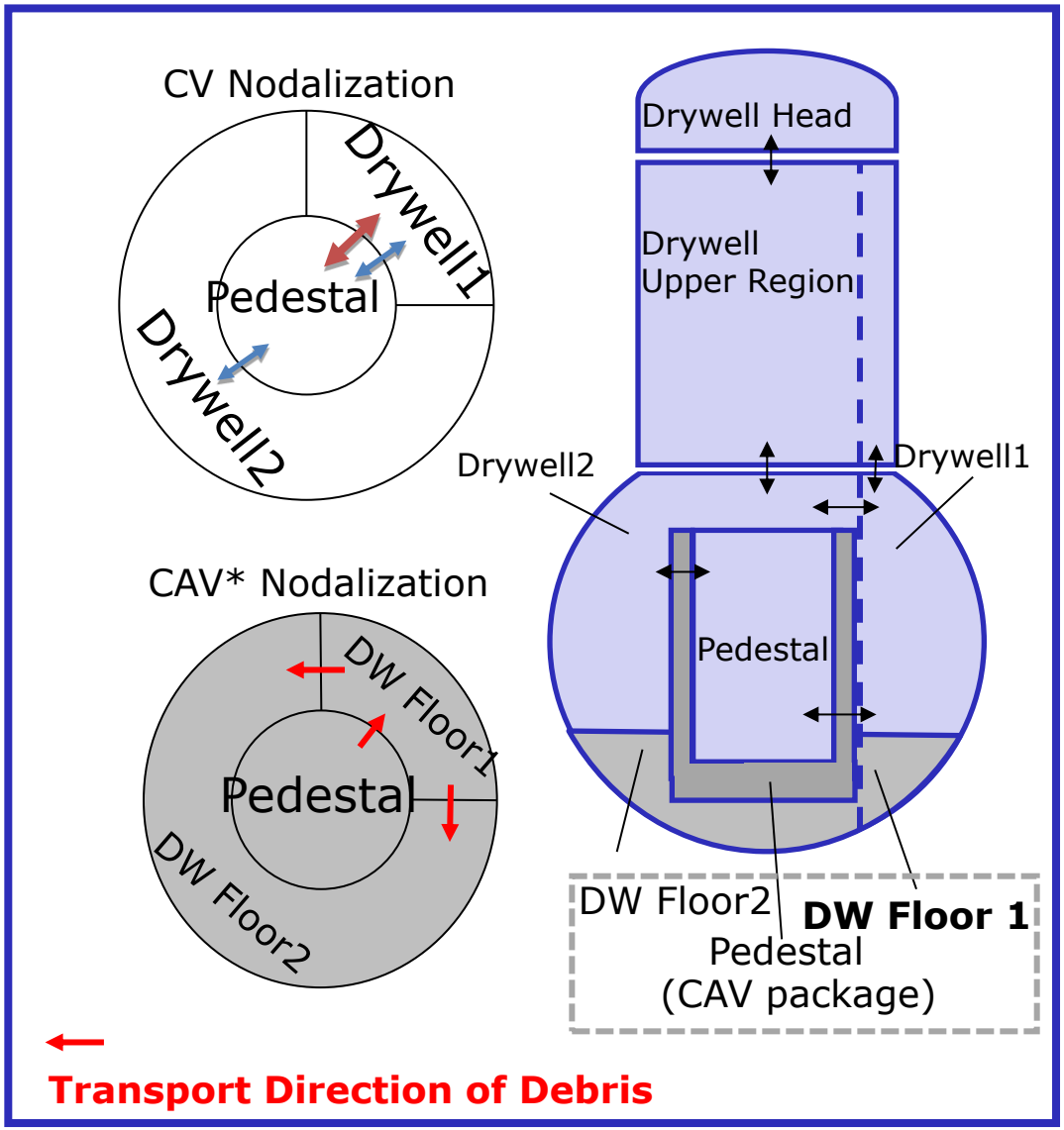


Ref.: TEPCO, "Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression Progress Report No. 2," Aug. 6, 2014

Nodalization to estimate melt spread

MELCOR nodalization is modified to estimate melt spread and MCCI





Control Rod Opening

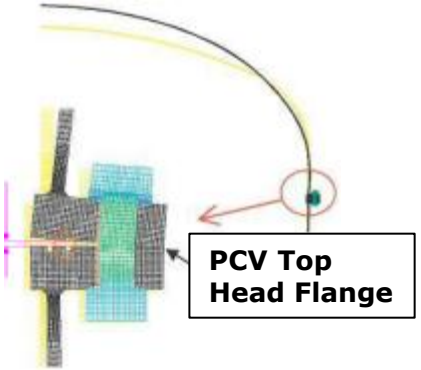
Pedestal Doorway

3. Estimation of Source Terms

- **Source terms suggest core degradation & PCV leakage**
- **Isotope ratio is finger print of radionuclide source & leak paths**

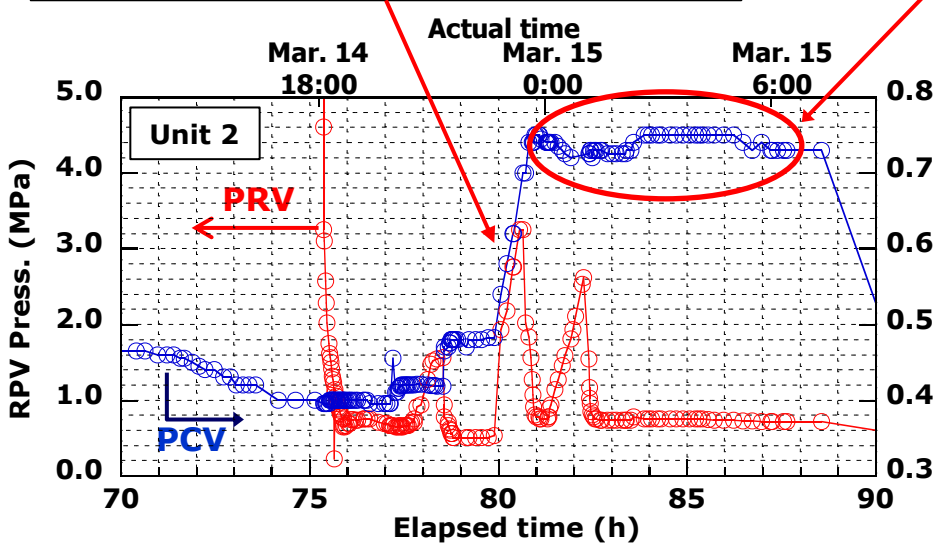
Possible Release from Unit 2

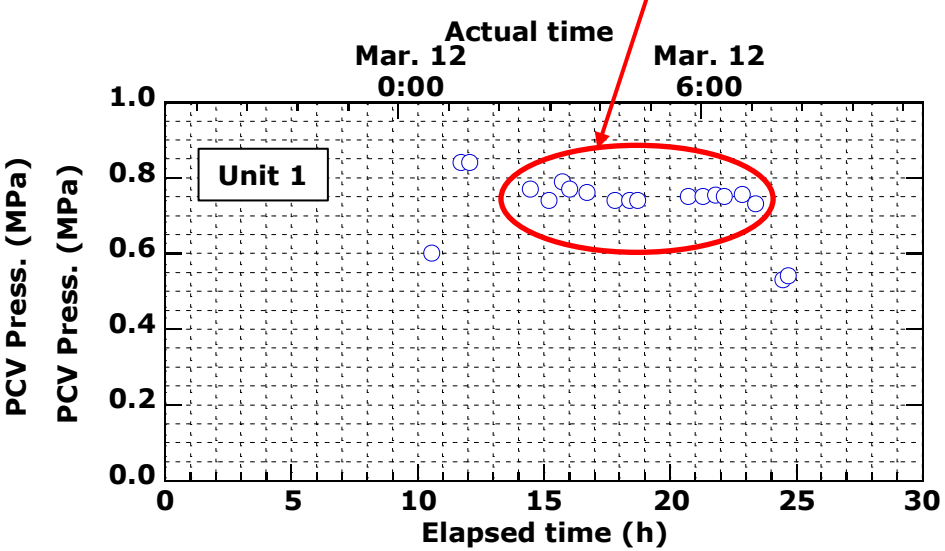
- **FP release, which corresponds to pressure peak of Unit2, was measured***
- **Aerosol, discharged from RPV to D/W, was released to the environment without pool scrubbing**



FP Release corresponds to RPV pressure peak*

Steam/H_2 generation ≈ Leakage





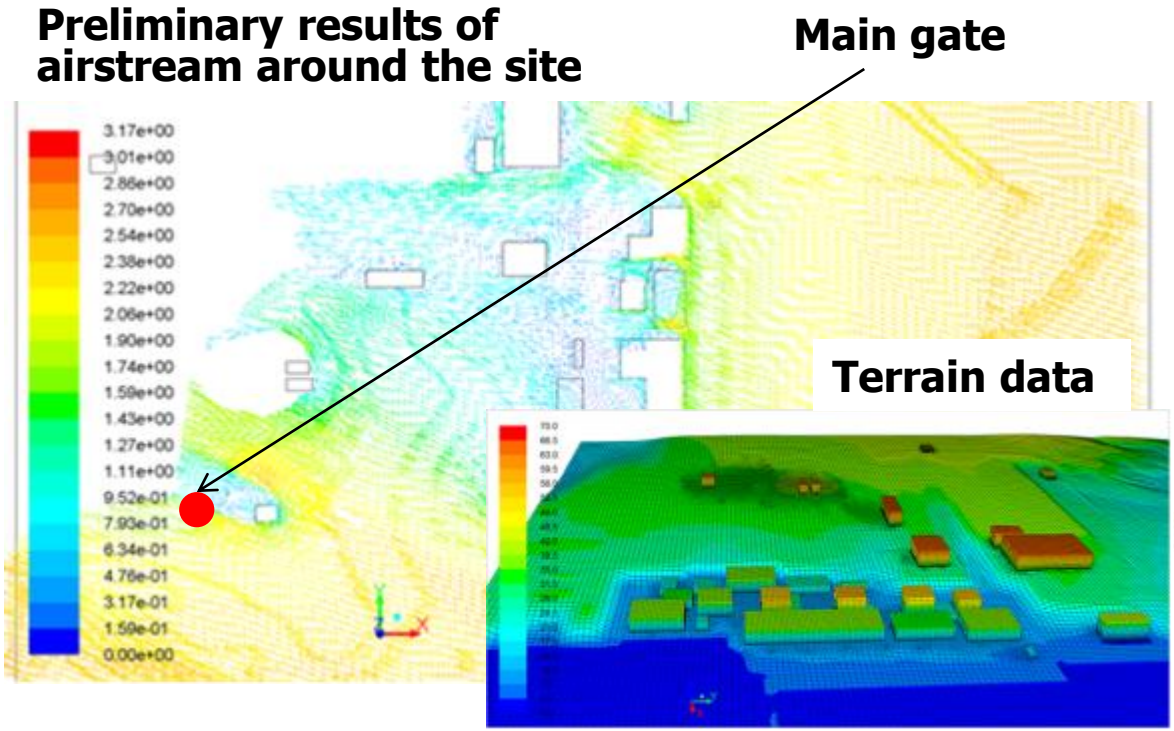
*G. Katata, et al., "Detailed source term estimation of the atmospheric release for the Fukushima Daiichi Nuclear Power Station accident by coupling simulations of atmospheric dispersion model with improved deposition scheme and oceanic dispersion model," Atmos. Chem. Phys. Discuss., 14, 14725–14832, 2014

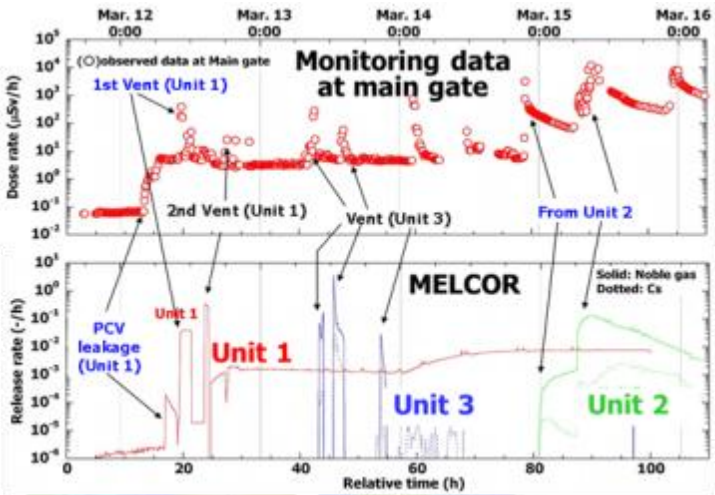
New Development for Source Terms

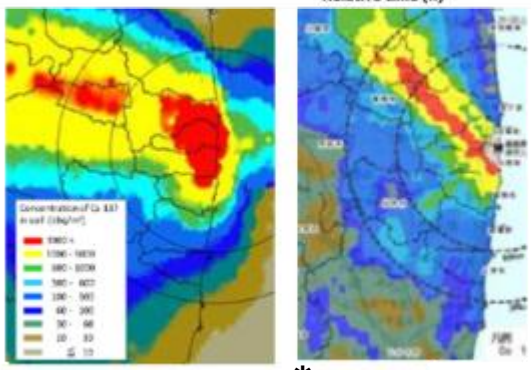
New development:

- In order to compare the **source terms** obtained by **MELCOR** with the **monitoring data** at the **main gate**, CFD calculations are being done for **airstream around the site** by using the terrain data and GPV meteorological data (140km x 140 km).

Preliminary results of airstream around the site

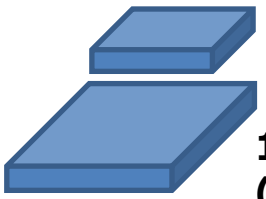






MELCOR – OSCAAR analysis *

CFD resolution

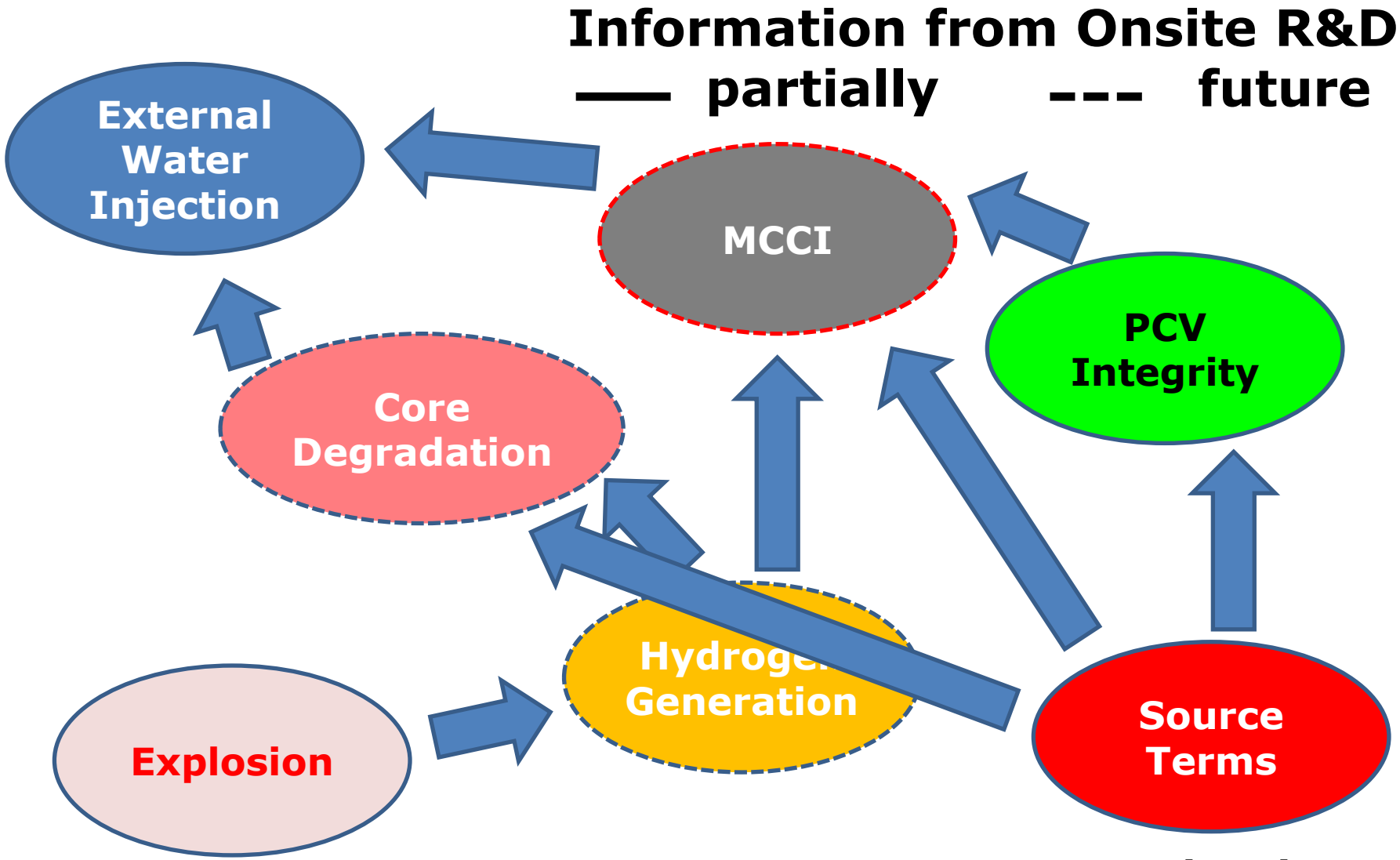


5 m x 5 m x 1 m (by the bldg.)

10 m x 10 m x 1 m (other region)

*H. Hoshi, et al., "Severe Accident Analyses of Fukushima-Daiichi Units 1 to 3," Side Event "Updated activities about TEPCO's Fukushima Dai-ichi NPS accident" At Fukushima Ministerial Conference on Nuclear Safety, Dec. 16, 2012

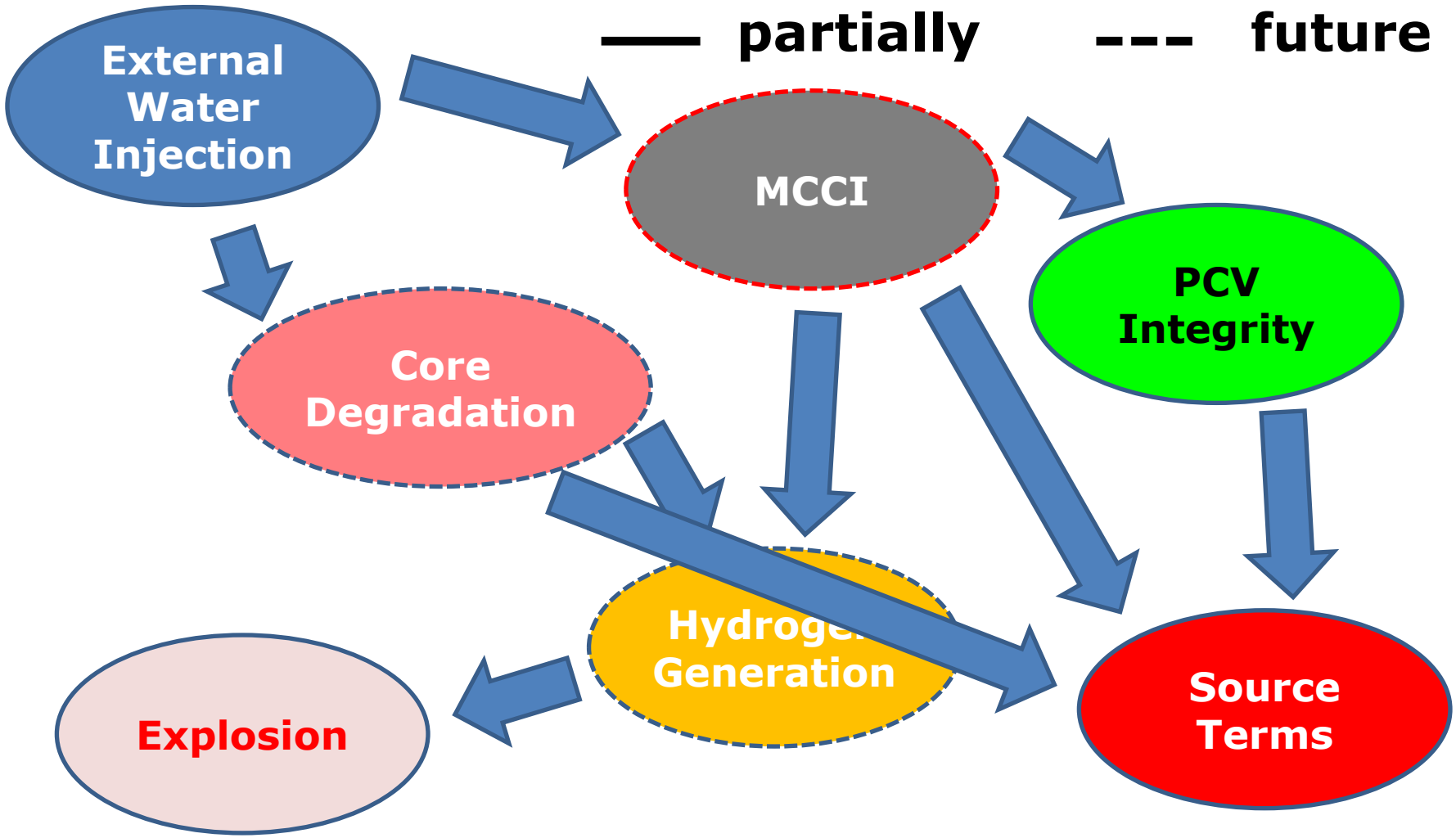
4. Further Investigation



4. Further Investigation

Information from Onsite R&D

—— partially --- future



Reduce uncertainties of forward estimation

5. Conclusion

- In the light of Fukushima Dai-ichi NPP accident, the NRA developed the new design requirements and established the new regulatory framework to ensure the safety of NPPs and other nuclear facilities.
- NRA launched new investigation committee for Fukushima Daiichi accident.
- NRA examined R/B to investigate impact of tsunami, hydrogen explosion, etc.
- Various analyses are in progress to estimate core status, PCV integrity, source terms, etc.
- TEPCO continues investigation with decommissioning
- Further investigation is still needed. However, multiple approaches are applied to reduce uncertainty.

Thank you for your kind attention